Sustainable Waste Management in Small Island Communities: the Case Study of Kinmen, Taiwan

Hsin-Tien Lin

Abstract

Waste management is often connected to the energy issues either directly by waste-to-energy technologies, or indirectly by resource recovery processes. Sustainable waste management can contribute to energy generation and energy conservation by different practices such as incineration or recycling. However, modern sustainable waste treatment practices are usually not feasible for small island communities due to the geographical and economical limitation of the small islands. Many literature described the difficulties and situations faced by the small islands in waste management issues, including illegal dumping, lack of recycling facilities, high operation fee, and fairness issue. However, only few have proposed strategies to improve the system or discussed the outsourcing situation of the waste management system in small islands.

This study evaluated the waste management system for small island communities by the case study of Kinmen, Taiwan. Three types of waste generated from the households were analyzed, including municipal solid waste, end-of-life vehicles, and waste electronic home appliances. The different treatment situations and requirements were clarified and the treatment strategies which can improve the systems are analyzed for each type of waste.

First, a waste shipments for energy recovery as a waste treatment strategy for small islands is evaluated for the treatment of municipal solid waste. The economic and environmental feasibility of the waste shipments system for energy recovery by refuse-derived fuels (RDF) are analyzed. The results revealed that transforming combustible waste into RDF provides opportunities for more shipment destination. Shipping distance, RDF gate fee/selling price, and greenhouse gases emission from RDF production are identified as the biggest factors affecting the cost and emission of the waste treatment system. The choice of RDF shipping destination with cost-effectiveness and reduced environmental impact can be evaluate by the methodology shown in this study. A generalized flowchart for analyzing the waste-to-energy strategies of small islands was developed for sustainable decision making for waste management in small islands.

Second, this thesis presents the investigation of the material flows and economic analysis on the end-of-life vehicles (ELVs) in small islands. The ELVs generation amount was estimated using the population balance model (PBM) and the results showed a steep increase in the future for both automobiles and motorcycles. The insufficient ELV treatment capacity has resulted to a significant informal treatment flow with a potential economic gain of 16.9 million TWD in 2050 from 1906 tons of items with market value. The results of the economic characterization of the local dismantling business clarified that profitability is the main hindrance for the development of new dismantling business due to high transportation costs. The results suggested that implementation of a different subsidy rate according to the treatment area under the current policy or creation of a new treatment flow with a direct shipment of ELVs for treatment is necessary to improve the utilization of the stocked materials from untreated ELVs.

Third, an optimum treatment for waste electronic home appliance in remote area by local pre-processing and outsourcing post-processing was analyzed. The cost reduction potential of the proposed treatment system is analyzed for main four types of electronic home appliances by the case study of Kinmen, Taiwan. Implementation of local pre-processing in Kinmen, Taiwan can provide 42, 54, 32, and 41 TWD unit cost reduction for television, washing machine, refrigerator, and air conditioner, respectively, compared to the current treatment system. The different treatment characteristics according to the type of the appliances is the major factor for the applicability and cost reduction potential of the local pre-processing system. The application of this system to other cases was presented by sensitivity analysis using relative labor cost and transportation distance as the parameters. The results and the analysis process can be applied to domestic systems in regions without recycling facilities, and international systems where one country is exporting the products to another country without proper recycling facilities and applying the extended producer responsibility to take back the products for recycling.

Last, the sustainability of the waste management strategies for small island communities was evaluated in this study from the economic, environmental, and social aspects. The limitations of local treatment and direct shipment are reviewed and presented. The environmental and social aspects of local pre-treatment strategy were discussed. Results showed that the local pre-treatment strategy provides more environmental benefits than direct shipment. Although the social acceptability remains problematic, the social equality and social function can be improved to support the system. Considering the environmental and social impact, the local pre-treatment system for small island waste management is suggested to be promoted and implemented.

In conclusion, it is difficult for the waste management system in small islands to be independent due to the geographical and economical limitations. However, different practices have been suggested in this thesis in order to solve the island waste management issues and contributed to economic and environmental benefit. Different outsourcing strategies and requirements for the economic and environmental feasibility is clarified in this thesis. The results of this thesis can provide insights for the small island municipalities searching for a sustainable waste management system to deal with the existing environmental issues. At the same time, the results are also useful for the researchers focusing on small island issues as a model for analyzing the environmental problems.

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Chapter 1 Introduction

1.1 Energy and waste management

Waste management and energy systems are often interlinked, either directly by waste-to-energy technologies, or indirectly as processes for recovery of resources[1]. In recent decades, waste management and energy supply are both under pressure due to economy and population growth[2]. The waste generation is increasing all over the world. World Bank reported that the global waste generation amount will increase to 2.2 billion tons per year by 2025[2]. Getting rid of the waste is becoming an important issue for sanitary and public, also for the environmental protection. At the same time, fossil fuels are currently the dominant energy supplying source in the society, but burning fossil fuels releases the carbon dioxide (CO_2) into the atmosphere. Humans have increased atmospheric CO_2 concentration by more than 40% since Industrial Revolution began, and the CO_2 has been the most important long-lived forcing of climate change[3]. Renewable energy is the energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat[4]. Shifting from using fossil fuels to renewable energy sources is essential for the sustainable development of modern society.

Waste management is an efficient method to both increase resource efficiency and replace fossil fuels with renewable energy[5]. Municipal solid waste (MSW) contains high fraction of organic compounds, including paper, food waste, wood and yard trimming, cotton, and leather, which are sources of biomass, and materials derived from fossil fuels plastics, rubber, fabrics are also found in MSW[6]. MSW has been seen as a renewable energy source by The U.S. Environmental Protection Agency if the MSW source stream is biogenic, or the non-renewable portion of MSW has been separated or accepted as part of the fuel[7]. Besides, extracting and processing raw resources to make usable materials consumes a lot of energy. Recycling can contribute to energy saving by replacing raw resources in manufacturing products[8].

1.1.1 Waste-to-energy

Waste-to-energy (WTE) or energy-from-waste (EfW) is the process of generating energy in the form of electricity and/or heat from the primary treatment of waste, or the processing of waste into a fuel source. WTE processes recover the energy from the waste through either direct combustion (e.g., incineration, pyrolysis, and gasification) or production of combustible fuels in the forms of methane, hydrogen, and other synthetic fuels (e.g., anaerobic digestion, mechanical biological treatment, and refuse-derived fuel)[6]. WTE has been seen as a key element for sustainable waste management[9]. There are also reports showing that the WTE technologies can contribute to environmental benefits. WTE facilities generate more than 14 billion kilowatt hours of renewable electricity annually from waste[10–13]. Every ton of MSW processed by WTE facilities reduces 1 ton- CO_2e of greenhouse gases (GHGs) emissions. U.S WTE facilities recover more than 730,000 tons of ferrous metals for recycling[10].

Combustion processes, or incineration, are the most commonly applied thermal treatments for different types of waste. Incineration with energy recovery is one of the WTE technologies treating waste with regard to sanitation and environmental protection, with the secondary objective to recover energy from the waste as possible. The schematic diagram of the incineration plant is shown in Figure 1.1. Incineration facilities are usually based on furnaces equipped with a boiler for energy recovery and a flue gas cleaning system to ensure that emission standards are met. Incineration has been used all over the world in total around 2,000 operating plants in the OECD countries[14]. Figure 1.2 shows the municipal waste disposal and recovery shares in OECD countries in 2011[14]. It appears that the percentage of MSW incinerated with energy recoveries in OECD countries varies significantly, ranging from 0 to more than 50%, averaging around 19%.

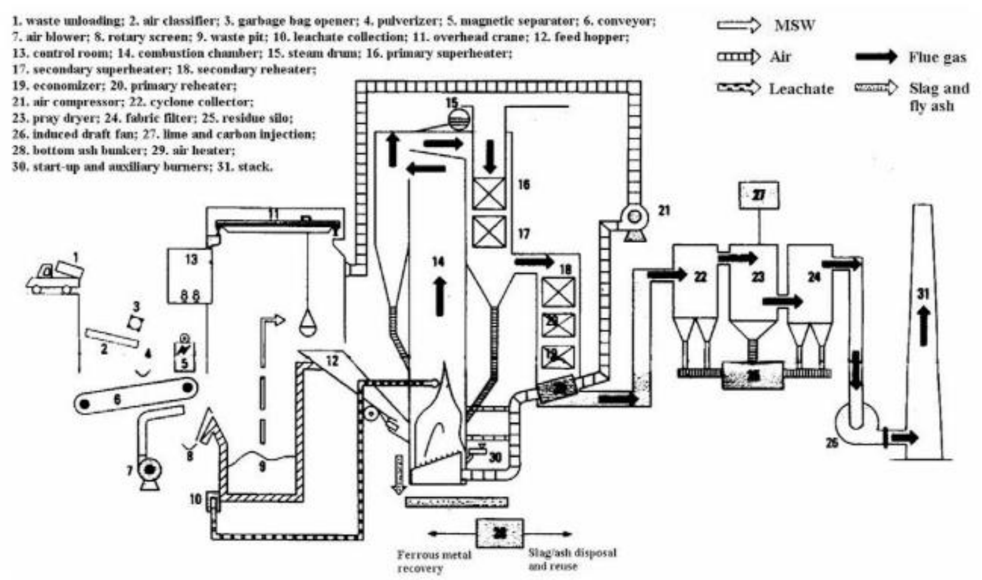


Figure 1.1 Schematic diagram of the incineration plant[6].

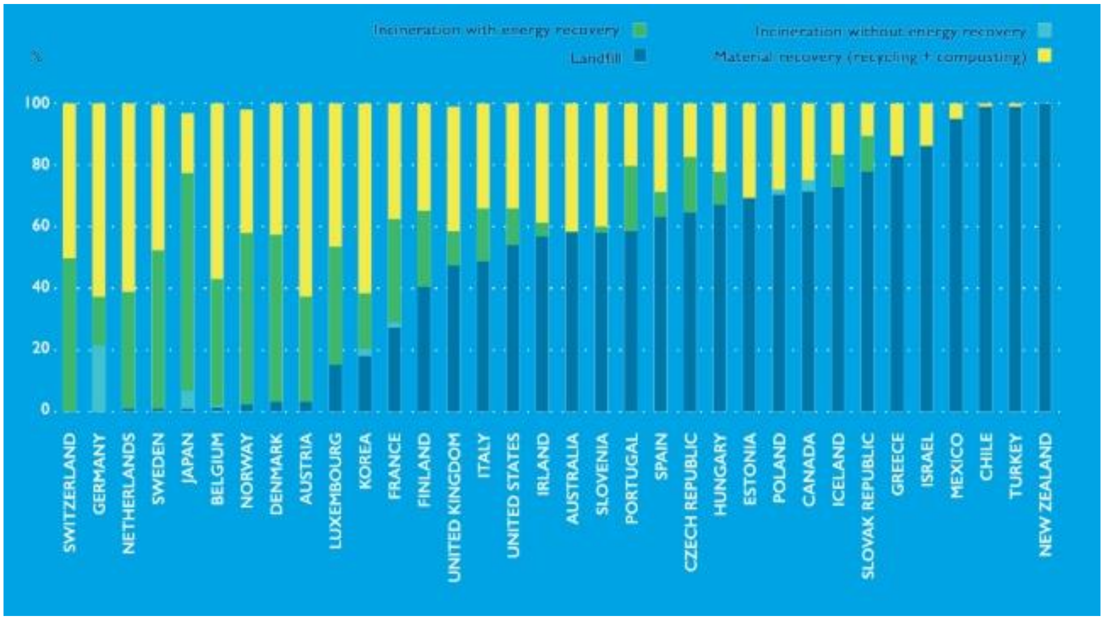


Figure 1.2 Municipal waste disposal and recovery shares in OECD countries in 2011[14]

Production of combustible fuels from waste feed is also seen as WTE technology. Anaerobic digestion (AD) of food waste for biogas production is a proven and effective solution for food waste treatment[15]. Food waste is traditionally incinerated with other combustible municipal waste for generation of heat or energy, but incineration of food waste can potentially cause air pollution and loss of chemical values of food waste[16]. Food waste has been used as the sole microbial feedstock for the development of various kinds of value-added bio-products, including methane, hydrogen, ethanol, enzymes, organic acid, biopolymers and bioplastics. The characteristics of food waste and the principles of AD are reviewed[15]. Mechanical biological treatment (MBT) system is a type of waste processing facility that combines a sorting facility with a form of biological treatment such as composting or anaerobic digestion. MBT technologies are developed in Europe for 15 years, and the MBT plants can produce a high quality solid recovered fuel (SRF)[17]. The performance of MBT has been reviewed in several researches[17–19]. MBT is crucial for the development of more sustainable MSW management systems in countries with high organic portions in the waste composition[19]. Refuse-derived fuel (RDF) is a fuel produced from waste materials by a series of mechanical processes to improve the physical and chemical characteristic of the input refuse materials[20]. RDF can be combusted in power plants, or be utilized in industrial processes for producing heat or steam[21]. Production of RDF has also been studied and applied in several countries as a WTE strategy[22–25].

WTE development in Europe has been reviewed[26]. This article pointed out that WTE is a key technology to promote circular economy because WTE has potential to enhance resource efficiency and improve energy efficiency. WTE technology is contributing to the EU member states to meet their targets in waste management, energy union, and environment. A survey in the US showed that 7.6% of the generation of MSW has been used as fuel in WTE power plants[27]. Their report also showed that WTE technology is more prevalent in the East Coast, with the highest region having 41% of MSW disposed by WTE. The current status and benefits of the operating WTE facilities in the US are also reviewed[28]. It is shown that WTE facilities serve about 30 million people in the US, and they contributed to reduced emissions, energy production, land savings, and material recovery.

In Asia, Korea and Japan intensively use state-to-art WTE facilities. There were 35 WTE facilities in operation in Korea in 2015, treating 3 million ton of waste per year[14]. A study on external benefit of WTE in Korea revealed that ratio of WTE consumption to primary energy consumption amounted to 1.89% in Korea. Korean Ministry of Environment (KMOE) has planned to expand the ratio of WTE to 5% by 2020[29]. To achieve this goal, KMOE has provided national subsidies for the establishment of WTE facilities. There were also WTE facilities in 19 regions under construction or in the planning stage[29]. In Japan, the high population density is a major influence on MSW management. The difficulty to locate landfills sites has made the MSW management in Japan emphasize on the reduction of MSW. Thus, incineration has become the predominant pretreatment practice[30]. Ministry of the Environment of Japan reported that 1,141 incinerators were in operation in 2015, with 348 facilities generated total 8,175 GWh of electricity yearly and 765 facilities utilized the heat from the incinerators [31]. The energy generation efficiency of the incinerators with energy recovery in Japan is in average 12.59%. The main strategy of MSW management in China is also changing from landfill to incineration due to current economic growth and massive urbanization. The waste incineration power industry is developing in China, with rapidly increasing of construction numbers of waste incineration power plants from 2005 to 2013[32]. Literature also revealed that the major challenges in WTE incineration in China are high capital and operational costs, equipment corrosion, air pollutant emissions, and fly ash disposal[6].

1.1.2 Energy conservation through recycling

The estimation of production energy conserved by recycling of the most commonly recycled materials has been reviewed in literatures[8, 33]. A number of energy saving potentials by recycling for different materials can be found for metals[34], papers, textiles[35, 36], plastics[37, 38], glasses[38], etc. For example, the effect of glass recycling on energy consumption is shown in Figure 1.3. This figure showed that increase of glass recycling rate can decrease the energy consumption. The recycled materials energy saving over virgin materials is also reviewed and their results are shown in Table 1.1[39]. For example, recycling of aluminum provides more than 90% energy saving[40], and recycling of iron and steel provides 74% of energy saving[41]. The publications comparing the global warming impact and total energy use of recycling versus incineration and landfilling were reviewed[42]. They revealed that producing materials from recycled resources is often, but not always, less energy intensive and causes less global warming impact than from virgin resources. It is also mentioned that for paper products, the savings of recycling are much smaller than other recycling of other materials.

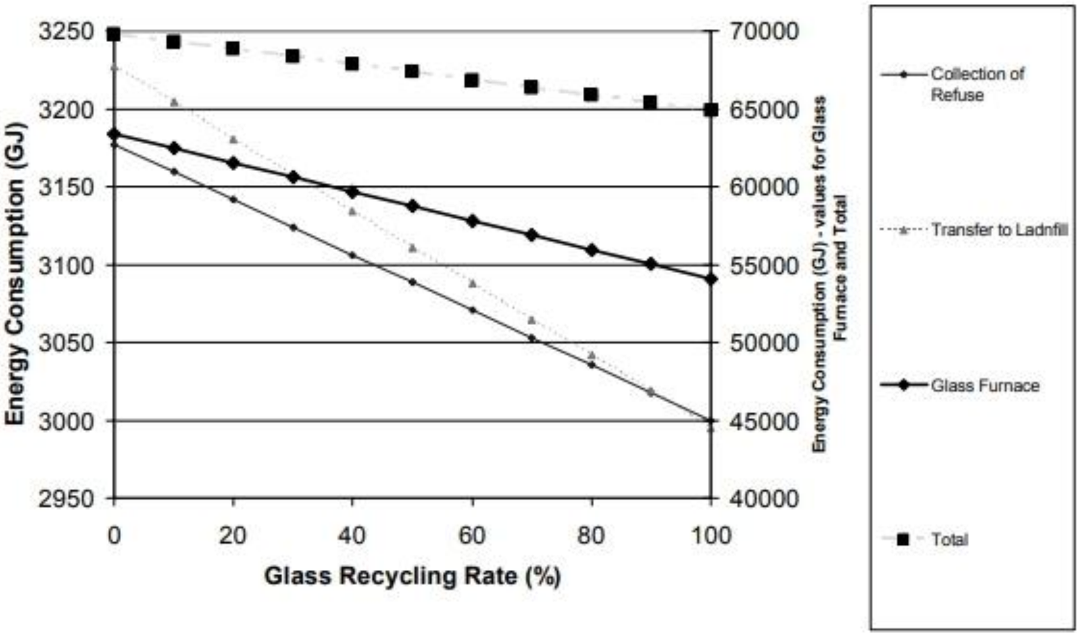


Figure 1.3 The effect of glass recycling on energy consumption (major components)[38]

Table 1.1 Recycled materials energy savings over virgin materials[39].

Materials	**Energy savings (%)**
Aluminum	95
Copper	85
Iron and steel	74
Lead	65
Zinc	60
Paper	64
Plastic	>80

Reuse or recycling in the industrial processes may also contribute to significant energy saving. For example, the Japanese building construction industry consumes about one third of all energy and resources of the entire industrial sectors. The comparison of energy consumption of new processing and recycling processing in the building construction industry in Japan is studied[43], and the results are shown in Figure 1.4. The results showed that energy consumption of building materials in all case-study housing can be saved by at least 10%, and the resource, measured by mass of building materials (kg) can be decreased by over 50%. Electronic waste is also increasing dramatically with the technological advancements and industrial development. Recycling of electronic waste can contribute to environmental pollution prevention and conservation of energy and resources. For example, the resource and energy saving by recycling of desktops and laptops are analyzed[44]. Recycling of desktop and laptop provides 80% and 87% resource saving respectively as shown in Figure 1.5.

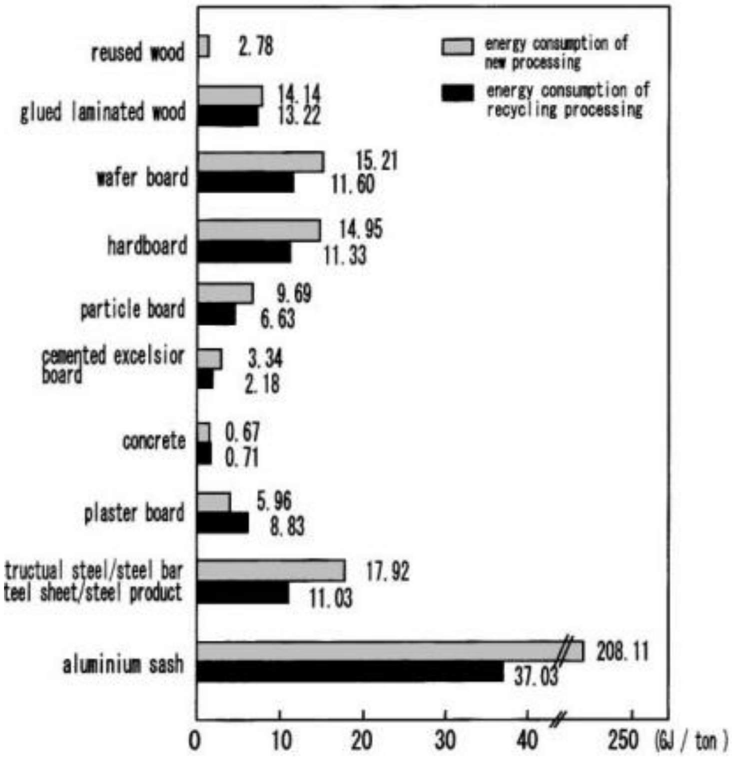


Figure 1.4 Energy consumption of new and recycling process in building construction industry[43].

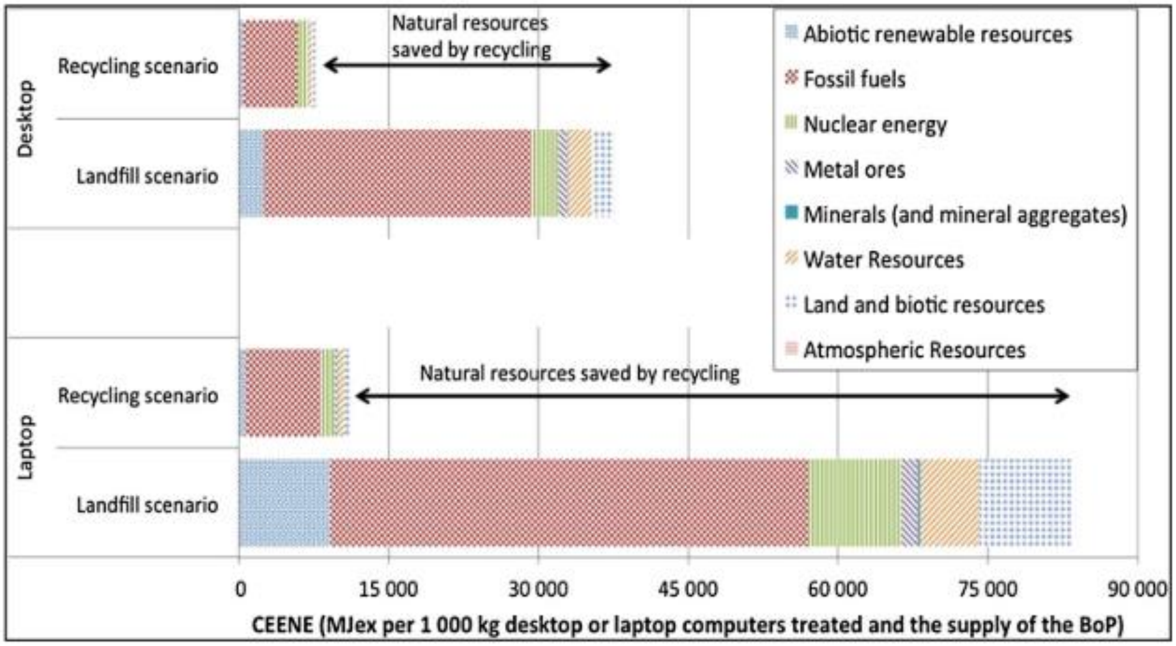


Figure 1.5 Resource and energy savings from recycling of desktops and laptops[44].

1.2 Sustainable waste management

Sustainability has become an important concept and has been applied to many aspects of the world after the “Brundtland Report of the World Commission on Environment and Development: Our Common Future” mentioned the keyword “sustainable development” in 1987[45]. In this report, the sustainability is defined as that “Sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” This also means that the society should have balance for the limited resources in the earth and the living of human. To achieve sustainable development, it is important to build the social system to make sure the resources and environment which is necessary for keeping the human’s basis living. For the usage of resources, Herman Daly suggests the following three operational rules defining the condition of ecological sustainability[46]:

1. Renewable resources such as fish, soil, and groundwater must be used no faster than the rate at which they regenerate
2. Nonrenewable resources such as minerals and fossil fuels must be used no faster than renewable substitutes for them can be put into place
3. Pollution and wastes must be emitted no faster than natural systems can absorb them, recycle them, or render them harmless

The Daly Rules for Sustainability also means that to build a sustainable society, human should not destroy the system balance of the earth environment, or to say, should not behave over the environmental capacity.

However, the modern human lifestyle is moving toward opposite direction of sustainability. Especially for developed countries, the economic activities and household livings both deeply rely on the high energy consumption. The fossil fuel as the main energy sources has contributed to the increasing CO_2 concentration in the atmosphere, which has caused global warming or other climate problems. Besides, the waste generated during the production activities and the everyday living are rising around the world, and it is approaching to the environmental capacity. In 2016, the world’s cities generated 2.01 billion tonnes of solid waste, amounting to a footprint of 0.74 kilograms per person per day[47]. Nevertheless, if the burden from the human activities is too big for the environment, it is going to have negative effects on the biodiversity. The result of this situation may also reduce the ecological services from the environment to human.

To achieve sustainable development, it is required for the corporation of the world. The “2030 Agenda” adopted in 2015 aimed to promote the sustainable development around the world by setting 17 global goal named “Sustainable Development Goals (SDGs).” The SDGs cover social and economic development issues including poverty, hunger, health, education, global warming, gender equality, water, sanitation, energy, urbanization, environment and social justice. Waste management affects various areas of sustainable development. The affected areas include living conditions, sanitation, public health, marine and terrestrial ecosystems, access to decent jobs, as well as the sustainable use of natural resources[48]. The relationship between SDGs and waste management mainly includes:

- SDG 3.2 End preventable deaths of children under 5 years
- SDG 3.3 End malaria and combat water-borne diseases
- SDG 3.9 Reduce illnesses from hazardous chemicals and air, water and soil pollution, and contamination
- SDG 6.3 Improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous materials
- SDG 7.2 Increase the share of renewable energy in the global energy mix
- SDG 8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead
- SDG 9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities
- SDG 11.1 Ensure access for all to adequate, safe, and affordable basic services; upgrading slums
- SDG 11.6 Reduce the adverse environmental impact of cities; special attention to waste management
- SDG 12.4 Environmentally sound management of chemicals and all wastes in order to minimize their adverse impacts on human health and the environment
- SDG 12.5 Reduce waste through prevention, reduction, recycling, and reuse 12.3 Halve global food waste and reduce food losses along production and supply chains

This SDG also contributes to SDG 2: Zero hunger—End hunger, achieve food security and improved nutrition, and promote sustainable agriculture

- SDG 13.B Promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing States, including focusing on women, youth and local and marginalized communities
- SDG 14.1 Prevent marine pollution of all kinds, in particular from land-based activities, including marine deb
- SDG 15.1 Ensure the conservation of terrestrial and inland freshwater ecosystems and their services

For many in the field, sustainability is defined through the following interconnected domains or pillars: environment, economic, and social. In the field of waste management, these three aspects of sustainability are also usually evaluated. Literature shows that most of the studies on waste management evaluated environmental and economic performances of the waste management systems or waste management strategies, while few of them considered the social aspects[49]. The environmental issues create the urgency to develop waste management system, while economic feasibility limits the implementation of the waste management facilities. This study evaluates the waste management system from these three aspects of sustainability. Among these three aspects, economic factor is the first concern because if a system is not economic feasible, it is not available and there will be no other discussions. After considering the economic feasibility, other factors such as environmental and social issues will be considered.

1.2.1 Development of waste management

Waste management represents all the activities and actions required to manage waste from its inception to its final disposal[50]. Waste hierarchy is a tool used in the evaluation of processes that protect the environment alongside resource and energy consumption to least favorable actions. The waste management hierarchy indicates an order of preference for action to reduce and manage waste, and is usually presented diagrammatically in the form of a pyramid[51]. The waste hierarchy is shown in Figure 1.6. On the top of the pyramid, it is the waste prevention, which is the most preferable option for waste management. Continuously, the lower parts are minimization, reuse, recycling, energy recovery, and disposal. The higher position in the waste hierarchy also means the higher potential to save energy and to reduce the GHG emission.

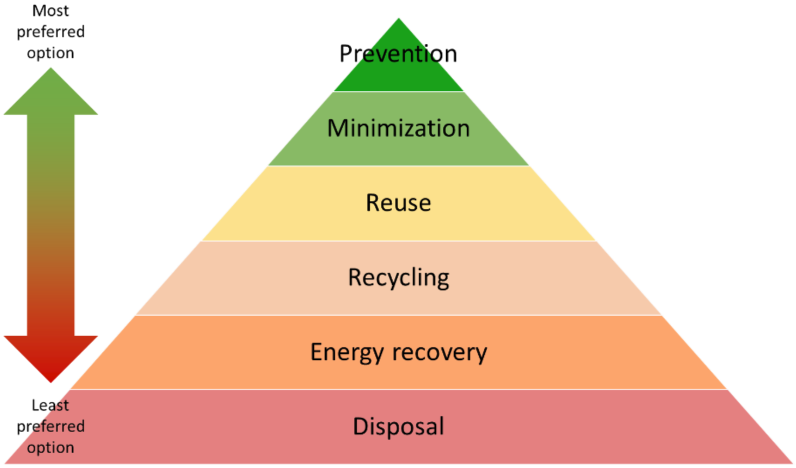


Figure 1.6 The waste hierarchy

Waste is not a major issue when the human population was small, but it will become a problem after population growth and urbanization. Today, the growing population living in urban areas has been causing local environment burdens accompanying with waste problem[52]. Poor waste management causes contamination of water, soil and atmosphere, further results in several impact to human health[53].

Different countries have adopted different strategies for the problem with waste. Most European countries introduced legal regulations regarding waste management in the 19th century[54]. At the same time, the scientific evidence revealed the relationship between overpopulation and hygienic problems. Waste management was recognized as a hygienic issue, and the purpose of waste management was to prevent the spread of diseases. In industrialized countries, the energy consumption and the material resources consumption per capita had a sharp increase during the decades after the end of the 2nd World War. The publication of the "The Limits to Growth" [55] in 1975 reported the limited economic and population growth with a finite supply of resources, and this concept had changed the focus of waste management from removal to waste prevention, minimization and recycling. New guidelines for waste management to manage the material flows were developed. In European countries, most of the waste management regulations came into force in the early eighties[56].

In the United States, the great economic growth happened during the 20th century. Much of the growth was with advances in manufacturing and chemical applications, which also had generated huge volume of waste with toxicity. Furthermore, there is few controls or regulations with respect to the handling of toxic materials or the disposal of waste products. Several regulations were promulgated on the state and federal levels to ensure the safety of public health and the environment. The Resource Conservation and Recovery Act 4 (RCRA), enacted by the United States Congress, first in 1976 and then amended in 1984, provides a comprehensive framework for the proper management of hazardous and non-hazardous solid wastes in the United States[57].

Among Asian countries, Japan has relatively complete systems of waste management and environmental protection regulations due to longer development history. Japan has experienced rapid economic growth period from 1980s. As a result of an increase in consumption and expansion of production activities, the amount of waste continued to increase. For the purpose of coping with an increase in the amount of waste and promoting the proper management of hazardous waste, the Japanese government strived to raise the general level of waste management by supporting the construction of waste management facilities in areas across Japan. Due to the difficulty to obtain the agreement of residents regarding the construction of new landfills, there was a shortage of landfills especially in large cities. Incinerators have been widely applied in Japan.

Now Japan focuses on 3R measures, the Reduce, Reuse and Recycle of waste, aimed at establishment of a sound material-cycle society. Container and Packaging Recycling Law has been enforced since April 1997 by the Ministry of the Environment to reduce the waste of glass containers, PET bottles and paper cartons. Other supportive laws for material recycling are also working. After implementation of the law, the collection and recycling improved and Japan’s country profile in Waste Atlas shows that in 2012 Recycling Rate was 20.8%. By the promotion of recycling, the final waste disposal has reduced from 20 million tons to 4.6 million ton from 1978 to 2012.

Waste management is a challenging problem in developing countries due to the high cost for the treatment, especially in the cities with increasing population levels and rapid urbanization[58]. They are facing several key issues including lack of legislation and policies, inadequate storage, limited collection, lack of proper disposal, and insufficient knowledge of basic principles[59]. Many researches have been done to improve the waste management in developing countries[60–64], and most of these countries are trying to apply the more preferable waste management strategies in the waste hierarchy to deal with the increasing waste problems.

1.2.2 Categories of waste

The categorization of waste is different among countries due to different legalization and treatment methods. In this section, the categorization of waste in Taiwan is listed as an example. In Taiwan, the waste has been categorized into municipal waste, industrial waste, and radioactive waste, according the relevant policies. The categorization is shown in Figure 1.7. The municipal waste and the industrial waste are categorized by the generation source of the waste. The municipal waste is the waste generated by households and the non-business entities, while the industrial waste is the waste generated by industries. The municipal waste can be further categorized into municipal solid waste and others, while others including feces, animal cadaver, and other wastes may cause sanitary problems. The municipal solid waste is the waste generated by human, including general waste, recyclable waste, food waste and hazardous waste.

Industrial waste can be categorized into general industrial waste and hazardous industrial waste. Hazardous industrial waste is the waste which is toxic or hazardous, or in which the concentration or amount is sufficient to affect human health or cause environmental pollution. Other nontoxic waste generated by industries is general industrial waste. Radioactive waste is the waste that contains radioactive material. The storage and treatment of radioactive waste is presented and reviewed by the International Atomic Energy Agency (IAEA)[65].

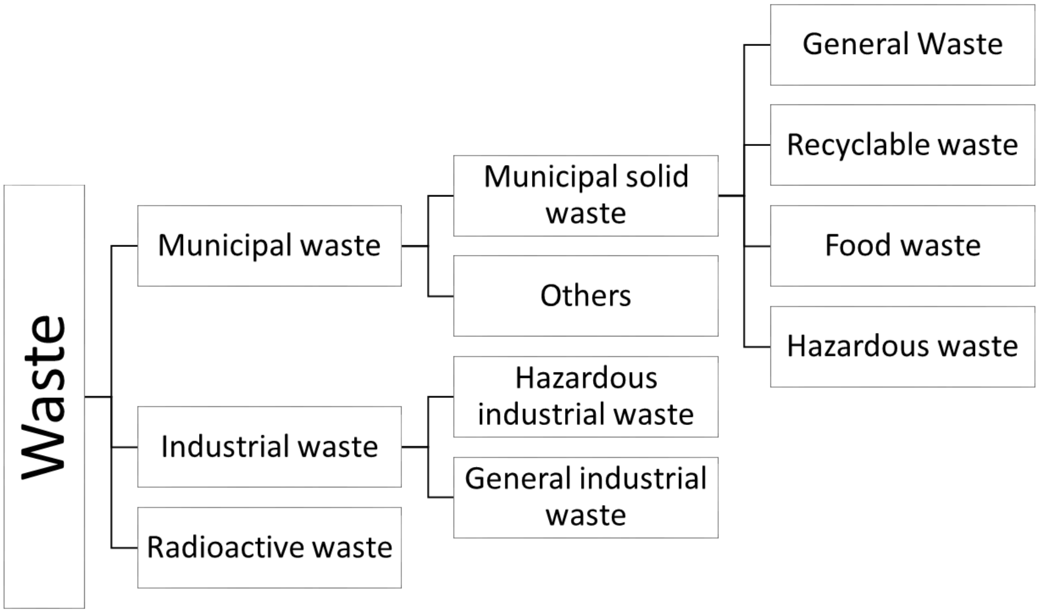


Figure 1.7 The categorization of waste in Taiwan

Different waste types require different treatment strategies, and especially industrial waste and radioactive waste require special cares due to their characteristics. Municipal solid waste has been an important study focus. General waste, which cannot be recycled after separation, is usually treated by landfill or incineration, while energy recovery of these two treatment strategies is possible under certain condition. Recyclable waste includes many categories, and the recycling items differ among countries due to regulations or market values of the materials. In Taiwan, recyclable waste includes paper, metals, plastics, glass, tires, clothes, home appliances, communication devices, batteries, lightings, and vehicles. Paper, metals, plastics, glass, tires, and clothes are materials which may be recovered as secondary resources. Home appliances, communication devices, batteries, lightings, and vehicles are devices with precious materials and also hazardous materials, which makes the recycling and management of these items an important issue. Food waste are usually treated by biological treatment and hazardous waste requires regulations for management.

1.2.3 Waste management strategies

In order to protect human health and the environment, environmental professionals must deal with problems associated with increased generation of waste materials. The solution must focus on both reducing the sources of wastes as well as the safe disposal of wastes. Waste management practices vary not only from country to country, but they also vary based on the type and composition of waste. Better choice of strategies and adoption of new waste management technologies can be applied for more sustainable management system. The brief introductions of the most common waste management strategies are presented in this section.

Waste prevention and minimization

Waste prevention is the ideal waste management alternative. Numerous technologies can be employed throughout the manufacturing, use, or post-use portions of product life cycles to eliminate waste. In many cases, waste cannot be outright eliminated, but some strategies can be implemented to reduce or minimize waste generation. Waste minimization refers to the collective strategies of design and fabrication of products or services that minimize the amount of generated waste. These two strategies may be considered the most sustainable solutions for waste management since it prevents the waste from generating. For industries, less waste means less raw materials becoming waste, which can reduce the cost of input materials and help industries save money. This may be preferable by industries. However, implement of the waste minimization design may need efforts and the modifying of the process at the first place. It will happen only at the case when some research has been done to prove the result of saving costs and when the technology is available. From the viewpoint of customers, it is the concept of "Reduce" in 3-Rs. Although the modern society is promoting mass consumption and the commercials are making people to shop more, reduction can also be realized by personal choice, or called, green consumption. For example, choosing products with less packaging, or longer life-time, may help minimize waste generated. Another possible way to reduce waste is using less single-use products. Single-use products have been invented to meet the need of people who pursue fast and convenient lifestyle. However, products which become waste after one use are not sustainable. Shopping with "my bag" instead of getting plastic or paper shopping has also become popular in many places.

Recycling

Recycling is defined as the process of changing waste materials into new products so as to not discard potentially useful materials, reduce the consumption of virgin raw materials, cut energy usage, decrease the need for traditional waste disposal (e.g., landfills and incineration) that could possibly incur negative impacts, and lower greenhouse gas emissions. Recycling refers to recovery of useful materials such as glass, paper, plastics, wood, and metals from the waste stream so they may be incorporated into the fabrication of new products. Recycling reduces the need of natural resource exploitation for raw materials, but it also allows waste materials to be recovered and utilized as valuable resource materials. Reuse and recycling are more accessible in industrials since used material in industries can be categorized simply. For the recycling of municipal solid waste, the categorization system is necessary. Government should enforce laws and regulations to encourage recycling and make the collection and processing of recyclables effective. The difficulty of recycling is that it is not possible to recycle 100% of waste materials. Even if all the recyclable materials are recycled in some percentage, after several life-cycles, there will still be huge material loss. On the other hand, the market of recycled materials also have impact on the recycling system.

Biological treatment

Biodegradation of wastes can be accomplished by using aerobic composting, or mechanical biological treatment (MBT) methods. If the organic fraction can be separated from waste material, aerobic composting or anaerobic digestion can be used to degrade the waste and convert it into usable compost. Compost material may be used in a variety of applications. In addition to its use as a soil amendment for plant cultivation, compost can be used remediate soils, groundwater, and stormwater. The anaerobic degradation process produces a combination of methane and carbon dioxide (biogas) and residuals (biosolids). Biogas can be used for heating and electricity production, while residuals can be used as fertilizers and soil amendments. Organic waste composting is a common treatment method to both developing and developed nations. The organic waste in the compost consisted mainly of leftovers, tea dregs, fruit peelings and yard trimmings. In rural areas or agricultural societies, compositing has been done at the household level. Good compositing practices minimize greenhouse gas emissions since it can keep methane generating organics out of landfills or lagoons However, composting can be labor-intensive, and the quality of the compost is heavily dependent on proper control of the composting process. Inadequate control of the operating conditions can result in compost that is unsuitable compost for beneficial applications. Some places with higher labor costs may not implement compositing into waste management system.

Incineration

Waste can be directly incinerated to produce energy. Incineration consists of waste combustion at very high temperatures to produce electrical energy. The byproduct of incineration is ash, which requires proper characterization prior to disposal, or in some cases, beneficial re-use. It is widely used in developed countries due to landfill space limitations. Despite all these advantages, incineration is often viewed negatively because of the resulting air emissions, the creation of daughter chemical compounds, and production of ash, which is commonly toxic. Many developed countries has applied incineration to conserve land and reduce the demand for landfill space. Incineration, sometimes called “thermal recovery” are considered to be another way of recycling the energy content in the waste. On the other hand, incineration facilities are expensive to build, operate, and maintain, which may not be affordable for some countries. The high cost and the difficulty of maintenance may encourage governments to seek other alternatives. Also, poor operation and pollution control may release smoke and ash into the environment and cause some human health effects and ecological problems. Some critics of incineration claim that incineration ultimately encourages more waste production because incinerators require large volumes of waste to keep the fires burning, and local authorities may opt for incineration over recycling and waste reduction programs.

Landfill

Landfills are engineered structures consisting of bottom and side liner systems, leachate collection and removal systems, final cover systems, gas collection and removal systems, and groundwater monitoring systems. New regulations concerning proper waste disposal and the use of innovative liner systems to minimize the potential of groundwater contamination from leachate infiltration and migration have resulted in a substantial increase in the costs of landfill disposal. Landfill may be the most convenient method for waste treatment, and some of the landfill sites developed techniques to utilize the gases given out by the waste to generate energy. However, the structures should be carefully designed to keep trash isolated from rest of the environment. Leachates happen when rain water falls on the landfills and penetrates into the deep level and the harmful toxins inside wastes can flow off and cause a very serious problem to deal with.

1.2.4 Small island waste management issues

The development of the sustainable waste management system or strategy requires investment on technology. The waste management development situation differs a lot between countries and regions. The ideal waste management option is also different according to economic, environmental, and social characteristic. Small islands usually suffer from limited physical and financial capacities speaking of waste disposal issues, especially considering the thriving tourism industry in recent decades. The common difficulties that the islands waste management is facing are limited land resources, lack of capital options, high operational cost, diseconomies of scale, no market for recycling and large seasonal fluctuations in waste volumes[66]. The physical barrier restricts the ability of islands to outsource of the waste management problems.

Lack of available land for waste disposal is one of the barriers to waste management in small islands. Landfill is usually the most feasible option for developing countries with limited capital for waste treatment, but it is sometimes not feasible for small islands due to limited land area. The proximity of existing residence or tourist facilities to suitable landfilling site also makes choosing prospective sites difficult for densely populated islands[66]. It is also difficult for local governments to secure financing for large waste management facilities such as incineration plants. This also resulted in higher operational costs and tipping fees for waste treatment in small islands. The size of island constrains the amount of available secondary materials, and the high shipping cost to the recycling market is also another potential economic barrier for recycling practices on islands[66]. On the other hand, in small islands, the goods are usually imported, and the resources accumulate easily inside without proper treatment.

All the aforementioned characteristics make the island waste management issue challenging. Sustainable waste management systems or strategies are necessary for the sustainable development of the island states under the waste generation pressure and the related environment problems. The environment and economic assessment of feasible waste management options for the small island cases is the tool for evaluating the feasible option under boundaries. Islands can be seen as model systems to conduct research due to their geographic boundaries that match with the political and accounting systems. For these reasons, the focus of this study is the waste management problems in small islands. The literature survey on waste management assessment methods and small island waste management practices is presented in the following sections.

1.3 Literature survey

1.3.1 Waste management assessment methods

Assessment tools are essential to understand and to measure the environmental sustainability. Numerous of assessment methods and tools for environmental and sustainability performance have been developed over the last decades. Environmental and economical assessment tools support the decision of suitable waste management strategy for a specific region. Many assessment tools have been applied in the research of waste management. Allesch and Brunner [49] reviewed the assessment methods used for solid waste management. They reviewed 151 studies and showed that most studies of waste management are based on life cycle assessments, multi-criteria-decision-making, cost-benefit analysis, risk assessments, and benchmarking. Figure 1.8 shows the percentage distribution of the assessment methods used in the reviewed articles. Life cycle assessment (LCA) is the commonly used method for waste management. LCA addresses the environmental aspects and potential environmental impacts[67]. Cost benefit analysis (CBA) was used by 6% of the reviewed articles. CBA defines benefits as increases in human wellbeing and costs as reductions in human wellbeing, and the costs and benefits are converted to monetary units[68]. Benchmarking is a continual comparison of products, services, methods, or processes to identify performance gaps, with the goals to learn from the best and to not out possible improvements[69]. Multi-criteria-decision-making (MCDM) is a decision-making tool that facilitates choosing the best alternative among several alternatives[70].

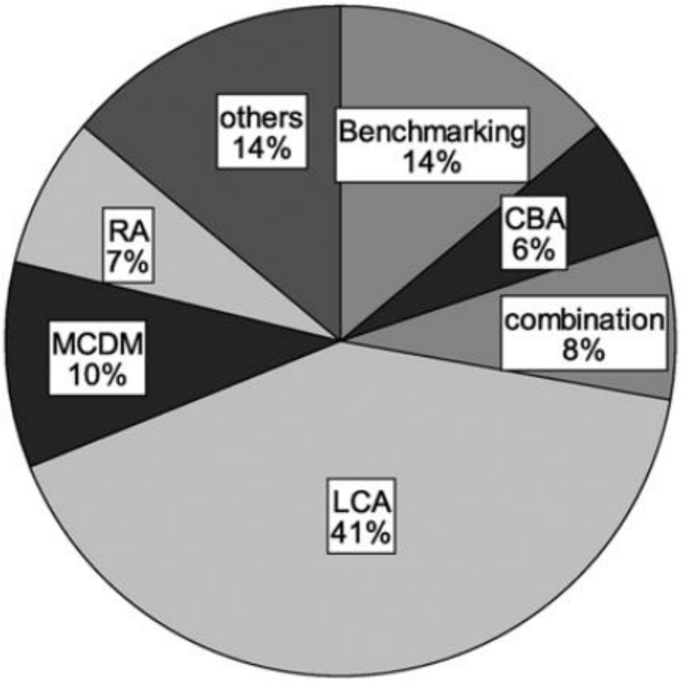


Figure 1.8 Assessment methods in the studies reviewed by Allesch and Brunner[49]. *CBA: cost-benefit analysis; LCA: life cycle assessment; MCDM: multi-criteria-decision-making; RA: risk assessment.*

1.3.2 Waste management in small islands

28 peer-reviewed journal papers about waste management on islands have been reviewed and the used methodologies and main results are categorized in this chapter. In these 28 papers, there are 3 review papers, 9 papers about current status survey, while 3 papers conducted cost evaluation, 2 papers used Life Cycle Assessment (LCA), 2 papers used Material Flow Analysis (MFA), 6 papers developed models or indicators, and 3 papers focused on others including technical report, policy study and other methods. The papers are listed in Table 1.2.

Mohee et al.[63] reviewed the current status of waste management in Small Island Developing States (SIDS) and the challenges that are faced in solid waste management. The waste generation rates of SIDS were compared within the three geographic regions namely Caribbean SIDS, Pacific SIDS and Atlantic, Indian Ocean, Mediterranean and South China (AIMS) SIDS and with countries of the Organization for Economic Co-Operation and Development (OECD). Eckelman et al.[66] discussed the waste management literature on islands to date, and present common advantages and disadvantages faced by island waste management challenges. There are nine papers conducted current survey. The target islands include islands in Greece[71, 72], Thailand[73, 74], Malaysia[60], Japan[75], USA[76], and island countries like Singapore[77] and Mauritius[78]. There are 3 papers focusing on cost evaluation. The cost required for food waste recycling[79], comparison of waste landfill versus waste treatment in a WTE facility[80], and comparison of different alternatives[81] are done in these works.

Life cycle assessment (LCA) has been applied extensively to waste management decisions and, in concert with economic models mentioned above, can offer valuable information to local companies and authorities about choosing management and technology options that are appropriate to island contexts. Kuo and Chen[82] studied the environmental loads from tourism in Penghu, Taiwan, including waste generation and management by LCA, and Fallah et al[83] applied LCA to evaluate the environmental performance of the waste management of Lavan island, Iran, for different scenarios.

Most small islands are highly import dependent. Most waste materials on these islands are originally produced somewhere else. We can use material flow analysis (MFA) to find out where these goods come from. MFA was applied to waste collected from Kayangel Island, Palau[84], to provide a characterization and spatial accounting of the inflow materials that become solid waste. In another study, MFA was performed using tire import, vehicle registration records, and projected per capita income to determine the expected accumulation of waste tires in Dominica[85]. Krausmann et al[86] studied the resource use in small island states by material flows in Iceland and Trinidad and Tobago, where have been high-income island economies with specific resource-use pattern. Chertow and Eckelman [87] presented the material flow on the Island of Hawaii for long-term waste management planning, and their results showed that 76% of material input in from imports, and 71% of material input came to additions to stock. Other analysis method such as analytic hierarchy process (AHP)[88], worth benefit utility analysis (WBU)[89], GIS modelling[90], and developed models[91]-[92] have also been applied to the waste management studies of islands.

Table 1.2 The summary of literature survey on small island waste management

Island(s) studied	Method/ Type of article	Year	Reference
SIDS	Review paper	2015	[63]
20 cases	Review paper	2014	[66]
Not identified	Review paper	2006	[93]
Greece islands	Current states survey	2003	[71]
Crete, Greece	Current states survey	2006	[72]
Samui island, Thailand	Current states survey	2012	[73]
Pha-ngan island, Thailand	Current states survey	2015	[74]
Langkawi, Pangkor, Tioman and Labuan, Malaysia	Current states survey	2008	[60]
Teshima Island, Japan	Current states survey	2003	[75]
Big island of Hawaii, US	Current states survey	2013	[76]
Singapore	Current states survey	1997	[77]
Mauritius	Current states survey	2011	[78]
Exuma, Bahamas	Cost evaluation	2014	[79]
Puerto Rico, US	Cost evaluation	2005	[80]
Green Island, Taiwan	Cost evaluation	2005	[81]
Penghu Island, Taiwan	Life cycle assessment (LCA)	2009	[82]
Lavan Island, Iran	Life cycle assessment (LCA)	2013	[83]

Kayangel Island, Palau	Materials Flow Analysis (MFA)	2011	[84]
Dominica	Materials Flow Analysis (MFA)	2011	[85]
Langkawi Island, Malaysia	Model construction	2011	[92]
Corfu, Greece	Worth benefit utility analysis (WBU) + life cycle analysis (LCA) model	2011	[89]
Santiago, Cape Verde	3D-GIS modelling	2009	[90]
Menorca Island, Spain	Dynamic regressions models	2013	[91]
Organisation of Eastern Caribbean States (OECS)	Public participation model	2006	[94]
Tortola, British Virgin Islands	Indicator	2006	[95]
US Virgin Islands	Technical report	2011	[96]
Lesvos island, Greece	GIS- based spatial analysis + Analytic Hierarchy Process (AHP)	2003	[88]
Mauritius	Direct weighing and physical testing method	2002	[97]

From the review of the initial literature, it is possible to identify that there is a lack of research of:

- Feasibility and limitation of treatment technology,
- Dependency on other economy for recovery practices,
- Investigation of specific waste types such as end-of-life vehicles and electronic waste,
- Sustainability evaluation of the waste management system.

In view of the limitations in previous works, this study aims to propose a sustainable waste management strategy to improve the cost effectiveness and sustainability performances of waste management systems in small island communities.

1.3.3 Small island characteristics

Islands are defined by the geographical characteristics, but other characteristics may differ greatly. Islands usually have great social-economic diversity, and this diversity makes the research results of one case difficult to be applied to another case. In this study, it is impossible to consider a system that is able to apply to all island cases. However, a group of islands feature similar characteristics is set as the study focus.

The special disadvantages faced by small islands are mainly due to small size, insularity, remoteness and proneness to natural disasters[98]. These common characteristics are also strongly related to waste management issues. The difficulties in small island waste management related to these characteristics are listed in section 1.2.4 and 1.3.2. Other than these general characteristics, other special characteristics also have effects on waste management issues. This study aims to propose a sustainable waste management system for small islands which are:

1. insufficient in scale to possess waste treatment facilities
2. remote and long distance transportation causing the high operational costs
3. tourist attractive with high tourists numbers
4. regulated by environmental policies in waste treatment issues
5. available financially to operate waste management system
6. dependent on mainland or bigger economy for waste treatment

The reason for choosing these characteristics is that we identify the economic factors caused by small scale and the remoteness are the main challenges causing the problems in waste management. Tourism is also causing high waste generation and seasonal fluctuation in waste generation amount, which cause difficulties in waste management planning. On the other hand, environmental policies are necessary to create incentives of constructing waste management system. The operation of waste management also requires financial affordability. These two characteristics ensure the feasibility of the implementation of the proposed system. Finally, we identify that it is impossible for a small island to treat all the waste materials on its own. The cooperation or assistance of other economy is necessary for the more sustainable treatment. This study targets on islands connected or dependent on mainland or bigger economy for treatment.

There are many islands in the group of islands of our study focus, which are mainly the outlying islands of developed countries, such as European countries, Japan, and Taiwan. These countries have relative longer developed waste management systems and available financial ability to operate the waste treatment systems. However, the common waste management difficulties and problems are also faced by these places. Among the cases, the case of Kinmen, Taiwan is chosen as the case study. The reason for choosing is that this study focuses on the dependency of the local system on other systems, while Taiwan has operated a special policy focusing on the waste transfer for its island territories. On the other hand, Kinmen has available data for analysis. The current development target of Kinmen is also sustainable development with better material circularity. These characteristics make Kinmen an ideal case study focus. The details of the waste management situation in Kinmen and in Taiwan will be introduced in section 2.2.

1.4 Study objectives

By the literature review, it is shown that many assessment methods are used for the evaluation of waste management systems and scenarios. However, for the studies of small island waste management, the focuses are mostly one current situation. There is a lack of research of the evaluation of the situation where the island waste management system is outsourcing and heavily dependent on other economies. It is required to evaluate the current situation of the waste management system in small islands in Taiwan and provide insights for the future development system.

This study aims to propose a sustainable waste management system for small islands by the combination of local and outsourcing treatment. Environmental and economic assessment tools are applied to show the performance of the proposed strategies. Three main types of waste generated from the households are studied, including municipal solid waste, end-of-life vehicles, and waste electronic home appliances. Different treatment systems for different types of waste are proposed and their environmental and economic benefits are revealed. Overall comparison and discussion on these three types of waste are also presented for their characteristics under the geographical limitations of small island cases.

1.5 Thesis structure

The overall structure of this thesis is as follows:

The significance and objective of this study were described in Chapter 1. Chapter 2 describes the methodology of the sustainability assessment tools, basic information of the focus of the case study, and the data preparation. Chapter 3 analyzes the treatment of municipal solid waste treatment by waste shipment from environmental and economic aspects. Chapter 4 quantifies the future material flows and material stocks in the end-of-life vehicle treatment process and evaluates the economic characterization for the future planning of the end-of-life vehicle treating system. Chapter 5 proposes a waste electronic home appliance treatment process by local pre-processing and outsourcing post-processing for the regions without recycling facilities including small islands. Chapter 6 evaluates the sustainability of the proposed waste treatment strategies. The discussion includes the limitation of the local treatment and the direct shipment. The discussion on environmental and social aspects is also presented Chapter 7 presents a summary of this study, limitation, and its recommendations for future research.

Chapter 2 Methodology and materials

2.1 Sustainability assessment tools

Sustainability includes three aspects: environmental, economic, and social. Many tools are developed to assess the sustainability of a process or system from these three aspects. The sustainability assessment tools are applied in this study to analyze the environmental and economic performance of the waste management system. The details of the tools applied are described as followings.

2.1.1 Life cycle assessment (LCA)

Life cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. The specialty of LCA is the evaluation of the environmental impacts of a product or a service from the “Life cycle aspect”. LCA is a holistic, system analytic tool and is now an established and integral part of the environment management tools. LCA is distinguished from other environmental assessment tools by two main features: Life cycle perspective and cross-media environmental approach[99]. Furthermore, LCA accounts for both the environmental burdens (e.g., GHG emissions from residual waste disposed of in landfill) and benefits (e.g., the recovery of recycling of waste materials to produce secondary products that replace the production of primary products). However, choices regarding system boundaries definition, and data selection can significantly affect the calculated results[100].

The LCA framework

The main reference system in performing LCAs is the international standards ISO 14040 and 14044[67, 101]. ISO 14044 details the requirement for conducting an LCA. There are four phases in an LCA study:

a) the goal and scope definition phase,

b) the inventory analysis phase,

c) the impact assessment phase, and

d) the interpretation phase.

The four phases are shown in Figure 2.1.The scope, including the system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA.

The life cycle inventory analysis phase (LCI phase) is the second phase of LCA. It is an inventory of input/output data with regard to the system to be studied. It involves collection of the data necessary to meet the goals of the defined study.

The life cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to help assess a product system's LCI results so as to better understand their significance of environmental impacts.

Life cycle interpretation is the final phase of the LCA procedure, in which the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

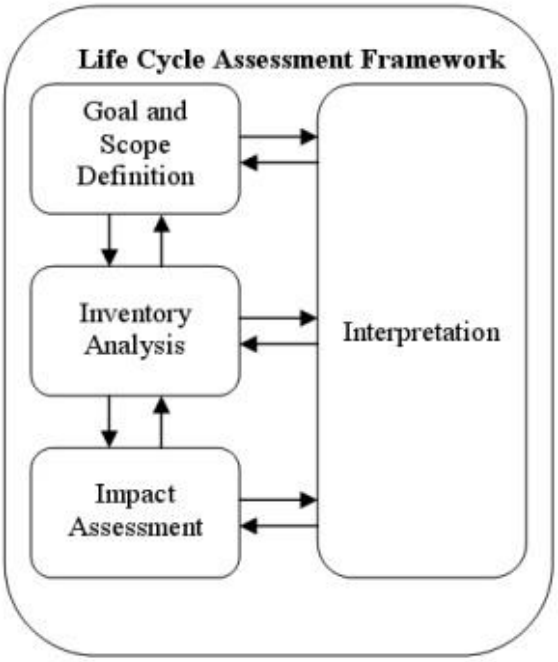


Figure 2.1 The four phases of an LCA[67]

Goal and Scope Definition

Goal and scope definition is the first phase of a LCA. According to ISO 14044, in defining the goal of an LCA, the following items shall be stated: the intended application, the reasons for carrying out the study, the intended audience, and whether the results are intended to be used in comparative assertions intended to be disclosed to the public. Once the goal is determined, the scope of an LCA must take into account and clearly describe the following elements: the product system to be studied, the function of the system, the functional unit, the system boundary, allocation procedures, life cycle impact assessment methodology and types of impacts, interpretation to be used, data requirements, assumptions, value choices and optional elements, limitations, data quality requirements. The scope may be adjusted based on information collected during the analysis.

Inventory Analysis

Inventory analysis is to quantify the inventory of the various flows of material extractions and substance emissions crossing the system boundary. Two methods to calculate the inventory currently prevail: the process-based approach and the input-output (I/O) approach. Although the principles of inventory calculation are relatively simple, the collection of data may require a substantial effort.

Impact Assessment

The third phase of LCA is the life cycle impact assessment (LCIA). The impact assessment links the inventory data with their environmental impacts and compares the impacts. The different steps of the impact assessment are the classification of emissions into different impact categories, characterization of midpoint impacts, and damage characterization. The weighting and the integration of the impacts are also required. The different steps of the impact assessment methods are simple to apply, though their development can be relatively complex.

Interpretation

The purpose of interpretation phase is to identify the life cycle stages at which intervention can substantially reduce the environmental impacts of the system or produce, as well as analyze the uncertainties involved[102]. The interpretation phase involves identification of critical points in the life cycle, as well as assessment of the quality and robustness of results using checks including quality control and sensitivity analysis. The process of the interpretation is reported as guideline for a proper interpretation of the results of an LCA study[103].

Application of LCA in this thesis

This thesis applied the life cycle concept to analyze the waste management systems in small islands. Chapter 3 is a study of municipal solid waste treatment by LCA to quantify the environmental loads by evaluating the CO_2 emission and the emission prevention potential. The LCA analysis process in this study only includes the goal and scope definition and inventory analysis. The impact assessment and interpretation are not covered in this study. The life cycle concept is also applied in chapter 4 and chapter 5 when considering the processes and the systems. However, inventory analysis and impact assessment are not included in the methodologies because main focuses have been put on the economic analysis.

2.1.2 Economic analysis

Economic analysis is also an important sustainability analysis. There are many tools to evaluate a system’s economic feasibility, profitability, or economic benefits, which is essential of the sustainable operation of a designed system. The combination of environmental and economic assessments is very common in waste management researches[104, 105]. Main economic analyzing tools are listed as following.

Life Cycle Cost (LCC) Analysis

Life cycle cost (LCC) analysis is a method for assessing the total cost of facility owner. It is also a tool to determine the most cost-effective option among different competing alternatives to purchase, own, operate, maintain, and dispose of an object or process[106, 107]. The scoping and decision of the system boundary for LCC is critical in the analysis. The LCC has been extended for applying to environmental decision-making. LCC is traditionally a type of investment calculus used to rank different investment alternatives[108]. The main difference between traditional investment calculus and the extended LCC is that the extended LCC approach has an expanded life cycle perspective, and thus considers not only investment costs, but also operating costs during the product’s estimated life-time[106], but the LCC does not include all environmental costs. The use of LCA, financial LCC, and environmental LCC as tools supporting the decision process is shown in Figure 2.2. In many cases, the LCC is used with accompanying LCA as an economic assessment tool. LCC is applied to waste management systems[109], end-of-life electrical home appliances[110] and electronic waste management[111].

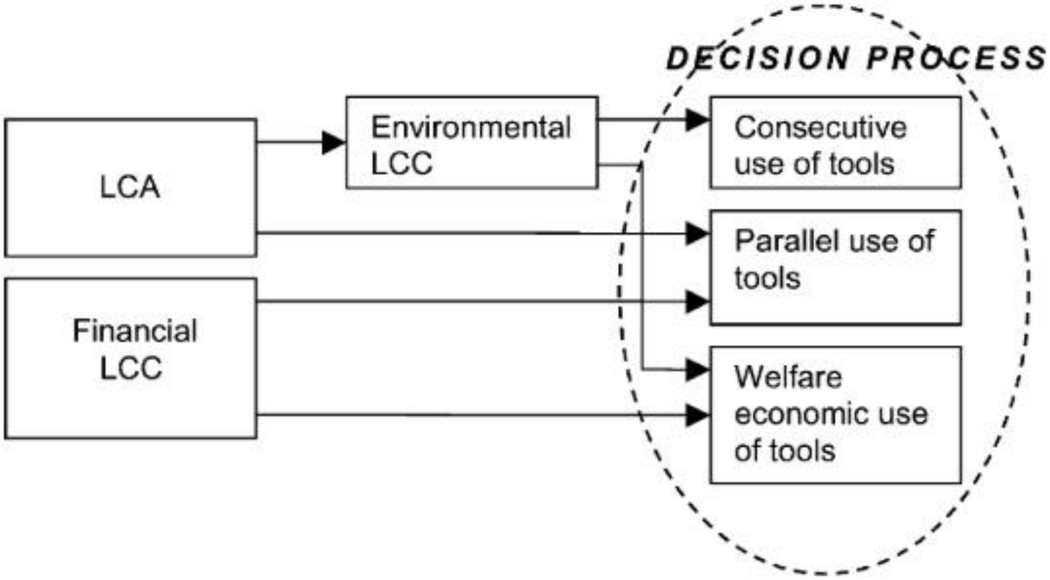


Figure 2.2 The use of LCA, financial LCC, and environmental LCC as tools supporting the decision process[104].

Cost Benefit Analysis (CBA)

Cost benefit analysis (CBA) is a systematic approach to estimating the strengths and weaknesses of alternatives. It is a widely used analyzing method in the economic field. By converting the environmental impacts and other effects to monetary units, it can also be applied to the environmental assessment field[49]. The essential theoretical foundations of CBA are defining benefits as increases in human wellbeing (utility) and costs as reductions in human wellbeing. All benefits are converted to monetary units. The cost component is the other part of the basic CBA equation[68]. CBA has been applied for analysis of ELVs[112, 113], MSW[114], RDF system[115], and product design and recyclability[116]

Application of the economic analysis in this thesis

The main purpose of using economic analysis tools in this study is to clarify the economic feasibility of the proposed waste management systems of strategies. The comparison of different systems in economic aspect is also possible by these tools. The economic analysis of MSW, ELV, and waste EHA is included in this study. In chapter 3, the economic analysis of MSW treatment system is based on the life-cycle level, which covers from the entering to the treatment system to the final disposal. In chapters 4 and 5, the economic analysis of ELV and waste EHA focuses on the process base, which aims to reveal the cost and benefit of the recycling and treatment process.

2.1.3 Material flow analysis (MFA)

Material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time[117]. The procedures of MFA are selection of substance, system definition, identification of relevant flows and stocks, determination of the flows and stocks, and assessment of total material flows and stocks. MFA has been widely used as a decision support tool for waste management[118].

Waste generation amount estimation methods

To do the MFA of waste management systems, the input amount, which is the waste generation amount, is the essential for the whole analysis processes. Different methods to estimate the waste generation amount are developed for different types of waste. Population Balance Model (PBM) is one of the useful tools to estimate the waste generation amount of durable goods, such as home appliances and vehicles. PBM estimated the future generation amount of waste durable goods by shipment number, possession number and lifespan distribution. The schematic diagram of PBM is shown in Figure 2.3. Many researchers have applied this method to estimate waste generation amount[119, 120].

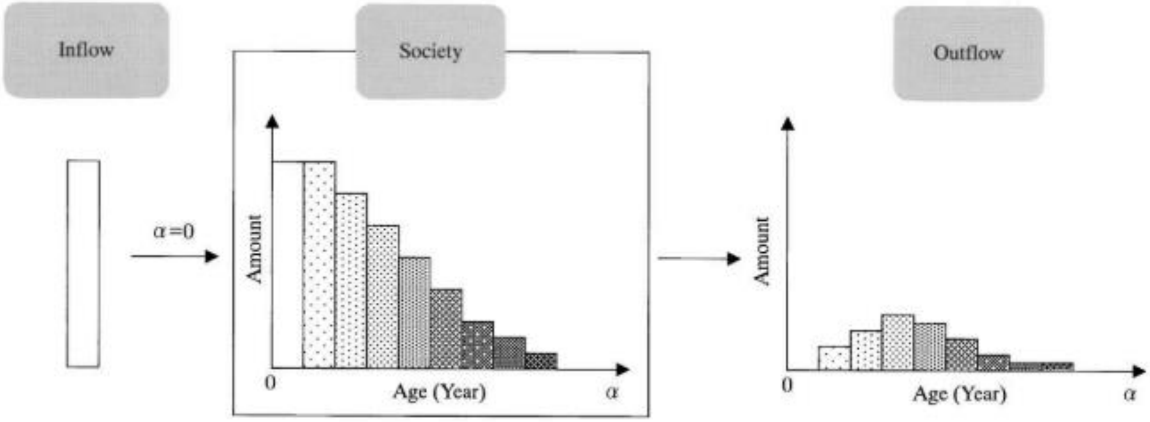


Figure 2.3 Schematic diagram of a population balance model. The states of inflow, accumulation in society and outflow at a time of t are shown. In society and at outflow, the amounts of products are arranged by age for service.[121]

Application of material flow analysis in this thesis

MFA is applied in this thesis in chapter 4 for the analysis of the flows and stocks of the ELVs treatment process. PBM is applied in this thesis to estimate the generation amount of ELVs following the processes designed by Tasagi et al. [122]. The quantification of the waste flow amount provides important information for designing the treatment system and for the further environmental and economic analysis to treat the corresponding amount. The quantification of the stock amount also clarifies the recycling potential and the potential contamination of the hazardous waste.

2.2 Focus of the case study

This study used the case of Kinmen, Taiwan as the case study to analyze the waste management system in small islands. The description of the basic information and waste generation characteristics are shown in this section.

2.2.1 Background of waste management in Taiwan and its surrounding islands

Taiwan has been developing waste management since the "Solid Waste Disposal Act" was established in 1974, and the policies relating to waste management in Taiwan are shown in Table 2.1. Firstly, the landfill has been set as the initial goal for waste treatment, while incineration as the long-term policy. There were 296 solid waste disposal sites in Taiwan, while the flow to the sanitary landfills only accounts only for 65.5 %, which is low and show a necessity to prevent illegal dumping and improve environmental sanitation. In 1991, 21 incineration plants were constructed under the "Construction Plan for Solid Waste Resource Recycling (Incineration) Plant", to deal with the increasing waste amount caused by the developing economy and industry the previous years. However, building the landfills and incineration had still facing the problem of the increasing waste generation amount. In 2001, the amended "Solid Waste Disposal Act" started to promote the "Zero Waste Policy", which focused on 4-Rs: Reduce, Reuse, Recycle, and Recovery. The focus of "source reduction" stresses recycling and encourages enterprises to engage in ecological design[123].

Table 2.1 The policies relevant to waste management in Taiwan

	Policy or strategy
1945	Open dumping
1974	Solid Waste Disposal Act
1984	Municipal Solid Waste Disposal Plan
1991	MSW Disposal Plan
1997	Four-in-one Resource Recycling Plan
2000	Pay-by Bag Collection Fee System

2001	Kitchen Waste Recycling
2002	Limit Plastic Bags and Plastic Disposal Tableware
2003	Waste Minimization and Resource Recovery
2003	Zero Waste Policy
2005	Mandatory MSW Sorting Limitation Policy
2006	Excessive Packaging Limitation Policy
2007	Resource Recycling Promotion Plan for General Waste
2010	Cradle to Cradle National Master Plan
2011	The Draft Plan on Resource Circulation Policy
2011	Reduce of Disposable Beverage Cups in Chain Beverage Retailers
2013	Reforming to Ministry of Environment and Resources

Several works revealed the performance of the recycling and waste minimization in Taiwan. For the recycling performance, Wen et al. reported the high collection rate to be a recycling performance indicator[124], while Chen and Lin reported the greenhouse gases emission prevention by the recycling system in Taiwan[125]. Other recycling practices including end-of-life vehicles[126, 127], electrical appliances[128–133], construction and demolition wastes[134, 135], industrial wastes[136], and some other materials[137–139] are also been studied. For the waste minimization, Lu et al. indicated that the amount of MSW began to decline after 1997, when the government enforced aggressive MSW management policies[140].

The waste management policy in Taiwan has shifted from sanitary landfill to incineration since 1991, and then focused on source separation, reduction and recycling since 2003.[123] In 2016, the recycling rate reached 58% of all MSW and the 24 large-scale incineration plants are treating more than 90% of unrecyclable general waste.[141] However, there is no small-scale MSW thermal treatment facilities in Taiwan. As a result, the general waste generated in remote and isolated areas such as mountains and small islands are transferred to cities for incineration or remain sanitary landfill.

Over Taiwan's 22 administrative divisions, 3 counties, Penghu, Kinmen, Lienchiang, are consisted by only small islands, presented in Figure 2.4. The waste management in these island counties is facing some problems. First is the higher MSW generation amount and the lower recycling rate comparing to Taiwan. The waste disposal characteristics of the island counties of Taiwan are shown in Table 2.2. The data show that the island counties has higher MSW generation rate. At the same time, the lower recycling rate can also be found in the data. The higher MSW generation rate makes the emission during the treatment process higher. On the other hand, despite the decreasing of the total waste amount in Taiwan, the waste generation amount in island areas is increasing constantly.

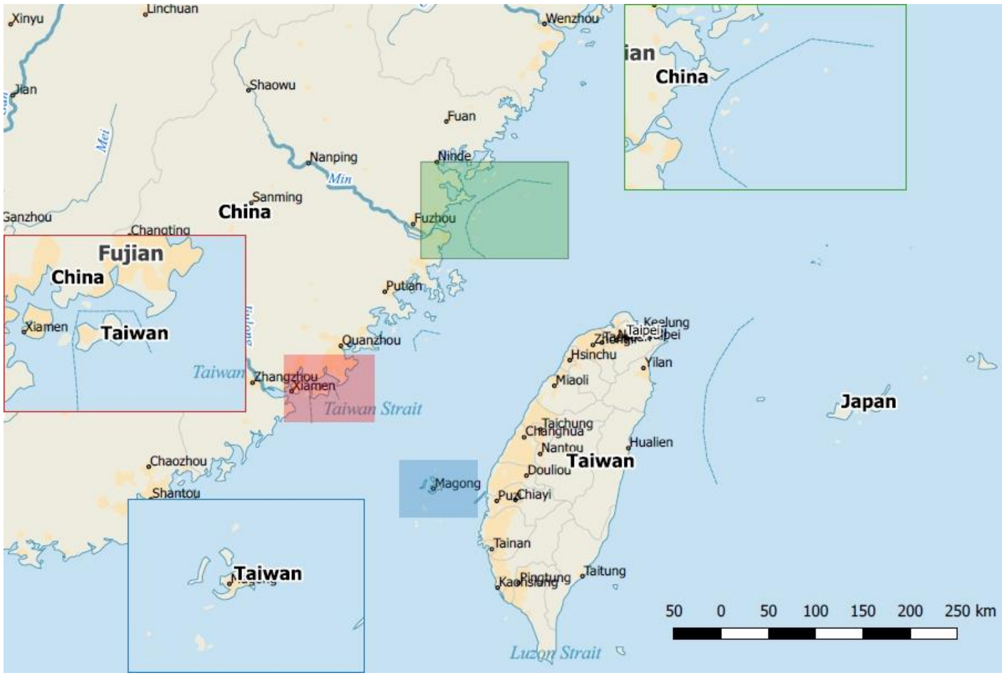


Figure 2.4 The map of Taiwan and its surrounding islands.

Table 2.2 Waste disposal characteristics of the island counties of Taiwan

	MSW generation rate (kg/capita-day)	Food waste recycling rate (%)	Recycling rate (%)
Penghu	0.436	10.6	44.55
Kinmen	0.482	6.89	45.67
Lianjiang	0.459	19.6	31.81
Taiwan average	0.364	7.77	49.13

In 2007, Penghu established the first waste transfer policy to deal with the problem of decreasing capacity of its landfill sites. Lienchiang also started the similar policy by 2008 and Kinmen by 2010. The waste transfer policy, which is to transfer the general waste to cities in Taiwan main island for incineration, provides an immediate solution the increasing waste generation and limited landfill capacities in the small island states, but the high cost of land and sea transportation fee and incineration fee has become a heavy financial burden to local governments. The outsourcing of waste treatment also means the disability to treat waste. On the other hand, due to lack of recycling facilities, the recyclable waste is also removed from the islands for further recovery processes. This has also limited the selling price of the recyclable materials.

2.2.2 Basic information about Kinmen

Kinmen has the highest economy and population development among three island counties of Taiwan. It is located just off the southeastern coast of mainland China and is composed of a group of islands, including Great Kinmen, Lesser Kinmen, Wuqiu and several surrounding islets. The total land area is 153 km^2 with the population of 132,799 in 2017. The location and the map of Kinmen County are shown in Figure 2.5. Due to the recent opening of relations between Taiwan and China, there has been a large influx of tourist into Kinmen to visit its rich ecosystems and the historic battlefields[142]. The increase of number of tourist visiting Kinmen is shown in Figure 2.6. Kinmen has limited natural and fossil fuel resources of energy, so the large number of visitors have also affected the ecosystem and energy consumption. Strategic Plan for the Sustainable Development of Kinmen, which focuses on maintaining the ecology of the islands and improving the quality of like of their residences, is published by Kinmen county government in 2004[142]. On July 2013, the central and Kinmen Governments committed to Kinmen Low-Carbon Island Plan which aims to turn Kinmen into a zero-carbon island by the year 2030[143]. The plan set targets for energy saving and carbon reduction. Six sub-projects of this plan includes green energy and low-carbon transportation project, low-carbon community and building project, resource recycling and biomass energy center project, low-carbon LOHAS promotion project. Sustainable development is one of the main focus of Kinmen County currently.

○Total area: 153 km^2
○210 km to west of Taiwan
○8 km to Xiamen(Amoy),Fujian, China
○Population: 132,799

Figure 2.5 Basic information about Kinmen County

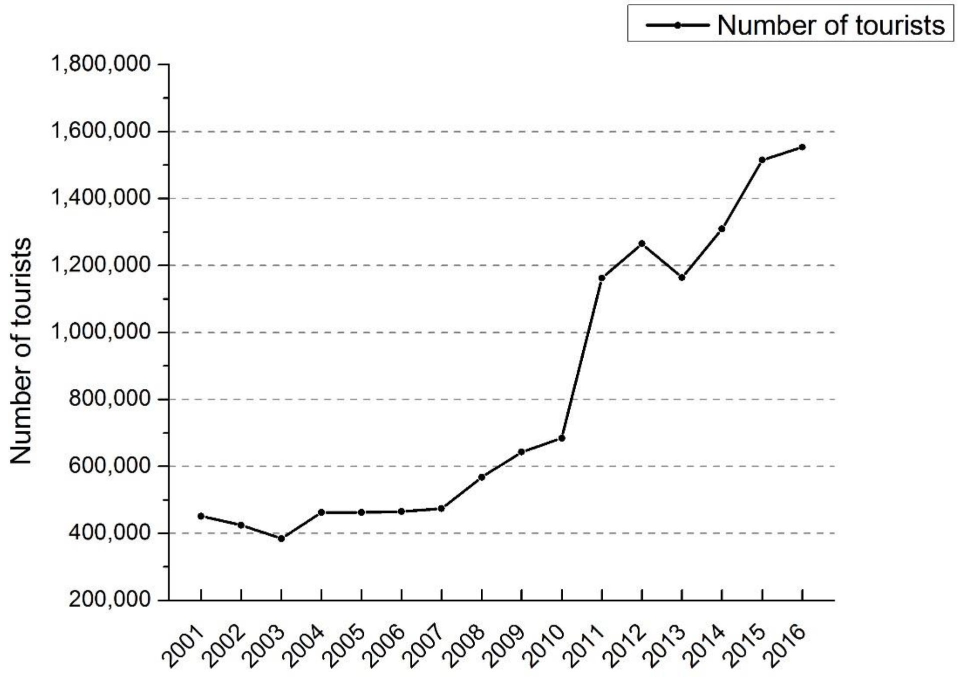


Figure 2.6 Number of tourists visiting Kinmen from 2001 to 2016

2.2.3 Waste generation in Kinmen

In Kinmen, MSW is classified by general waste, recyclable waste, kitchen waste, and incombustible waste. Figure 2.7 shows the current waste management system and the unit cost for treating each of the categories. The waste treatment cost in Kinmen differs among treatment methods and categories. The general waste and recyclable waste will travel through Taiwan Strait for 157 nautical miles (= 291km) to reach Taiwan main island for incineration and recycling, while kitchen waste treated by composting and incombustible waste disposed in landfill. The unit treatment cost of general waste and incombustible waste is 4,467 TWD/ton and 4,620 TWD/ton, respectively. For the kitchen waste, the composting is operating under annual cost of 1,226,000 TWD/year, which is equivalent to unit treatment cost of 574 TWD/ton on 2016 kitchen waste generation basis. The recyclable waste is sold to local recycling companies, and the selling revenue for the 14,145 ton of materials in 2016 is 9,527,672 TWD.

There are several advantages of the waste transfer policy operating in Kinmen. First, waste transfer ensures sufficient incineration amount which could improve the efficiency of existing incinerator. Second, waste transfer can reduce the investment and environmental impact of building new incinerator. Third, Centralized ash treatment could reduce the potential risk of transporting and treatment problem. However, the long-distance transportation could increase the environmental impact, and increased amount of incinerated waste could cause increased environmental impact in areas with existing incinerator. The high transportation cost is also one of the critical issues of the waste transfer policy.

Table 2.3 shows the municipal waste generation characteristic of Kinmen County in 2017.The sum of general waste and recyclable waste account for 92% of the total MSW, which means Kinmen can only treat 8% of its MSW generation. On the other hand, although the recyclable waste can be sold to get revenue, the high transfer fee and incineration fee for combustible waste required more than 63 million TWD to treat the generated 14,174 ton of general waste, which is about twice as higher as the cost for other cities in Taiwan by treatment unit basis.

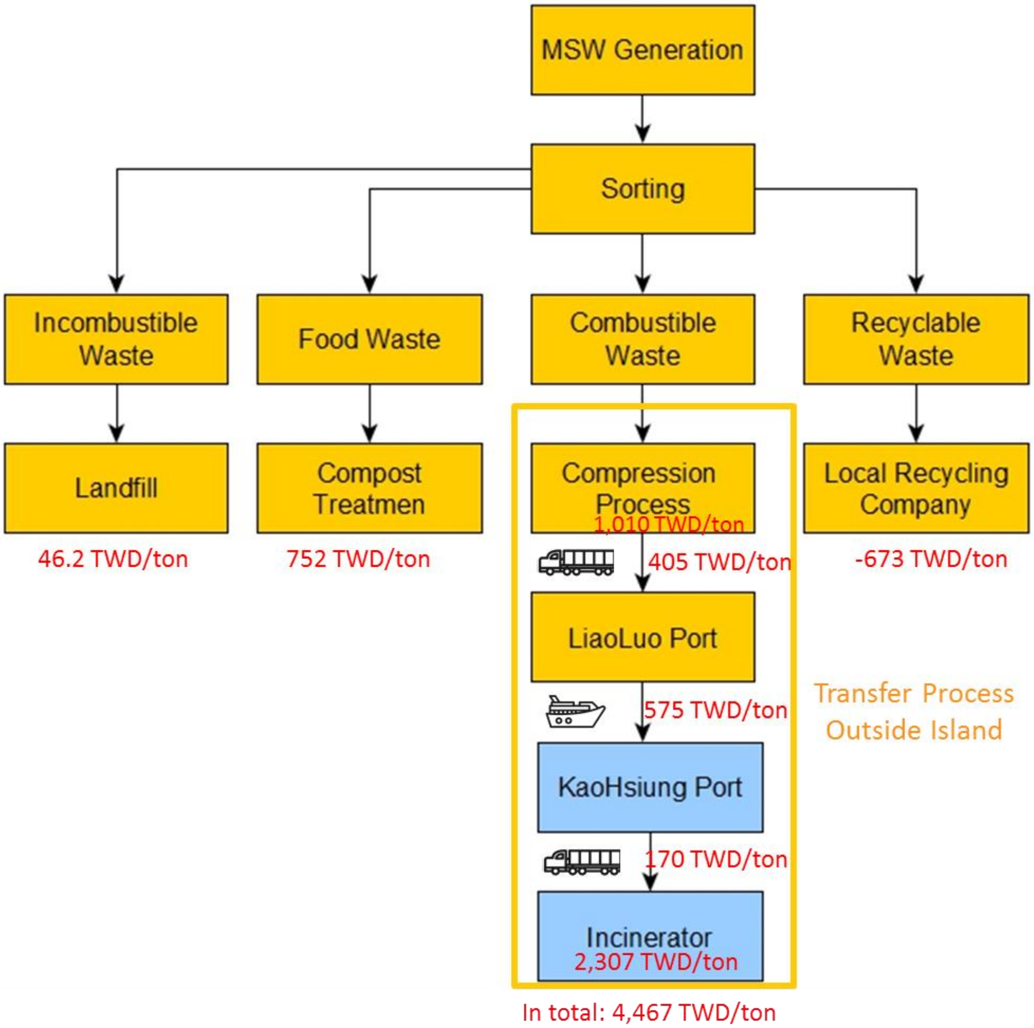


Figure 2.7 Current waste management system and unit cost for treatment. (100TWD=3.43USD in 2018).

Table 2.3 The MSW generation amount in categories in Kinmen County in 2016.

MSW generation	**Kinmen Country**		**Taiwan overall**	
	Amount (t)	Percentage	Amount (t)	Percentage
General waste	14,174	46%	3,045,298	41%
Recyclable waste	14,145	46%	3,640,753	49%
Kitchen waste	2,135	7%	575,932	8%
Incombustible waste	518	2%	88,283	1%
Total (MSW)	30,972	100%	7,411,184	100%
MSW generation capita^{-1} day^{-1}	1.047 kg		0.863 kg	

Comparing the general waste amount daily per capital, the value for Kinmen County is 0.482 g per capita per day, which is also higher than the country average of 364 g per capita per day. The recycling rate for recyclable materials and kitchen waste is also slightly lower in Kinmen comparing to Taiwan. Several reasons contributed to the increasing waste generation rate of Kinmen County. One is the increase of tourist number. The tourist number in Kinmen County show a great increase since 2011. As shown in Figure 2.6, the annual tourist number increased since 2007, especially after year 2011. The corresponding trend of the increase of general waste generation and tourist number reveals that tourists contributed high amounts of solid waste in Kinmen. An LCA report of Kinmen tourism activities shows that per capita waste discharge of Kinmen tourist is more than that of local people[144]. A clear correlation between increase of waste generation amount and the increase of inhabitants and visitors can be seen in Figure 2.8.

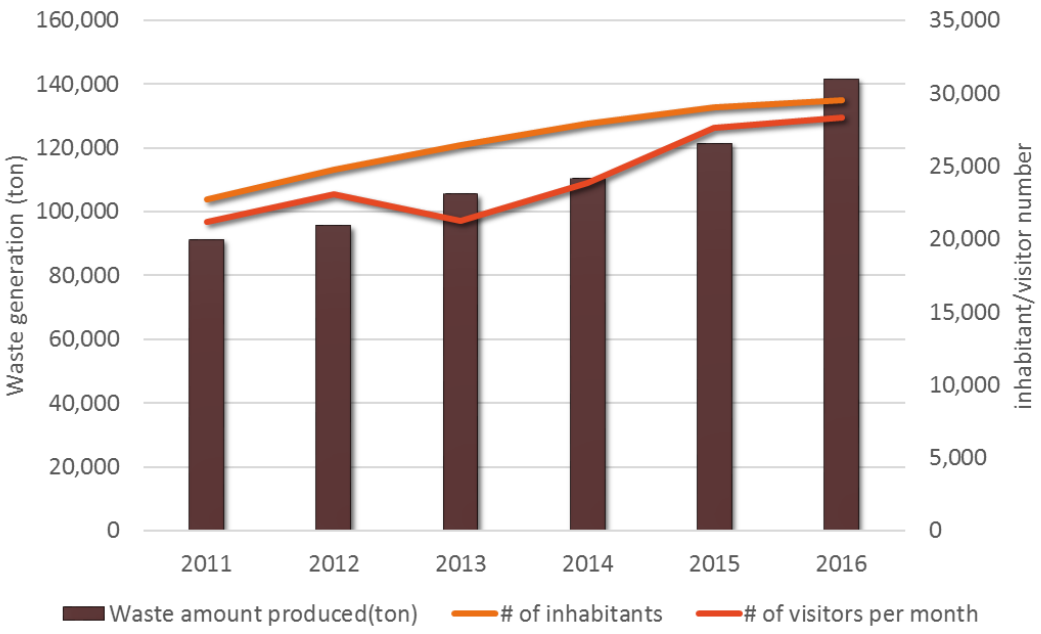


Figure 2.8 Waste generation amount and the number of inhabitants and visitors in Kinmen

Table 2.4 details the data on physical composition of general waste in Kinmen. The low percentage of incombustible contents indicates high performance of source separation of the metals and glass as recyclable materials. There is 97.38% of combustible materials and 2.62% of incombustible materials. The general waste has high heating value (HHV) of 2432 kcal/kg and low heating value (LHV) 1923 kcal/kg, which is not so different with other cities in Taiwan. This composition is suitable for energy recovery in the incineration plants.

On the other hand, although there is a separation system for the food waste for composting, the kitchen waste still accounted for 37.3 % in the general waste. The treatment cost of kitchen waste is lower than the general waste, which means if more kitchen waste can be separated from general waste, the total waste disposal cost can be reduced. Besides, there exists high percentage of paper and plastics in the general waste. As the paper and plastics recycling system has already established in Kinmen, selling of the recycled materials is possible. Improving the recycling of paper and plastics can turn the cost of treatment into revenues.

Table 2.4 Composition of general waste generated in Kinmen

Physical composition (unit: %)	
Paper	37.50
Textiles	4.84
Yard waste	1.19
Food waste	37.31
Plastic	16.16
Leather and rubber	0.11
Other combustible materials	0.28
Incombustible materials	2.62

The collection of recyclable items in Kinmen is operating under the Taiwanese Solid Waste Disposal Act. Several items are identified to be recyclable and must be separated from municipal solid waste. The recyclable items include paper, metal, plastics & rubber, glass, home appliances, batteries, and IT devices. The collection amount of recyclable materials in Kinmen reported by Taiwan EPA is shown in Table 2.5. The generated recyclable items are collected by the cooperation of the local municipality and the inhabitants, and the values are constantly increasing from 2001 to 2017. However, the treatment facilities are very limited in Kinmen

Table 2.5 The reported collection amount of recyclable materials in Kinmen form 2001 to 2017

	Subtotal (t)	Papers (t)	Metals (t)	Plastics & Rubber (t)	Glass (t)	Home appliances (t)	Batteries (t)	IT devices (t)	Others (t)
2001	1,697	766	18	276	7	45	10	7	569
2002	2,371	1,233	578	241	32	50	5	5	228
2003	2,773	1,325	1,000	309	51	63	10	8	7
2004	3,515	1,737	1,032	444	139	81	58	15	9
2005	3,945	2,053	902	572	283	73	23	17	23
2006	4,613	2,599	957	651	259	69	31	23	25
2007	4,871	2,980	705	687	344	71	28	28	28
2008	4,906	2,997	704	638	375	64	25	28	75
2009	5,349	3,092	659	853	377	76	51	30	211
2010	5,590	3,162	668	925	401	92	23	31	288
2011	6,412	3,583	736	1,039	539	101	28	64	322
2012	7,315	4,010	1,003	1,106	546	150	25	69	407
2013	9,240	4,509	2,327	1,040	692	244	57	65	306
2014	10,099	5,239	2,340	1,295	651	214	76	73	213
2015	10,915	6,179	2,148	1,267	658	272	61	91	239
2016	14,145	7,606	2,799	1,583	771	321	110	112	845
2017	16,319	9,387	2,853	1,894	647	342	142	142	912

Management of end-of-life vehicles (ELVs) is also an important issue in considering abandoned vehicle problems and resource conservation. There is no statistical data for the collected ELVs number, but the registered vehicle number in Kinmen can be seen in Table 2.6. The registered vehicle number has increased greatly in the past decade. This may result in increasing ELV generation amount after the lifespan of the vehicles.

Table 2.6 The registered vehicle numbers in Kinmen.

	Automobiles	**Motorcycles**
1999	11,174	24,107
2000	12,028	25,199
2001	11,793	26,512
2002	13,143	27,888
2003	13,879	28,647
2004	15,085	29,572
2005	16,587	30,965
2006	17,562	32,128
2007	18,704	34,343
2008	19,699	36,689
2009	21,396	39,425
2010	22,856	41,260
2011	24,675	43,922
2012	26,928	46,747
2013	29,292	47,887
2014	31,993	50,991
2015	35,004	55,050
2016	37,133	58,247
2017	39,308	61,556

2.3 Data preparation

The primary data and information used in this study are mainly acquired by interviews with Kinmen Environmental Protection Bureau by phone and mails. The interviewing periods are from October 2017 to November 2017 for the municipal solid waste, and from October 2018 to December 2018 for the end-of-life vehicles and waste electronic home appliances. Data about the waste generation amount, recycling rates, waste categorization, illegal dumping amount, subsidy system, and operation situations of waste management system are obtained from the open access reports of Environment Resource Database published by Taiwan EPA[145].

For the environmental assessment, the emission factors for this case is mainly collected from Taiwan EPA Carbon Footprint Calculation Platform[146]. However, this platform does not include all the necessary data for this study. The inventory data which is not available in this platform are acquired in other relating researches. The data from Japanese and Korean LCA researches are often used due to the similarity of the operation system. The details of the data source are included in the methodology sections in each chapter. The data for the economic analysis are mostly primary data obtained from interviews. The data for the economic analysis of the proposed systems are estimated based on a series of assumptions.

Chapter 3 Waste shipments for energy recovery as a waste treatment strategy for small islands

3.1 Introduction

3.1.1 Waste management in small islands and waste shipments

Small islands usually suffer from limited physical and financial capacities speaking of waste disposal issues, especially considering the thriving tourism industry in recent decades. The common difficulties faced by islands waste management are limited land resources, lack of capital options, high operational cost, diseconomies of scale, no market for recycling and large seasonal fluctuations in waste volumes[66]. Many studies revealed the effects of tourism activities on the waste generation in island communities[76, 79, 91]. Landfilling is the least desired option according to the waste management hierarchy, but it is highly practiced in many small island developing states[63]. Thermal treatment has the ability to reduce the volume and the weight of the waste for final disposal, and can recover useful energy contents from waste. Considering the limited physical space and high independence on imported energy for island communities, the thermal treatment with energy recovery, or Waste-to-Energy (WTE), seems to be a reasonable option in waste management strategy[147]. For the highly populated and developed islands, such as Singapore, Hong Kong, and Japan, the incineration with energy recovery is a feasible option[148, 149]. The WTE availability in island communities is studied in several researches by cost estimation[80], life cycle assessment[83], and energy analysis[90]. These studies showed the planning and development of self-sufficient solutions for waste management in islands. However, for islands with lower waste generation amount and high seasonal fluctuations, it is difficult to achieve incineration with electricity generation (generally required a capacity more than 100 ton/day and stable waste input). Shipments of combustible portion of waste outside of the island provides a possibility for the combustible waste to recover as energy.

Transforming combustible waste into the form of refuse derived fuel (RDF) improves the feasibility for long-distance domestic and international waste movement. RDF is a fuel produced from waste materials by a series of mechanical processes to improve the physical and chemical characteristics of the input refuse materials. RDF can be combusted in power plants, or be utilized in industrial processes for producing heat or steam. Basel Convention restricts the movements of hazardous waste between nations[150], but for the transfer of non-hazardous waste, including combustible waste, the restriction is based on national or regional regulations. Waste Shipment Regulation (WSR) regulates the waste movement in European Union (EU) [151, 152]. Under Waste Shipment Regulation, the export and import waste within the EU is categorized into three categories: green list, recovery, and disposal. The green list requires no prior approval to export, while recovery requires prior notification, and disposal is generally not permitted to export. The movement of combustible waste is possible after being produced into refuse derived fuel (RDF), and only if it is recovered. As a result of the rising landfill tax in some countries and the incineration overcapacity in others, there is a dynamic waste trade for energy recovery in EU. United Kingdom (UK), the largest exporter of RDF within the EU, experienced a steep rise in RDF export over the last few years, as a result of the landfill tax increase and the absence of incineration capacity[153].

In the literatures about small island waste management, seldom has the transboundary shipments of waste been mentioned. A study about the waste management in Green island, Taiwan[81], evaluated the cost effectiveness of waste treatment alternatives, which included the shipment of waste after the landfill site is full. This study showed the waste shipment as a costly alternative, but the environmental aspect is not yet considered. The environmental benefit of shipping waste for energy recovery may be more significant than the environmental impacts of transportation, especially in the scale of small islands where power generation by incineration is not feasible. The focus of the present research is on evaluation of the waste shipments for energy recovery in a small island scale, while the cost and environment evaluation included. The case of Kinmen, Taiwan, was selected as a case study.

3.1.2 Waste management in Taiwan and its surrounding islands

The waste management policy in Taiwan has shifted from sanitary landfill to incineration since 1991, and then focus on source separation, reduction and recycling since 2003.[123] In 2016, the recycling rate reached 58% of all municipal solid waste (MSW) and the 24 large-scale incineration plants are treating more than 90% of unrecyclable general waste.[145] However, there is no small-scale MSW thermal treatment facilities in Taiwan. As a result, the general waste generated in remote and isolated areas, such as mountains and small islands, are transferred to cities for incineration or remaining sanitary landfill.

Over Taiwan’s 22 administrative divisions, 3 counties, Penghu, Kinmen, and Lienchiang, consists of only small islands. In 2007, Penghu established the first waste transfer policy to deal with the problem of decreasing capacity of its landfill sites. Lienchiang also started the similar policy in 2008 and Kinmen in 2010. The waste transfer policy, which is to transfer the general waste (mostly combustibles) to cities in Taiwan main island for incineration, provides an immediate solution for the increasing waste generation and limited landfill capacities in these islands.

Kinmen has the highest economy and population development among three island counties. Figure 3.1 shows the current waste management system of Kinmen. There is a source separation system for MSW in Kinmen, and the collection of MSW is separated into recyclable waste, kitchen waste, bulk waste, and general waste. The general waste and recyclable waste will travel for 157 nautical miles (= 291km) through Taiwan Strait to reach Kaohsiung City in Taiwan main island for incineration and recycling. Meanwhile, kitchen waste will be treated by composting and bulk waste disposed in landfill.

The waste transfer policy has been judged for its high cost comparing to the Taiwan average, but considering the environmental aspect, while the electricity generation become possible, it might be beneficial for the global scale considering the greenhouse gas (GHG) emissions. On the other hand, following by the experience of waste shipment in EU, transforming the waste into RDF makes international trade of waste for energy a possible option. By RDF production, lower transportation fee, longer storage time, and higher energy efficiency is also achievable.

Kinmen has a well operating waste collecting system with source separation, which leads to high material recycle rate of 46% and kitchen waste of 7%[145]. The general waste contains low moisture contents and incombustible components, and high heating value, which is suitable for RDF production. Kinmen is located in the central of East Asia and Southeast Asia, and the special geographical location gives it more options to RDF utilization destination. Within 6000 km from Kinmen, there are developed countries possessing energy-efficient incineration plant, and also developing countries demanding for substitutional fuel as an energy source. These characteristics make Kinmen an ideal study objective for waste shipment for energy recovery by small island scale.

For these motivations, the main objective of this study is to evaluate the environmental benefit of waste shipment for energy recovery accompanying with the cost estimation. Case studies of the current waste transfer system and scenarios with RDF production plant in Kinmen are analyzed from the economic and environmental aspects. Life cycle inventory (LCI) analysis is adopted to evaluate CO_2 emission over the cases. Asia-Pacific scale RDF trade is evaluated and the results revealed the cost-effective and environmental beneficial determining methodology. The study of waste transfer in Kinmen can provide information to small island states searching for sustainable waste management solutions.

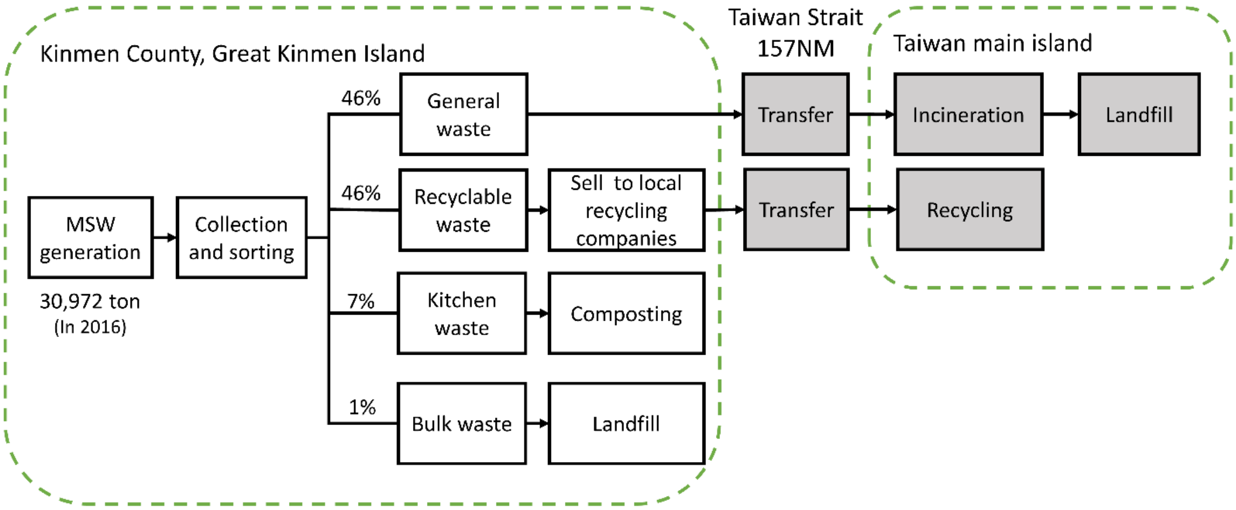


Figure 3.1 Flow diagram of MSW treatment in Kinmen County

3.2 Materials and methodology

Figure 3.2 shows the process flow of the case studies. Life Cycle Inventory (LCI) analysis is applied to evaluate the CO_2 emission over the processes in the waste treatment system. This research focuses on the treatment of the general waste, therefore the analysis system boundary is set as starting at the treatment of general waste. The waste generation process, collection and sorting process, and the treatment for other waste categories are not included. The collected waste in Taiwan is categorized into four categories: recyclable waste, food waste, bulk waste and general waste, and general waste is defined as all the waste apart from other three categories. The characteristic of general waste generated in

Kinmen County in 2016 is shown in Table 3.1[145].The functional unit is defined as treating 1 ton of general waste in Kinmen. Four cases are analyzed in this study, including:

- Case 1: direct shipment to Kaohsiung, Taiwan for incineration (current waste transfer system)
- Case 2: RDF production and shipment to Kaohsiung, Taiwan, for incineration
- Case 3: RDF production and shipment to Quanzhou, China, for incineration
- Case 4: RDF production and shipment to other destinations, for incineration or substitutional fuel

Case 1, shown in Figure 3.2 (a), is the current waste transfer system in Kinmen County. The process of this case is direct shipment of generated waste outside of Kinmen for incineration. The system boundary covers the compression and packing process, the land and sea transportation processes, the incineration process, and ash disposal process. The incineration plant used here is an existing moving grate incineration plant, with designed treating amount of 1,350 ton/day and designed heating value of 2,500 kcal/kg. This incineration has a power generation system with reported energy efficiency of 18%. Figure 3.2 (b) is the process flow of case 2, case 3, and case 4, where the generated waste is first produced into RDF, and shipped outside of Kinmen. For these three cases, it is assumed that the Waste Shipment Regulation of EU is applied to the Asia Pacific countries, which means that the export and import of RDF is permitted among these countries. The process flow in these three cases includes the RDF production process, residuals treatment process, RDF transportation process, and RDF utilization process. The RDF production mentioned here is a series of mechanical processes including shredding, drying, conditioning and pelleting. The product of the process, called densified-RDF or RDF-5, has constant and high heating value with same pellet size. For case 2, the RDF is assumed to be shipped to the same destination as case 1: an incineration plant in Kaohsiung, Taiwan main island, for treatment and energy recovery. For case 3, the RDF is assumed to be shipped to an existing incineration plant in Quanzhou City, China, where is closer to Kinmen comparing to Kaohsiung, with a shipping distance of 72 km. The incineration plant holds a treating capacity of 2,000 t/day, and the gate fee for incineration is 203 RMB/t (approximate 936 TWD/t in 2018). For case 4, the overall cost and emission evaluated considering RDF shipment to the Asia Pacific countries within 6,000 km is discussed. The analysis included the RDF utilized in incineration for power generation, and as a substitutional fuel of coal to generate heat and steam.

Table 3.1 Characteristic of the general waste generated in Kinmen County in 2016

Physical composition (unit: %)	
Paper	37.50
Textiles	4.84
Yard waste	1.19
Food waste	37.31
Plastic	16.16
Leather and rubber	0.11
Other combustible materials	0.28
Incombustible materials	2.62
Proximate analysis (unit: %)	
Moisture	53.82
Combustible	38.60
Ash	7.59
Energy content(unit: kcal/kg)	
Dry base heating value	5296
Wet base HHV	2432
Wet base LHV	1923

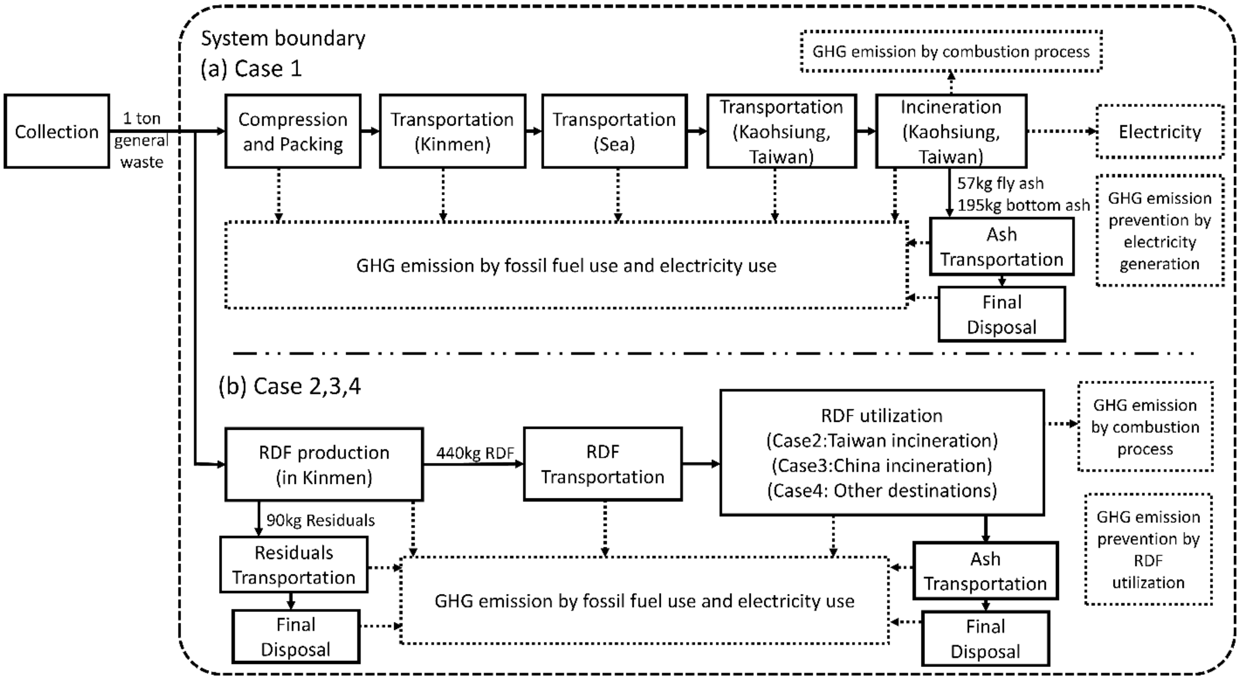


Figure 3.2 Process flow of the analyzing cases; The upper part represents the process flow of case 1 and the lower part represents the process flow of case 2, case3, and case 4

3.2.1 Cost analysis

The details and costs for the current waste management practices are obtained by the interview of Kinmen Environmental Protection Bureau. In case 1 of the current waste transfer system, the compression and packing process, the sea transportation process, and the land transportation process are operated by private company under contract with Kinmen Environmental Protection Bureau. The incineration in Kaohsiung City, Taiwan, treats the transferred waste with a fixed rate. All of the cost components are from real data.

For cases 2, 3, and 4, the RDF production cost is estimated under several assumptions. The assumptions are listed in Table 3.2. The RDF production plant is designated to be on the existing waste transfer station in Xintang, Kinmen. The construction, personnel, operation and maintenance are included in the cost of the RDF production plants. The construction cost is estimated by the equation(3.1)[154]:

$$\frac{C_a}{C_b} = \left(\frac{A_a}{A_b}\right)^n , \tag{3.1}$$

where A is the plant cost attribute, C is the purchased cost of the plant, n is the cost exponent (often use n = 0.6, refer to equation as the 6/10 rule); a is unit with required attribute, and b is unit with base attribute. The capacity of RDF production plant is set as treating 40 ton of general waste per day, and the calculation is based on one existing municipal waste RDF production plant in Taiwan[155]. The construction cost of the plant can be converted into annuity by net-present-value method[109] as follows:

$$Annunity = \frac{P}{\left[\frac{(1+ir)^n - 1}{ir(1+ir)^n}\right]}, \tag{3.2}$$

where P, n, ir represent the present value, lifetime of the plant and interest rates, respectively. The life time of the plant is assumed as 20 years and follow with the interest rate as 1.375%[156]. The maintenance fee is assumed to be 1.5% of the construction fee per year. The operation cost is estimated by the material and electricity use of the system, and the personnel cost based on calculation by salary level information provided by Kinmen government and number of workers required is projected from the existing RDF production plants[23].

For the cost of RDF transportation process, the costs for land transportation and sea transportation are estimated by linear projection of distance. For the RDF utilization process, in case 2 and case 3, the RDF gate fee is set as the same as the incineration fee for general waste. In case 4, the cost for the RDF utilization is considered that it is treated with paying gate fee, or it is sold to get revenue. The highest gate fee is set as the same as the incineration fee of the Kaohsiung incineration plant. The highest possible selling price of RDF is estimated by the price of coal multiplied to the relative heating value between RDF and coal. All the cost in this study is shown in New Taiwan dollar (TWD), the currency for New Taiwan dollar to US dollar is about 100TWD=3.43USD (January, 2018).

Table 3.2 Basic assumptions for RDF production plant

Parameter	Assumptions	Remarks
Treatment capacity	40 ton waste/day	Based on daily general waste generation amount in Kinmen County in 2016[18]
RDF production rate	44%	Based on reports of one RDF plant in Taiwan[20]
Residuals generation rate	9%	Based on reports of one RDF plant in Taiwan[20]
General waste input HHV	2432 kcal/kg	Based on general waste generation analysis in Kinmen County in 2016[18]
RDF HHV	4870 kcal/kg	Based on reports of one RDF plant in Taiwan[20]
Workers required	14 people	Based on projected from the existing RDF production plants [23]
Worker's salary	28,500 TWD/month	By interview of Kinmen Environmental Protection Bureau

HHV: higher heating value

3.2.2 CO_2 emission estimation

The emission factors in this case is mainly collected from Taiwan EPA Carbon Footprint Calculation Platform[146]. The emission factors of electricity and fossil fuel used in this study are shown in Table 3.3. For case 1, the CO_2 emissions of the compression and packing process, and transportation process, are from the fossil fuel use. The compression and packing process requires diesel oil in average 2.65 L to treat one ton of waste. The CO_2 emissions for land transportation is obtained from the aforementioned database as consuming diesel oil of 0.069 L per ton per kilometer. The land transportation distance is obtained from the route estimated by Google Maps. Considering data availability, ton-kilometer method [157] is applied to calculate the CO_2 emissions of the sea transportation, for it provides relatively simple estimation method with by shipping distance and shipping amount weight as follows:

$$CO_2\ Emissions = distance(km) \bullet weight(ton) \bullet CO_2\ emission\ factor \tag{3.3}$$

, where the *emission factor* for ship transportation in this method is reported as 39 g-CO_2/t-km[158]. The shipping distance is estimated by Marine Traffic[159]. The CO_2 emission of combustion of waste is calculated according to IPCC guideline[160] based on the MSW composition as:

$$CO_2\ Emissions = MSW \bullet \sum_j \left(WF_j \bullet dm_j \bullet CF_j \bullet FCF_j \bullet OF_j \right) \bullet \frac{44}{12}, \tag{3.4}$$

, where *MSW* is the total amount of MSW at wet weight, WF_j is fraction of waste type of component j in MSW, *dm* is dry matter content , *CF* is fraction of carbon in the dry matter, *FCF* is fraction of fossil carbon n the total carbon, and *OF* is the oxidation factor. The fraction of every waste type used here is the waste physical composition of general waste in Kinmen in 2016 shown in Table 3.1. The values used for calculation here are listed in Table 3.4. The energy efficiency of electricity generation by incineration is set as 18%, which is obtained from based on the real data of Kaohsiung Gangshan Incineration plant[161]. The emission prevented though generated electricity is calculated based on the electricity emission factor in Taiwan. By treating 1 ton of waste, the incinerator generates 57 kg of fly ash and 195 kg of bottom ash. The ash is assumed to be sent to landfill for final disposal. The CO_2 emission from the transportation of ash is estimated by aforementioned factor for land transportation, and the CO_2 emission by the energy used for landfill is obtained from literature.[162]

In cases 2, 3, and 4, the CO_2 emission in RDF production process is from usage of electricity and crude oil, and the consumption amount is from data of the existing plant. The CO_2 emission from the RDF utilization process, which is a combustion process, is assumed to be the same as the direct combustion of the input waste, and the valued is calculated by IPCC method[160]. The emission prevention of RDF utilization is considered as a substitutional fuel of coal. According to the relative heating value of RDF and coal, 1 ton of RDF can be substituted for 0.47 ton of coal. The energy efficiency of heat and steam production is 80% [163], this value is multiplied to the emission factor of coal to estimate the prevented emission[164]. Although the construction of the RDF plants is included in the cost estimation, it is neglected in the CO_2 emission estimation in this study. The reason for this is that literature showed the emission during the construction process is small comparing to the operation process and can be neglected[165].

Table 3.3 Emission factors of electricity and fossil fuels in Taiwan [24]

	Emission factors
Electricity	0.192 kg-CO_2/MJ
Diesel oil	0.74 kg-CO_2/L
Crude oil	3.98 kg-CO_2/L
Coal	2.016 kg-CO_2/kg

Table 3.4 The values used for calculating CO_2 emission for incineration in this study [28]

Composition	**MSW (t)**	**WF**	**dm**	**CF**	**FCF**	**OF**	**Conversion Factor**	**Fossil CO_2 Emissions (t)**
Paper	1	38%	90%	46%	1%	100%	3.67	0.006
Textiles	1	5%	80%	50%	20%	100%	3.67	0.015
Food waste	1	37%	40%	38%	0%	100%	3.67	0.000
Yard waste	1	1%	40%	49%	0%	100%	3.67	0.000
Rubber and leather	1	1%	84%	67%	20%	100%	3.67	0.004
Plastics	1	16%	100%	75%	100%	100%	3.67	0.440
							Total	0.465

3.3 Results and discussions

3.3.1 Cost estimation results

The results of cost estimation comparison among cases 1, 2, and 3 are shown in Figure 3.3. For case 1, the current waste transfer system, the cost can be categorized into incineration part and transportation part. The unit waste treatment cost of case 1 is 4,467 TWD/t, which is very high comparing to other cities in Taiwan. For case 2 and case 3, the cost components includes incineration, transportation, and RDF production. The RDF produced in case 2 and case 3 are assumed to be treated in incineration with paying gate fees, thus the incineration fee in these cases are equivalent to RDF gate fee. The RDF production cost accounts for high percentages of the total unit cost for case 2 and case 3. However, comparing case 2 to case 1, the transfer destination is the same incineration plant, but reduced weight of waste by RDF production makes the transportation cost and incineration cost reduced greatly. For case 3, further cost reduction is achieved by lower shipping distance and lower incineration gate fee. The unit waste treatment cost of case 3 is 3,825 TWD/t, which is 14% lower than case 1 and 17% lower than case 2. Case 3 is the most cost effective waste treatment option among three cases for its low transportation fee and incineration fee. The low transportation fee is due to the shorter shipping distance to Quanzhou, China, in case 3, and also the smaller incineration fee is due to the lower RDF gate fee required in a different incineration plant. Under the condition of case 3, the break-even distance for the total cost is the same 807.5 km for case 1 and case 3. Within this distance from Kinmen, there are many cities within Fujian, Zhejiang, and Guangdong, China, all ports of Taiwan main island, Hong Kong and Macao, and some islands of Okinawa, Japan.

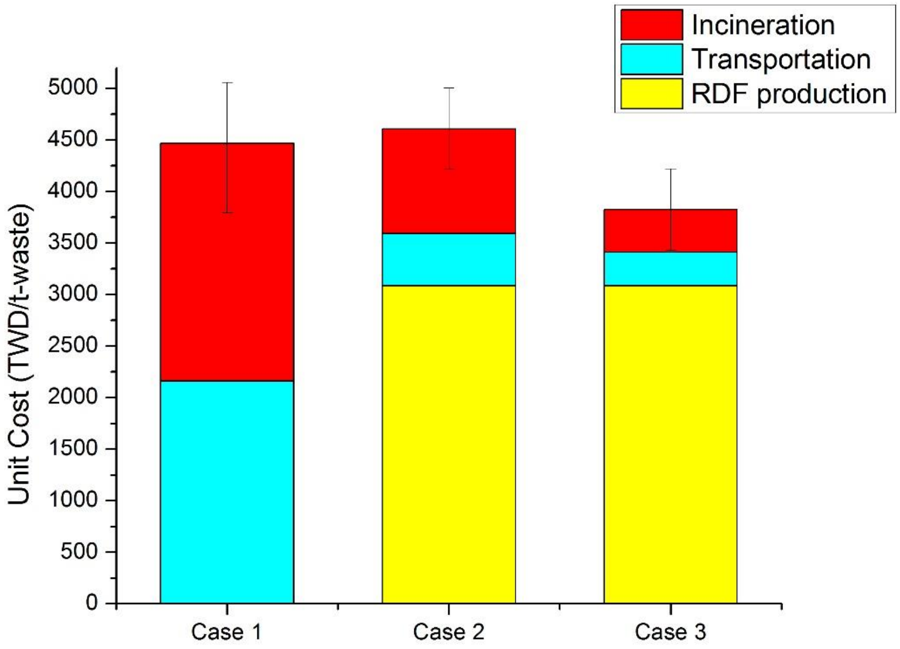


Figure 3.3 The cost comparison among case 1, 2, and 3

Table 3.5 shows the unit cost of treating general waste for the year 2017 in case 1. The compression and packing process is the essential preparation process for shipping to prevent environment effect during the transfer process, and this process accounts for 23% of the total cost. The Kinmen road transportation mentioned here represented the transfer process from the waste transfer center to the port, while the Kaohsiung road transportation represented the transfer process from the port to incineration plant. The road and sea transportation processes account for 26% of the total treatment cost.

Table 3.5 Unit cost of each stages of case 1. Source: Kinmen Environmental Protection Bureau

		unit cost (TWD/t-waste)
Transfer fee	Compression and packing	1,010
	Kinmen road transportation	405
	Sea transportation	575
	Kaohsiung road transportation	170
Incineration fee		2,307
Subtotal		4,467

Figure 3.4 presents the change of the cost in case 1 during 2010 to 2017. Since the start of waste transferring in 2010, the cost for the transfer process has been decreasing continuously. The change of the transfer fee depends on the contracts between operating companies and local governments. Before 2015, there is only one company providing the waste transfer business. Another company has joined the business since 2016, which has made the lower cost possible through the competition between companies. In contrast, for the incineration fee charged by Kaohsiung incineration plant, it kept constant at 1,000 TWD/t before 2014, and rose to 2,307 TWD/t after 2014. The rise is owing to the increased operation fee and the bottom ash treatment problems happened in Kaohsiung incineration plant, as this plant was timeworn and requires more repairs. The change of cost shows that the cost of the system is highly dependent on external factors, especially on the incineration fee. These external factors create uncertainties to the local Kinmen community.

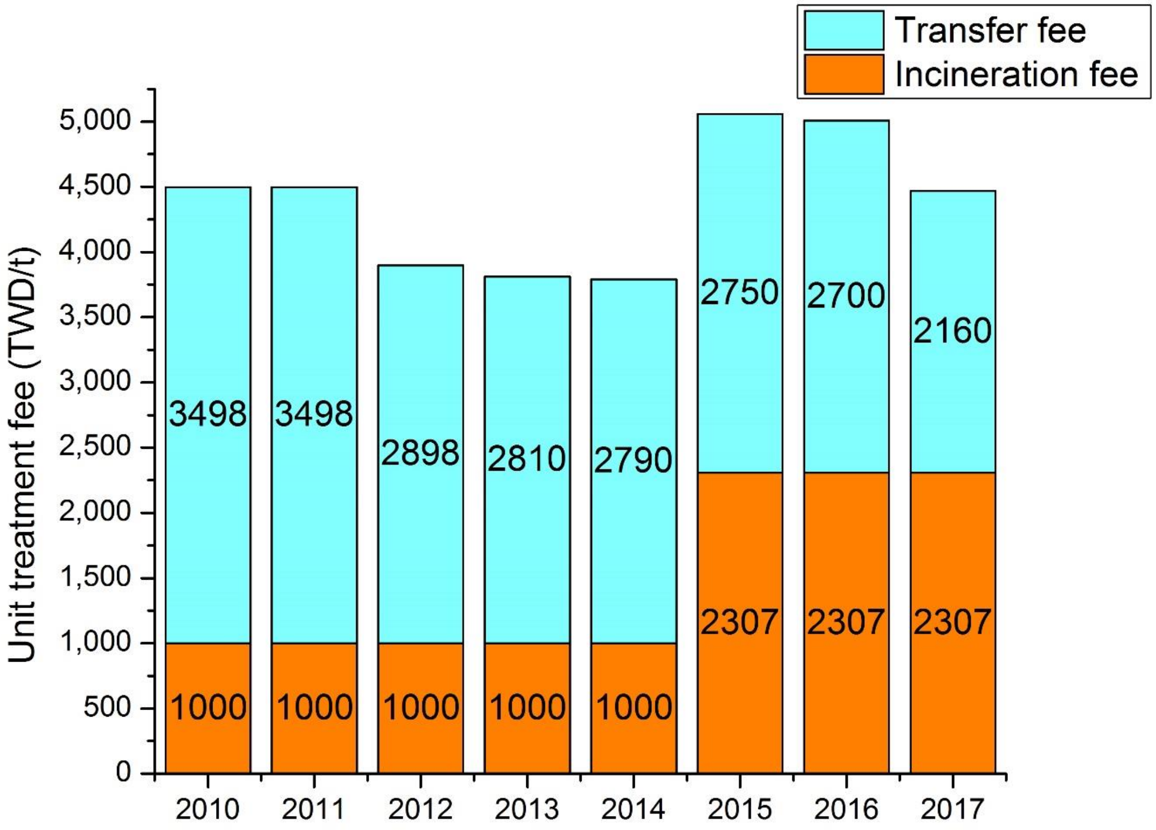


Figure 3.4 Unit treatment costs for case 1 from 2010 to 2017

Table 3.6 details the transportation cost for case 2 and case 3. Weight reduction and change of shipping distance contribute much to the transportation cost reduction. Table 3.7 lists the unit costs of RDF production in case 2, case 3, and case 4. The cost of treating 1 ton of waste by RDF production is 3,087 TWD, producing 0.44 ton of RDF, which means the production of 1 ton RDF is 7,015 TWD. A sensitivity analysis is done to reveal the uncertainties in the cost components. The factors considered in sensitivity analysis are listed in Table 3.8. The sensitivity analysis results are shown in Figure 3.5. The possible treatment cost is in the range of 2,691 to 3,483 TWD/t-waste. The crude oil price and crude oil consumption have the highest effects on the unit treatment cost. The life span of the RDF production plant is also considered as an important factor.

Table 3.6 The detailed comparison of transfer fee for case 2 and case 3.

	unit cost (TWD/t-waste)	
	Case2	Case 3
Local road transportation	178	178
Sea transportation	253	59
Treatment destination road transportation	75	88
Subtotal	506	322

Table 3.7 The unit costs of RDF production

	Capital cost (TWD/t)	**Personnel cost (TWD/t)**	**O/M cost (TWD/t)**	**Subtotal (TWD/t)**
RDF production	985	328	1,774	3,087

Table 3.8 Sensitivity analysis variables

	Low	**Base**	**High**
Plant life span (year)	15	20	25
Interest rate (%)	1	1.375	1.50
Electricity consumption (kWh/t)	107.5	153.6	199.7
Electricity Price (TWD/kWh)	1.72	2.45	3.19
Crude oil consumption (L/t)	66.1	94.4	122.7
Crude oil price (TWD/L)	10	14	18
Salary (TWD/month/person)	23500	28500	33500
Maintenance fee	1%	1.5%	2%

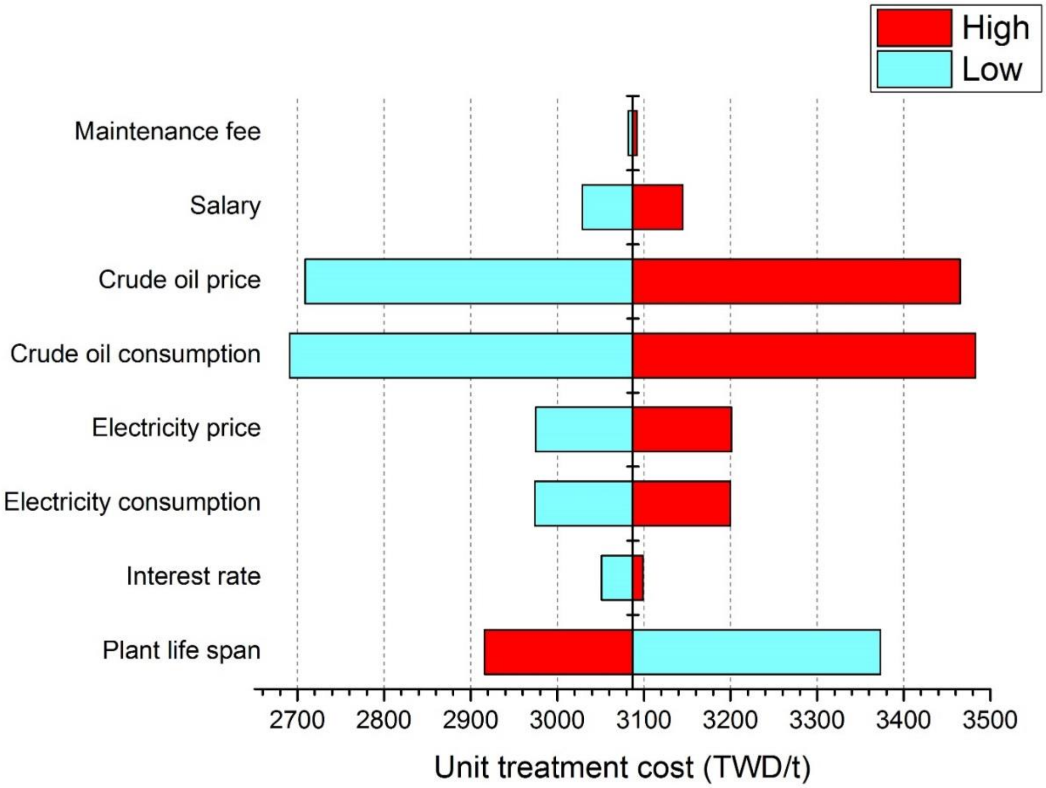


Figure 3.5 RDF production unit cost sensitivity analysis results

3.3.2 CO_2 emissions estimation results

The comparison of CO_2 emissions of cases 1, 2, and 3 are shown in Figure 3.6. For case 1, the highest CO_2 emission happens during the incineration process. The detailed life cycle inventory analysis results of case 1 are shown in Table 3.9. During the waste transfer processes, the long-distance sea transportation is the most fuel consuming process, and next followed by the compression and packing process. For all the process of the waste transfer before entering incineration, the CO_2 emission is 29.9 kg-CO_2/t-waste. The electricity generation by incineration provides an emission prevention of 352.13 kg-CO_2/t-waste, which is more than 11 times greater than the CO_2 emission of waste transfer processes. From this comparison, it is obvious that the environmental benefit considering CO_2 emissions prevented by energy generation can surpass the CO_2 emissions during the transfer process.

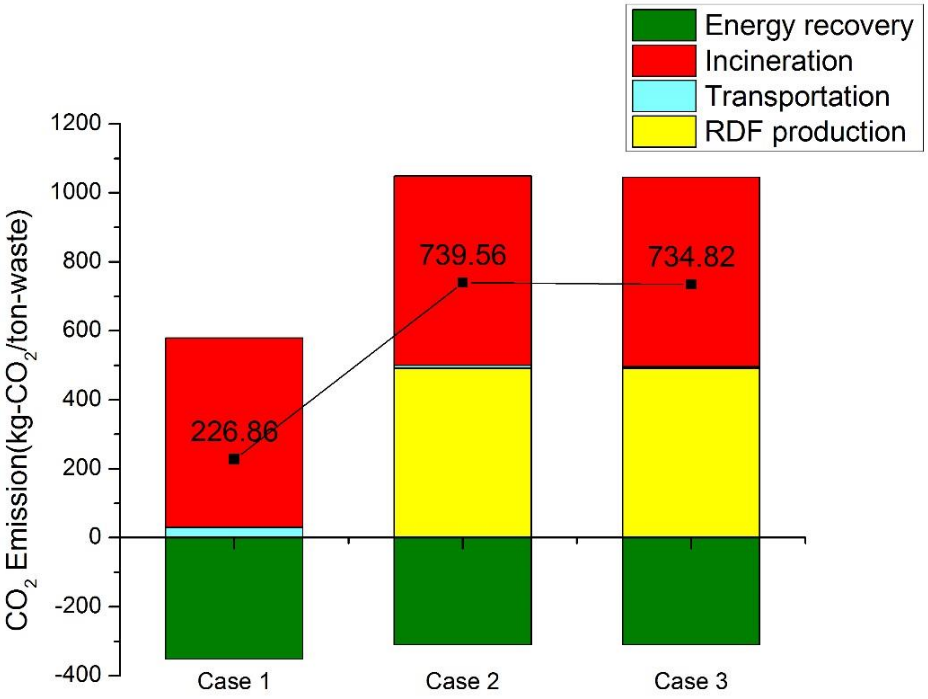


Figure 3.6 The CO_2 emission comparison among case 1, 2, and 3

Table 3.9 Life cycle inventory analysis result of case 1

	Input item	**Value**	**CO_2 emission (kg-CO_2/t-waste)**
Compression and Packing	Diesel oil (L)	2.65	9.14
Road transportation (Kinmen)	Diesel oil (L)	0.138	0.48
Sea transportation	Diesel oil (L)	4.01	13.83
Road transportation (Kaohsiung)	Diesel oil (L)	1.863	6.43
Incineration (Kaohsiung)	Diesel oil (L)	0.94	3.24
	Electricity (MJ)	414	79.49
	General waste (t)	1	465.00
Transportation of ash	Diesel oil (L)	0.16	0.55
Landfill	Diesel oil (L)	0.24	0.83
Subtotal			578.99
Emission prevented	Electricity (MJ)	-1834	-352.13
Total			226.86

Table 3.10 shows the life cycle inventory analysis result of the case 2. The CO_2 emissions shown in this table are all in unit of kg-CO_2/t-waste. For case 2 and case 3, the RDF production is a high energy-consuming process and requires usage of crude oil and electricity, which in total contributed to generation of equivalent 481.89 kg-CO_2/t-waste. The high crude oil consumption is required in the drying process and the deodorizing process. By utilizing RDF in incineration plant, 1615 MJ/t-waste of electricity can be generated per ton of input waste, which can provide emission prevention of 310.08 kg-CO_2/t-waste. Although the energy recovery is possible by RDF utilization, it is difficult for the emission prevented to surpass the emissions during the RDF production process, because of the high consumption of crude oil. The CO_2 emissions for case 3 is almost the same as case 2, only the emissions from sea transportation process are lower than for 3.7 kg-CO_2/t-waste for case 2.

Although the case 3 is a cost effective option, the CO_2 emissions are higher than case 1. Comparing three cases with direct incineration without energy recovery in Kinmen, which produces CO_2 emissions of 549.11 kg-CO_2/t-waste, case 1 is lower, and both case 2 and case 3 are higher. Case 2 and case 3, the RDF production plant cases, are difficult to be environmentally beneficial due to high emissions in RDF production process.

Table 3.10 Inventory analysis results for case 2

	Input item	**Value**	**CO_2 emission (kg-CO_2/t-waste)**
RDF production	Crude oil (L)	94.4	375.71
	Electricity (MJ)	553	106.18
Transportation of residual	Diesel oil (L)	2.5	8.63
landfill of residual	Diesel oil (L)	0.235	0.81
Transportation of RDF	Diesel oil (L)	2.38	8.21
Utilization of RDF	Diesel oil (L)	0.94	3.24
	Electricity (MJ)	414	79.49
	RDF (t)	0.44	465.00
Transportation of ash	Diesel oil (L)	0.16	0.55
Landfill	Diesel oil (L)	0.24	0.83
Total			1041.48
Emission prevented	Electricity (MJ)	-1615	-310.08
Total			731.40

3.3.3 RDF production and shipment to other destinations

The cost and emission analysis of shipping to countries within 6000 km from Kinmen are shown as case 4. The distances from Kinmen to the main ports of these Asian Pacific countries are shown in Table 3.11. One main port of every country is listed as a potential destination for evaluation. However, China has many main ports and big cities with different distances within this range, so more than one ports are included. For cost estimation, the RDF production cost is assumed to be constant. The sea transportation cost is the linear projection of shipping distance. For the RDF utilization process, it is possible for the RDF to be treated with paying a gate fee, or be sold to gain revenue. RDF gate fee of 2000 TWD/t, 1000 TWD/t, and zero gate fee, and RDF selling price of 400 TWD/t and 800 TWD/t are considered.

The cost analysis results of different shipping distances and RDF utilization costs are shown in Figure 3.7. The X-axis represents the shipping distance, and the Y-axis represents the unit waste treatment cost. Different colored lines represent the different cost for RDF utilization process. Positive value means RDF gate fee charged by a receiver, and negative value means the RDF selling price paid by the receiver. The cost estimation values of case 1, case 2, and case 3 are shown by the horizontal dot lines for comparison. The values in the figure show the distance to the ports where the cost is same as case 1 to case 3. As shown in the figure, for zero gate fee, RDF selling price 400 TWD/t, and RDF selling price 800 TWD/t, the unit cost is possible to be lower than case 3 when shipping distance is shorter than 539 km, 741 km, and 943 km, respectively. For RDF gate fee of 2000 TWD/t and 1000 TWD/t, the unit cost is higher than case 3, but it will be lower than case 1 when shipping distance is shorter than 268 km and 770 km, respectively.

Table 3.11 Distance to the main ports in Asia Pacific from Kinmen

	Distance (km)
Xiamen, China	43
Quanzhou, China	72
Kaohsiung, Taiwan	291
Hong Kong	544
Naha, Japan	1011
Shanghai, China	1083
Manila, Philippines	1241
Haiphong, Vietnam	1361
Busan, Korea	1596
Dalian, China	1804
Osaka, Japan	2056
Singapore	3061
Bangkok, Thailand	3072
Tanjung Pelepas, Malaysia	3095
Jakarta, Indonesia	3600
Darwin, Australia	4445
Yangon, Myanmar	5106
Moresby, Papua New Guinea	5652

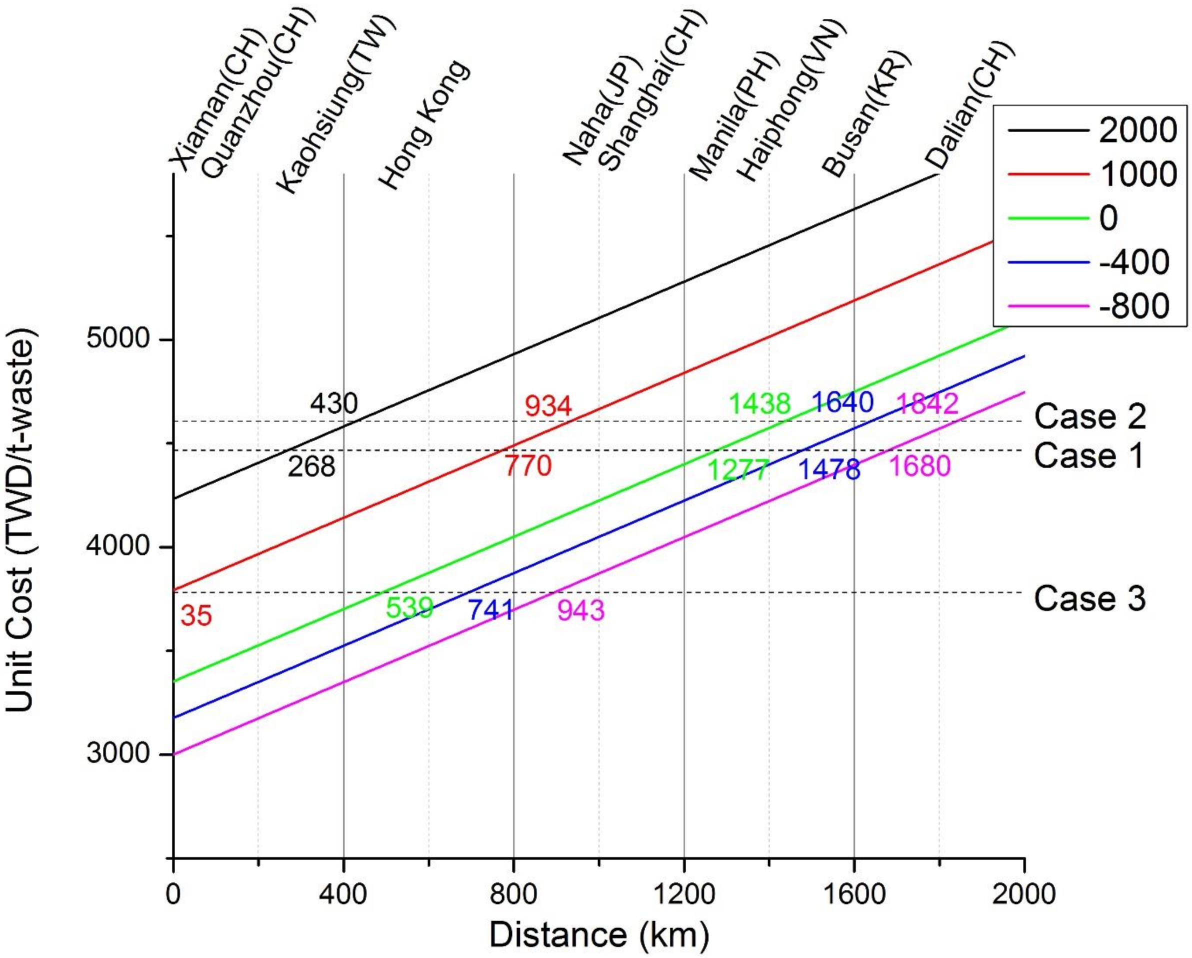


Figure 3.7 The cost analysis results of case 4; The different color lines represent different RDF gate fee or selling price. The place names listed on the tops represent the corresponding possible shipment destinations

In case 2 and case 3, the high fuel and electricity consumption from RDF production process is the main cause for high CO_2 emissions. In the literatures, lower CO_2 emission from RDF production process is reported, and some values are 299.9 kg-CO_2/t-waste[21], 187.8 kg-CO_2/t-waste[115], and 97.9 kg-CO_2/t-waste[165]. Comparing these values to the LCI analysis results in the present study, it is realized that the reduction of CO_2 emissions from the RDF production process is achievable. In the emission analysis, the emissions from RDF utilization process are assumed to be constant. The emissions from RDF production is assumed to be 600 kg-CO_2/t-waste, 450 kg-CO_2/t-waste, 300 kg-CO_2/t-waste, and 150 kg-CO_2/t-waste as RDF A, RDF B, RDF C, RDF D, respectively. The emissions from sea transportation is determined with a linear equation of shipping distance. The emission prevented are calculated based on power generation by incineration plant with energy efficiency of 18%, and RDF as a substitutional fuel to coal to generate heat and steam with energy efficiency of 80%. RDF utilization by incineration contributes to emission prevention of 310.08 kg-CO_2/t-waste, while RDF utilization as a substitutional fuel to coal contributes 336.36 kg-CO_2/t-waste.

The results of CO_2 emission analysis are shown in Figure 3.8. The emission values of case 2, case 3, and incineration without energy recovery are shown by the horizontal dot lines for comparison. The values in the figure show the distance where the emission is same as these three cases. For the results of the RDF utilization in incineration, it is shown that if operating as RDF D, RDF production emission of 150 kg-CO_2/t-waste, the total CO_2 emission of whole system will be lower than direct incineration without energy recovery. For RDF C, the total emission will be higher than direct incineration without energy recovery, but it will be lower than case 2 and case 3. For RDF B, the emission is lower than case 3 when shipping distance shorter than 2649 km, and for RDF A, the emission is higher than case 2 and case 3 for all shipping distance. For results of RDF utilization as substitutional fuel, it is shown that RDF C and RDF D are able to have emissions lower than incineration without energy recovery, and RDF B can be lower emission than case 2 and case 3.

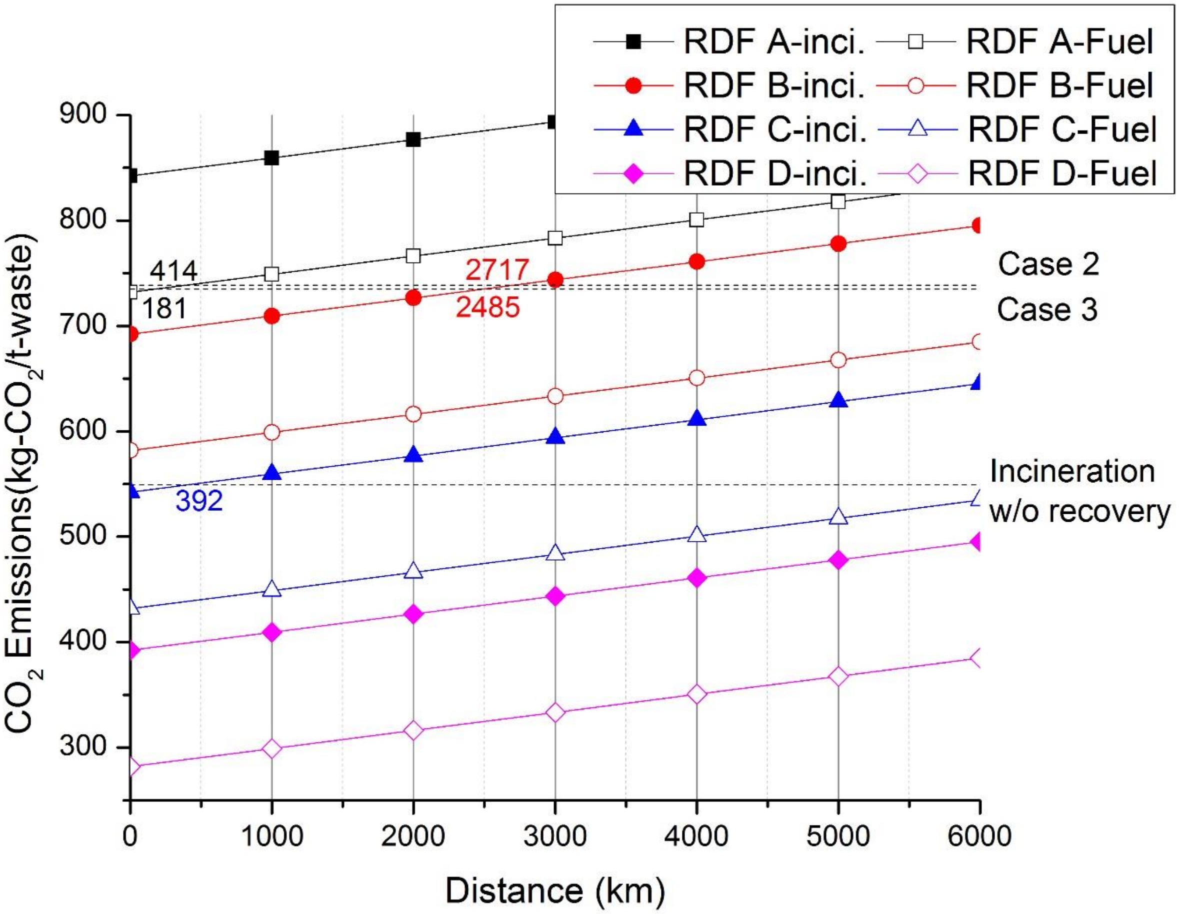


Figure 3.8 The emission estimation result of case 4. The different color lines represent different RDF production plants generating different amount of CO_2 emission during the RDF production process, while the lines with filled symbols represents RDF utilization in incineration and the lines with unfilled symbols represents RDF utilization as substitutional fuel

Setting the cost of case 1 as the cost baseline, and the CO_2 emissions from incineration without energy recovery as the emissions baseline, the cost lower than cost baseline can be seen as cost-effective and emissions lower than the emission baseline as environmentally beneficial. Figure 3.9 can be created to reveal the important factors for the cost effective or environmentally beneficial waste treatment strategy for small island communities. The red area, following the left Y-axis, represents the condition for the RDF shipment to be cost-effective than case 1. The green area and yellow area, following the right Y-axis, represents the condition for the RDF shipment to have lower total CO_2 emissions than incineration without energy recovery, while green area represents RDF utilization in incineration and yellow area represents RDF utilization as substitutional fuel.

The possible cost effective and environmentally beneficial waste management strategy criteria are shown in the figure. For giving RDF shipping destination with its shipping distance and RDF gate fee, and knowing the CO_2 emission of RDF production, plot on this phase chart can be located. By the location of the condition, the cost effectiveness and environmental performance of the choice of RDF destination can be realized.

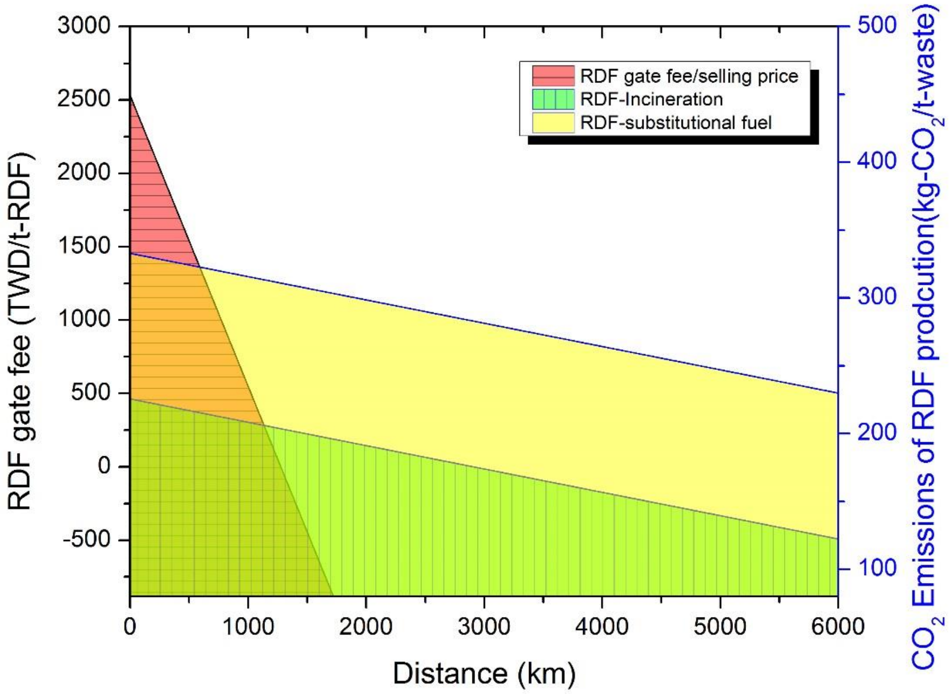


Figure 3.9 The cost effective and environmental beneficial determining methodology derived from the result of case 4

Figure 3.10 revealed the flowchart for analyzing the WTE strategies of small islands under the results and analyzing processes of this study. The WTE strategies considered here included incineration with energy recovery, RDF production and RDF utilization, because of this study focuses on the treatment of combustible waste. The flow starts from the waste generation amount. If the waste generation amount in the island is larger than 200 t/day, an inside island incineration plant with energy recovery is a feasible option. If not, consider the domestic incineration plant availability. For the case like Taiwan, Japan, Thailand or other countries with similar geographic conditions, which includes small islands with other bigger islands or land area, the domestic waste shipment for incineration may be an option. However, cost is a problem requiring consideration under this case. If shipment to domestic incineration is not available or cost is not acceptable, RDF production holds the potential to make WTE in small islands possible. After RDF production, consider RDF utilization destination. Local utilization is the most feasible option, but if it is not available, the analysis of RDF utilization destination can be applied to determine the preferable shipping destination.

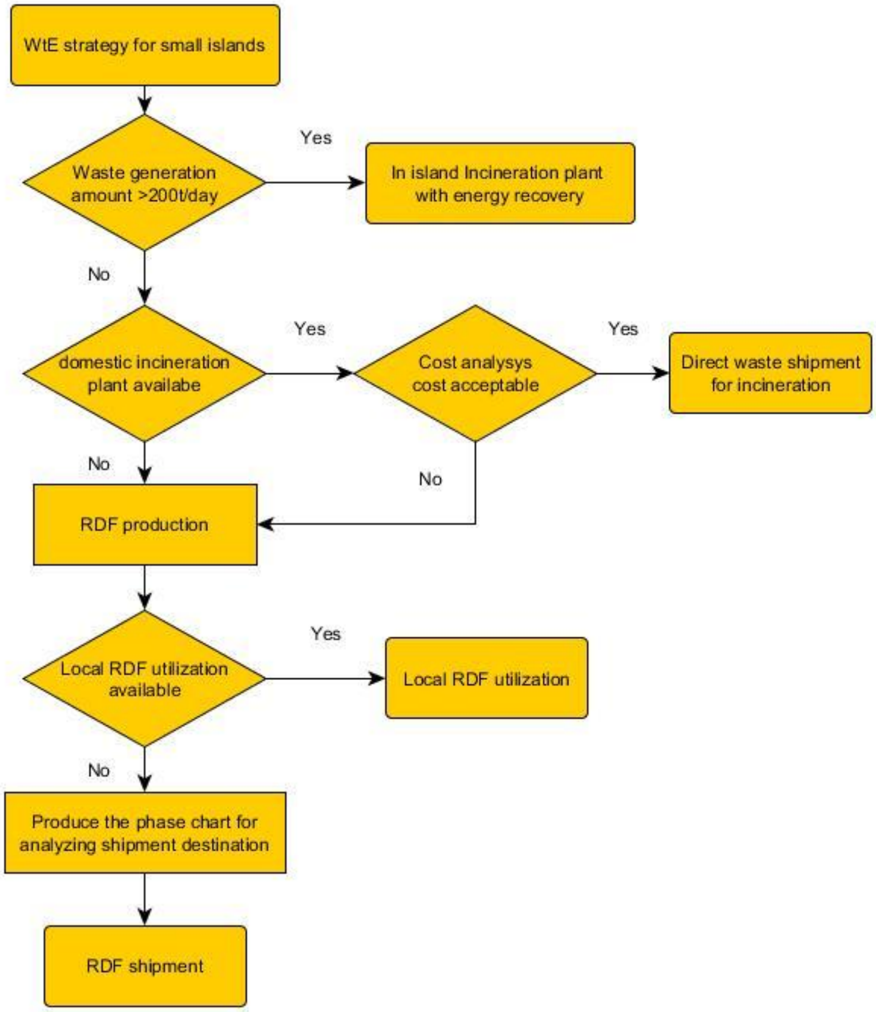


Figure 3.10 Flowchart for analyzing the WTE strategies of small islands

3.4 Conclusion

A cost and environmental assessment of waste shipments for energy recovery in small islands by the case study of Kinmen, Taiwan is studied. The results revealed current waste transfer system in Kinmen is costly, but considering the total CO_2 emissions, it is environmentally beneficial because energy recovery can be realized. Transforming combustible waste into RDF provides opportunities for more shipment destination. Shipment to places with shorter shipping distance and lower incineration gate fee can reduce the treatment cost. However, the high emissions from RDF production process is difficult to be surpassed by emission prevented by energy recovery. By technology improvement and higher quality of input waste material, the emissions from RDF production process can be reduced, and the reduced emission can result in positive environmental impact over no energy recovery case. Shipping distance, RDF gate fee/selling price, and emission from RDF production are the biggest factors affect the cost and emission of the waste treatment system. The choice of RDF shipping destination with cost-effectiveness and reduced environmental impact can be evaluated by the methodology shown in this study. A generalized flowchart for analyzing the WTE strategies of small islands is proposed for the needs of islands sustainable decision for waste management.

Chapter 4 Recycling of End-of-Life Vehicles in small islands

4.1 Introduction

The vehicle ownership over the world has increased greatly in the past few decades, which resulted in a rapidly growing number of end-of-life vehicles (ELVs)[166]. ELV contains large amounts of secondary resources, and recycling of these materials can contribute to the conservation of usage of primary materials, which can further reduce the energy use and emissions of greenhouse gases[167]. The improper management of ELVs may cause severe environmental problems by lead batteries, refrigerant gases, mercury, and mechanical oils[168]. The poor treatment of ELVs may also cause heavy metal soil pollution[169] and groundwater pollution[170]. The legislation on ELV recycling exist EU, Japan, Korea, China and Taiwan, but in many countries and regions where automobile ownership is rapidly increasing, the recycling systems and policies are not yet established[168]. Developing countries are lagging in the establishment of legislation due to economic and social circumstances, but the environmental awareness and depletion of natural resources have driven many of these countries in adapting strategies towards sustainable management of ELVs[171].

Furthermore, in small islands, the recycling is more difficult and the abandoned vehicle problem is especially serious due to the absence of local ELV treatment business and high shipment fee in removing the ELVs. Shioji reported the problem of abandoned vehicles problem in Pacific Ocean islands countries[172]. His study revealed that the smallness, remoteness and scatteredness of these island countries make the scrapping and recycling business unprofitable. These problems are faced not only for island countries, but countries with small surrounding islands also faced similar problems. Smink reported the vehicle recycling regulations in Denmark and mentioned that the abandoning of ELV in its small islands had become a serious problem[173]. Hiratsuka et al. reported the current status in ELV recycling in Japan[174]. It is also mentioned that the illegal dumping of ELV is especially serious in the remote islands because of the additional cost of the marine transportation of ELVs[175]. However, the number of abandoned ELV has decreased significantly owing to the subsidy policy. All these reports and studies have shown that management strategy for ELVs in small island territories is necessary.

ELV treatment has some similarity with other solid waste treatment, and several researches have been done to investigate the waste management situations and strategies in small island communities. However, most of the works are focusing on treating the municipal solid waste or organic waste. There are three review papers focusing on the small island waste management [63, 66, 93], but the works they reviewed did not contain any study on ELV problems in small islands. The review papers implied that the common difficulties of waste management in island territories are lack of available land, lack of capital, high operational costs, and insufficient quantities for economies of scale. The same situation can also be seen in ELV treatment cases. In small islands, the goods are usually imported, and the resources accumulate easily inside without proper treatment. Eckelman and Chertow investigated the material flow in Oahu, Hawaii, and they revealed that 76% of material input was from imports and 71% of material input came to additions to stock[66] Owens et al. reported that in Kayangel Island, 93% of the solid waste end-up accumulated inside the island[84]. This situation is more serious in ELV treatment since treating the ELVs requires the existence of several relating industries, and moving out of vehicles for treatment is more expensive than moving out other resources.

Taiwan has developed the ELV recycling regulation for 20 years, and the ELV recycling rate has increased to 95% in 2009 including the thermal recovery[176]. However, the recycling rate reported here is the percentage of recycled or recovered materials in the ELVs in the formal recycling flow. The recycling rate of the ELVs in the informal recycling sectors is unclear, and the informal flow is significant in some specific areas. Chen et al. reviewed the development of ELV recycling system in Taiwan[127]. They reported the role of Recycling Fund Management Board (RFMB) for the establishment for the ELV recycling system in Taiwan, and pointed out that RFMB needs to provide strong economic incentives to further increase the recycling rate. Cheng et al. evaluated operation performance of ELV operators in Taiwan[126] and suggested that the improvement of the operational performance is expected in the future. However, these studies only focused on the overall policy and performance, and the regional differences and treatment difficulties in rural areas were not mentioned.

Despite the high development in ELV recycling in Taiwan, in its island communities, the management of ELV is facing problems due to its growing population and growing tourism industries. This leads to a growing amount of ELV generation over the current treatment capacity in the future. Besides, in the case of Taiwan, the vehicle usage style in islands is usually different from other places, which resulted in different disposal pattern. For example, due to the geographic limitation, the driving distance is limited, which makes the lifespan of vehicle longer. On the other hands, due to short distance usage, purchasing of second-hand vehicles is more popular than buying new cars. Small islands have also become an export destination of other places. Finally, due to the remoteness and requirement of marine transportation, the ELV is easily accumulated inside islands without proper treatment.

To study the ELV problem in island communities, Kinmen, Taiwan, was selected as a case study. Kinmen has the local ELV collecting system, dismantling business and ELV treatment capacity[145]. However, the aforementioned ELV problems, such as increasing ELV generation amount, insufficient treatment capacity, unutilized material stocks, and abandoned vehicle problems, are also happening in Kinmen. To solve these problems and improve the ELV treatment system, an investigation about the island ELV treatment is necessary.

With these motivations, the objective of this study is to clarify the island ELV problem by applying material flow analysis and economic analysis to the ELV treatment system in the case of Kinmen. The first step in this study is to quantify the ELV generation amount in Kinmen, and identify different trends of ELV generation between Taiwan and Kinmen. Secondly, we categorize the formal and informal flows of ELVs, and reveal the material contents in informal flows and potential economic gain from these materials. Thirdly, we conduct economic characterization of the local dismantling business. Finally, we propose policy recommendations for treatment strategies to the Kinmen case.

4.2 Materials and methodology

4.2.1 Background of the ELV treatment in Kinmen

The ELV treatment process in Kinmen is shown in Figure 4.1. The process (a) represents the generation of ELVs, and the process (b), including three sub-processes, represents the treatment of ELVs by the certificated recycling operators. Under the policy of Environmental Protection Administration (EPA) of Taiwan, a certificated dismantling company can get subsidies by conducting the environmental pretreatment, which includes removing oil, tires, battery and coolant. After the environmental pretreatment, the dismantling business will remove the reusable parts, which can be sold to customers or vehicle related businesses. The remaining metal scraps and vehicle hulk will be sent to recyclers and shredding plants.

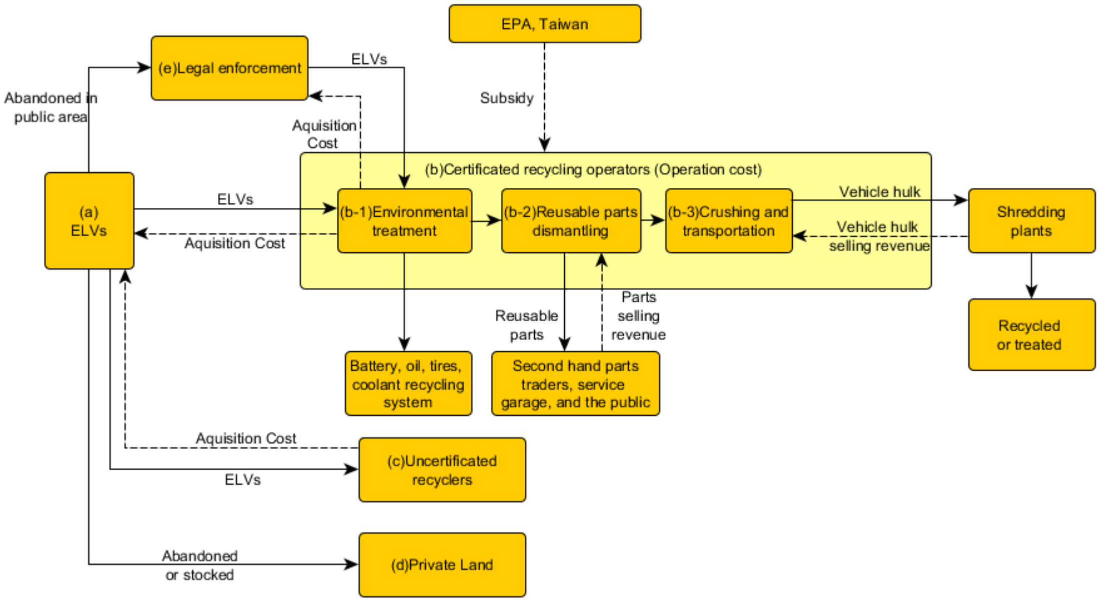


Figure 4.1 ELV treatment process in Kinmen. Dashed lines represent monetary flows and solid lines represent material flow.

Figure 4.1 also revealed the informal flows of the ELV, including (c) treated in the uncertificated recyclers, (d) stocked in private land, and (e) abandoned in public area. According to the report of RFMB, there are 207 certificated dismantlers in all 306 businesses in Taiwan, while in Kinmen there is only one in three [177], that is 68% and 33% in Taiwan and Kinmen, respectively. This difference revealed that the flow into the uncertificated recycling business is more significant in Kinmen. The uncertificated recycling operators are not required to do the environmental pretreatment and may have lower control of hazardous materials. The improper treatment may cause environmental pollution. On the other hand, the recycling and recovery of the secondary resources can contribute to environmental benefits such as energy consumption reduction and conservation of primary resources. These environmental benefits from the recycling and recovery may also be lost due to lower recovery rate in the informal flows.

EPA also reported the abandoned vehicle problem in Kinmen[178], and mentioned that 11 vehicles related businesses have accumulated ELVs in either public land area or private land area. The abandoned vehicles in public land areas can be treated by legal enforcement. The Road Traffic Management and Penalty Act[179] states that “Abandoned vehicles occupying roadways shall be cleaned away by their owners within a designated time period upon notification by police authority after being reported by the general public, the police authorities, or the competent environmental protection authorities.”. However, the ELVs accumulated in the private areas cannot be removed by this policy. The number of illegal abandoned vehicles in public area are reported by EPA, Taiwan[141]. By defining that the ratio of abandoned vehicle number to the total registered vehicle number as the abandoned vehicle rate, the values of Taiwan and Kinmen are shown in Table 4.1. The data revealed that the abandoned vehicle is happening at a higher percentage in Kinmen compared to Taiwan overall. For the quantity of the flows shown in Figure 4.1, the amount of (b) certificated recycling operator is 1,106 units of automobiles and 2,251 units of motorcycles, and amount of the (e) abandoned vehicles is 138 units of automobiles in 2017. The flows into (c) and (d) are defined as informal sectors, and the quantification of the material flows of the informal sectors is shown in the following sections. Only passenger cars and motorcycles are evaluated. Other types of vehicles such as trucks or buses are excluded. New generation vehicles such as electric vehicles or hybrid vehicles are also excluded due to low current penetration rate.

Table 4.1 The abandoned vehicle rates comparing Taiwan and Kinmen.

	Automobile	**Motorcycle**
Taiwan	0.045%	0.207%
Kinmen	0.135%	0.139%

4.2.2 ELV generation estimation by population balance model

There are statistical reports about the ELV collection amount in Taiwan, but the data for Kinmen and the generation amount is not clear. To quantify the number of ELVs generated from process (a) in Figure 4.1, we estimated the amount of ELV generation by population balance model (PBM) developed by Tasaki et al.[122], which is applied in many researches[121, 180, 181]. The PBM method estimated the future generation amount of waste durable goods by shipment number, possession number and lifespan distribution. The main calculation processes are shown as followings.

$$f_t(i) = F_t(i) - F_{t-1}(i-1) \tag{4.1}$$

$$W_t(y) = 1 - \exp\left\{ -\left[\frac{y}{y_{av}} \right]^b \cdot \left[\Gamma\left(1 + \frac{1}{b} \right)^b \right] \right\} \tag{4.2}$$

$$F_t(i) = W_t(i + 0.5) \tag{4.3}$$

$F_t(i)$ is the cumulative lifespan distribution, which represents the percentage of the products reached end-of-life from the shipment year $t-i$ to the end of year t (in other words, reached end-of-life of age i. $F_{t-1}(i-1)$ is the percentage of products that reached end-of-life from the shipment year $(t-1)-(i-1)=t-i$ to the end of year t-1. The difference of $F_t(i)$ and $F_{t-1}(i-1)$ is the products shipped in year $t-i$ that reached end-of-life in year t, represented by $f_t(i)$ as lifespan distribution in Eq. (4.1). There are several methods of estimating the lifespan distribution. Weibull distribution is widely used for fitting the lifespan distribution and its applicability is proved in researches[119, 120]. Weibull distribution is used to express the cumulative discard rate $F_t(i)$ as shown in Eq. (4.2), where y is the product age adjusted by putting y in the middle of the year i (i.e. $y = i + 0.5$) as shown in Eq. (4.3), while y_{av} is the average life span, b is the distribution shape parameter, and Γ is the gamma function.

The distribution shape parameter *b* here is set to be 3.6 as a constant, because a research proved that setting the shape parameter as 3.6 has little effect on the estimation result of waste generation number[182]. The lifespan of the vehicles in Taiwan is calculated from the possession number of the vehicle categorized by age, with the data provided by the Ministry of Transportation and Communications (MOTC), Taiwan. The average lifespans of the vehicles in Taiwan and Kinmen are both 18 years[183].

$$F_t(i) = 1 - \left(\frac{N_{t,t-i}}{P_{t-i}} \right) \tag{4.4}$$

$$N_t = P_t + \sum_{i=1} \left[P_t \cdot \{1 - F_t(i)\} \right] \tag{4.5}$$

$$G_t = \sum_{i=1} \{ P_{t-i} \cdot f_t(i) \} \tag{4.6}$$

$$P_t = N_t - N_{t-1} + G_t \tag{4.7}$$

$F_t(i)$ can also be represented as the discard rate as Eq. (4.4), where $N_{t,t-i}$ represents the ownership number of products in year t with shipment year of $t-i$, and P_{t-i} represents the total shipment number in year $t-i$. N_t is the ownership number of products in year t, and the calculation of it is shown in Eq. (4.5). Using the lifespan distribution analysis, the discard rate can be calculated, then the quantity of the end-of-life product amount, G_t, can be calculated by Eq. (4.6). The future shipment number, P_t, can also be calculated by Eq. (4.7).

The vehicle ownership number before 2017 is the statistical data collected from MOTC, Taiwan[183]. The future ownership number is calculated by population multiplied to vehicle ownership per capita, while the future population projection is done by National Development Council[184] and the vehicle ownership is assumed to be saturated[185]. The shipment number is set as the sales number in the domestic market, which is in detail the domestic production subtracted exports and adding imports. The data is available in MOTC[183] and Taiwan Transportation Vehicle Manufacturer Association (TTVMA)[186]. In this part, not only the result of Kinmen is estimated, but also the result for Taiwan overall. This is to reveal the difference of trend in ELV generation amount between Kinmen and Taiwan. The estimation period is 1960-2050.

4.2.3 Material contents in informal flows of ELVs

Based on the ELV generation amount estimated by PBM and by knowing the treatment capacity of the existing dismantler in Kinmen, we assumed that the ELV generation amount beyond the dismantler treatment capacity is the untreated ELV number. By multiplying the value of the untreated ELV number to the weight composition of each vehicle type, we can obtain the material contents in the informal flow, as shown in Eq. (4.8), where MF_i represents the flow of material i in the informal sectors, G_t represents the ELV generation in year t, C represents the treatment capacity of the dismantler, and w_i represents the weight composition of material i in ELVs.

$$MF_i = \left(G_t - C\right) \cdot w_i \tag{4.8}$$

For the weight composition, we used the data of the weight composition of the ELVs in Taiwan investigated by Liu et al.[176], and the details are shown in Table 4.2. The engine oil, tire, battery and coolant, which require removal at the first stage of dismantling, are the four items causing environmental pollution. Iron, aluminum, and copper, which enter the secondary resources recovery plants after dismantling or shredding, are the items with market value. Plastic, glass, foam and others are not be recycled under the current ELV management system in Taiwan. These materials are seen as the residues of the ELV system, and they are treated in incineration for energy recovery or sent into landfill sites.

Table 4.2 The weight composition of the ELVs in Taiwan used in this study[176]

Materials	**Automobiles**		**Motorcycles**	
	Weight(kg)	**Percentage**	**Weight(kg)**	**Percentage**
Engine oil	6.0	0.58%	0.7	0.77%
Tire (Rubber)	27.3	2.64%	3.5	3.85%
Battery	12.0	1.16%	2.4	2.64%
Coolant	0.5	0.05%	-	-
Iron	671.0	64.89%	44.8	49.28%
Iron(engine)	149.9	14.50%	19.4	21.34%
Aluminum	40.6	3.93%	2.3	2.53%
Plastic	31.8	3.08%	10.9	11.99%
Glass	37.5	3.63%	-	-
Foam	14.8	1.43%	0.8	0.88%
Wires(Copper)	4.3	0.42%	0.7	0.77%
Others	38.3	3.70%	5.4	5.94%
Subtotal	1034		90.9	

4.2.4 Economic analysis

The potential economic gain of the untreated material flow is calculated in this part to reveal the potential of recycling for contribution to the local economy. The calculation of potential economic gain of material *i*, EG_i , is shown in Eq. (4.9). By multiplying the flow of material i , MF_i, to its market unit price, UP_i , the potential economic gain of material i can be obtained.

$$EG_i = MF_t \cdot UP_i = \left[\left(G_t - C \right) \cdot w_i \right] \cdot UP_i \tag{4.9}$$

The unit price of the materials contained in ELVs used in this study are shown in Table 4.3. For the metal scraps, the unit price may be fluctuating, but here we use the constant number for simplification. In the collected ELVs, there are some parts can be directly sold to second hand parts traders, service garage, or the public for reuse. These parts mainly include automobile exhaust catalysis, engine, gearbox, alternator, starter motor, head-lamp assembly, etc. However, the unit price of reusable parts of automobiles and motorcycles has huge difference due to different usage situation. The unit price of the reusable parts used here is calculated by dividing the average selling price by the average selling weight of the parts in both automobiles and motorcycles to make the units of all materials same.

Table 4.3 The unit price of the materials contained in ELVs used in this study[187]

Material	**Unit Price (TWD/kg)**
Iron	6.8
Aluminum	50
Copper	100
Reusable parts (Automobiles)	3.9
Reusable parts (Motorcycles)	4.5

On the other hand, the cost and revenue evaluation of certificated dismantler, seen in Figure 4.1 process (b), is also studied. The costs of the dismantling business can be categorized into acquisition cost, operation cost, and transportation cost. The evaluation is based on the interview with the dismantling company combined with some literature data. The acquisition cost of a vehicle is based on the market price reported in Taiwan in 2017[188]. The operation cost is the combination of maintenance cost and personnel cost, while reported data is used as the maintenance cost, which includes the land fee, factory maintenance, electricity use, and residue disposal[176]. The personnel cost is calculated by the local salary multiplied by the required time for dismantling reported[187]. The transportation cost is calculated based on the weight of the material multiplied by the shipment rate reported in a study about waste shipment[20].

The revenues of the dismantling business include reusable parts selling revenue, scraps selling revenue, and subsidies from the government. The former two revenues are calculated by the Eq. (4.9), while the subsidy from the government used the current value[127]. The subsidy from RFMB was the budget collected from the producers and the importers. In Taiwan, the current recycling system of ELVs is based on the "polluters pay principle (PPP)", which implies that the producers and importers are only obliged for paying the recycling fees to the RFMB, and the RFMB undertakes the recycling work[133].

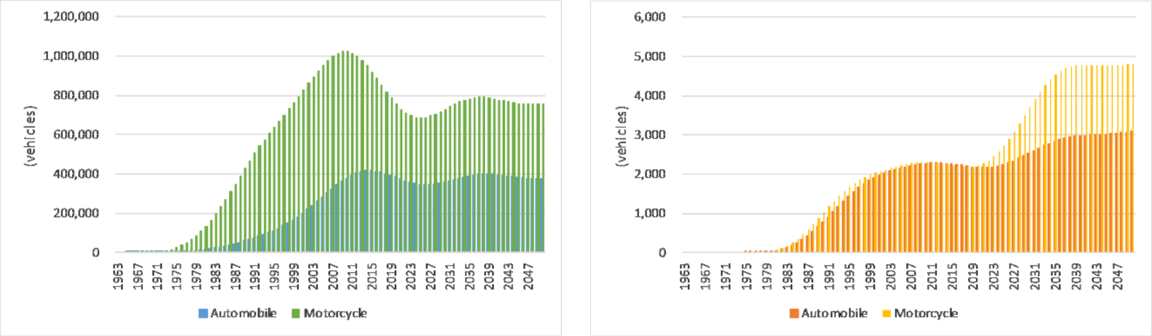
The recycling businesses can receive a recycling subsidy form RFMB for processing the ELVs. All the economic characterization result is shown as the cost or revenue of treating one vehicle.

4.3 Results

4.3.1 ELV generation amount estimation results

The ELV generation amount of Taiwan and Kinmen is shown in Figure 4.2. In Figure 4.2 (a), the end-of-life automobile generation amount in Taiwan has reached a peak in 2017, and it is slightly decreasing until 2027, and will become stable in the future. The main reason for this trend is that the automobile sales amount has the highest peaks in 1997 and 2007, which caused the highest ELV generation amount after 20 years. On the other hand, the population in Taiwan is going to be saturated in 2024 and starts to decrease. This also affects the future vehicles and ELV numbers. The results for end-of-life motorcycle is different from automobiles. The ELV generation peak happened in 2012, owing to the high motorcycle sales amount during 1987-1998. The registered motorcycle number is also decreasing since 2013. The ELV generation of motorcycle will become stable at about 800,000 units per year after 2023.

However, as shown in Figure 4.2(b), the island county of Kinmen has different ELV generation pattern comparing to Taiwan. Due to late development and recent high population growth, the registered vehicle numbers are continuously increasing in recent decades, which resulted in an increasing ELV generation amounts of automobiles. The ELV number will increase steadily until 2020 followed by a sharp increase until 2040. The ELV generation of motorcycle in Kinmen shows a similar trend to the automobile, which is continuously increasing from now on. The number will increase to more than 3,500 units/year in 2,029 and highest more than 4,800 units/year in 2050.



(**a**) (**b**)

Figure 4.2 ELV generation estimation results of (a)Taiwan and (b)Kinmen

4.3.2 Material contents in informal flows of ELVs

Material flows from ELV have been classified as items that (a) have market value, (b) require environmental pretreatment, or (c) residues. Iron scraps, aluminum scraps, copper scraps, and reusable parts that have a market value in the informal sectors can be seen in Figure 4.3. The ELV generation number of motorcycles are higher than automobiles, but considering on the weight basis, the amount of materials from the motorcycles is relatively small. Combining the total amount of automobiles and motorcycles, there will be 1,276 tons of Fe, 87.2 tons of Al, and 10.4 tons of Cu by the year 2050.

Rubber from tires, lead acid battery, coolants, and engine oil are the four items that are listed as required environmental pretreatment. They may caus a serious problem due to the presence of hazardous materials. Their total weight is amounting to 49.2 tons and 109.0 tons in 2020 and 2050, respectively, as shown in Figure 4.4.

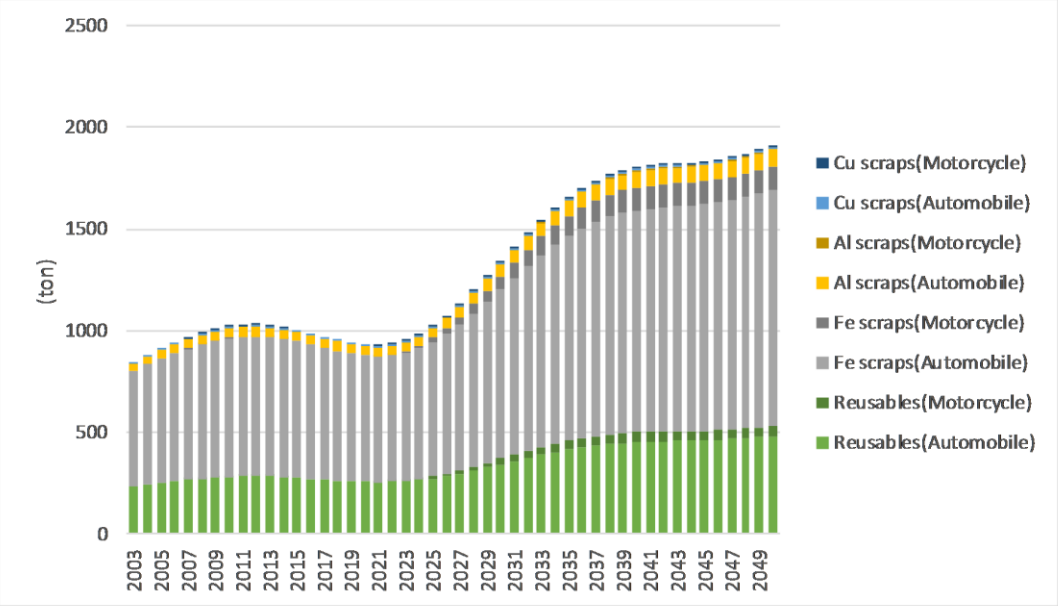


Figure 4.3 Informal ELV material flows with market value on weight basis

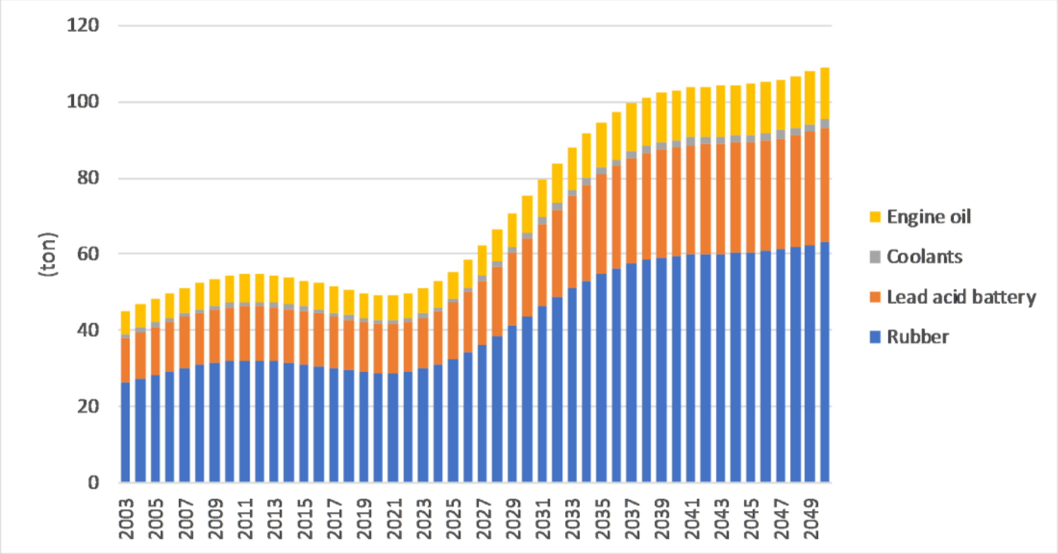


Figure 4.4 Informal ELV material flows require environmental pretreatment

4.3.3 Economy incentives for recycling and management

The potential economic gain embedded in untreated ELVs is shown in Figure 4.5. The potential economic gain from ELVs is bigger in automobiles than motorcycles. The highest amount is the revenue from Fe scraps, ranging from 4.16 to 9.38 million TWD from 2018 to 2050. The Al and Cu scraps are little in weight percentage, but considering the unit price, the amounts are still high. Al scraps and Cu scraps account for 4.3 million and 1 million, respectively. Utilization of this amount can contribute to the island economy.

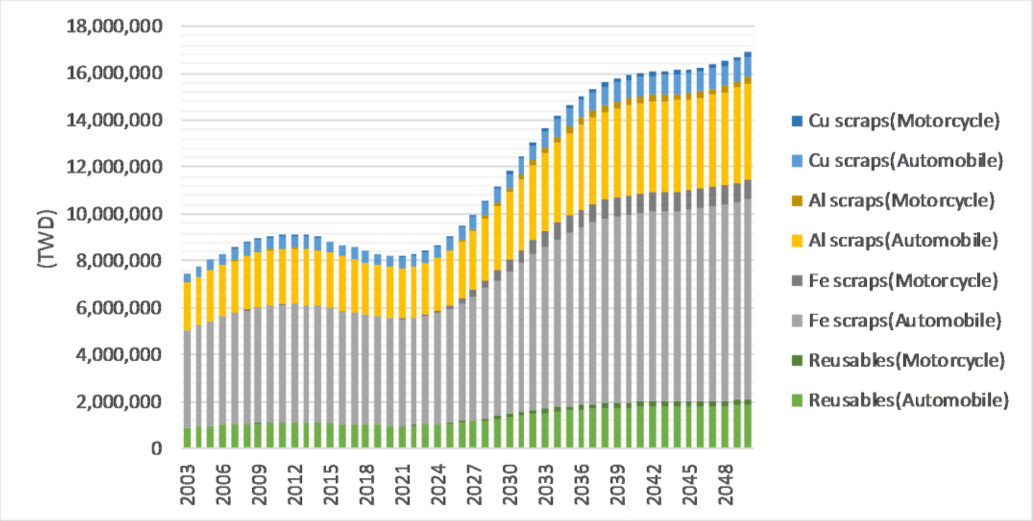


Figure 4.5 The potential economic gain in the untreated ELVs. (1000 TWD=34.3 USD in year 2018)

The economic evaluation results of the dismantling process are shown in Table 4.4. The total revenues of the dismantling business for automobile and motorcycle in average are 8,014 TWD and 720 TWD per unit, respectively. The acquisition costs are varying depending on the weight of the vehicle and the vehicle condition. One significant item in the costs is the transportation cost for the vehicle hulk and the recyclable parts to enter the shredding plants and other recycling business outside of the island. The transportation cost accounts for 10% and 7.5% of the total revenues for automobiles and motorcycles, respectively. The high cost may limit the profit of the dismantler company, or limit the acquisition cost for the dismantling business to pay for buying ELV from the owner. For the dismantling business to be profitable, the limitation for acquisition cost for ELVs are 5,065 TWD and 378 TWD for automobile and motorcycle, respectively. For the side of the vehicle owners, the lower ELV selling price will also reduce the willingness of the people to surrender the ELV. This may result in ELVs abandoned in the private land or ELVs sold to the uncertificated recycler for a higher selling price.

Table 4.4 Economic characterization of the dismantler in Kinmen (1000 TWD=34.3 USD)

	Automobile	**Motorcycle**
Cost (TWD/vehicle)		
Acquisition cost [1]	5500-14000	300-1000
Operation cost [2]	2235	288
Transportation cost [2]	714	54
Revenue (TWD/vehicle)		
Reusables selling [2]	950	91
Scraps selling [2]	6294	444
Subsidy [3]	770	185

[1] Value range reported for Taiwan in 2017[188], depended on the vehicle type and lifetime.

[2] Calculated by this study by the processes mentioned in 2.4.

[3] Constant value decided by RFMB since 2005[127].

4.4 Discussion

4.4.1 Increment of the ELV generation and untreated material stocks

The results showed that the ELV generation number in Kinmen will increase greatly. Based on our estimation, the ELV generation number in 2050 will become 140% and 221% of the current number of automobiles and motorcycles, respectively. The number is much higher than the current ELV treatment capacity in Kinmen. These results show that if the ELV treatment capacity does not increase, the ELVs will be accumulated or flow into uncertificated treatment facilities without proper treatment. The material contents and the potential economic gain of the informal flows are also evaluated in the result part. The result shows that these materials may not be able to be utilized without the improvement of the certificated flow. To prevent the ELVs from entering the informal flow, we recommend to improve the profitability of the dismantling business, and create direct transportation of ELV to the main island for treatment.

4.4.2 Improve the profitability of certificated dismantling business

For treating the untreated material stocks, one possible way to increase the treatment capacity is to have new dismantling business. The cost and revenue analysis of the dismantling process in Kinmen revealed that the low profitability is the main hindrance for growing a dismantling business. It is also reported that the formal recycling sectors are in a financial disadvantage by much higher running costs compared to the informal sectors[189]. The biggest difference in the economic characteristic of the dismantling business in island case is the high transportation fee, whose values are estimated to be 714 TWD for automobiles and 54 TWD for motorcycles. Comparing this value to the current subsidy value, it is 93% of the subsidy of the automobile and 29 % for motorcycles. The rates show that especially for the automobile, the subsidy can barely cover the transportation fee due to the higher weight to be transported by shipping. Now based on the current RFMB policy, the subsidy for dismantling business is the same for everywhere. However, due to different transportation fee required to connect to other recycling businesses, the operation of a dismantling business seems difficult for specific areas. The subsidy rate is calculated and designed to cover the collection process of the end-of-life products[133], while the different operation processes are not taken into consideration. Based on the evaluation in our study, we suggest that the subsidy rate is required to consider the local difference in operation process at the same time. For the certificated business in the island communities to be profitable, more subsidy is necessary. Increasing the subsidy also ensure higher profit of the vehicle owners when they sell their vehicles. This also provides the economic incentives for the vehicle owners to surrender their ELVs to certificated operators instead of other businesses.

4.4.3 Create a new flow: direct transportation of ELV to the main island

Direct shipping of the ELVs to the main island may also be a possible strategy to deal with the capacity problem. If the local treatment is not feasible, the direct removal of the ELV as a whole vehicle can make recycling possible. Treatment in a bigger economy usually means higher recycling and recovery rate. Considering from the aspect of environmental protection, this may be the most straightforward solution of the accumulated material problem. The main difficulty of this strategy is the high transportation cost. If applying the direct shipment strategy to the Kinmen case, the transportation cost will be approximately 8,000-12,000 TWD/vehicle[190]. The identification of the person or group responsible to pay this amount is an important issue. Under the current policy, RFMB takes the responsibility for recycling and pays the transportation fee. The fee will be 99.8%-149.7% of the potential economic gain of the ELVs, which means no benefit for this business. Comparing the direct shipping to the subsidy to the local dismantling business, the subsidy strategy is a more economically feasible option.

4.4.4 Political measures supporting the implementation of the proposals

Both strategies proposed in this study require financial support and policy implementation. The management of contamination arising from improper disposal and illegal dumping has been identified as a major factor in the recycling system in Taiwan[191]. The subsidy supporting the recycling related business is also designed to cover the cost of collecting the vehicles[127]. The improvement in the environmental aspect has always been the main target when Taiwanese government applies subsidy, promotes recycling system, or proposes policies. On the other hand, Taiwan government is now promoting “Kinmen low-carbon island plan”, which aims to gradually reduce the CO_2 emission per year per capita from 3.79 ton-CO_2/year-capita in 2009 to carbon neutral (zero carbon) in 2030[142, 143]. In the 6 sub-projects in this plan, there is one focuses on resources circulation, which aims to improve the recycling performance. A statistical survey done by EPA reveals that in 2013, 431.5 million TWD was spent on Kinmen’s low carbon infrastructure[143]. The improvement of ELV management proposed in Kinmen can become one part of the low-carbon plan because it can contribute to the CO_2 emission reduction by recycling the secondary resources[192], which corresponds with the recent target of Taiwan EPA.

4.4.5 Comparison with international ELV management systems

As mentioned in the introduction section, most of the island countries and developing countries do not have legalized ELV management system. Taiwan has a relative high recycling rate and recovery technology[127]. By improving the local dismantling business or creating the ELV transportation flow to the main island, the same recycling rate as the main island can be achieved. In the countries with legislation on ELV recycling systems, only Japan, a country with many island communities, has the special strategy for ELV treatment in small islands. Japan has successfully operated “Remote Islands Supporting Program,” which started in 2005 to deal with the abandoned vehicle problem. This program is based on the Japanese law[193] on ELV recycling and performed by Japan Automobile Recycling Promotion Center. This program supports the removal of the ELVs from remote island territories to Japan main island and supports up to 80% of the total transportation fee[194]. This supporting program was proven to have decreased the abandoned vehicle number in the island areas of Japan[174]. However, the party responsible for paying the recycling cost is a key difference between the ELV treatments in Taiwan and Japan. In Japan, the vehicle owners have the responsibility to pay the recycling cost for the ELVs, but in Taiwan, the ELVs are traded as a valuable secondary resource. This difference makes the subsidy strategy for the ELV treatment in small islands focus on different direction. The Japanese program focuses on subsidizing for reducing the cost paid by the vehicle owner, but the strategies proposed in this study focus on ensuring the profitability of the local dismantling businesses and the vehicle owners.

4.5 Future prospects

1. The adoption of extended producer responsibility (EPR) concept: Under the current "polluters pay principle (PPP)", the producers only pay the recycling fee to the RFMB, while RFMB manages the recycling system. However, it is shown in this study that the PPP is not enough to provide economic incentives to improve the recycling in rural areas like islands. Changing from PPP to EPR makes the producer take the responsibility to recycle the ELVs in all areas. Through this concept, the responsibility of the producers covers not only the fee of recycling but all the processes, including the regional differences emphasized in this work. The current PPP also cannot provide any incentive to promote design for dismantling (DfD), or to improve the recycling rate form the producer side[195]. If the DfD can be improved, the local dismantling and recycling may also be improved, which may make local treatment possible.
2. Other types of vehicles: In our study, we only considered passenger cars and the results showed increasing ELV numbers. However, island territories usually are seen as tourist attractions, which means buses may also be a great ELV source. The percentage of buses in all vehicles in Kinmen is 80% higher than Taiwan, and the bus is even more challenging to treat. Investigation on the treatment of other types of vehicles is a prospective future research direction.
3. Application to other island cases: In this work, we studied the case of Kinmen, Taiwan, which has relatively complete local municipality and ELV related business. Our results revealed the possibility to reduce the informal flow and improve the local treatment business. However, for many cases, the certificated businesses or recycling operators do not even exist. In these cases the abandoned vehicle problems still need to be solved by other methods in the future.

Chapter 5 An optimum treatment for waste electronic home appliance in small islands

5.1 Introduction

The generation amount of waste electrical and electronic equipment (WEEE, or e-waste) is rapidly increasing all over the world[196]. Management of WEEE is an important issue because WEEE contains toxic substances such as cadmium, mercury, and lead which may cause environmental pollution without proper treatment[39, 189]. WEEE also contains valuable resources which can be recycled to substitute the use of primary resources, including iron, copper, aluminum, gold, and other metals. Transboundary movement of WEEE has been intensively discussed in the literature. Due to the lower labor cost in developing countries, the high benefits become an incentive for the illegal transboundary shipment of WEEE from the developed countries[197]. Basel Action Network (BAN) and Silicon Valley Toxics Coalition (SVTC) warned that the main WEEE traffic routes directed towards Asia, and the primitive recycling system have caused significant environmental damage due to the hazardous materials it contains[198]. The transboundary movement of WEEE is regulated by the Basel Convention to prevent the dumping of hazardous wastes. Although exporting of WEEE to developing countries has been prohibited by laws in many regions, the transboundary movement still exists in many regions under the form of humanitarian aids or used products[198, 199].

The transboundary movement of some components in WEEE from countries and regions without or remote from proper treatment facilities for treatment is necessary to achieve the environmentally sound treatment of the hazardous materials and to achieve resource recovery. For example, the formal export of critical components, such as waste cathode ray tube (CRT) glass and printed circuit boards (PCBs), to OECD countries for treatment is a common practice in Indonesia and the Philippines due to a lack of infrastructure for environmentally sound recycling technologies[200]. Treating the components with state-of-the-art technologies provides higher recovery rates and contamination control. However, the high cost for the outsourcing treatment fee and transportation is the main hindrance for this option.

An example of the high cost for the outsourcing treatment fee and transportation is the recycling practices in remote regions such as small islands. The local treatment costs are usually high due to insufficient quantities of secondary material for recycling economies of scale, and the profitability of the recycling business is limited due to the distance to the recycling market in small islands. For processing the hazardous waste, such as WEEE, higher cares and costs are required in disposing of the wastes relative to nonhazardous wastes[66]. In many island cases, the only option for the treatment of WEEE is removing the WEEE by direct shipment and treated it in a larger neighboring economy, which causes the even higher management cost due to the transportation[201]. These high costs are causing illegal dumping[172, 174, 202], which has significant environmental impacts including soil and groundwater contamination.

This situation is more serious for waste electronic home appliances (EHA) generated from the households due to the large volume and weight, which makes the EHA difficult to be removed and leads to higher shipping costs at the same time[203]. The waste large EHA accounts for 49.07 % of collected WEEE in the EU[189]. The difference of collection cost of waste EHA between Japan and its island communities is reported by Nishi[201]. It is shown that the collection cost of a TV set in island regions is about four to eleven times higher than those in main-island regions. The same problem also arises in the island counties of Taiwan. For the case of Kinmen, an island County of Taiwan, the local government need to spend extra 7.8 million TWD/year (1000 TWD = 33 USD) to support the transportation of the waste EHA to Taiwan main-island due to lack of treatment facility in Kinmen. This extra transportation cost has become a financial burden to the local government. Improving the recycling system of waste EHA is remote regions is an important issue. Local pre-processing and outsourcing post-processing seems to be an effective way to improve both the cost effectiveness and the provide solution to the illegal dumping of waste EHA.

The studies about recycling of WEEE or waste EHA are mostly based on the country scale[128, 200, 204–207] or international comparison[191, 208–210]. The studies about the transboundary movement of WEEE are mostly focused on the movement from developed countries to developing countries[189, 196–198]. Wang et al. showed that the integration of pre-processing in developing countries to manually dismantle WEEE and end-processing in the international end-processing facilities to treat hazardous and complex fractions is the most preferable option of WEEE treatment[211]. However, they did not consider the transportation cost of valuable materials and the waste materials, which may be significant reported by previous reports. The cost reduction of different stages of the treatment process is not clearly presented. To apply the local pre-processing concepts to remote area lack of treatment facilities, it is necessary to analyze quantitatively using realistic data and consider different types of waste EHA.

This study aims to quantify the cost reduction potential for waste EHA treatment by the implementation of local dismantling system. As a case of small island waste EHA treatment system, Kinmen, Taiwan is selected to represent the region without recycling facilities and outsourcing for proper treatment. Four main types of waste EHA, televisions, washing machines, refrigerators, and air conditioners are evaluated. The cost in different stages of the treatment process is evaluated based on the current data. The extension of the results to other cases is also discussed.

5.2 Materials and methodology

5.2.1 Cost analysis system boundaries

The total generation amount of waste EHA in Kinmen is 342 ton in 2017, which is estimated to be 2,667 televisions, 1,905 washing machines, 1,226 refrigerators, and 3,145 air conditioners. Taiwan has developed legalization on waste EHA recycling since 1998. After developing the waste EHA recycling system for 20 years, there are 17 waste EHA treatment facilities with modern recycling technologies in 2018.

The current waste EHA system in Taiwan main-island (hereafter, Taiwan means Taiwan main-island) and Kinmen is shown in Figure 5.1 (a). The upper part, case A, shows the processes of waste EHA treatment in Taiwan, including dismantling, shredding and separation, and residue disposal. The valuable components and materials collected in the dismantling and separation process are sold to the secondary resources market to get revenue. The residues and hazardous waste enter the corresponding waste management including incineration and landfill. On the other hand, in Kinmen, the waste EHA treatment process is to transport all the collected waste EHA directly to Taiwan main-island. The unit cost of each process is shown in Figure 5.1 as C_i, which is all in TWD/unit. The value represents the unit revenue when the value is negative.

Figure 5.1(b) shows the process flow when local dismantling is applied. The collected waste EHA are dismantled manually and locally in Kinmen. The valuable components dismantled are sold into the market and the other parts are transported to Taiwan main-island for post-processing. α_1 represents the dismantling rate, and α_2

represents the separation rate at the shredding process. All the parameters differ among the types of EHA. Four main types of EHA including television, washing machine, refrigerator, and air conditioner are analyzed in this study.

The system boundaries are also shown in Figure 5.1. System boundary A and B are for the analysis of the treatment costs of two different systems. The analysis does not include the collection process.

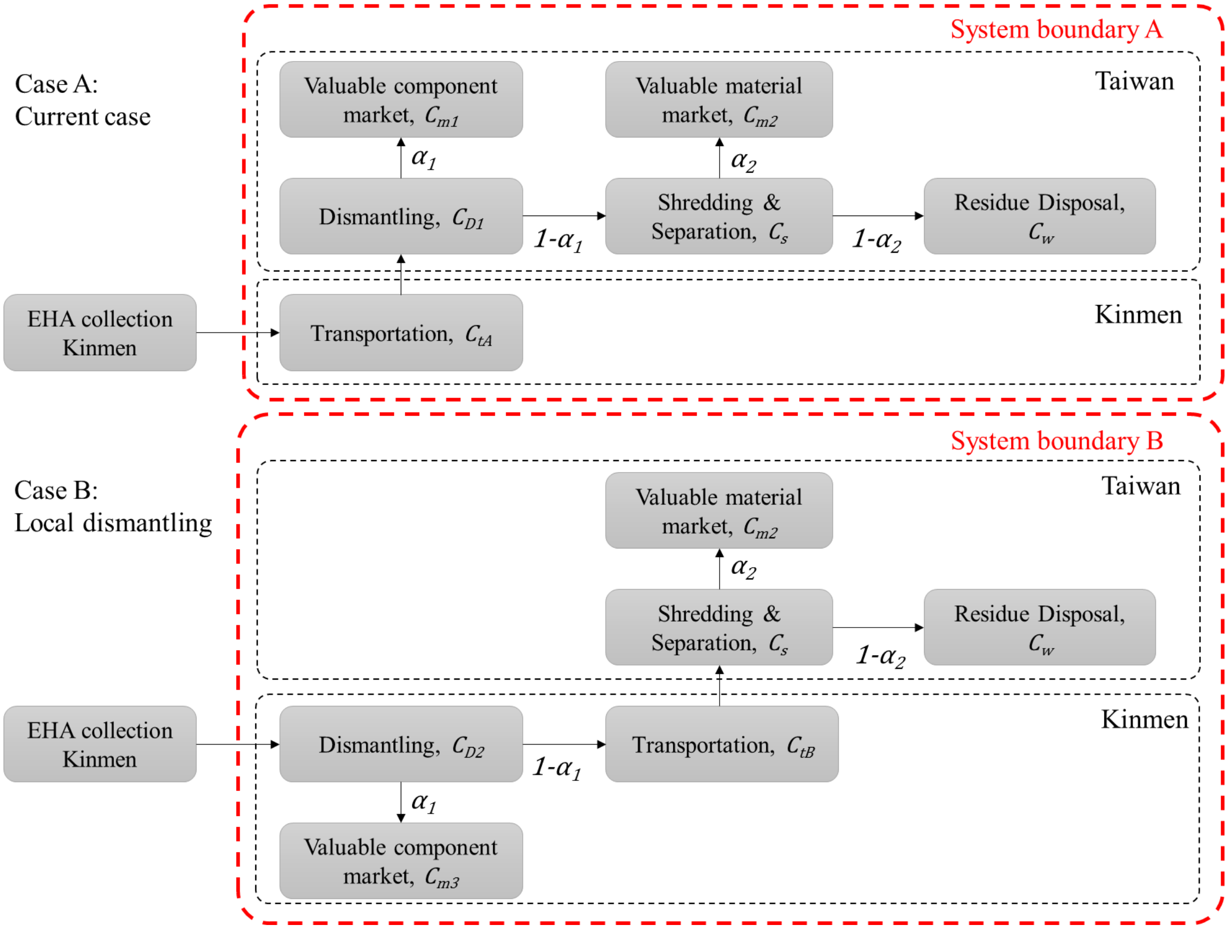


Figure 5.1 The process flow of the system. (a)case A is the current case, and (b) case B is the system applying local dismantling system in Kinmen.

Assuming the total cost of each process is proportional to the weight of the treatment amount, then the analysis of the cost can be simplified by analyzing the unit cost of treating one appliance. The unit treatment costs of systems A and B are shown in (5.1) and (5.2), and the unit cost difference of local dismantling is shown in (5.3).

$$C_A = C_{tA} + \left[C_{D1} + C_{m1}\right] + \left[C_s + C_{m2} + C_w\right]_A \tag{5.1}$$

$$C_B = \left[C_{D2} + C_{m3}\right] + C_{tB} + \left[C_s + C_{m2} + C_w\right]_B \tag{5.2}$$

$$C_B - C_A = \underbrace{\left(C_{pre,B} - C_{pre,A}\right)}_{\substack{\text{unit cost difference}\\ \text{in pre-processing}}} + \underbrace{\left(C_{post,B} - C_{post,A}\right)}_{\substack{\text{unit cost difference}\\ \text{in post-processing}}} + \underbrace{\left(C_{t,B} - C_{t,A}\right)}_{\substack{\text{unit cost difference}\\ \text{in transportation}}} \tag{5.3}$$

where,

$$C_{pre,A} = C_{D1} + C_{m1} \tag{5.4}$$

$$C_{pre,B} = C_{D2} + C_{m3} \tag{5.5}$$

$$C_{post} = C_s + C_{m2} + C_w \tag{5.6}$$

As shown in (5.3), the unit cost difference between systems A and B can be categorized into three items, including unit cost difference in pre-processing, unit cost difference in post-processing, and unit cost difference in transportation. C_{post} differs when dismantling level changes, so $C_{post,A}$ and $C_{post,B}$ are used to represent the different post-processing cost of case A and case B, respectively.

5.2.2 Case analysis and data preparation

Three cases are analyzed in this study: Case A, case B1, and case B2. Case A is the current situation, which means the direct transportation of waste EHA from Kinmen to Taiwan for treatment. Case B1 is the application of the local dismantling processing in Kinmen, and the dismantling level remains the same as Taiwan. As suggested by Wang et al., higher dismantling level should be applied if dismantling is in place with lower labor cost[211]. Thus, case B2 is the application of the local dismantling processing in Kinmen with dismantling level higher than the current level in Taiwan. The dismantled components of three cases for four types of waste EHA are listed in

Table 5.1. The dismantling rates of each EHA in three cases are shown in Table 5.2. All the ratios in Table 5.2 are calculated by the material contents analysis reported by Matsuto

et al.[212]. The materials diverted from post-processing processing are iron, copper, and aluminum. Their selling revenues are considered in the analysis.

Table 5.1 The dismantled components assumed in different cases for four types of waste EHA.

	Dismantled components in case A and case B1	**Additional dismantled components in case B2**
Television	Power cord, deflect yoke, CRT, PCB	Demagnetized coil, Power transformer, Speaker
Washing machine	Power cord, motor, PCB	Power transformer, condenser, drain hose
Refrigerator	CFCs, oil, power cord, power unit, compressor	Packing
Air conditioner	CFCs, oil, power cord, copper pope, Heat exchanger, PCB, motor, compressor	Power transformer, condenser

Table 5.2 The dismantling rate (weight basis) of cases A, B1, and B2 of four types of EHA.

	Television	**Washing Machine**	**Refrigerator**	**Air Conditioner**
Case A and case B1				
α_1	56.00%	20.50%	14.00%	57.50%
α_2	89.34%	50.21%	65.06%	61.48%
Case B2				
α_1	67.40%	39.10%	15.85%	57.56%
α_2	87.73%	38.30%	68.24%	63.95%

To calculate the unit treatment costs for case A and case B1, the values have been estimated using data and some assumptions. Costs of the EHA management in Taiwan are reported by literature[133]. However, the costs are only reported in the unit of total recycling cost and the total revenue. The detailed costs of each process in all the recycling process, including C_{D1}, C_S, C_{m1}, C_{m2}, and C_W, are estimated by assuming the same cost characterization proportion in the literature[197]. The unit treatment cost in Taiwan is assumed to be the same with and without the waste EHA from Kinmen due to the relative low generation amount. The cost of dismantling is mainly personnel cost. The cost of dismantling in Kinmen, C_{D2}, is assumed to be proportional to the relative labor cost. The relative labor cost comparing Kinmen to Taiwan is 87.2%[213]. C_{m3} is estimated by C_{m1} added with the transportation cost of the valuables components to recycling market, while the distance is assumed to be same as Kinmen to Taiwan, and the unit transportation cost is the data obtained in the literature[20]. The values of C_{m3} may become positive when the transportation cost of the valuable components surpasses the selling revenue. The transportation cost of the waste EHA, C_{tA}, is obtained from the interviews to Environmental Protection Bureau, Kinmen County. The transportation cost of the items after dismantling, C_{tB}, is assumed to be proportional to the transportation weight, which means $C_{tB}=(1-\beta_1)C_{tA}$. The values of all these items are listed in Table 5.3.

Table 5.3 The data used in this study for case A and case B1. unit: TWD/unit

	Television	**Washing Machine**	**Refrigerator**	**Air Conditioner**	**Reference**
C_{D1}[1]	135.55	338.17	135.73	154.70	[133, 197]
C_S[1]	184.59	323.65	361.70	224.20	
C_{m1}[1]	-5.62	-22.45	-27.55	-200.92	[133, 197]
C_{m2}[1]	-17.56	-69.47	-133.75	-96.57	[133, 197]
C_W[1]	81.83	58.79	64.44	18.41	[133]
C_{D2}[2]	118.13	294.71	118.28	134.82	[213]
C_{m3}[3]	3.39	-18.67	-22.88	-186.71	[20]
C_{tA}[4]	64.40	73.60	133.40	98.90	Interview
unit weight(kg)	28	32	58	43	[214]

[1] *Estimated by the total cost multiplied by the fraction of each cost.*
[2] *Estimated by* C_{D1} *multiplied by the relative labor cost between Taiwan and Kinmen.*
[3] *Estimated by* C_{m1} *added with the transportation of the valuables components to recycling market, transportation distance assumed to be the same as* C_{tA}.

The unit cost components change when the dismantling level change. The assumptions and processes to estimate the unit treatment cost of case B2 are shown as follows. The dismantling cost, C_{D2} is assumed by current dismantling cost times a coefficient[197]. The shredding and separation consist of the electricity cost and the investment cost. C_S is estimated by assuming the electricity portion of the shredding and separation process proportional to treatment amount $(1-\alpha_1)$, while the investment fraction remains the same. The dismantled components selling revenue, C_{m3}, and separated materials selling revenue, C_{m2}, of the higher dismantling level are calculated by the weight of components and materials multiplying the unit price. The transportation of the dismantling components is also considered in the calculation. The residue disposal costs, C_W, are assumed to be proportional to the treating amount $(1-\alpha_1)(1-\alpha_2)$. The values used for case B2 are shown in Table 5.4. Other cost items in case B2 are remaining same as case A and case B1.

Table 5.4 The data used in this study for case B2. unit: TWD/unit

	Television	**Washing Machine**	**Refrigerator**	**Air Conditioner**	**Reference**
C_S	182.86	318.89	361.17	224.19	[197]
C_{m2}	-18.51	-68.90	-133.75	-94.49	[197]
C_W	69.79	55.81	57.32	17.21	[197, 212]
C_{D2}	153.57	383.12	153.77	175.26	[197]
C_{m3}	4.13	-17.08	-34.40	-189.70	[20, 212]

5.3 Results

5.3.1 Unit treatment cost for four types of waste EHA

Table 5.5 and Table 5.6 shows the unit pre-processing costs and unit post-processing costs of the four types of EHA in three cases, respectively. In Table 5.5, the unit pre-processing costs are positive for televisions, washing machines, and refrigerators, while that of air conditioner has a negative value. This is due to the higher amounts of valuable components embedded in air conditioners. The unit pre-processing cost in case B1 is lower than case A due to the 13% reduction of labor cost in all four appliances, even considering the disadvantage of long distance to the component market. The unit pre-processing cost in case B2 is the highest among three cases due to more labor input to achieve the higher dismantling level.

In Table 5.6, the unit post-processing cost is the same for case A and case B1 due to the same material contents entering the post-processing stage. Case B2 has a lower unit post-processing cost due to lower shredding and separation cost and lower residue disposal cost. The shredding and separation cost is reduced 31%, 24%, 2%, 34% and residue disposal cost is reduced 23%, 5%, 7%, 1% for television, washing machine, refrigerator, and air conditioner, respectively.

Table 5.5 Unit costs of pre-processing for three scenarios. Unit: TWD/unit

Cpre			
	Case A	Case B1	Case B2
Television	129.93	121.12	157.70
Washing machine	315.72	276.04	366.04
Refrigerator	108.18	95.41	119.37
Air conditioner	-46.23	-51.89	-14.44

Negative values mean unit revenue.

Table 5.6 Unit cost of post-processing for three scenarios. Unit: TWD/unit

Cpost			
	Case A	Case B1	Case B2
Television	248.86	248.86	234.14
Washing machine	312.97	312.97	305.79
Refrigerator	292.39	292.39	284.73
Air conditioner	146.05	146.05	146.91

5.3.2 Treatment costs of three cases for each home appliance

The unit treatment costs of case A, case B1, and case B2 are shown in Figure 5.2. Comparing unit treatment cost of case B1 to case A, cost reduction potentials can be observed in all four types of the EHA, which is 42, 54, 32, and 41 TWD/unit cost reduction for television, washing machine, refrigerator, and air conditioner, respectively. It is 10%, 8%, 6%, and 21% cost reduction rate for television, washing machine, refrigerator, and air conditioner, respectively. As shown in Eq. (5.3), the cost difference consist of three items, including unit cost difference in the pre-processing, unit cost difference in the post-processing, and unit cost difference in transportation. The sharing of the cost difference is shown in Figure 5.3. Since case B1 is assumed to be the same dismantling level as case A, so the cost difference in post-processing does not exist. The results showed that the cost difference in pre-processing is more significant for washing machine than other three types. This is due to the higher labor input in the dismantling process of washing machine and lower contents of valuable component dismantled. The cost difference due to the transportation cost is more significant for television and air conditioner. The reason for this is the higher dismantling rate and larger average weight for these two appliances.

Comparing case B2, a higher dismantling level case, to case A, cost reductions can be achieved in television, refrigerator, and air conditioner. However, if considering the sharing of the cost difference, then different trend can be observed. The fraction of four items of cost difference is shown in Figure 5.4. Although the lower relative labor cost reduced the pre-processing cost, the higher dismantling level requires more labor input. As a result, extra cost for pre-processing exists for four types of EHA. For post-processing, there are cost reductions for television, washing machine, and refrigerator. This is due to lower shredding and separation cost and lower residue disposal cost. The post-processing cost increased for air conditioner, the extra cost is due to the valuable materials which used to be separated to create revenue has been dismantled in the pre-processing stage. The cost difference of transportation process is larger in case B2 than case B1 due to the higher weight reduction by higher dismantling rate. The increase is higher in television and washing machine due to a bigger change in dismantling rate.

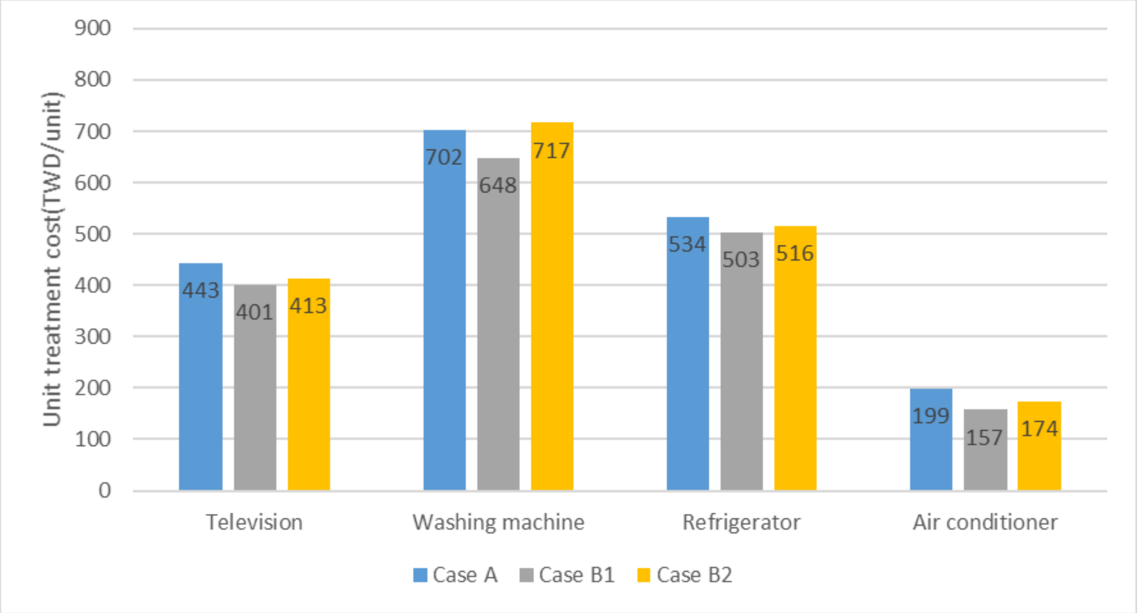


Figure 5.2 Unit treatment cost of each type of EHA

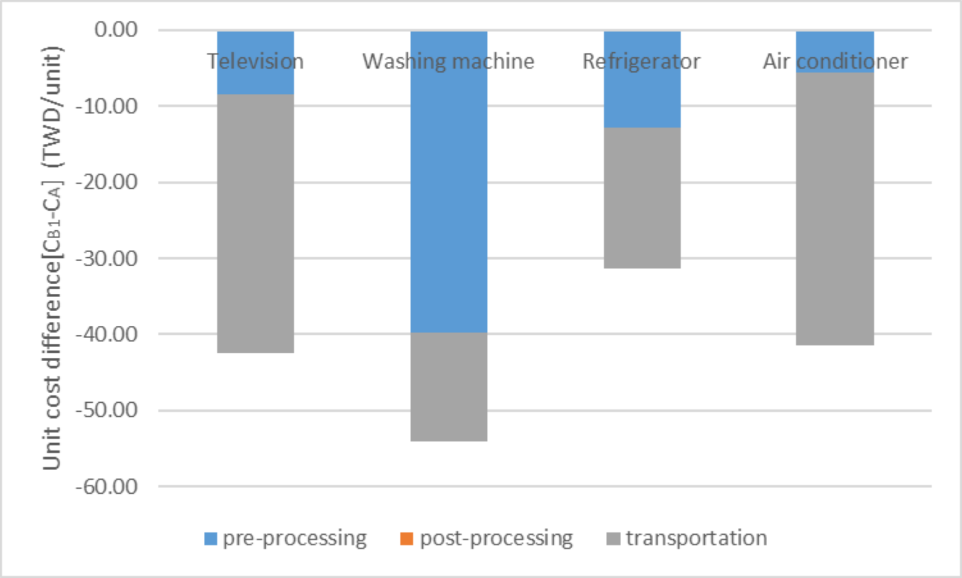


Figure 5.3 The cost differences between case A and case B1

Figure 5.4 The cost differences between case A and case B2

5.4 Discussion

5.4.1 Treatment characteristics of four types of EHA

Four types of EHA considered in this study have different characteristics in the treatment process. Dismantling rate, total weight, and valuable components of different appliances are the main factors affect the cost reduction potential when applying the proposed system in this study. For example, treatment of washing machine requires high dismantling cost, so the effect of low labor costs is significant. However, if the dismantling rate increased, the cost reduction is limited due to less revenues from the dismantled components. Washing machine is usually lighter in weight and has low dismantling rate, which limits cost reduction potential in the transportation process.

In contrast, for refrigerator and air conditioner, the cost reduction can be achieved due to the transportation cost reduction through large component weight and high dismantling rate. Television, refrigerator, and washing machine require a higher cost for the residue disposal than air conditioner. This characteristic is significant when a higher dismantling rate is achieved in the proposed system. Reduced residue disposal amount can achieve cost reduction in the post-processing stage.

By the discussion of the treatment characteristics of four types of EHA, it can be concluded that the heavy appliances with high dismantling rate potential are suitable for applying the local dismantling system due to the transportation cost reduction potential. The appliances require large labor input but a less of valuable components should apply the local dismantling system if labor cost is relatively low, but the increase of dismantling level is not suggested if more dismantling can only provide limited revenue.

5.4.2 Indirect benefits of local dismantling system

Other than the economic benefit by the cost reduction of the local dismantling system presented in this study, there are other indirect benefits including environmental and social benefits can be created by applying the system. First, the higher dismantling level can contribute to environmental benefits including 3R practices, material circulation, and landfill conservation. From the results shown in section 3.2, it can be realized that if applying the proposed system, there is still cost reduction potentials while the dismantling rate increases. The increase in dismantling rate is usually limited by high labor costs, but the proposed system can reduce the labor costs due to the regional average wage difference. Utilization of the local labor can make the higher dismantling rate possible.

Besides, the current treatment system in remote regions is highly dependent on other economies, while the treatment fees are determined by others. The dependency of the waste EHA treatment system can be express by the percentage of the fees required for outsourcing treatment. It also represents the sensitivity to the variation of the outsourcing treatment fee. The dependency of four types of waste EHA in three cases is shown in Table 7. Table 7 showed that case A is greatly affected by the outsourcing destination for television, washing machine, and refrigerator. Only air conditioner has lesser effects due to a large amount of valuable components. Implementation of local dismantling system can improve the independence of the local system, as shown in Table 5.7. By possessing the local treatment system, flexibility can be achieved to deal with the changing treatment fee and generation amount. Other social benefits including job opportunity creation and business provision for local material recycling business and repairing business can also be expected.

Table 5.7 The dependency of the treatment system for three cases.

	Television	**Washing machine**	**Refrigerator**	**Air conditioner**
Case A	85%	90%	75%	50%
Case B1	62%	48%	58%	93%
Case B2	60%	44%	57%	84%

5.4.3 Application to other cases

This study uses the case of Kinmen, Taiwan to reveal the economic benefit of the local pre-processing system. This system can also be applied to other regions without post-processing facilities. The sensitivity analysis of the results has been done to present how the results are affected by the change of parameters. Two parameters are considered in the sensitivity analysis, including relative labor cost and the transportation distance. The current relative labor cost is 87.2% and the transportation distance is 290 km. The change of the relative labor cost has effects on the difference in dismantling cost reduction and the transportation distance has the main effect on transportation cost. Table 5.8 shows the sensitivity of the unit treatment cost to relative labor cost, S_{labor}, and transportation distance, $S_{distance}$,.

Table 5.8 Sensitivity to relative labor cost and transportation distance.

	Television	**Washing Machine**	**Refrigerator**	**Air Conditioner**
S_{labor}[1] **(TWD/%)**	135.55	338.17	135.73	154.70
$S_{distance}$[2] **(TWD/km)**	0.093	0.036	0.047	0.074

[1] Calculated by Δunit treatment cost/Δrelative labor cost. Relative labor cost is comparing to Taiwan current level.

[2] Calculated by Δunit treatment cost /Δtransportation distance

The results showed that relative labor costs have significant effects on unit treatment cost. The effect is similar for television, refrigerator, and air conditioner, but a higher sensitivity to labor cost is observed in washing machine. This is because the treatment process of washing machine is more labor intensive, and there are less valuable materials embedded. On the other hand, the treatment cost increases with transportation distance. The transportation distance has more effects on treatment cost for television and air conditioner, but lower effects on washing machine. The results represent that when this system is considered to be applied to other cases, relative labor cost and transportation distance are two main factors that should be considered.

Besides, for the case study in this work, the generation amount of waste EHA is 342 ton/year, which makes the implementation plant of local shredding and separation unavailable due to the small scale. If consider bigger community with enough collection amount to implement a local shredding and separation plant, the total treatment cost can be further reduced due to reduced transportation cost. Taking Taiwan as an example, the average capacity of waste EHA shredding plant is about 7000 ton/year[145]. Local post-processing can also take into consideration when the scale can be reached.

A straightforward application of this strategy is the product take-back system under extended producer responsibility concept. If the international WEEE treatment system applies extended producer responsibility concept, then the producer has the whole responsibility for the recycling process of the products even after the products exported to other countries. In cases that the products are exported to countries without proper recycling facilities, the recycling can be achieved by either direction transportation or transportation after local dismantling is necessary for the treatment of the products. The producer has the responsibility of the whole system regardless of the location. The proposed local dismantling strategy can be applied to the case when the producer evaluates the cost difference between direct transportation case and local dismantling case.

5.5 Conclusion

The economic benefit of waste EHA treatment by local pre-processing and outsourcing post-processing is analyzed by the case study for Kinmen, Taiwan. The results revealed that the implementation of local pre-processing can contribute to the cost reduction for four main types of EHA, due to the lower labor costs in the local system and the reduced transportation cost. Increasing the dismantling level in the local pre-processing system requires an extra cost for the pre-processing, but the cost reductions in post-processing and transportation still provide economic benefits for most of the appliances. For the case of Kinmen, the optimal treatment in terms of economic aspect is applying the local pre-processing with the dismantling level remains the same. However, if consider the environmental aspect, higher dismantling level in Kinmen is also feasible, and cost reductions can still be achieved.

The application of the system to other regions is also presented in this research by the sensitivity analysis of relative labor costs and transportation distances. The results showed the significance of labor costs for labor-intensive EHA and significance of transportation distance for EHA with heavy weight and high dismantling level. The treatment characteristics of each type of EHA are the main factors affecting the suitability of the proposed strategy. The analysis process can be applied to the domestic systems with regions without recycling facilities, and also the international systems while one country exporting the products to another country without proper recycling facilities and applying the extended producer responsibility to take back the products for recycling.

Chapter 6 Sustainability evaluation of waste treatment strategies in small islands

6.1 Introduction

Most of the small island communities struggle in waste management issues due to the their special characteristics[63, 66]. It is very difficult for the small island communities to apply the modern waste management strategies due to financial challenges, technical challenges, and educational challenges[63]. According to waste hierarchy, recycling and energy recovery is more preferable than disposal such as landfill and incineration without energy recovery. However, recycling and energy recovery are not feasible to small islands due to financial and technical limitations. In many island waste management cases, the only available waste treatment strategy is open dumping or landfill, and landfill is the least desired option according to the waste management hierarchy. On the other hand, the untreated waste materials are also accumulated and becoming additional to stock[84, 87]. These facts showed that the material input into islands is difficult to be recycled and easily accumulated inside islands without proper treatment.

The application of some sustainable waste management strategies can only be achieved when the island connected to a larger economy with available waste treatment facilities or bigger secondary material market. For example, the waste electronic home appliances (EHA) and the end-of-life vehicles (ELVs) generated in the remote islands of Japan are transported to bigger cities for proper treatment and recycling[194]. The treatment of municipal solid waste (MSW) and recyclable materials in small island communities of Taiwan is also by direct transportation to cities with incineration or recycling plants. The high transportation costs make the treatment cost higher and the price of secondary materials less competitive. The high cost has caused several problems including illegal dumping and the unstable situation of the waste treatment process.

Facing these difficulties in small island waste management, the authors of the present study have studied local pre-processing and outsourcing post-processing waste treatment systems for small islands for MSW[20], ELV[202], and waste EHA[215] by the case study of Kinmen, Taiwan. The previous results showed that local pre-processing and outsourcing post-processing can improve the economic efficiency of the waste treatment system in small islands comparing to the current direct removal system. However, the environmental and social aspects of the proposed system are not yet discussed.

Many literature pointed out the challenges of the waste management in small islands and most of the papers on island waste management investigated the current waste management situation. Eckelman et al. reviewed the barrier for small islands to conventional solid waste management such as limited physical space and lack of capital and financing options[66], and Mohee et al. reviewed the current status of solid waste management in small island developing states(SIDS)[63]. These articles revealed the relationship between island characteristics and waste management strategies, and both of them focused on challenges faced by the small islands. However, there is no discussion on the feasibility of the waste treatment practices under the island characteristic limitation. The required financial support and required scale for the waste management system in small islands is not clear for the future waste management planning.

This study aims to evaluate the sustainability of the sustainable waste management strategies for small island communities. First, the review of the limitations of current island waste management strategies include local treatment and direct transportation are presented by reviewing research papers. Second, the local pre-treatment and outsourcing post-treatment strategy proposed by the authors is evaluated in three dimensions of sustainability. Finally, the scenario analysis of the local treatment, direct shipment, and local pre-treatment is presented to show the benefits and disadvantages of each system. Suggestions for policymakers and waste management planner are provided for the sustainable waste management system in small islands.

6.1.1 Limitations of the island waste management

6.1.2 Local treatment strategies

The focuses of the literature on small island waste management are mostly waste generation characteristics[71, 72], waste from tourism[73, 74, 76], marine litter[84, 216], and collection systems[90, 217]. Landfill is highly practiced in many small island developing states (SIDS)[63] , but the siting of new landfills is difficult in small islands due to land resource limitations. Applying other waste management strategies is urgent for the sustainable development in small islands. Some studies proposed waste management strategies in small islands including waste-to-energy (WTE) and recycling practices. WTE is a reasonable choice for small islands considering the limited physical space and high dependence on imported energy[20, 80], and recycling also contributes to material circulation and reduce the dependency of imported goods.

Successful implementation of WTE facilities by incineration in islands can be found in Mauritius[63, 78], Singapore[149], and Oahu, USA[87]. However, for the smaller islands, the incineration with energy recovery is not feasible. For example, there were seven mini incinerators in operation in certain islands of Malaysia, but no energy generation is available[60]. Small scale incinerators are also found in small islands in Japan. The reports showed that among 552 small scale incinerators (capacity less than 100 ton/day), only 1.8% generate electricity and 34% utilize heat[31]. Many of these incinerators without energy recovery abilities are located in remote islands.

In the literature, the recycling practices including food waste[79], paper[218] and waste tires[85] are discussed. The scenario analysis for small island MSW management in many literatures also includes recycling of materials including metal, glass, paper, and plastics[81, 83, 89, 219, 220]. However, in most cases, the scale of the island is not enough to possess the recycling plants or operate it economically due to the insufficient recyclable material amount. Treating different types of waste requires different scale due to the technology. The requirements differ from countries and regions by economic situation and policy. Scale are depending on regulation, economic condition, labor cost, and many other factors. If the enough scale or waste generation amount cannot be reached, it is necessary to consider the outsourcing treatment strategies.

6.1.3 Direct shipment

When local treatment is not feasible, one potential solution is to search for outsourcing treatments, which means the removal of waste materials from the island to regions with available treatment facilities. However, the long distance transportation of the waste material is usually very expensive. Literature shows that recycling practices in Pacific island countries is unlikely to be economic due to the cost of shipping it out[221]. There are also reports showing the high cost of removal of ELV and EHA from the remote islands of Japan has causing problems such as illegal dumping [174, 201]. Same problems are also found in Pacific Ocean island countries[172].

Financial support is necessary for the direct shipment of the waste materials. For example, the Japanese island supporting program subsidizes the collection system of the EHA and ELVs to deal with illegal dumping problems[194]. The treatment of municipal solid waste(MSW) and recyclable materials in small island communities in Taiwan also heavily dependent on the supporting system from the Taiwan Environmental Protection

Administration due to lack of treatment facilities and high transportation cost[222]. Many Pacific island countries depend heavily on foreign aid for their environmental issues[223].

6.1.4 Local pre-treatment strategies

Since local treatment has limitations due to the island characteristics and direct shipment has problems relating to high transportation costs, an optimum waste treatment system with the combination of local pre-processing and outsourcing post-processing was proposed by the authors of the present study. Local pre-treatment strategy is proposed for MSW, ELV, and EHA. Considering the limitations of small islands, the important treatment characteristics of these three types of waste are listed in Table 6.1.

Table 6.1 Treatment characteristics according to waste types

	MSW	**ELV**	**EHA**
Technology requirement	Medium	High in end-process	High in end-process
Required treatment scale	Small	Big	Big
Economic benefit	Low	High	Medium
Transportability	-	Low	Medium

As shown in Table 6.1, the technology requirement and treatment scale requirement are higher in ELV and EHA than MSW. The recycling and recovery of the ELV and EHA requires investment of the treatment plants and large treatment scale to achieve economic efficiency, which is not feasible for the small island cases. However, the economic value embedded in the waste material is also higher in ELV and EHA, which drives the necessity of the treatment. There is almost no valuable contents in MSW. The most valuable material in the ELVs is the iron from the vehicle hulk and many components, which is constitutes more than 75% of the total weight[202]. However, for waste EHA, the PCBs, which contain a significant portion of the value embedded into waste EHA, only constitute from 3% to 6% of total weight[199]. The transportability of MSW is not evaluated here because it is not common to transport MSW for long distance for treatment. ELV and EHA are bulk and heavy, so the direct transportation is very costly, and the transportability is very low.

The concept of local pre-treatment proposed is improving transportability and increasing economic value. The local pre-treatment for MSW is refuse-derived-fuels (RDF) production and for ELV and EHA is local manual dismantling. RDF production provides better transportability and longer storage time for MSW. On the other hand, treatment of

MSW usually requires gate fee paid to the treatment facilities, but RDF can be utilized as an energy source with can provide benefits. Manual dismantling of ELV and EHA can contribute to volume and weight reductions, which can reduce the transportation costs. Dismantling also enables the selling of the valuable components embedded in the ELV and EHA directly and creates the revenues for the local recycling and repairing business. The lower labor costs in small islands also contributes to cost reduction of the treatment system.

6.2 Methodology

6.2.1 Sustainability evaluation

Evaluation of the performance of three dimensions of sustainability are adopted for analysis. Three dimensions are economic aspect, environmental aspect, and social aspects.

The economic assessment directly applies the previous results of the authors. The economic assessment mentioned here is the unit treatment cost. For MSW, it is the treatment fee of 1 ton of waste, while for ELV and EHA, it is the treatment fee of 1 unit of vehicle or device. The environmental impacts and benefits of the proposed strategies are discussed in this section. Greenhouse gases (GHG) emission, energy recovery, and material recovery are the three main aspects considered[224]. The social sustainability of waste management system mainly represents three aspects, social acceptability (the waste management system must be acceptable), social equity (the equitable distribution of waste management system benefits and detriments between citizens), and social function (the social benefit of waste management systems)[49].

6.2.2 Scenario analysis

Three scenarios including total local treatment, local pre-treatment, and direct shipment are compared in this section. The total local treatment scenario is assumed that the MSW is incinerated without energy recovery, and the ELV and EHA enters the informal recycling sector, which means lower recycling rate and lower environmental requirements. Direct shipment scenario is assumed as the waste transfer policy in Taiwan, which transfer MSW and all recyclable materials to state-of-the-art treatment facilities for treatment. Local pre-treatment scenario assumes the application of the proposed aforementioned strategies. Total local treatment is set as the baseline for comparison.

6.3 Results

6.3.1 Environmental assessment results

For GHG emission, although transportation process is very expensive, its environmental impact considering the GHG emission is low because marine transportation is relative low emission[20]. For the RDF production for MSW, the GHG emission of the marine transportation of the produced RDF in Kinmen only accounts of 1.12% of the total GHG emission. Comparing to the energy recovery potential and material recovery potential, the GHG emission of the transportation process is negligible. In the case of ELV and EHA recycling, the transportation and the recycling process require energy input which generates GHG emission, but the material recovery and the substitution of the use of primary material is proved to contribute to the GHG emission reduction comparing to the emission during the recycling process[44].

For the aspect of energy recovery, previous sections showed that local incineration of MSW in small islands is difficult to achieve energy recovery. The energy recovery is made possible by production of RDF. The produced RDF can be utilized by power generation as well as substitution of fossil fuel. The fossil fuel substitution is shown to be able to provide more environmental benefit than power generation. The fossil fuel substitution can also contribute to reduce the dependency on imported energy source for small islands.

The strategy of local pre-treatment of ELV and EHA recycling has more significant effects on material recovery. The local pre-treatment of ELV and EHA has the potential to solve the illegal dumping and material stock problem, which enables the materials entering the recycling loop. On the other hand, our previous results show that higher level of dismantling can be achieved due to the lower local labor costs. Literature has shown that higher dismantling level contributes to higher recycling and recovery rate, which provides environmental benefit[211].

6.3.2 Social assessment results

Although treatment facilities are necessary for the community, the identification of the suitable sites is difficult due to limited land resources and “Not In My Back Yard (NIMBY)” syndrome. In small islands, the NIMBY syndrome may be more serious due to small and densely populated land mass[94]. For the case of Taiwan, NIMBY conflicts has transformed from technical problem to political problem due to lack of proper public participation in the decision process[225].

Inequality is happening in most stages of the waste treatment system, and the most apparent inequality is in the economic aspect. The high operation costs of the treatment facilities and the high waste disposal fee is the main reason of inequality. The high operation costs also result in lower selling price of ELV and waste EHA, which may reduce the willingness for the consumer to surrender their products. On the other hand, the direct shipment strategy increases the environmental impacts of the waste treatment facilities, which means the local island communities has also transfer the environmental impacts and the treatment responsibility outside. The local pre-treatment strategies can improve the equality by cost reduction and treatment responsibility improvement.

The local pre-treatment strategies can also provide social function such as improving environmental consciousness and environmental education. The lack of waste treatment facilities causes the lower awareness of the waste issue for local people. The introduction of the local pre-treatment facility also enables the opportunity for environmental education, which can further contribute to the waste management system.

6.3.3 Scenario analysis results

The comparison of the direct shipment scenario and local pre-treatment scenario in economic, environmental, and social aspects to the baseline is shown in Table 6.2. Plus (+) means the improvement or benefit and minus (-) represents negative effects or more impacts.

Table 6.2 The scenario analysis results

	Economic	**GHG emission**	**Energy recovery**	**Material recovery**	**Social acceptability**	**Social equity**	**Social function**
Direct shipment	--	+	+	+	+	-	-
Local pre-treatment	-	++	++	++	-	+	+

Direct shipment and local pre-treatment both require more costs than the baseline local treatment scenario, but the local pre-treatment requires lower cost, which is better in economic aspect. Considering environmental aspects including GHG emission, energy recovery, and material recovery, both direct shipment and local pre-treatment are improved in the three environmental aspects due to enabling the energy recovery and recycling practices. Local pre-treatment has better performance due to higher energy recovery potential by RDF production and the higher material recovery rate by potential higher dismantling rate. At the social aspects, the direct shipment does not require the local treatment facilities, so there is no NIMBY problem. However, it has negative effect on social equity and social function. The local pre-treatment scenario may face the social acceptability problem, but it has positive effects on social equity and social function. By this analysis, it is clear that the local pre-treatment is holistically a preferable option among three scenarios considering environmental and social aspects.

6.3.4 Application in different cases

The sustainability evaluation results vary in different island cases due to the different characteristics. The economic performance is greatly affected by the scale of the island and remoteness to other economies. For environmental aspects, GHG emissions can be reduced by energy recovery and material recovery improvement, while energy recovery and material recovery potential are affected by technology investment and relative labor costs. For social aspects, the social acceptability is related to the scale of the island. Social equity and social function are affected by treatment capacity and independency. For the case of Kinmen, the results are as shown in Table 6.2. However, for other island case, it may have different results due to its characteristics.

6.4 Conclusions

The sustainability of the waste management strategies for small island communities is evaluated in this study from the economic, environmental, and social aspects. The limitations of local treatment and direct shipment are reviewed and presented. The environmental and social aspects of local pre-treatment strategy are discussed. Our results showed that the local pre-treatment strategy provides more environmental benefits than direct shipment. Although the social acceptability remains problematic, the social equality and social function can be improved to support the system. Considering the environmental and social impacts, the local pre-treatment system for small island waste management is suggested to be promoted and implemented.

Chapter 7 Conclusions

7.1 Summary

This study has investigated the waste treatment systems in small island communities. Three types of waste treatment are analyzed including municipal solid waste, end-of-life vehicles, and waste electronic home appliances. Waste management systems or strategies to improve the cost effectiveness are proposed by this study. The discussion on the environmental and social aspects for the proposed system is also presented.

In Chapter 3, waste shipments for energy recovery in small islands is studied. The results revealed current waste transfer system in Kinmen is costly, but considering the total CO_2 emissions, it is environmentally beneficial because energy recovery can be realized. Transforming combustible waste into RDF provides opportunities for more shipment destination. Shipment to places with shorter shipping distance and lower incineration gate fee can reduce the treatment cost. However, the high CO_2 emissions from RDF production process is difficult to be surpassed by reduced emission by energy recovery. By technology improvement and higher quality of input waste material, the emissions from RDF production process can be reduced, and the reduced emission can results in positive environmental impact over no energy recovery case. Shipping distance, RDF gate fee/selling price, and emission from RDF production are the biggest factors affecting the cost and emission of the waste treatment system. The choice of RDF shipping destination with cost-effectiveness and reduced environmental impact can be evaluated by the methodology shown in this study. A generalized flowchart for analyzing the WTE strategies of small islands is proposed for the needs of islands sustainable decision for waste management.

In Chapter 4, the material flows and economic analysis on the ELVs in small islands is investigated. The ELVs generation amount is estimated using the population balance model (PBM) and the results showed a steep increase in the future for both automobiles and motorcycles. The insufficient ELV treatment capacity has resulted in the significant informal treatment flow, which will be the total weight of 1906 tons of items with market value, with a potential economic gain of 16.9 million TWD in 2050. The results of the economic characterization of the local dismantling business clarified that profitability is the main hindrance for the development of new dismantling business due to high transportation costs. Our results suggested that implementation of the different subsidy rate according to the treatment area under the current policy or creation of a new treatment flow with a direct shipment of ELVs for treatment is necessary to improve the utilization of the stocked materials from untreated ELVs.

In Chapter 5, the economic benefit of waste EHA treatment by local pre-processing and outsourcing post-processing is analyzed. The results revealed that the implementation of local pre-processing can contribute to the cost reduction for four main types of EHA, due to the lower labor costs in the local system and the reduced transportation cost. Increasing the dismantling level in the local pre-processing system requires an extra cost for the pre-processing, but the cost reductions in post-processing and transportation still provide economic benefits for most of the appliances. For the case of Kinmen, the optimal treatment in terms of economic aspect is applying the local pre-processing under the same dismantling level. However, if consider the environmental aspect, higher dismantling level in Kinmen is also feasible, and cost reductions can still be achieved. The application of the system to other regions is also presented in this research by the sensitivity analysis of relative labor costs and transportation distances. The results showed the significance of labor costs for labor-intensive EHA and significance of transportation distance for EHA that requires high dismantling rate EHA and with heavy weight. The treatment characteristics of each type of EHA are the main factors affecting the suitability of the proposed strategy. The analysis process can be applied to the domestic systems with regions without recycling facilities, and also the international systems while one country exporting the products to another country without proper recycling facilities and applying the extended producer responsibility to take back the products for recycling.

In Chapter 6, the sustainability evaluation on the proposed systems are presented. The sustainability are evaluated from three aspect by three aspects of economic aspect, environmental aspect, and social aspect. For environmental aspects, GHG emissions, energy recovery, and material recovery are considered. The local pre-treatment system has better performance in all these three aspects comparing other two scenarios. The social aspects include social acceptance, social equity, and social function. The local pre-treatment may have social acceptance problem due to NIMBY syndrome, but the other two aspects are improved. It is shown that the local pre-treatment can provide not only the economic benefit comparing the current direct shipment system, but also have better environmental and social performance.

7.2 Limitations and recommendations

Although this study reveals environmental and economic evaluation of waste management strategies in small island communities, there are several limitations of its application and recommendations that should be acknowledged in this study.

1. The economic analysis presented by this study are mainly based on the data reported by Environmental Protection Administration of Taiwan. The data for whole system of Taiwan is available, but regional data is very limited in many cases. In many cases when the regional data is not available, the analysis must be based on estimated data with assumptions. However, islands usually possess special and unique characteristics. The situation of one island is difficult to be applied to another one. The determination of the assumption to estimate the situation in islands is very difficult. This issue needs to be considered when utilizing the results from the study.
2. The proposed systems is proved to have economic benefits in the case of Kinmen, Taiwan. Kinmen is under the Taiwanese environmental regulations and policies, which requires high sanitary standard and deeply concerns about the environmental protection. However, for the regions without environmental protection regulations, the treatment cost issues do not exist because there is no incentive for the waste treatment if the treatment process does not create revenue. The implementation of the environmental potential regulations is a necessary requirement before applying the concept proposed in this study in the island case.
3. Our results showed that there is significant waste treatment cost difference between Kinmen and Taiwan main-island. Financial support or different subsidy rate is necessary to ensure the operation of the waste management system in island communities. For the case of islands belonging to a country with bigger economies, it is possible to be supported by domestic budget source. However, many waste management issues are happening in the island countries where domestic supports is not available. Furthermore, bigger domestic economies also provide potential treatment facilities and abilities, which are also not available for island countries. For the island countries such as small island developing states, international supports are expected.
4. Our results suggest to utilizing the local labor power. The 3R practices including reduce, reuse, and recycling are not limited by the geographical or financial situations of small islands. Source separation or pre-treatment can be achieveds locally. Environmental awareness and education can support the development of

these practices. This study also presented that adapting the extended producer responsibility concept is helpful for developing the waste management system especially under the limitation of small island situations. Circular economy, ecological industries, and close-loop concepts may also have their specific contribution and limitation under the small island cases. More discussion on the applicability of these concepts is suggested.

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List of publications

Papers related to this thesis

① Chapter 3

Hsin-Tien Lin, Eiji Yamasue, Keiichi N. Ishihara, Hideyuki Okumura,

"Waste shipments for energy recovery as a waste treatment strategy for small islands: the case of Kinmen, Taiwan"

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② Chapter 4

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③ Chapter 5

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④ Chapter 6

Hsin-Tien Lin, Keiichi N. Ishihara,

"Sustainability evaluation of waste treatment strategies in small island communities"

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Conference presentation

① Hsin-Tien Lin, Keiichi Ishihara, and Hideyuki Okumura, “Waste Management on small islands: The case of Kinmen, Taiwan,” *廃棄物資源循環学会平成 29 年度春の研究発表会*, Jun. 2, 2017, Kawasaki, Japan.

② Hsin-Tien Lin, Keiichi Ishihara, and Hideyuki Okumura, “Improvement of island material cycle and cost effectiveness by introducing RDF plant to waste management system in Kinmen, Taiwan,” *4th International Conference on Final Sink (4th ICFS)*, Oct. 24-27, 2017, Kyoto, Japan.

③ Hsin-Tien Lin, Keiichi Ishihara, and Hideyuki Okumura, “Cost-Effectiveness Analysis of Waste Management Strategies on Small Islands: The Case of Kinmen, Taiwan,” *Global Waste Management Symposium 2018 (GWMS 2018)*, Feb. 11-14, 2018, Indian Wells, California, USA.

④ Hsin-Tien Lin, Keiichi Ishihara, “Material consumption and material stocks in small island communities: case study of end-of-life vehicles (ELVs) treatment in Kinmen, Taiwan,” *The 13th Biennial International Conference on EcoBalance (EcoBalance 2018)*, Oct. 9-12, 2018, Tokyo, Japan.