CHAPTER IV
RESULTS AND DISCUSSION

4.1 Life Cycle Inventory

A life cycle inventory (LCI) is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity (EPA 1993). In this research, LCI is performed on the production of three petrochemical products, polyurethane foam (PU), general purpose polystyrene (GPPS), and high impact polystyrene (HIPS), in the cradle-to-gate framework which covers from raw materials acquisition, transportation, production and disposal/recycle of the wastes from the production processes, packaging, and injection. This results in 3 life cycle inventories being generated for the corresponding three petrochemical products.

4.1.1 Polyurethane Foam Inventory

Polyurethane foam production involves mixing of formulated polyol produced by Dow Chemical Company with isocyanate and HCFC 141b and injecting the mixture to form PU foam at Sanyo Universal Electric Public Company Ltd. (SUE). The foam is then used as an insulator in refrigerators manufactured by Sanyo. This inventory includes all processes which involve a production of formulated polyol at Dow Chemical Company (from raw materials acquisition and preparation process to mixing process) and injection process at SUE to get 1 kg of polyurethane foam. All processes of polyurethane foam producing are shown in Figure 4.1. Details of input and output data collection of polyurethane production are shown in Table 4.1 which consists of raw materials, utilities, packaging, transportation and all emissions. Process flow diagram of each process in the PU production is shown in Figures 4.2, 4.3, and 4.4. Details of the input-output of the corresponding process are described in Tables 4.2 to Table 4.15. Raw materials of each process are shown in Tables 4.2, 4.6, and 4.10. Products and all wastes are shown in Tables 4.3, 4.7, and 4.11. Energy consumption of mixing and injection process are shown in Tables 4.8 and 4.12. Transportation of raw material and product is shown in Tables 4.5 and 4.14.

Packaging used for all chemicals are listed in Tables 4.4 and 4.13. Lastly, all emission details are described in Tables 4.9 and 4.15. For transportation, there are three modes for both domestic and international transportations. For domestic transportation, some of polyether polyol (raw material) and the product (formulated polyol) are transported by pipe and 10-wheel truck and for international transportation, raw materials including polyether polyol, silicone surfactant, amine catalyst, HCFC, and isocyanate are transported by shipment (container ship). Figure 4.5 shows the input-output of overall process of the production of 1 kg polyurethane foam.

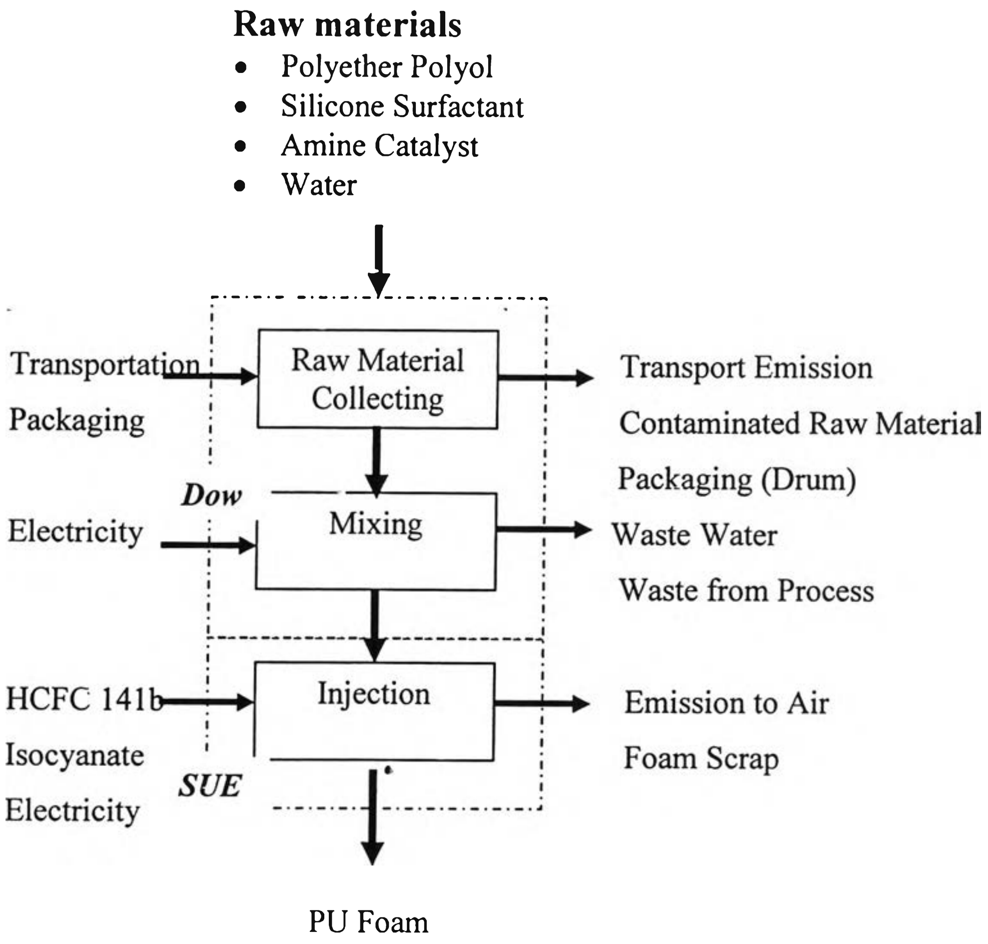

Figure 4.1 Polyurethane foam production processes.

Table 4.1 Input-output data of polyurethane foam production

Input Data		Output Data	
Type	Unit	Type	Unit
Raw Materials		**Product**	
Polyether Polyol	kg	Polyurethane Foam	kg
Silicone Surfactant	kg	**Solid Wastes**	
Amine Catalyst	kg	Foam Scrap	kg
HCFC 141b	kg	Contaminate Raw Material Packaging	kg
Isocyanate	kg	**Emission to Air**	
Utilities		CN^-	mg
Water	m^3	NO_2	mg
Electricity	kWh	SO_2	mg
Others		CO	mg
Packaging		CO_2	mg
- Steel Drum	kg	VOCs	mg
Transportation		**Emission to Water**	
- 10 Wheel	Times	pH	
- Shipment	Times	TOC	mg
		TDS	mg
		SS	mg
		COD	mg
		BOD	mg
		Oil & Grease	mg
		Others	
		Flushing Polyol from Blender	kg
		Off-Spec. Formulated Polyol	kg

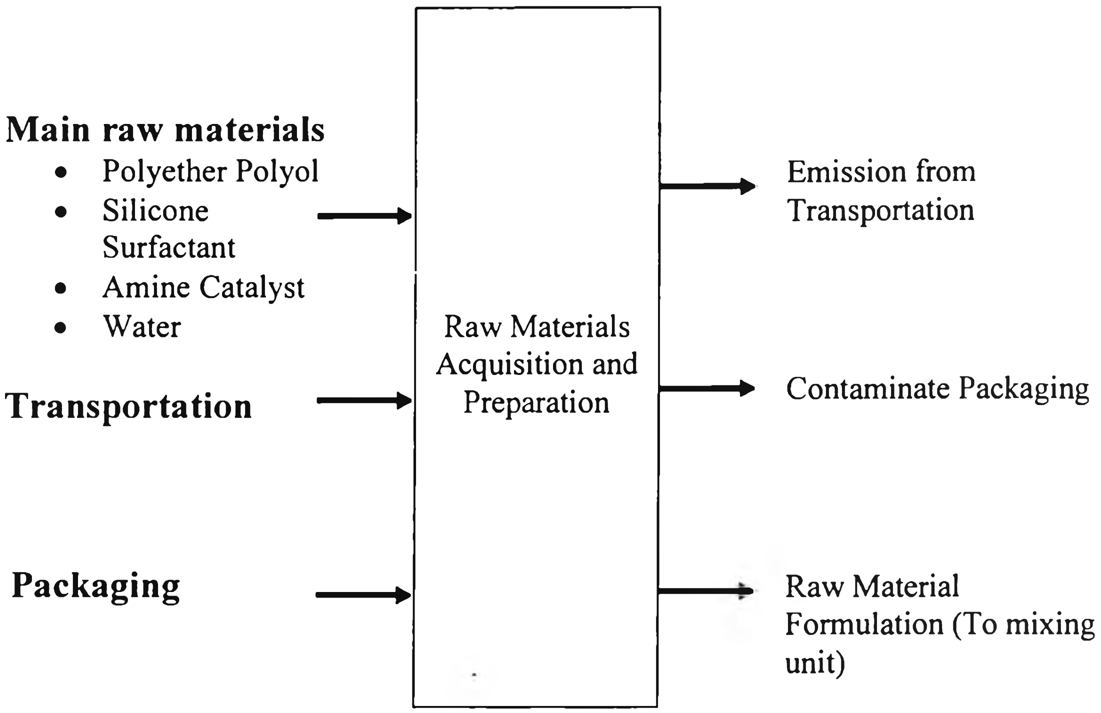

Figure 4.2 Input-output of raw materials acquisition and preparation.

Table 4.2 Input details of raw materials acquisition and preparation process

Input	
Type	Amount (kg)
Polyether Polyol	0.3344
Silicone Surfactant	0.0134
Amine Catalyst	0.0042
Water	0.005

Table 4.3 Output details of raw materials acquisition and preparation process

Output	
Type	Amount /unit
Raw material Formulation	***0.357 kg***
Emission from Transport	From program calculation

Table 4.4 Packaging details of raw materials acquisition and preparation process

Packaging		
Type	Amount (kg)	Remarks
Packaging (Steel Drum x3)	0.0352	Steel drum 21 Kg contains 200 L of each substance

Table 4.5 Transportation details of raw materials acquisition and preparation process

Transportation		
Type	Amount (kgkm)	Transport by
Polyether Polyol (20%)	$3.344E^{-3}$	Pipe
Polyether Polyol (80%)	727.168	Shipment
Silicone Surfactant	69.828	Shipment
Amine Catalyst	9.977	Shipment

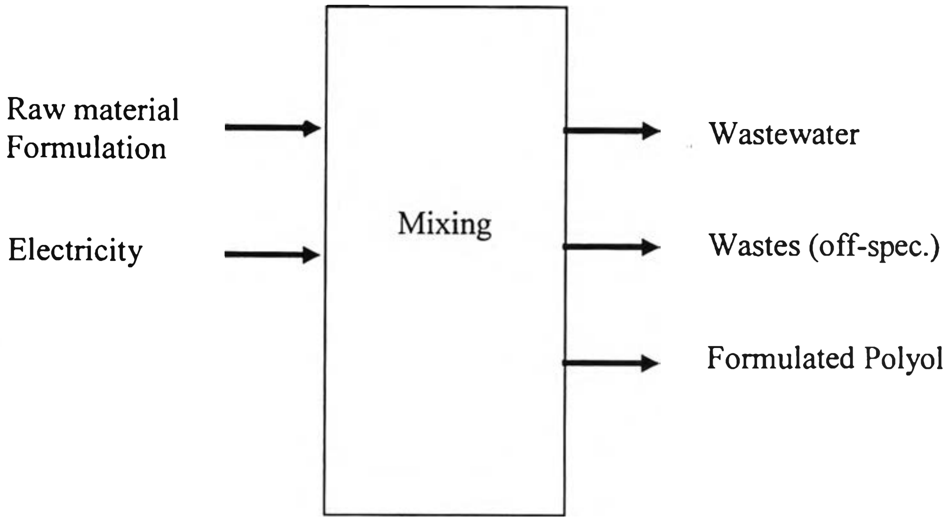

Figure 4.3 Input-output of mixing process.

Table 4.6 Input details of mixing process

Input	
Type	Amount /unit
Raw Material Formulation	0.357 kg

Table 4.7 Output details of mixing process

Output	
Type	Amount (kg)
Formulated Polyol	***0.3552***
Flushing Polyol from Blender	$4.55E^{-4}$
Discontinued Off-Shelf formulation Product	$1.35\ E^{-3}$

Table 4.8 Energy consumption of mixing process

Energy Consumption	
Type	Amount /unit
Electricity	0.0504 kWh

Table 4.9 Characteristics of wastewater from mixing process

Wastewater	
Type	Amount (mg)
TOC	$5.33E^{-3}$
TDS	0.2879
SS	$5.33E^{-3}$
COD	0.0213
BOD	$2.25E^{-3}$
Oil & Grease	$4.10E^{-4}$

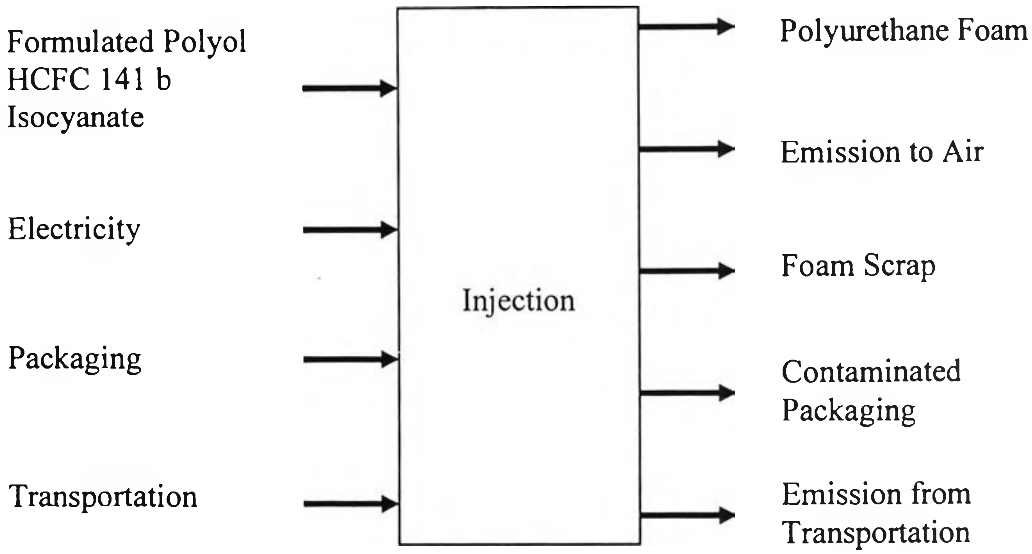

Figure 4.4 Input-output of injection process.

Table 4.10 Input details of injection process

Input	
Type	Amount (kg)
Formulated Polyol	0.3552
HCFC 141b	0.1065
Papi 27 (Isocyanate)	0.5433

Table 4.11 Output details of injection process

Output	
Type	Amount /unit
Polyurethane Foam	***1 kg***
Foam Scrap	0.005 kg
Emission from Transport	From program calculation

Table 4.12 Energy consumption of injection process

Energy Consumption	
Type	Amount /unit
Electricity	0.0124 kWh

Table 4.13 Packaging details of injection process

Packaging		
Type	Amount (kg)	Remarks
Packaging (Steel Drum x3)	0.101	Steel drum 21 Kg contains 200 L of each substance

Table 4.14 Transportation details of injection process

Transportation		
Type	Amount (kgkm)	Transport by
Formulated Polyol	71.04	10 wheel
HCFC 141b (50%)	134.8258	Shipment
HCFC 141b (50%)	60.9545	Shipment
Papi 27 (Isocyanate)	6,858.6953	Shipment

Table 4.15 Details of air emission from injection process

Emission to Air	
Type	Amount (mg)
CN^-	$8.55E^{-8}$
VOCs	$3.49E^{-8}$
CO_2	0.0262
CO	$4.81E^{-5}$
NO_2	$8.21E^{-6}$
SO_2	$8.55E^{-8}$

Raw Material	Unit (kg)
Polyether Polyol	0.3344
Silicone Surfactant	0.0134
Amine Catalyst	0.0042
Water	0.005
HCFC 141b	0.1065
Isocyanate (MDI)	0.5433
total	1.0068

Type	Unit
Transportation	7,931 kgkm
Electricity	0.081 kWh
Packaging (Steel Drum x 6)	0.129 kg

Polyurethane

Product	Unit (kg)
Polyurethane Foam	*1*

Waste	Unit (kg)
Flushing Polyol from Blender	3.4E^{-4}
Discontinued Off-Shelf formulation Product	0.0010
Contaminated Packaging	0.129

Solid Waste	Unit(kg)
Foam Scrap	0.0050

Wastewater	Unit
Water	32.75 l/day
TOC	425.75 mg
TDS	299,302mg
SS	425.75 mg
COD	1,703 mg
BOD	180.125 mg
Oil & Grease	32.75 mg

Emission to Air	Unit (mg)
CN^-	8.55E-08
VOCs	3.49E-08
CO_2	0.0262
CO	4.81E-05
NO_2	8.21E-06
SO_2	8.55E-08

Figure 4.5 Overall input-output of polyurethane foam production (based on 1 kg).

4.1.2 General Purpose Polystyrene (GPPS) Inventory

The processes for the production of general purpose polystyrene or GPPS are shown in Figure 4.6. Basically, there are 7 processes which include mixing of raw materials, which are styrene monomer, ethyl benzene, initiator (organic peroxide), and some additives, polymerization, devolatilization, styrene monomer recovery, extrusion, packaging, and injection. All processes except injection are performed at Dow Chemical Company whereas the injection is done at SUE to produce some parts of Sanyo refrigerator such as shelf, egg tray, etc. Consequently, LCI is performed on these 7 processes based on the production of 1 kg GPPS. Details of input and output data collection are shown in Table 4.16. Process flow diagram of each process is shown in Figures 4.7 to 4.13. Details input-output of each process step are described in Table 4.17 to Table 4.38. Raw materials and energy consumption of each process are described in Tables 4.17, 4.20, 4.22, 4.25, 4.28, 4.30 and 4.34 whereas the products and all emissions are shown in Tables 4.18, 4.21, 4.23, 4.26, 4.29, 4.31, and 4.35. Details of transportation (mode and distance) of raw materials, products and packaging materials for both domestic and international are demonstrated in Tables 4.19, 4.32, and 4.36. Raw materials are transported in domestic by pipe and in international by shipment (container ship) whereas the products are transported by 6-wheel and 10-wheel trucks. Packaging materials for GPPS pellet (polyethylene film) and clear shelf (polypropylene film) are also transported by trucks (both 6 wheels and 10 wheels). The amounts of packaging materials used are shown in Tables 4.33 and 3.37. Details of the emissions are described in Tables 4.24, 4.27 and 4.38. Figure 4.14 shows overall input-output of the production of 1 kg GPPS.

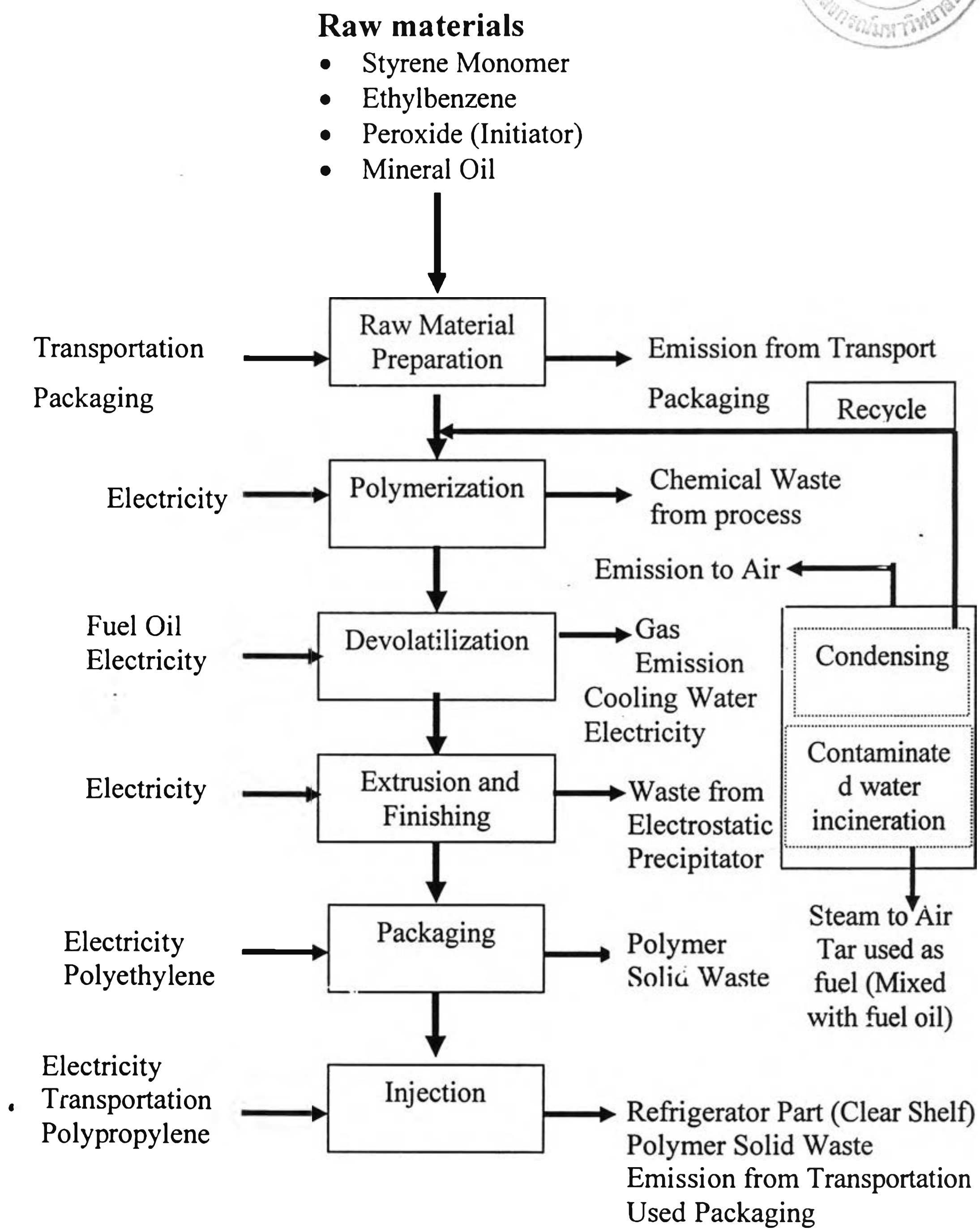

Figure 4.6 General purpose polystyrene production processes.

Table 4.16 Input-output data of general purpose polystyrene production

Input Data		Output Data	
Type	Unit	Type	Unit
Raw Materials		**Product**	
Styrene Monomer	kg	General Purpose Polystyrene Pellet	kg
Ethylbenzene	kg	**Solid Wastes**	
Peroxide (Initiator)	kg	Polystyrene Scrap	kg
White Mineral Oil	kg	Contaminate Raw Material Packaging	kg
Utilities		**Emission to Air**	
Water	m^3	TSP	mg
Electricity	kWh	NO_2	mg
Others		SO_2	mg
Packaging		CO	mg
- Polypropylene	kg	CO_2	mg
- Polyethylene	kg	Total Hydrocarbon (THC)	mg
Transportation		Antimony (Sb)	mg
- 10 Wheel	Times	VOCs	mg
- Shipment	Times	**Others**	
		Chemical Waste	kg

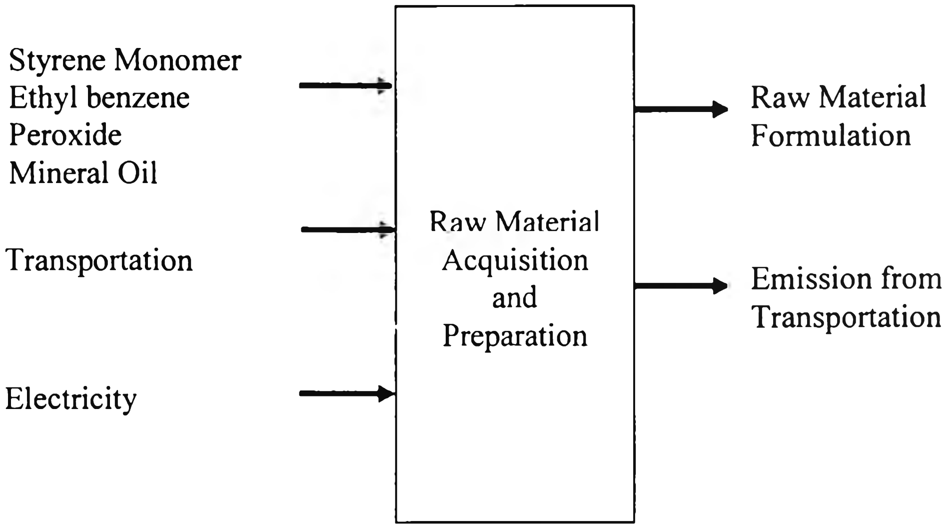

Figure 4.7 Input-output of raw material acquisition and preparation process.

Table 4.17 Input details of raw materials acquisition and preparation process

Input	
Type	Amount /unit
Styrene monomer	0.8392 kg
Ethyl Benzene	0.0859 kg
White Mineral Oil (Naphtha)	0.0303 kg
Peroxide	0.0556 kg
Electricity	0.1342 kWh

Table 4.18 Output details of raw materials acquisition and preparation process

Output	
Type	Amount /unit
Raw Materials Formulation	***1.011 kg***
Emission from Transportation	From program calculation

Table 4.19 Transportation details of raw materials acquisition and preparation process

Transportation		
Type	Amount (kgkm)	Transport by
Styrene monomer	1.6784	Pipe
Ethyl Benzene	0.17178	Pipe
White Mineral Oil	81.922	Shipment
Peroxide	882.089	Shipment

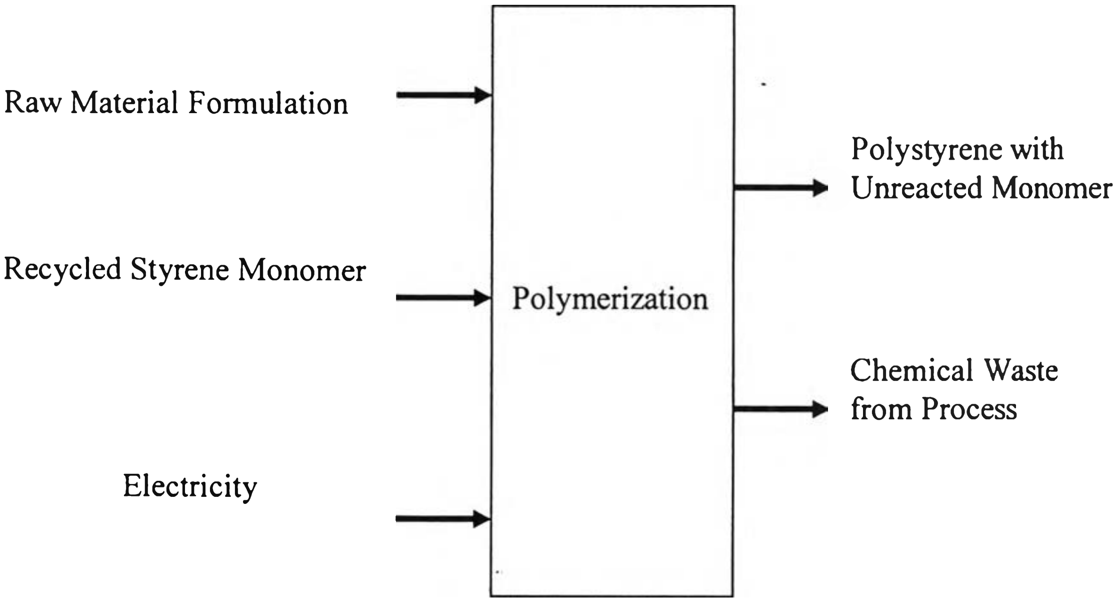

Figure 4.8 Input-output of polymerization process.

Table 4.20 Input details of polymerization process

Input	
Type	Amount /unit
Raw Materials Formulation	1.011 kg
Recycled Styrene Monomer	$4.92E^{-3}$ kg
Electricity	0.0451 kWh

Table 4.21 Output details of polymerization process

Output	
Type	Amount (kg)
Polystyrene with Unreacted Monomer	***1.0121***
Chemical Waste from Process	$3.89E^{-3}$

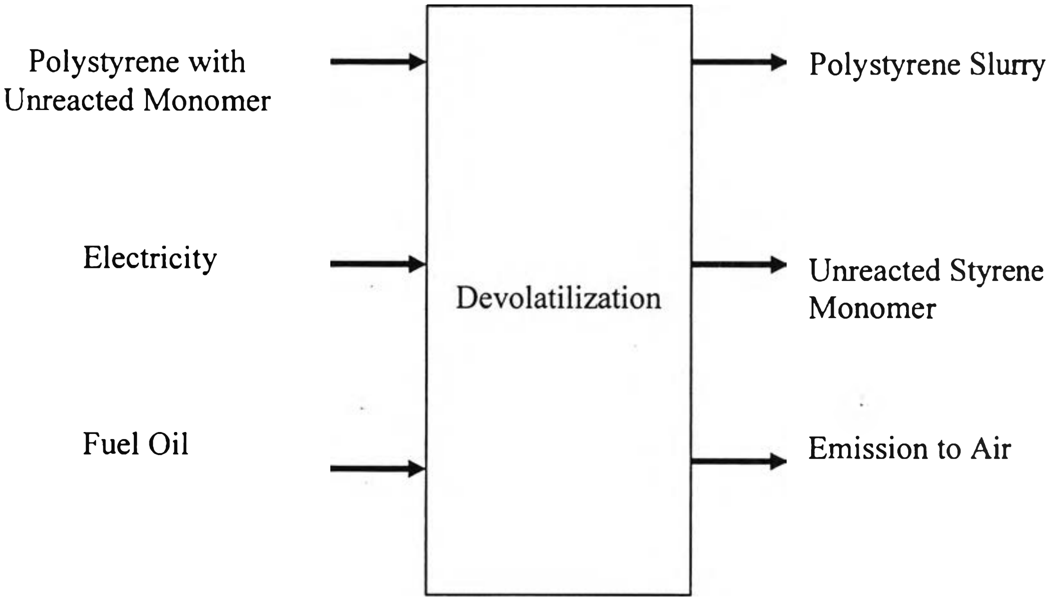

Figure 4.9 Input-output of devolatilization process.

Table 4.22 Input details of devolatilization process

Input	
Type	Amount /unit
Polystyrene with Unreacted Monomer	1.0121 kg
Electricity	0.1426 kWh
Fuel Oil	5.76 Btu

Table 4.23 Output details of devolatilization process

Output	
Type	Amount (kg)
Polystyrene Slurry	***1.0051***
Unreacted Styrene Monomer	$7E^{-3}$

Table 4.24 Details of air emission from devolatilization process

Emission to Air	
Type	Amount (mg)
TSP	0.48
NO_2	2.87

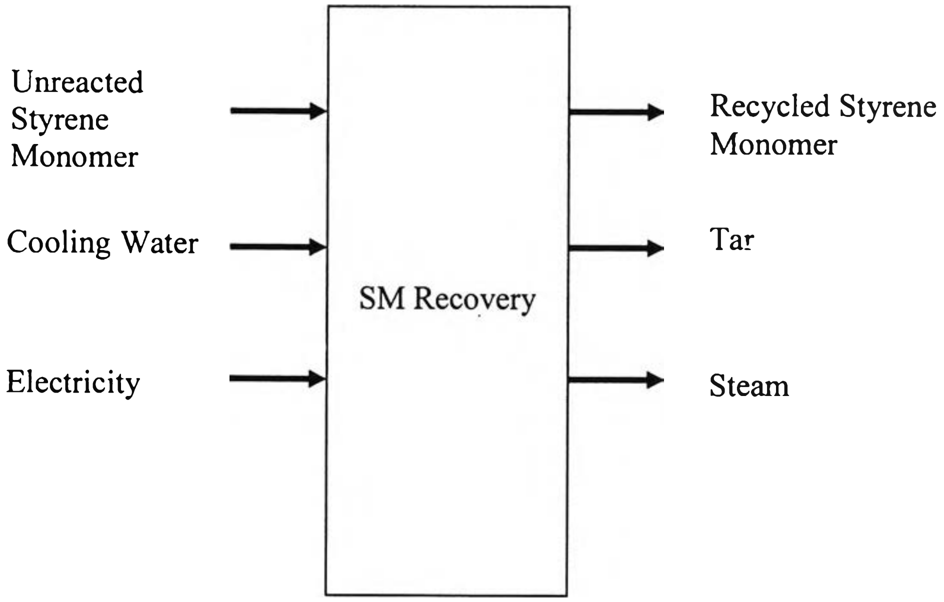

Figure 4.10 Input-output of SM recovery process.

Table 4.25 Input details of SM recovery process

Input	
Type	Amount /unit
Unreacted Styrene Monomer	$7E^{-3}$ kg
Cooling Water	5.9496 kg
Electricity	0.0441 kWh

Table 4.26 Output details of SM recovery process

Output	
Type	Amount (kg)
Recycled Styrene Monomer	$4.92E^{-3}$
Tar	$2.08E^{-3}$
Steam	5.9496

Table 4.27 Details of air emission from SM recovery process

Emission to Air	
Type	Amount (mg)
TSP	83.38
NO_2	4.59
CO	0.89
THC	0.69

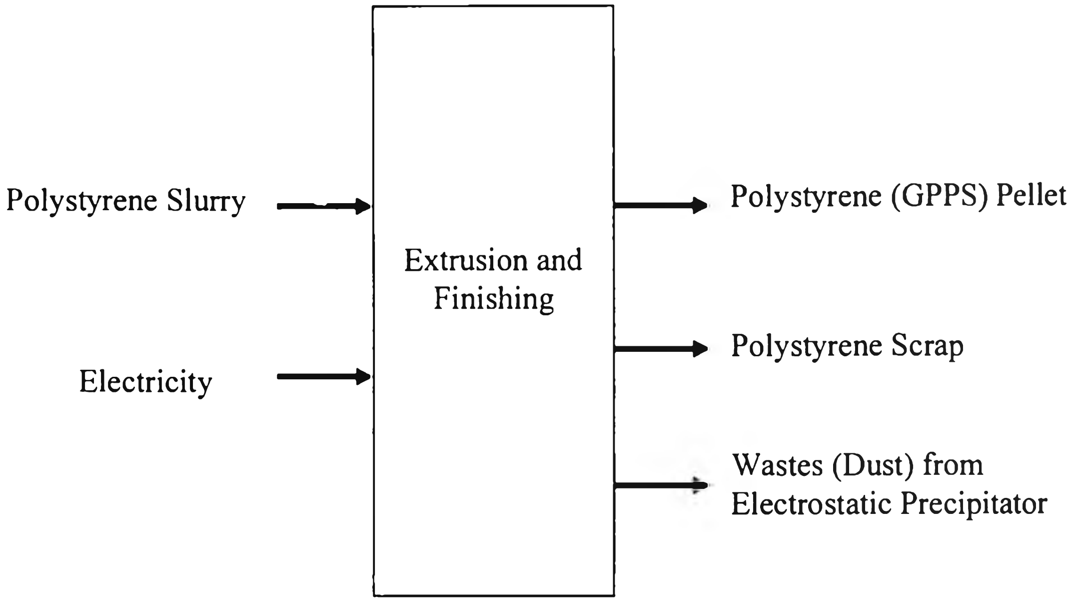

Figure 4.11 Input-output of extrusion and finishing process.

Table 4.28 Input details of extrusion and finishing process

Input	
Type	Amount /unit
Polystyrene Slurry	1.0051 kg
Electricity	0.0124 kWh

Table 4.29 Output details of extrusion and finishing process

Output	
Type	Amount /unit
Polystyrene (GPPS) Pellet	***1 kg***
Polystyrene Scrap	4.52E^{-3} kg
Wastes (Dust) from Electrostatic Precipitator	
TSP	0.47 mg
THC	0.24 mg
Sb	5.87E^{-4} mg

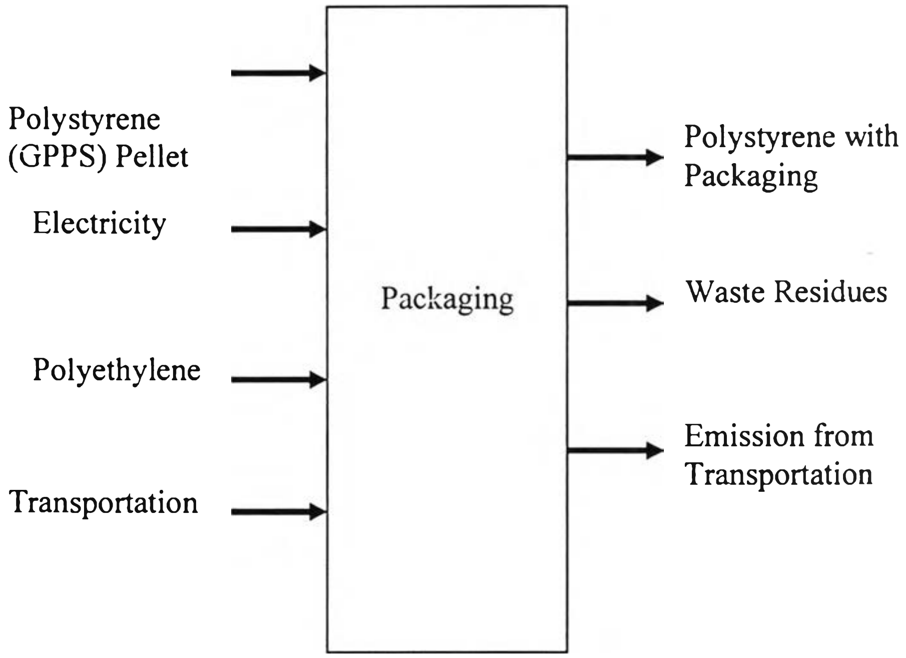

Figure 4.12 Input-output of packaging process.

Table 4.30 Input details of packaging process

Input	
Type	Amount /unit
Polystyrene (GPPS) Pellet	1 kg
Electricity	0.0117 kWh

Table 4.31 Output details of packaging process

Output	
Type	Amount /unit
Polystyrene with Packaging	***1.0044 kg***
Waste Residues	$1.72E^{-3}$ kg
Emission from Transportation	From program calculation

Table 4.32 Transportation details of packaging process

Transportation		
Type	Amount (kgkm)	Transport by
Polyethylene	1.5361	10 Wheel

Table 4.33 Packaging details of packaging process

Packaging	
Type	Amount /unit
Polyethylene	$6.12E^{-3}$ kg

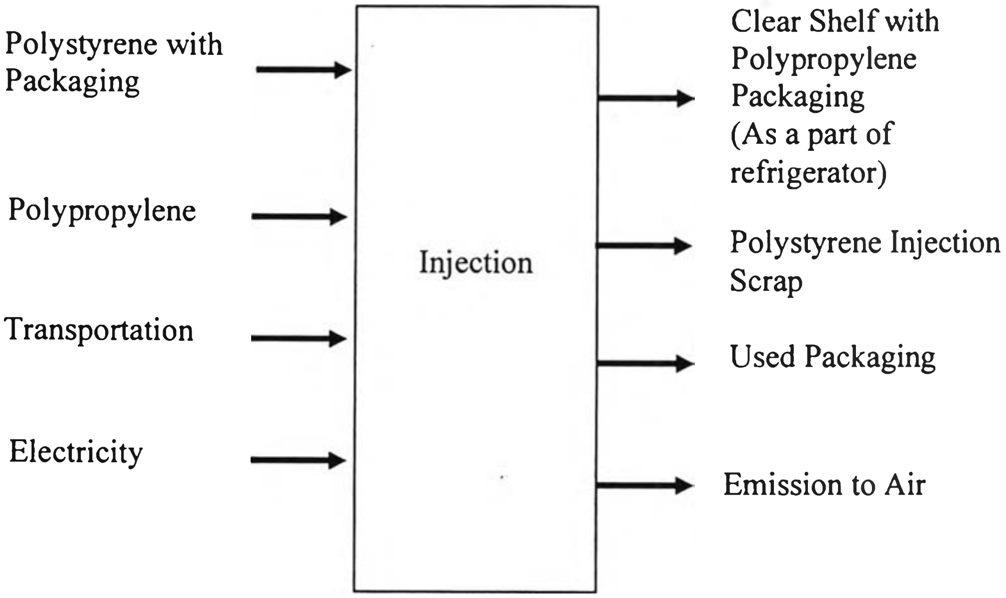

Figure 4.13 Input-output of injection process.

Table 4.34 Input details of injection process

Input	
Type	Amount /unit
Polystyrene with Packaging	1.0044 kg
Electricity	3.552 kWh

Table 4.35 Output details of injection process

Output	
name	Amount /unit
Clear Shelf with Polypropylene Packaging	***0.7937 kg***
Polystyrene Injection Scrap	0.2113 kg
Used Packaging	0.0044 kg
Emission from Transportation	From program calculation

Table 4.36 Transportation details of injection process

Transportation		
Type	Amount (kgkm)	Transport by
Polystyrene with Packaging	376.65	6 Wheel
Clear Shelf with Polypropylene Packaging	297.6375	6 Wheel
Polypropylene Film	0.15	6 Wheel

Table 4.37 Packaging details of injection process

Packaging	
Type	Amount (kg)
Polypropylene Film	5.0E^{-3}

Table 4.38 Details of air emission from injection process

Emission to Air	
Type	Amount (mg)
TSP	0.91
SO_2	0.001
NO_2	0.01
CO	0.057
CO_2	285.712
VOCs	$4.08E^{-4}$

Raw Material	Unit (kg)
Styrene Monomer	0.8432
White Mineral Oil (Naphtha)	0.0305
Solvent (Ethylbenzene)	0.0864
Peroxide (Initiator)	0.0559
total	1.016

Packaging	Unit (kg)
Polyethylene	6.12E^{-3}
Polypropylene	5.0E^{-3}

Type	Unit
Water	5.9496 kg
Fuel Oil	5.76 Btu
Transportation	1,349.136 kgkm
Electricity	3.9421 kWh

GPPS

Product	Unit (kg)
Polystyrene (GPPS) Pellet	*1*

Waste	Unit (kg)
Steam	5.9496
Tar	2.08E-03

Solid Waste	Unit (kg)
Waste Residues	1.72E-03
Chemical Waste from Process	3.89E-03
Polystyrene scrap	4.52E-03
Polystyrene Injection Scrap	0.2113
Used Packaging	0.0044

Emission to Air	Unit (mg)
TSP	85.24
NO_2	7.47
THC	0.93
Sb	5.87E-04
CO	0.947
CO_2	285.71
SO_2	0.001
VOCs	4.08E-04

Figure 4.14 Overall input-output of general purpose polystyrene production.

4.1.3 High Impact Polystyrene (HIPS) Inventory

The processes for the production of high impact polystyrene or HIPS are similar those of GPPS as shown in Figure 4.15 which consist of 7 processes including raw materials mixing and preparation, polymerization, devolatilization, styrene monomer recovery, extrusion, packaging, and injection. The only difference between HIPS and GPPS processes is in raw materials where HIPS also include polybutadiene rubber to improve the quality of the polystyrene. All processes except injection are performed at Dow Chemical Company whereas the injection is done at SUE to produce some parts of Sanyo refrigerator such as side air duct, etc. Similar to GPPS, LCI is performed on these 7 processes based on the production of 1 kg HIPS. Details of input and output data collection are shown in Table 4.39. The process flow diagram of each process of HIPS production is illustrated in Figures 4.16 to 4.22. Details input-output of each process step are described in Table 4.40 to Table 4.60. Raw materials and energy consumption of each process are shown in Tables 4.40, 4.43, 4.45, 4.48, 4.51, 4.53 and 4.57. Products and all waste emissions are demonstrated in Tables 4.41, 4.44, 4.46, 4.49, 4.52, 4.53, and 4.58. Transportations of raw material, products, and packaging materials for both domestic and international are described in Tables 4.42, 4.55, and 4.59. Transportation modes for raw materials, product, and packaging are similar to those of GPPS. Details of HIPS pellet packaging is shown in Table 4.56 whereas the emission details are described in Tables 4.47, 4.50 and 4.60. Figure 4.23 shows overall input-output of the production of 1 kg HIPS.

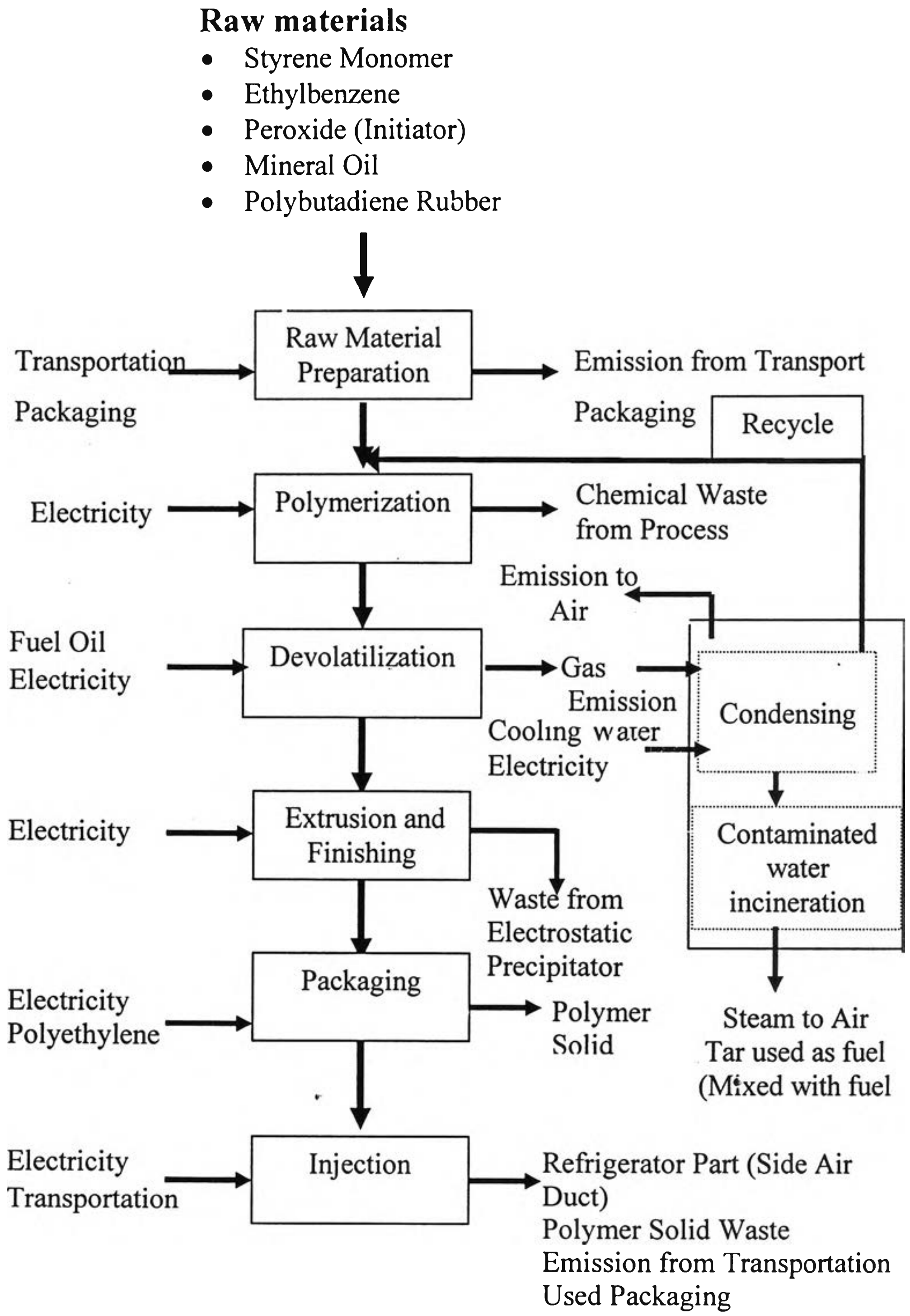

Figure 4.15 High impact polystyrene (HIPS) processes.

Table 4.39 Input-output data of high impact polystyrene (HIPS) production

Input Data		Output Data	
Type	Unit	Type	Unit
Raw Materials		**Product**	
Polystyrene Monomer	kg	High Impact Polystyrene Pellet	kg
Ethylbenzene	kg	**Solid Wastes**	
Peroxide (Initiator)	kg	Polystyrene Scrap	kg
Butadiene Rubber	kg	Contaminate Raw Material Packaging	kg
White Mineral Oil	kg	Rubberized Slurry	kg
Utilities		**Emission to Air**	
Water	m^3	TSP	mg
Electricity	kWh	NO_2	mg
Others		SO_2	mg
Packaging		CO	mg
- Polyethylene	kg	CO_2	mg
Transportation		Total Hydrocarbon (THC)	mg
- 10 Wheel	Times	Antimony (Sb)	mg
- Shipment	Times	VOCs	mg
		Others	
		Chemical Waste	kg

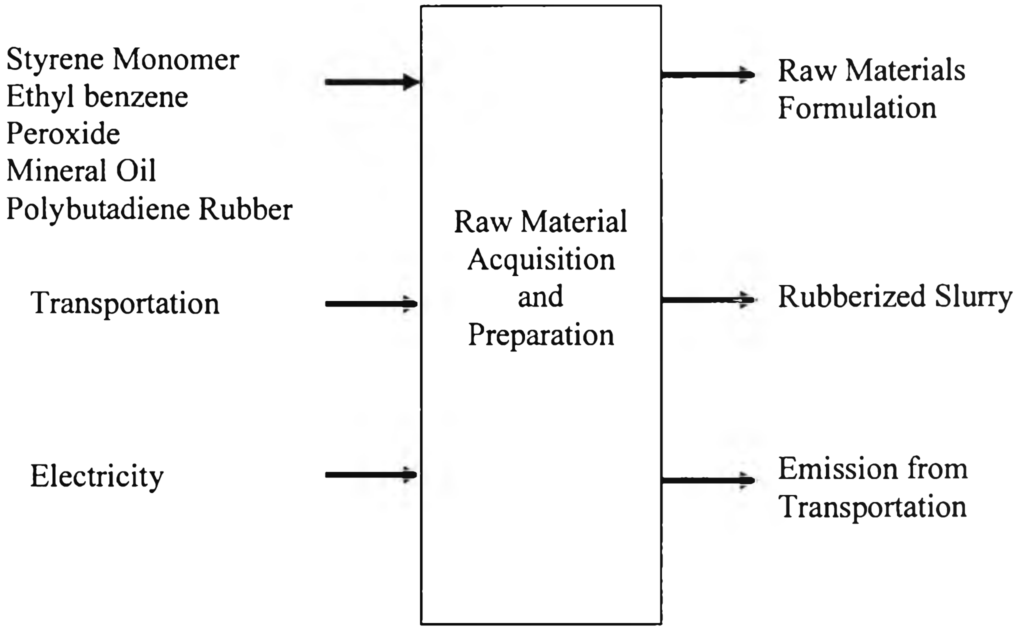

Figure 4.16 Input-output of raw material acquisition and preparation process

Table 4.40 Input details of raw material acquisition and preparation process

Input	
Type	Amount /unit
Styrene monomer	0.84 kg
Polybutadiene Rubber	0.12 kg
Ethyl Benzene	0.03 kg
White Mineral Oil (Naphtha)	0.028 kg
Peroxide	0.058 kg
Electricity	0.0482 kWh

Table 4.41 Output details of raw material acquisition and preparation process

Output	
Type	Amount /unit
Raw Materials Formulation	***1.048 kg***
Rubberized Slurry	0.028 kg
Emission from Transportation	From program calculation

Table 4.42 Transportation details of raw material acquisition and preparation process

Transportation		
Type	Amount (kgkm)	Transport by
Styrene monomer	1.68	Pipe
Ethyl Benzene	0.06	Pipe
Polybutadiene Rubber	1903.7892	Shipment
White Mineral Oil	75.7035	Shipment
Peroxide	920.1648	Shipment

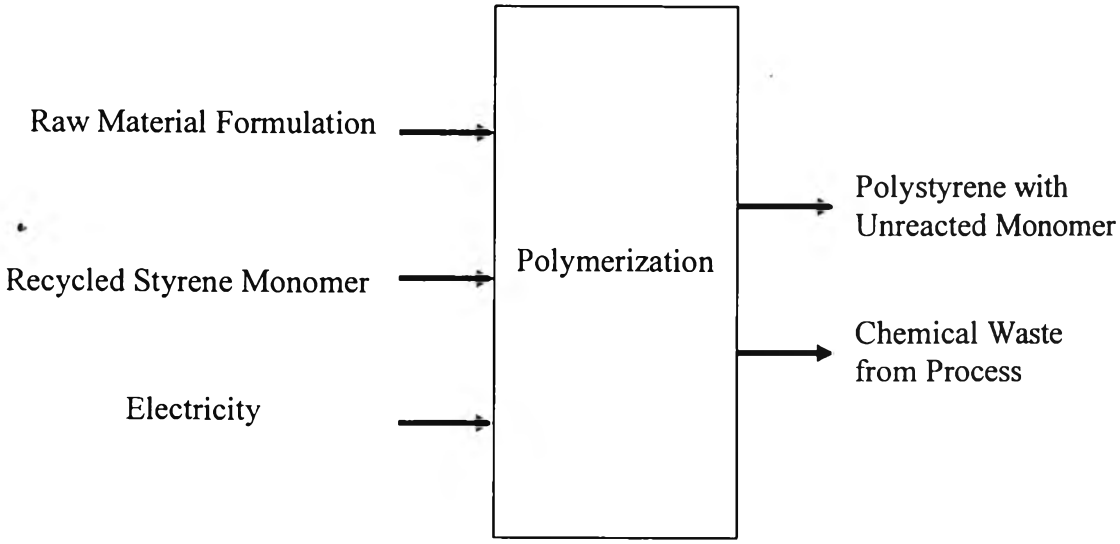

Figure 4.17 Input-output of polymerization process.

Table 4.43 Input details of polymerization process

Input	
Type	Amount /unit
Raw Material Formulation	1.048 kg
Recycled Styrene Monomer	5.0E^{-3} kg
Electricity	0.0161 kWh

Table 4.44 Output details of polymerization process

Output	
Type	Amount (kg)
Polystyrene with Unreacted Monomer	***1.0141***
Chemical Waste from Process	3.89E^{-2}

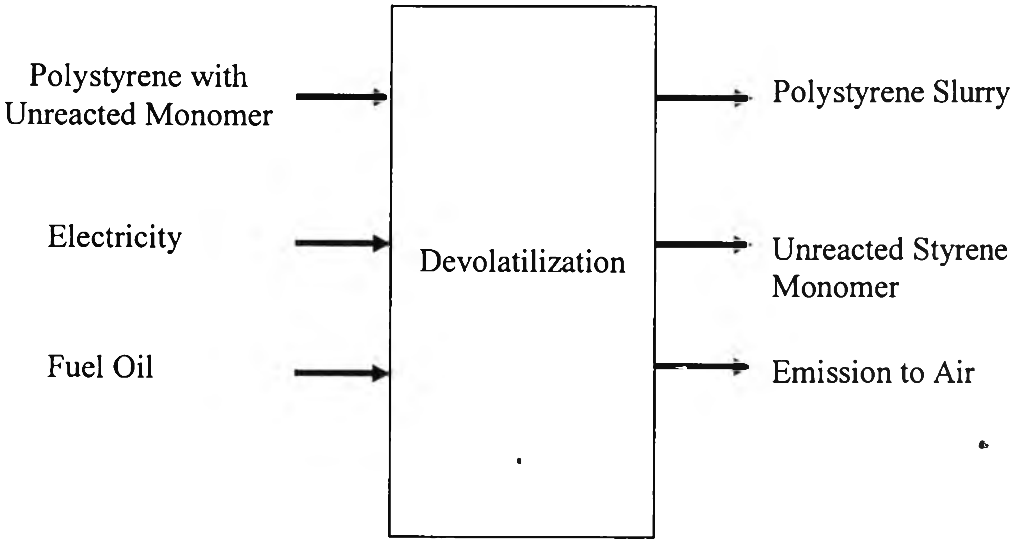

Figure 4.18 Input-output of devolatilization process.

Table 4.45 Input details of devolatilization process

Input	
Type	Amount /unit
Polystyrene with Unreacted Monomer	1.0141 kg
Electricity	0.051 kWh
Fuel Oil	2.05716 Btu

Table 4.46 Output details of devolatilization process

Output	
Type	Amount (kg)
Polystyrene Slurry	***1.0067***
Unreacted Styrene Monomer	$7.4E^{-3}$

Table 4.47 Details of emission to air from devolatilization process

Emission to Air	
Type	Amount (mg)
TSP	1.475
NO_2	26.964

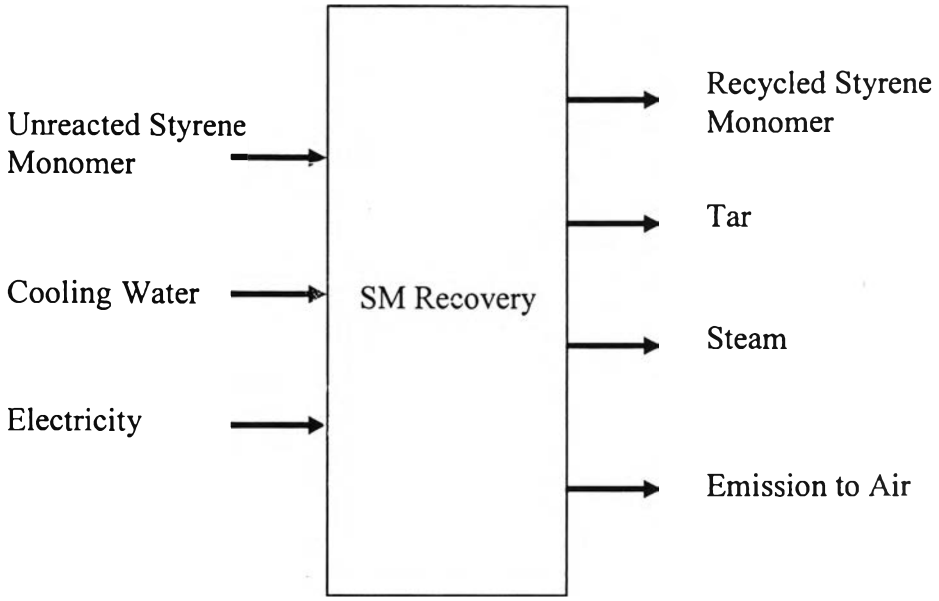

Figure 4.19 Input-output of SM recovery process.

Table 4.48 Input details of SM recovery process

Input	
Type	Amount /unit
Unreacted Styrene Monomer	$7.4E^{-3}$ kg
Cooling Water	5.9496 kg
Electricity	0.0158 kWh

Table 4.49 Input details of SM recovery process

Output	
Type	Amount (kg)
Recycled Styrene Monomer	***$5.0E^{-3}$***
Tar	$2.08E^{-3}$
Steam	5.9496

Table 4.50 Details of emission to air from SM recovery process

Emission to Air	
Type	Amount (mg)
TSP	244.672
NO_2	12.858
CO	2.502
THC	1.94

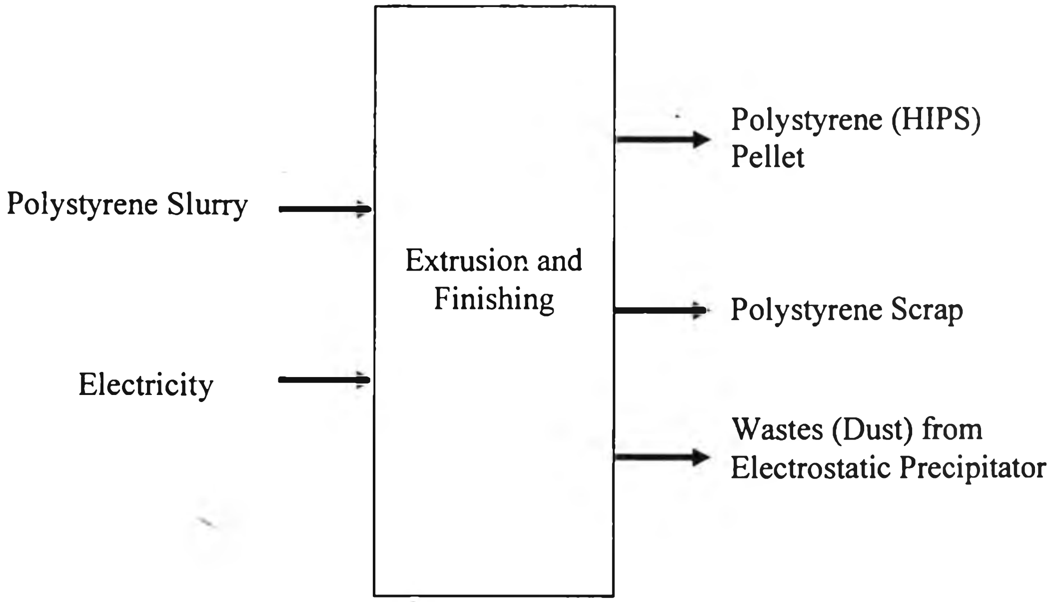

Figure 4.20 Input-output of extrusion and finishing process.

Table 4.51 Input details of extrusion and finishing process

Input	
Type	Amount /unit
Polystyrene Slurry	1.0067 kg
Electricity	$4.4E^{-3}$ kWh

Table 4.52 Output details of extrusion and finishing process

Output	
Type	Amount /unit
Polystyrene (HIPS) Pellet	***1 kg***
Polystyrene Scrap	6.6E^{-3} kg
Wastes (Dust) from Electrostatic Precipitator	
TSP	0.468 mg
THC	0.678 mg
Sb	1.6E^{-3} mg

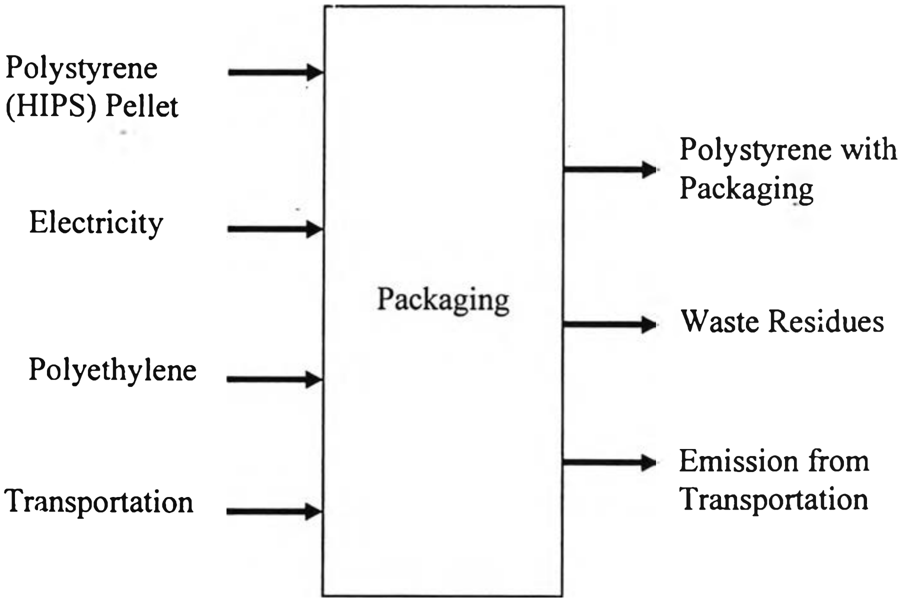

Figure 4.21 Input-output of packaging process.

Table 4.53 Input details of packaging process

Input	
Type	Amount /unit
Polystyrene (HIPS) Pellet	1 kg
Electricity	4.2E^{-3} kWh

Table 4.54 Output details of packaging process

Output	
Type	Amount /unit
Polystyrene with Packaging	***1.0044 kg***
Emission from Transportation	From program calculation
Waste Residues	1.72E^{-3} kg

Table 4.55 Transportation details of packaging process

Transportation		
Type	Amount (kgkm)	Transport by
Polyethylene	1.5361	10 Wheel

Table 4.56 Packaging details of packaging process

Packaging	
Type	Amount /unit
Polyethylene	6.12E^{-3} kg

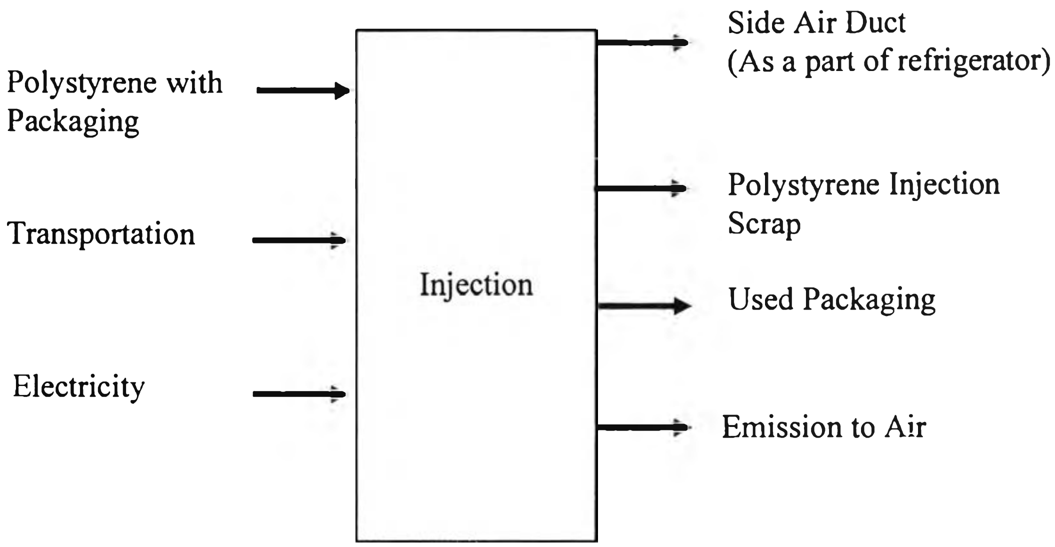

Figure 4.22 Input-output of injection process.

Table 4.57 Input details of injection process

Input	
Type	Amount /unit
Polystyrene with Packaging	1.0044 kg
Electricity	3.552 kWh

Table 4.58 Output details of injection process

Output	
Type	Amount /unit
Side Air Duct	***0.5261 kg***
Polystyrene Injection Scrap	0.4739 kg
Used Packaging	0.0044 kg
Emission from Transportation	From program calculation

Table 4.59 Transportation details of injection process

Transportation		
Type	Amount (kgkm)	Transport by
Polystyrene with Packaging	376.65	6 Wheel
Side Air Duct	197.2875	6 Wheel

Table 4.60 Details of air emission from injection process

Emission to Air	
Type	Amount (mg)
TSP	0.916
SO_2	0.001
NO_2	0.012
CO	0.057
CO_2	285.712
VOCs	$4.0E^{-4}$

Raw Material	Unit (kg)
Styrene Monomer	0.8424
Polybutadiene Rubber	0.1202
White Mineral Oil (Naphtha)	0.0284
Solvent (Ethylbenzene)	0.0307
Peroxide (Initiator)	0.0588
total	1.081

Packaging	Unit (kg)
Polyethylene	6.12E-3

Type	Unit
Water	5.9496 Kg
Fuel Oil	2.057 Btu
Transportation	3044.571 kgkm
Electricity	3.6917 kWh

HIPS

Product	Unit (kg)
Polystyrene Pellet (HIPS)	1

Waste	Unit (kg)
Steam	5.9496
Tar	2.08E-03

Solid Waste	Unit (kg)
Waste Residues	1.72E-03
Chemical Waste from Process	3.89E-03
Rubberized Slurry	0.028
Polystyrene Scrap	6.64E-03
Polystyrene Injection Scrap	0.4739
Used Packaging	0.0044

Emission to Air	Unit (mg)
TSP	247.531
NO_2	39.834
THC	2.618
Sb	1.60E-03
CO	2.559
CO_2	285.712
SO_2	0.001
VOCs	4.08E-04

Figure 4.23 Overall input-output of HIPS processes.

4.2 Environmental Impact Assessment

After the life cycle inventory (LCI) was carried out, life cycle impact assessment (LCIA) could then be performed based on the quantitative information attained from LCI study in order to identify the environmental impacts from the production of the three model petrochemical products, PU foam, GPPS, and HIPS. This was done by using the commercial LCA software - SimaPro 5.1 - with Eco-Indicator 95 and Eco-Indicator 99 for environmental impact assessment. Eco-Indicator 95 is a mid-point approach to the impact assessment whereas Eco-Indicator 99 is an end-point approach. The environmental categories being the focus in this research are global warming, stratospheric ozone depletion, acidification, recourse depletion, and carcinogenic affect from carcinogen substances (human health damage). In this part of the study, the results from Eco-Indicator 95 were firstly presented followed by the results from Eco-Indicator 99. In addition, the comparison between the two methods was also discussed.

4.2.1 Environmental Impact Assessment of Polyurethane Foam

Using Eco-indicator 95, the overall results of the production of 1 kg PU foam shown in Figure 4.24 indicates the environmental impacts mainly come from raw materials used in the manufacturing processes which are chemicals such as polyether polyol and isocyanate (MDI) as indicated by the level of the bar in each block diagram. Figure 4.25 reveals that heavy metals and acidification are the major environmental impact categories of the overall PU process. The comparison of the environmental impact for all 5 phases of PU foam production shown in Figure 4.26 illustrates that the manufacturing phase contributes most followed by the use phase (injection) and transportation whereas the contributions from packaging and disposal phases are shown to be negligible. In the manufacturing phase, Figure 4.27 shows that the environmental impact is essentially from polyether polyol of which its production contributes mainly in heavy metals and acidification. Figure 4.28 shows the environmental impact assessment for the use phase where the main contribution is from isocyanate (MDI). Heavy metals, acidification, greenhouse gases, and carcinogens are the main impact categories resulted from MDI production.

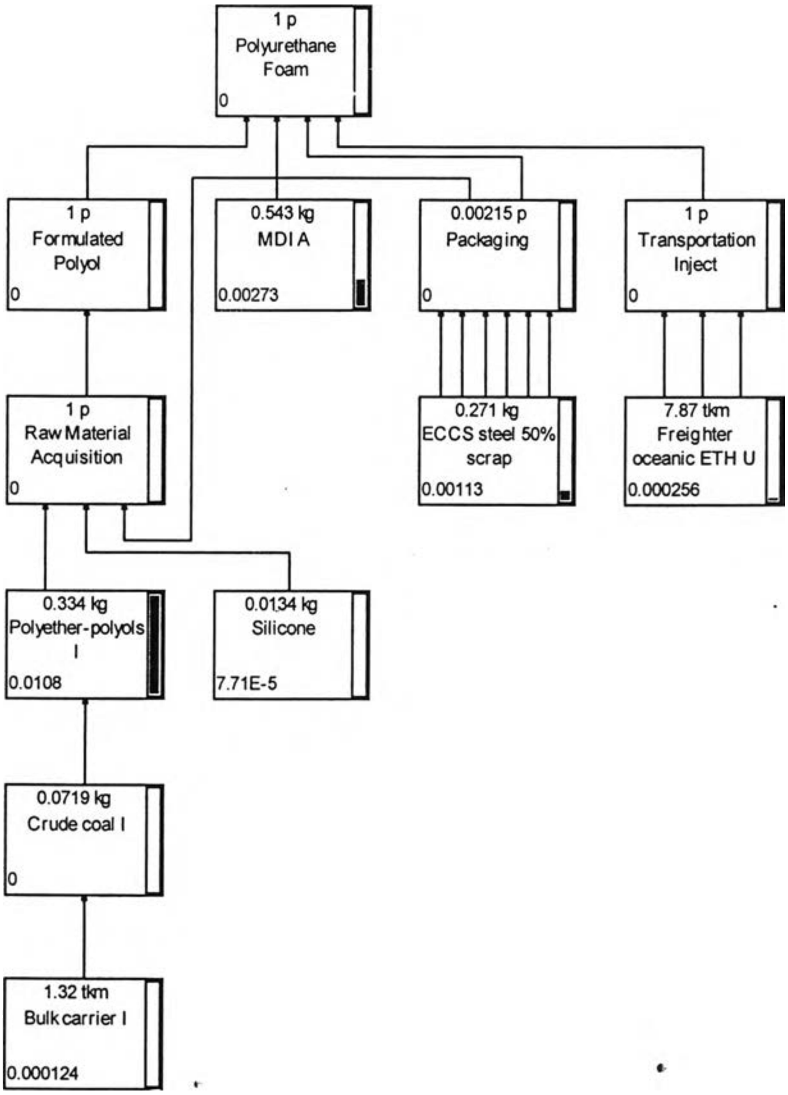

Figure 4.24 Overall results of the environmental impact assessment of the production of 1 kg polyurethane obtained by using Eco-Indicator 95.

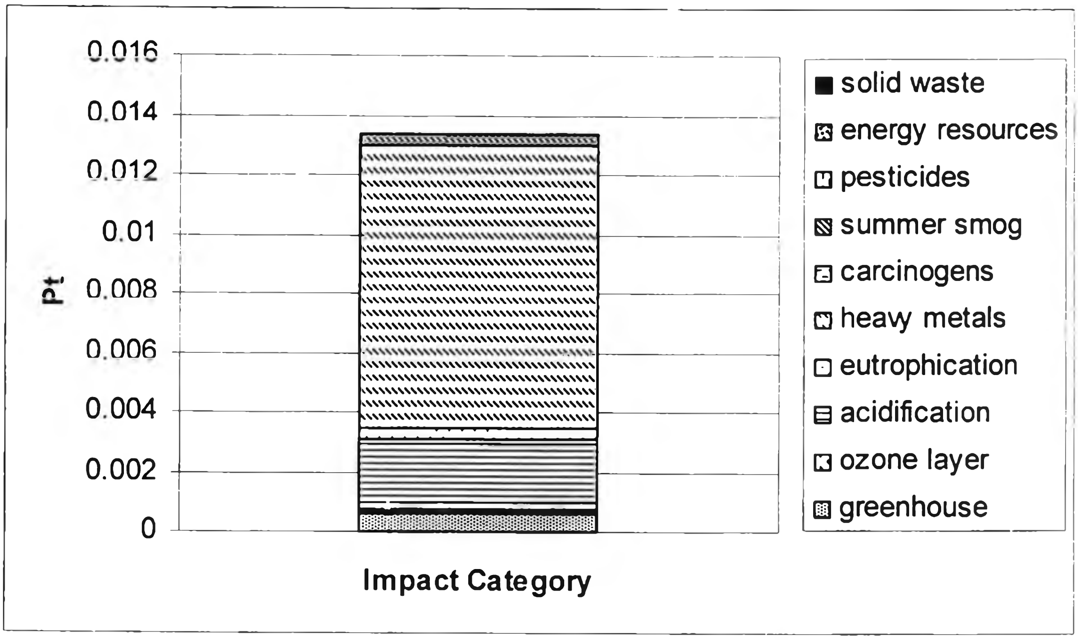

Figure 4.25 Environmental impact categories of 1 kg polyurethane foam production obtained by using Eco-indicator 95.

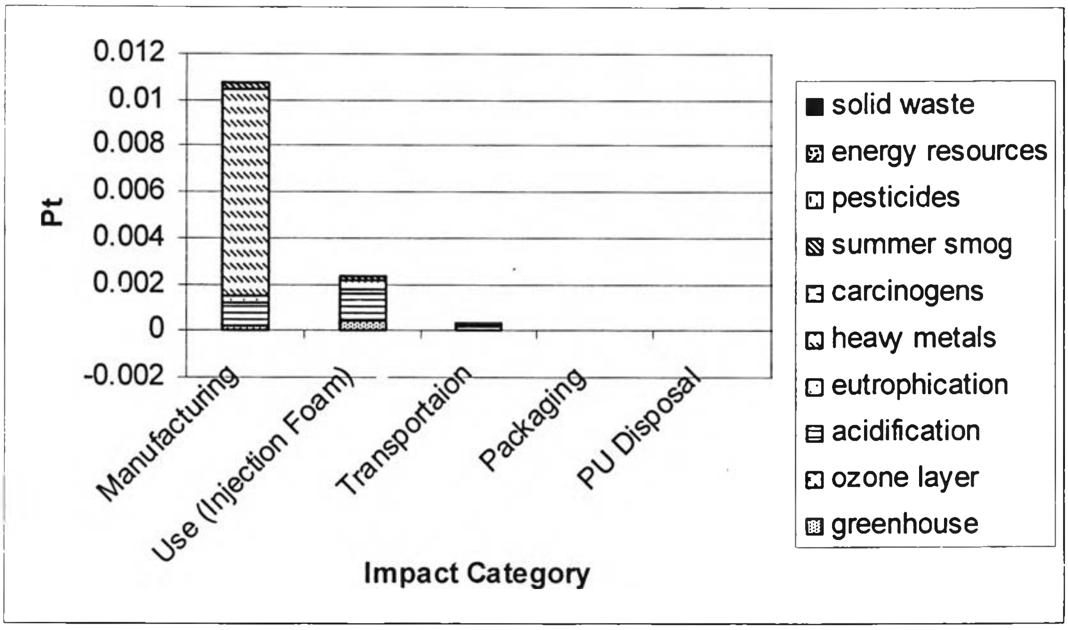

Figure 4.26 Environmental impact categories of each phase in the production of 1 kg polyurethane foam obtained by using Eco-indicator 95.

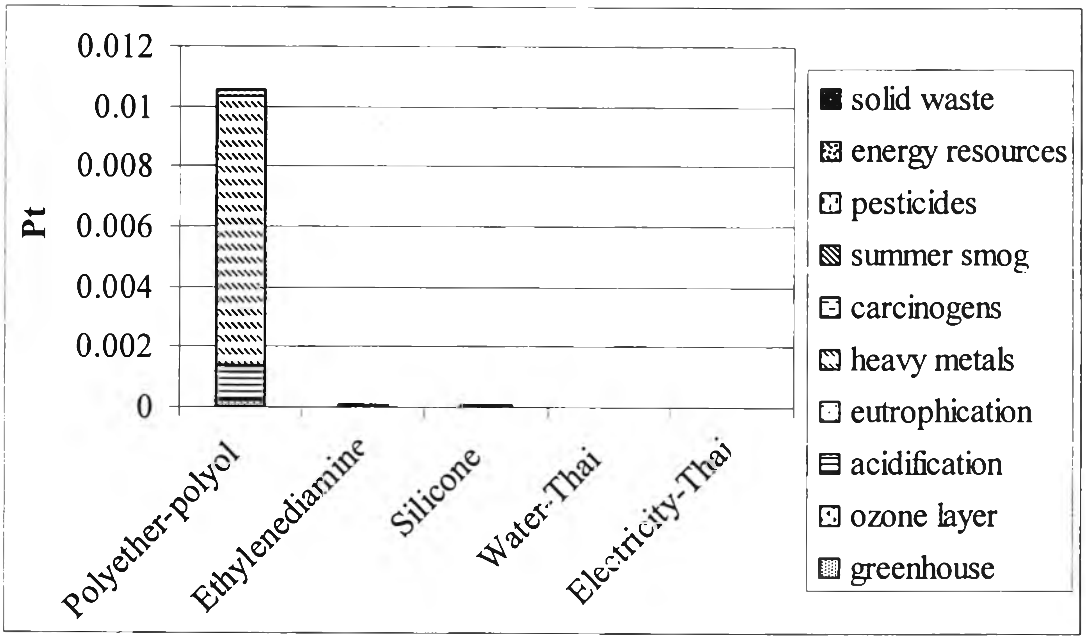

Figure 4.27 Environmental impact categories of the manufacturing phase in the production of 1 kg polyurethane foam obtained by using Eco-Indicator 95.

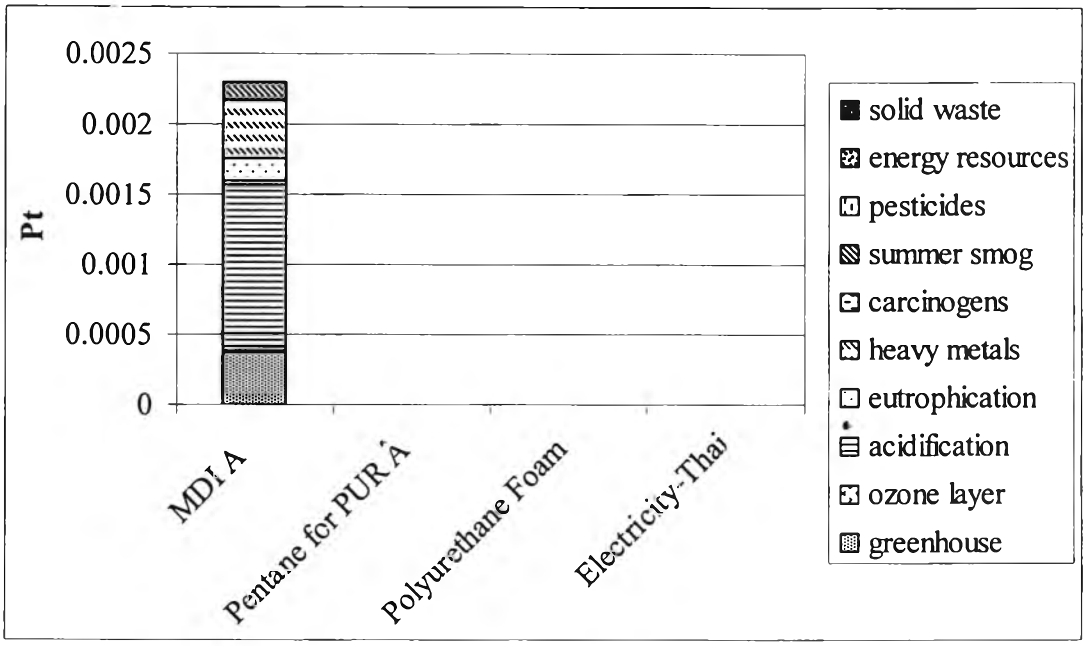

Figure 4.28 Environmental impact categories of the use phase in the production of 1 kg polyurethane foam obtained by using Eco-Indicator 95.

Table 4.61 shows the results of the environmental impact assessment using Eco-indicator 95 and presented in terms of equivalent units for each impact category for the production of 1 kg polyurethane foam. It can be seen that the production of 1 kg of PU foam utilizes energy resources equivalent to 79.9 MJ LHV and generates green house gases equivalent to 3.34 kg of CO_2, solid wastes 1.76 kg, acidification equivalent to $2.7E^{-2}$ kg of SO_2, heavy metals $1.04E^{-4}$ kg of Pb equivalent, ozone layer depletion substances equivalent to $3.47E^{-7}$ kg of CFC11, and carcinogenic effect equivalent to $8.34E^{-9}$ kg of benzo(a)pyrene. Energy is mostly consumed in the use phase (approximately 64%) which involves injection of formulated polyol and other chemicals to produce PU foam. Greenhouse gases are generated mainly from manufacturing and use phases which account for 38% and 58%, respectively. Manufacturing phase also contributes most to the solid wastes being generated in the production of PU foam (38%). For acidification, the manufacturing and use phases share 40% and 50% of the total SO_2 kg-equivalent emitted in the production of PU foam. For packaging phase, the result gives minus value in summer smog and carcinogens. This means, it benefits for environment because PU foam packaging dispose by 20% recycle and 20% incineration for using as energy.

Table 4.62 and Table 4.63 show the environmental impacts in equivalent units for the manufacturing phase and use phase, respectively. For manufacturing phase, it can be obviously seen from the result that polyether polyol contributes most in almost all impact categories, except ozone layer depletion and carcinogens where silicone-based surfactant and ethylenediamine are the main contributors. For use phase, isocyanate (MDI), extensively used in injection process, has been shown to contribute most in all impact categories.

Table 4.61 Environmental impact in equivalent units for each impact category for the production of 1 kg polyurethane foam

Impact Category	Unit	Total	Manufacturing	Use	Packaging	Transportation	PU Disposal
Energy resources	MJ LHV	79.9	27.2	51.5	9.55E^{-2}	1.09	0
Greenhouse	kg CO$_2$	3.34	1.28	1.95	2.61 E^{-2}	7.96 E^{-2}	0
Solid waste	kg	1.76	6.64 E^{-1}	7.28 E^{-2}	2.12 E^{-2}	0	1
Acidification	kg SO$_2$	2.69 E^{-2}	1.1 E^{-2}	1.38 E^{-2}	8.88 E^{-5}	2.07 E^{-3}	0
Eutrophication	kg PO$_4$	2.96 E^{-3}	1.62 E^{-3}	1.2 E^{-3}	7.18 E^{-6}	1.31 E^{-4}	0
Summer smog	kg C$_2$H$_4$	2.67 E^{-3}	1.65 E^{-3}	9.65 E^{-4}	-5.36 E^{-5}	1.08 E^{-4}	0
Heavy metals	kg Pb	1.04 E^{-4}	9.8 E^{-5}	4.47 E^{-6}	505 E^{-7}	3.14 E^{-7}	3.83 E^{-7}
Ozone layer	kg CFC11	3.47 E^{-7}	1.2 E^{-7}	8.65E^{-8}	3.27E^{-9}	1.38 E^{-7}	0
Carcinogens	kg B(a)P**	8.34E^{-9}	4.37E^{-9}	2.4E^{-9}	-2.3E^{-9}	3.86E^{-9}	0
Pesticides	kg act.subst***	0	0	0	0	0	0

Note: * Dust and SO$_2$

** Benzo [a] Pyrene- it applies in particular to the group of PAHs (Polycyclic Aromatic Hydrocarbon)

*** Active Ingredient Substances

Table 4.62 Environmental impact in equivalent units for each impact category for the manufacturing phase of PU foam production

Impact category	Unit	Total	Polyether-polyol	Silicone	Ethylenediamine	Water-Thai	Electricity-Thai	Formulated Polyol
Energy resources	MJ LHV	27.2	25.5	5.33 E^{-1}	4.63 E^{-1}	9.9 E^{-2}	6.56 E^{-1}	0
Greenhouse	kg CO2	1.28	1.19	3.71 E^{-2}	2.92 E^{-2}	1.87 E^{-3}	2.37 E^{-2}	0
Solid waste	kg	3.09 E^{-1}	3.04 E^{-1}	0	2.22 E^{-3}	1.04 E^{-3}	5.59 E^{-5}	1.8 E^{-3}
Acidification	kg SO2	1.1 E^{-2}	1.05 E^{-2}	1.91 E^{-4}	1.57 E^{-4}	9.18 E^{-6}	1.41 E^{-4}	0
Eutrophication	kg PO4	1.62 E^{-3}	1.51 E^{-3}	2.13 E^{-5}	3.35 E^{-5}	6.17 E^{-7}	1.47 E^{-5}	3.75 E^{-5}
Summer smog	kg C2H4	1.65 E^{-3}	1.59 E^{-3}	1.11 E^{-5}	2.28 E^{-5}	1.84 E^{-5}	3.55 E^{-6}	0
Heavy metals	kg Pb	9.8 E^{-5}	9.75 E^{-5}	3.92 E^{-7}	1.53 E^{-7}	1.81E^{-9}	2.25E^{-9}	0
Ozone layer	kg CFC11	1.2E^{-7}	7.39E^{-11}	2.51E^{-8}	9.43E^{-8}	2.06E^{-10}	4.41E^{-13}	0
Carcinogens	kg B(a)P	4.37E^{-9}	4.98E^{-10}	2.41E^{-9}	5.29E^{-10}	8.87E^{-10}	3.78E^{-11}	0
Pesticides	kg act.subst	0	0	0	0	0	0	0

Table 4.63 Environmental impact in equivalent units for each impact category for the use phase of PU foam production

Impact category	Unit	Total	Pentane for PUR A	MDI A	Polyurethane Foam	Electricity Thai
Energy resources	MJ LHV	51.5	3.3 E-1	51	0	1.19 E-1
Greenhouse	kg CO2	1.95	9.57 E-4	1.95	2.62E-8	4.29 E-3
Solid waste	kg	7.28 E-2	2.98 E-6	6.78 E-2	5 E-3	1.01 E-5
Acidification	kg SO2	1.38 E-2	9.96 E-6	1.38 E-2	5.83E-12	2.54 E-5
Eutrophication	kg PO4	1.2 E-3	1.73 E-6	1.2 E-3	1.07E-12	2.65 E-6
Summer smog	kg C2H4	9.65 E-4	3.26 E-6	9.61 E-4	9.05E-14	6.42 E-7
Heavy metals	kg Pb	4.47E-6	0	4.47 E-6	0	4.07E-10
Ozone layer	kg CFC11	8.65E-8	0	8.65E-8	4.19E-15	7.97E-14
Carcinogens	kg B(a)P	2.4E-9	0	2.4E-9	3.07E-18	6.83E-12
Pesticides	kg act.subst	0	0	0	0	0

Using the end-point approach, Eco-indicator 99 results in a single score for the environmental impact assessment based on weighting factor assigned for each impact category. In addition, Eco-indicator 99 also accounts for resource depletion which was not accounted for in Eco-Indicator 95. In Eco-indicator 99, damage categories are divided into resources, ecosystem quality, and human health. Impact categories include fossil fuels, minerals, land use, acidification/eutrophication, ecotoxicity, ozone layer, radiation, climate change, respiration of organics and inorganics, and carcinogens.

Apart from the fact that the results obtained from Eco-indicator 99 also include resource depletion, other environmental impacts are in the same trend as obtained from Eco-Indicator 95. For damage assessment (Figure 4.29), the damages are mainly in the resources depletion and human health which resulted from depletion of fossil fuels, respiration of inorganic substances and carcinogenic effect on human as shown in Figure 4.30. The impact assessment for various phases in the production of PU foam is shown in Figure 4.31. It can be seen that the environmental impact is mainly in the manufacturing phase and use phase (injection) which is similar to the results obtained by using Eco-indicator 95. However, when the resource depletion is accounted for, the use phase contributes more than the manufacturing which is not the case for Eco-indicator 95 (Fig. 4.26). This is due to the extensive utilization of electricity generated from fossil fuels in the use phase. Figure 4.31 reveals that the second highest impact is in respiration of inorganics in both manufacturing and use phases followed by carcinogens. This is attributed to the use of polyether polyol and isocyanate (MDI) in manufacturing and use phases, respectively, as shown in Figures 4.32 and 4.33.

The comparison of the results obtained from Eco-indicator 95 and Eco-indicator 99 is shown in Figures 4.34 for each impact category. Although the percentages may be different but similar trend is clearly observed between these two impact assessment methods.

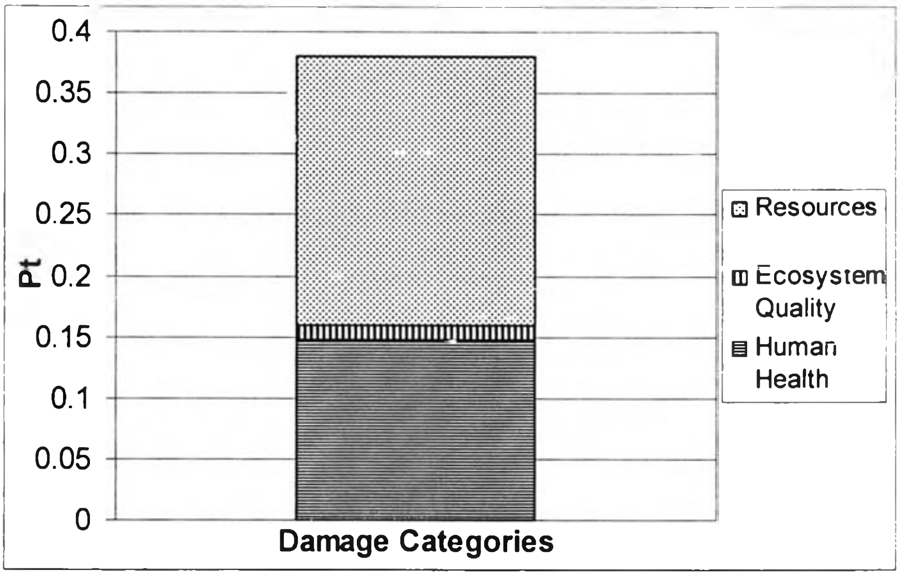

Figure 4.29 Damage assessment for the production of 1 kg polyurethane foam by using Eco-indicator 99.

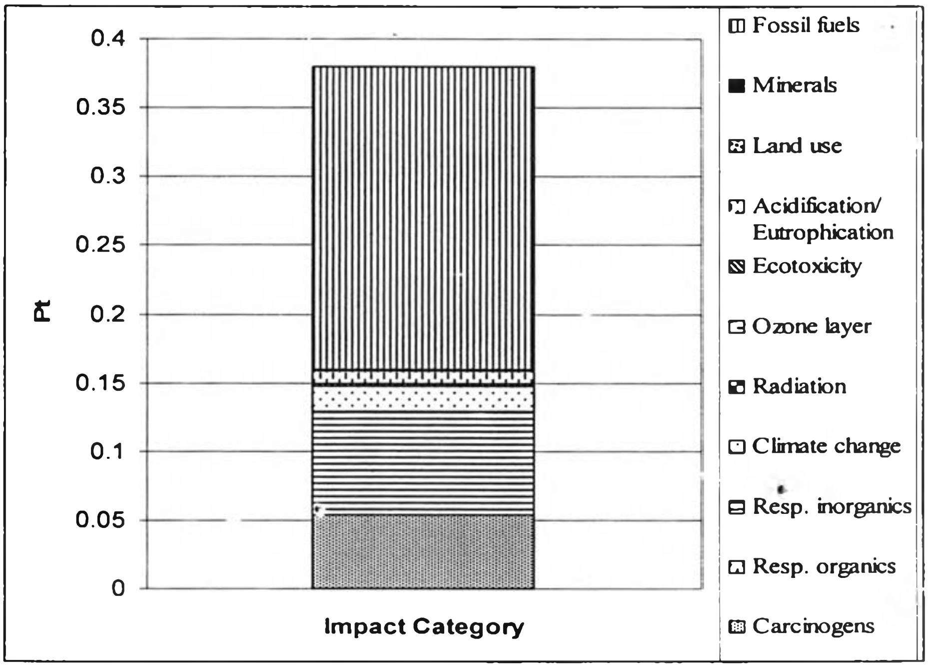

Figure 4.30 Impact assessment by category for the production of 1 kg polyurethane foam by using Eco-indicator 99.

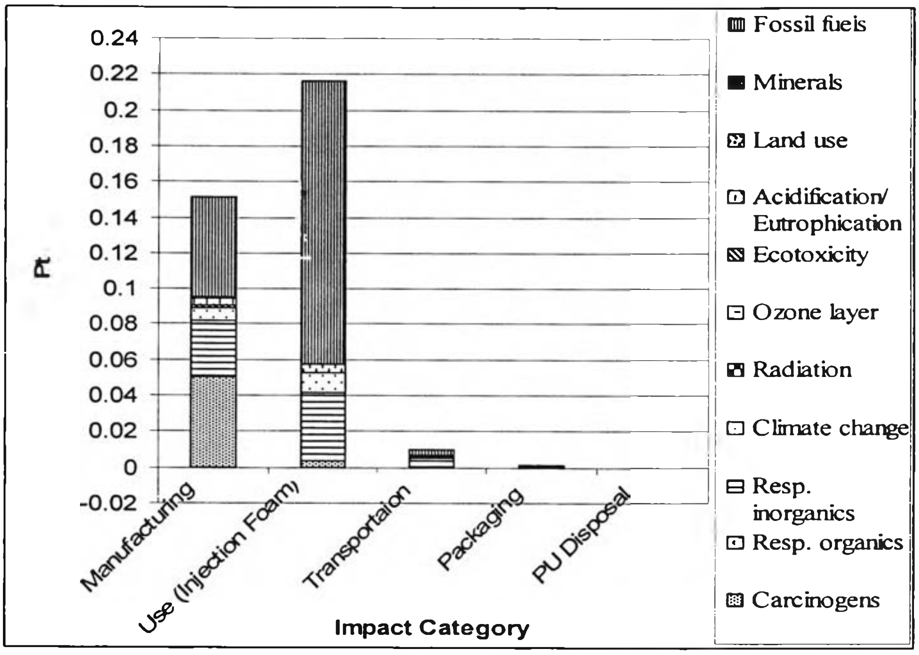

Figure 4.31 Impact assessment for each phase in the production of 1 kg polyurethane foam by using Eco-indicator 99.

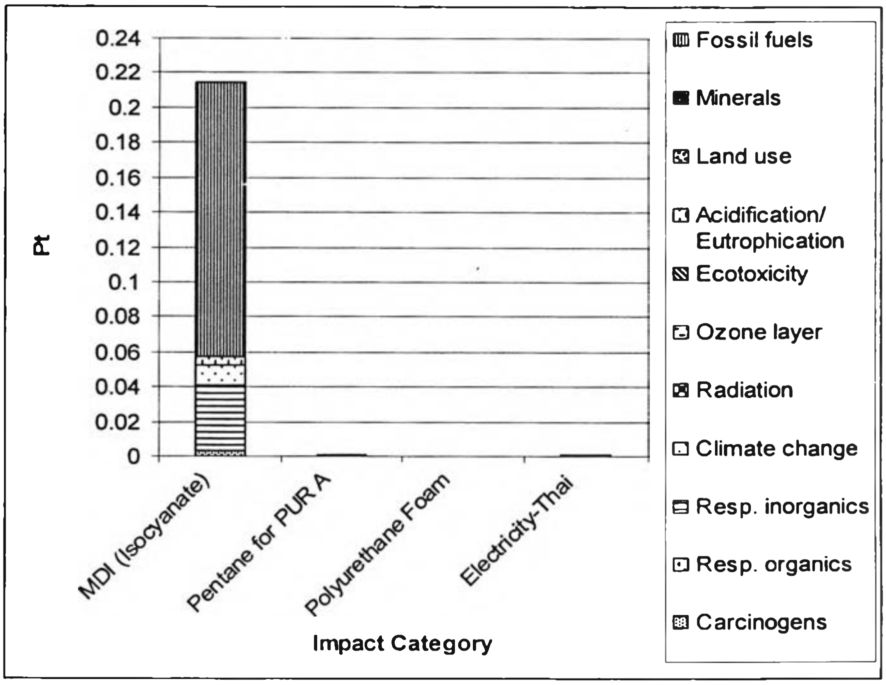

Figure 4.32 Impact assessment of use phase in the production of 1 kg polyurethane foam by using Eco-indicator 99.

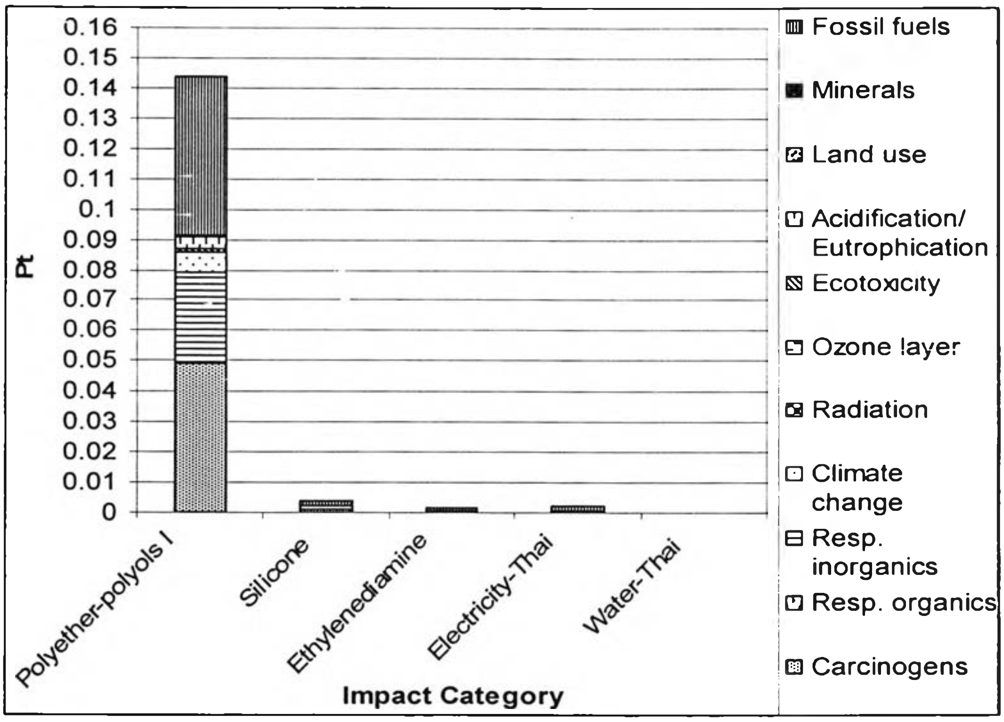

Figure 4.33 Impact assessment for manufacturing phase in the production of 1 kg polyurethane foam by using Eco-indicator 99.

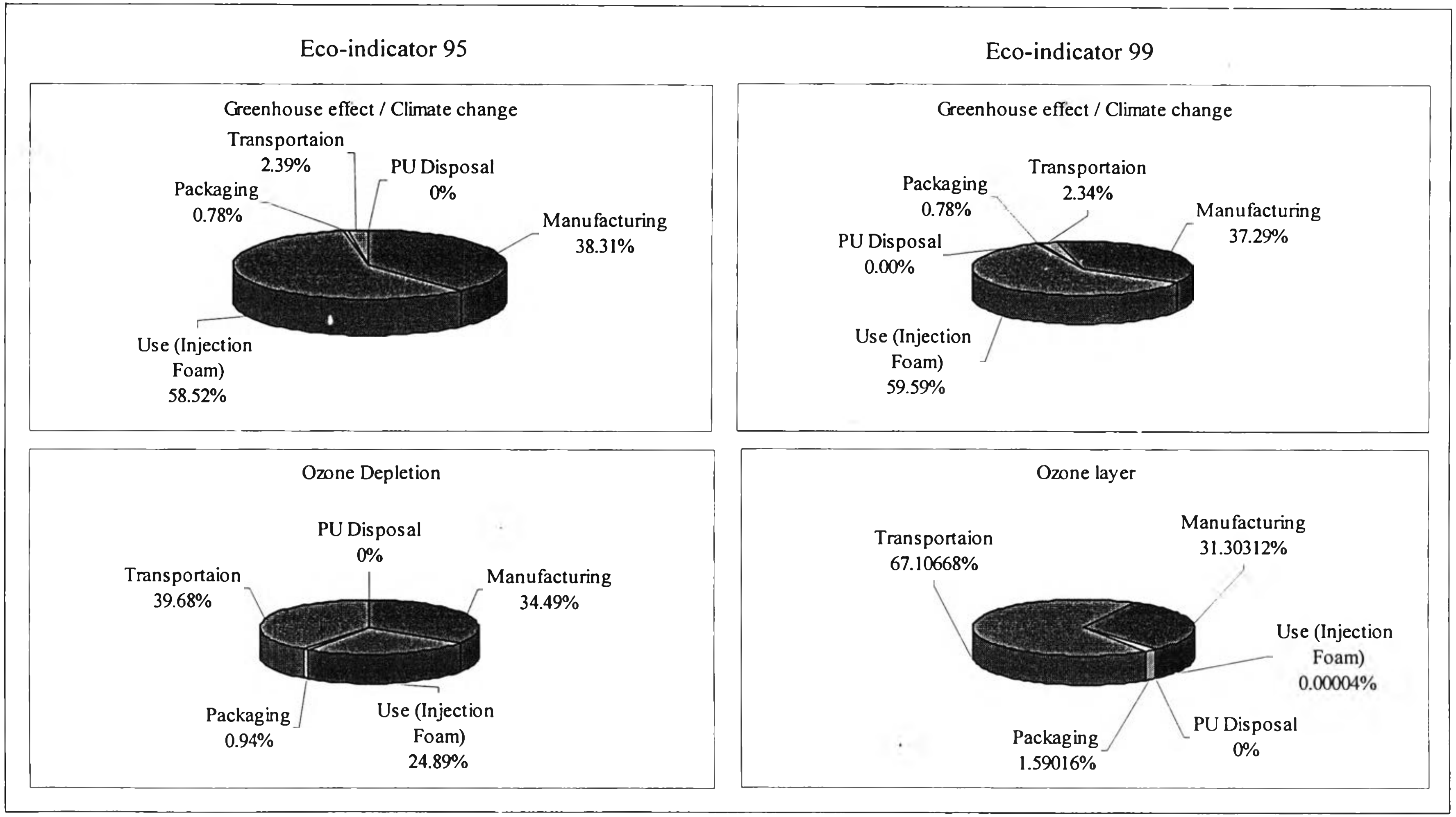

Figure 4.34 Comparison of the environmental impacts assessed by Eco-indicator 95 and Eco-indicator 99 for 1 kg PU foam.

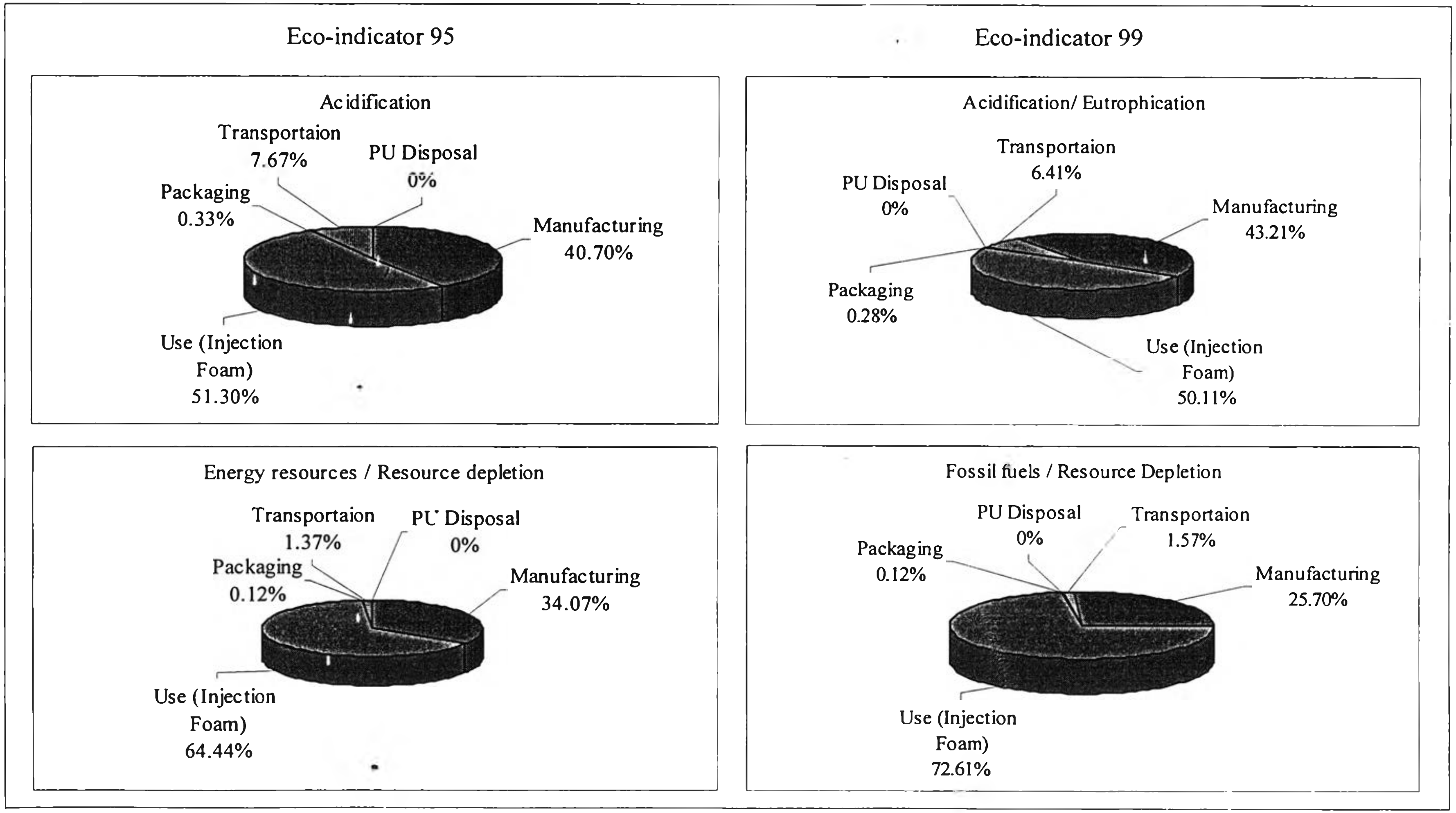

Figure 4.34 Comparison of the environmental impacts assessed by Eco-indicator 95 and Eco-indicator 99 for 1 kg PU foam (continued).

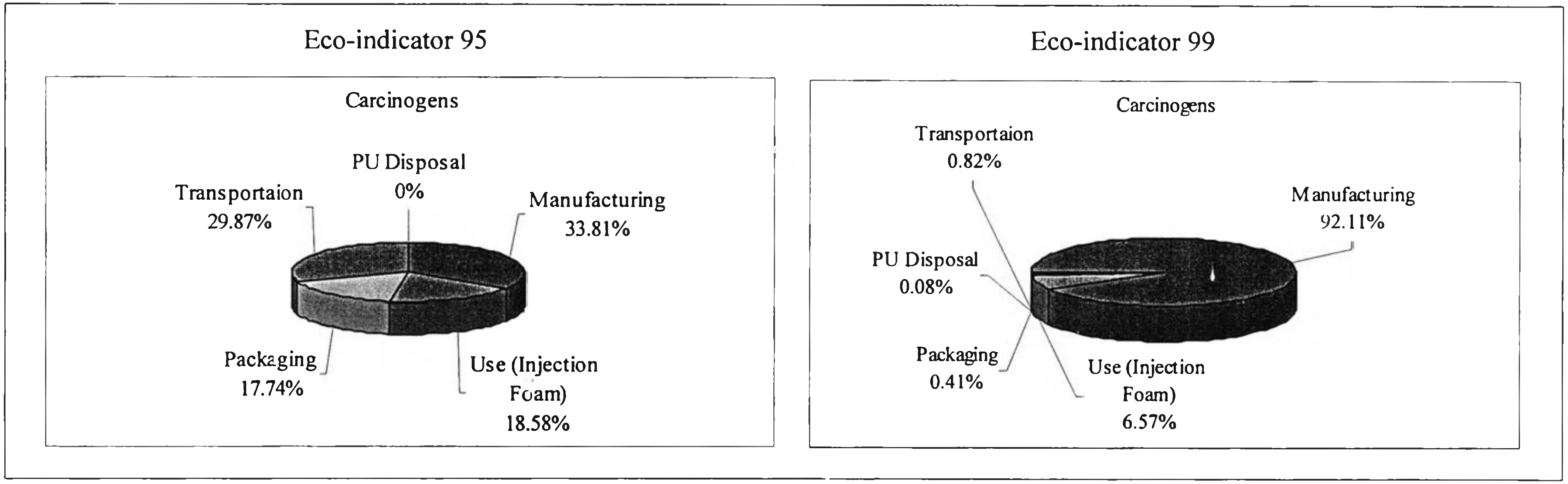

Figure 4.34 Comparison of the environmental impacts assessed by Eco-indicator 95 and Eco-indicator 99 for 1 kg PU foam (continued).

4.2.2 Environmental Impact Assessment of General Purpose Polystyrene

Using Eco-indicator 95, the overall results of the production of 1 kg GPPS shown in Figure 4.35 indicates that the environmental impacts mainly come from styrene monomer which is the raw material used in the manufacturing process. Figure 4.36 reveals that acidification and summer smog formation are the major environmental impact categories of the overall GPPS process. The comparison of the environmental impact for all 5 phases of GPPS production shown in Figure 4.37 illustrates that the manufacturing phase contributes most followed by the use phase (injection) and transportation whereas the contributions from packaging is shown to be negligible. In contrast, the disposal phase contributes the positive effect to the environment as shown from minus value in the result which is due to the recycle process that can reduce the use of materials in the manufacturing phase. In manufacturing phase, processes consist of raw material preparation, polymerization, devolatilization, styrene monomer recovery (SM recovery), and extrusion and finishing. Environmental impact is identified in raw material preparation process and SM recovery respectively which is illustrated in Figure 4.38. For raw material preparation process, Figures 4.39 shows that the environmental impact is essentially from styrene monomer of which its production contributes mainly in acidification and summer smog. In SM recovery process, the environmental impact is mainly in the production of water in Thailand which contributes most in summer smog, acidification, and carcinogenic effect as illustrated in Figure 4.40. Figure 4.41 shows the environmental impact assessment for the use phase where the main contribution is from electricity in Thailand. Acidification, greenhouse gases, and eutrophication are the main impact categories resulted from electricity production.

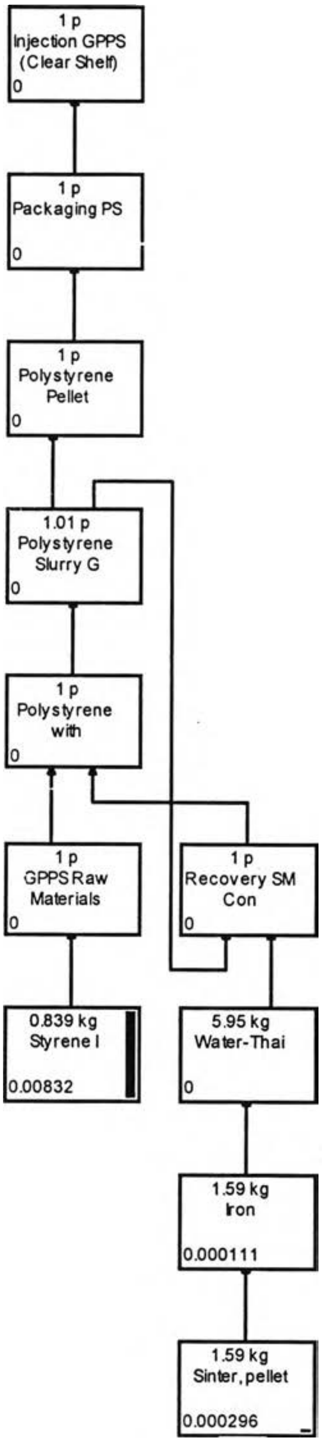

Figure 4.35 Overall results of the environmental impact assessment of the production of 1 kg General Purpose Polystyrene (GPPS) obtained by using Eco-indicator 95 .

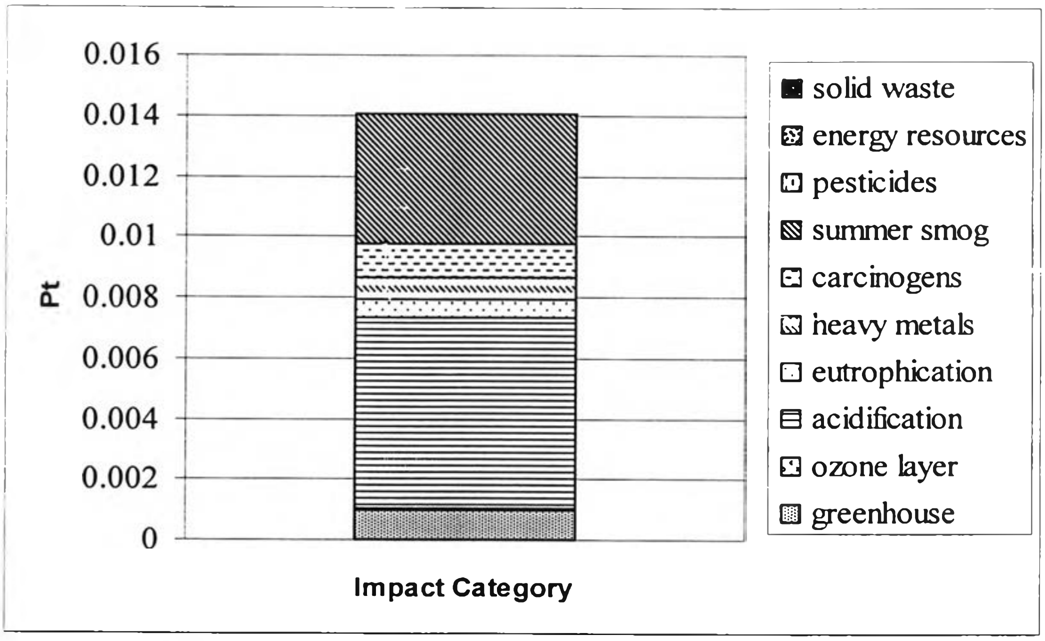

Figure 4.36 Environmental impact categories of 1 kg GPPS production obtained by using Eco-indicator 95.

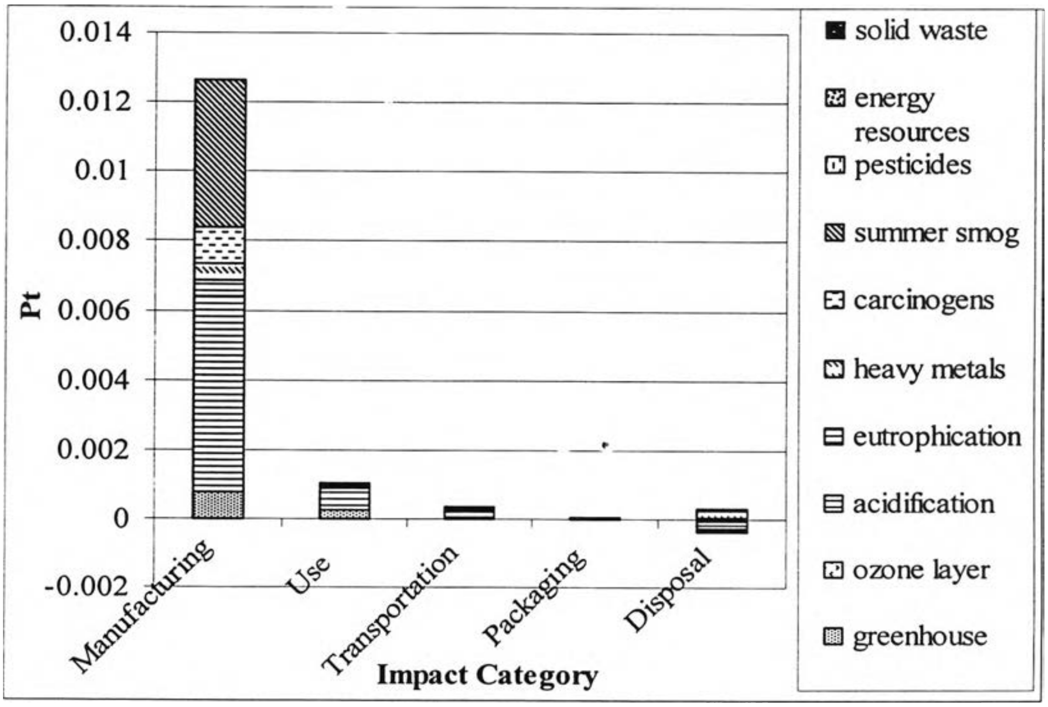

Figure 4.37 Environmental impact categories of each phase in the production of 1 kg GPPS obtained by Eco-indicator 95.

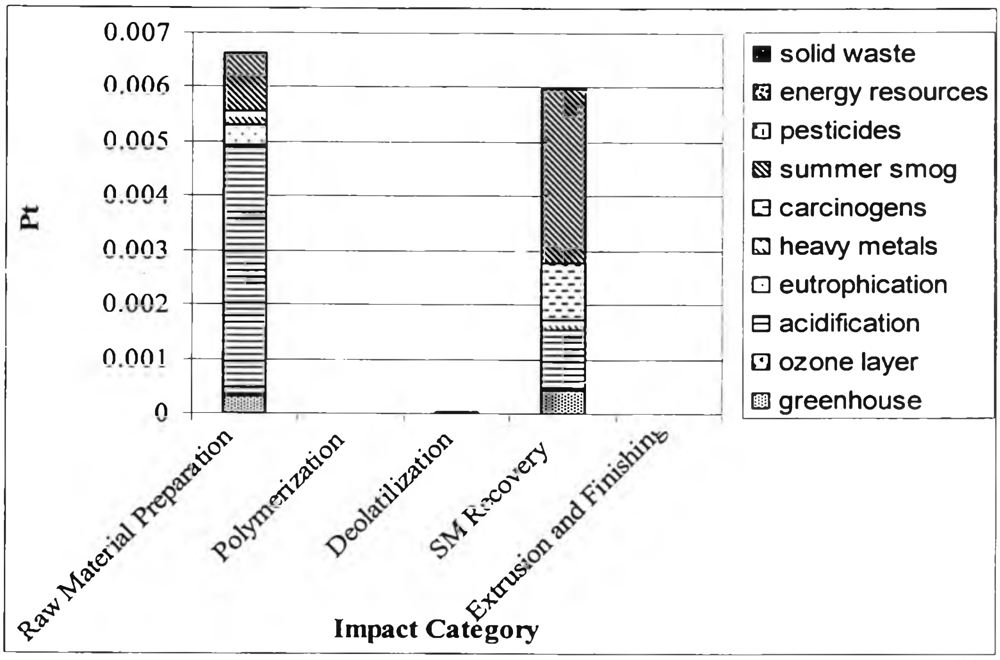

Figure 4.38 Environmental impact categories of each process in the manufacturing phase of 1 kg GPPS production obtained by using Eco-indicator 95.

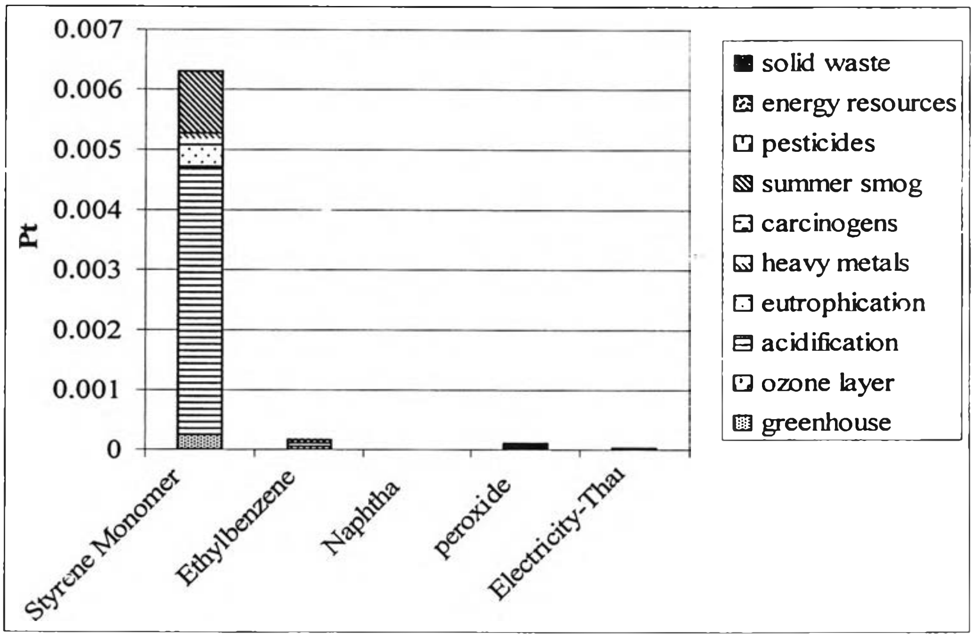

Figure 4.39 Environmental impact categories of raw material preparation process in the manufacturing phase of 1 kg GPPS production obtained by using Eco-indicator 95.

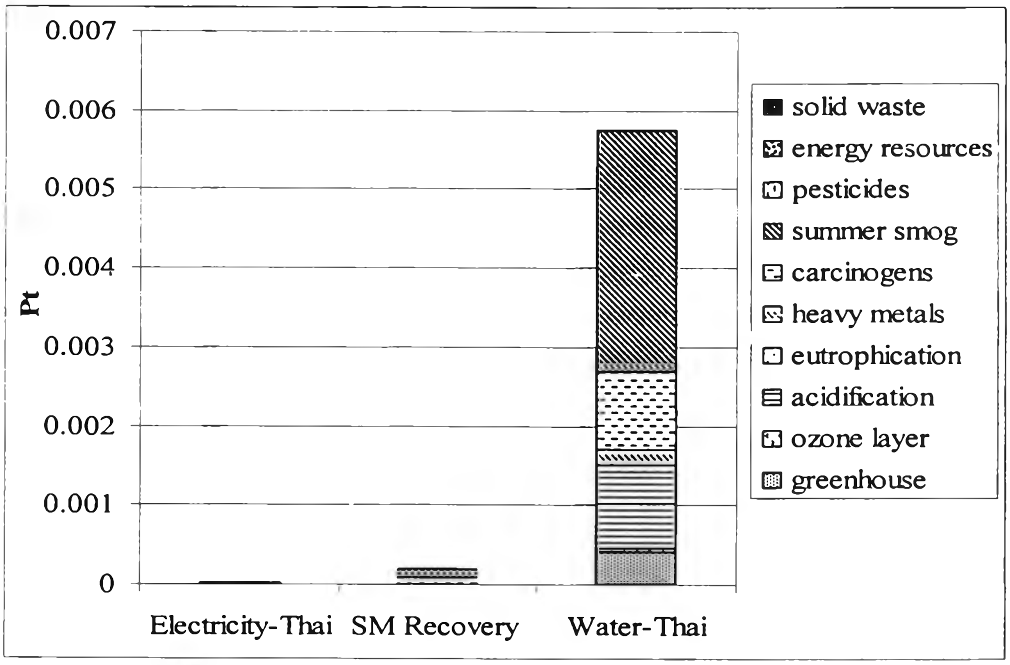

Figure 4.40 Environmental impact categories of SM recovery process in the manufacturing phase of 1 kg GPPS production obtained by using Eco-indicator 95.

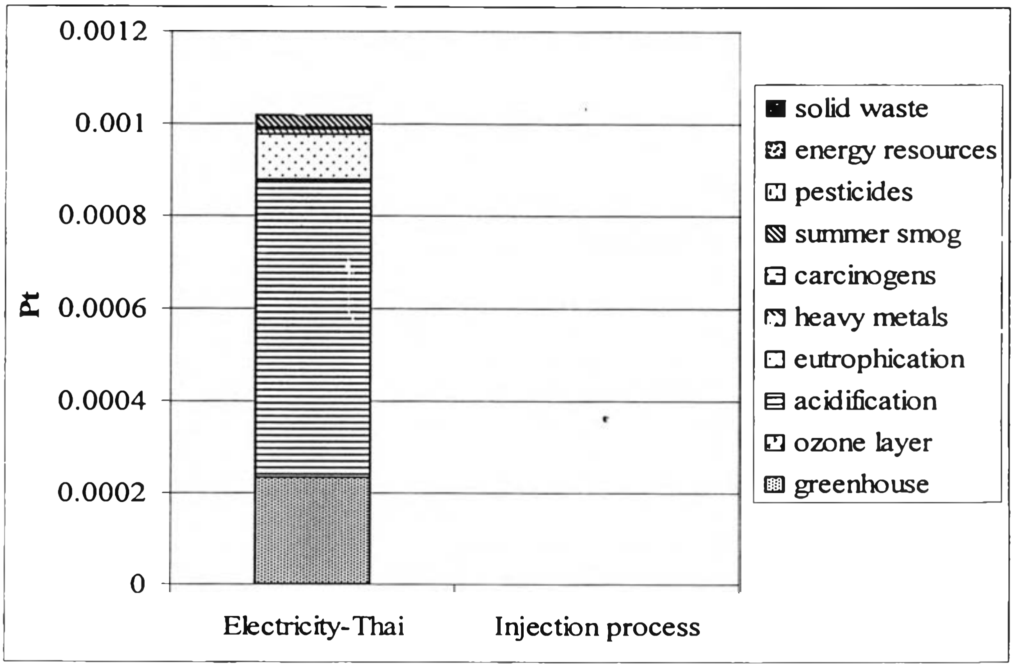

Figure 4.41 Environmental impact categories of the use phase in the production of 1 kg GPPS obtained by using Eco-indicator 95.

Table 4.64 shows the results of the environmental impact assessment using Eco-indicator 95 which are presented in terms of equivalent units for each impact category for the production of 1 kg GPPS. It can be seen that the production of 1 kg of GPPS utilizes energy resources equivalent to 229 MJ LHV and generates green house gases equivalent to 5.19 kg CO_2, solid wastes 1.96 kg, acidification equivalent to $7.1E^{-2}$ kg of SO_2, heavy metals $7.96E^{-6}$ kg of Pb equivalent, ozone layer depletion substances equivalent to $4.95E^{-7}$ kg of CFC11, and carcinogenic effect equivalent to $1.17E^{-6}$ kg of benzo(a)pyrene. Energy is mostly consumed in the manufacturing phase (approximately 91%) which involves in production of styrene monomer. Greenhouse gases are generated mainly from manufacturing and use phases which account for 77% and 24%, respectively. Manufacturing phase also contributes most to the solid wastes and acidification being generated in the production of GPPS which approximately contribute 65% and 89%.

Tables 4.65 and 4.66 show the environmental impacts in equivalent units for the manufacturing phase and use phase, respectively. For manufacturing phase, the environmental impacts emphasize on raw material preparation process and SM recovery process. It can be obviously seen from the result that styrene monomer contributes most in almost all impact categories in raw material preparation process and water in Thailand contributes most in almost all impact categories in SM recovery process. For use phase, electricity, which is extensively used in injection process, has been shown to contribute most in all impact categories. For disposal phase, Table 4.69 shows the benefit of the recycle process to the environment as indicated by the minus values in various impact categories.

Table 4.64 Environmental impact in equivalent units for each impact category for the production of 1 kg GPPS

Impact category	Unit	Total	Manufacturing	Use	Packaging	Transportation	Disposal
Energy resources	MJ LHV	229	209	33.9	1.1	2.33	-17.3
Greenhouse	kg CO2	5.19	4	1.23	$4.19E^{-2}$	0.177	$-2.54E^{-1}$
Solid waste	kg	1.96	1.28	$7.29E^{-3}$	$1.21E^{-2}$	$7.42E^{-5}$	$6.64E^{-1}$
Acidification	kg SO2	$7.1E^{-2}$	$6.32E^{-2}$	$7.26E^{-3}$	$3.76E^{-4}$	$2.61E^{-3}$	$-2.47E^{-3}$
Eutrophication	kg PO4	$4.33E^{-3}$	$3.6E^{-3}$	$7.57E^{-4}$	$2.3E^{-5}$	$3.67E^{-4}$	$-4.13E^{-4}$
Summer smog	kg C2H4	$3.08E^{-2}$	$3.06E^{-2}$	$1.84E^{-4}$	$5.83E^{-5}$	$3.02E^{-4}$	$-3.62\ E^{-4}$
Heavy metals	kg Pb	$7.96E^{-6}$	$4.91E^{-6}$	$1.16E^{-7}$	$1.78E^{-7}$	$3.69E^{-8}$	$2.72E^{-6}$
Ozone layer	kg CFC11	$4.95E^{-7}$	$2.61E^{-7}$	$7.18E^{-11}$	$2.42E^{-9}$	$1.56E^{-8}$	$2.17E^{-7}$
Carcinogens	kg B(a)P	$1.17E^{-6}$	$1.15E^{-6}$	$1.95E^{-9}$	$2.47E^{-10}$	$4.66E^{-10}$	$1.72E^{-8}$
Pesticides	kg act.subst	0	0	0	0	0	0

Table 4.65 Environmental impact in equivalent units for each impact category for the manufacturing phase of kg GPPS production

Impact category	Unit	Total	Raw Material Preparation	Polymerization	Deolatilization	SM Recovery	Extrusion and Finishing
Energy resources	MJ LHV	209	89.1	0.431	1.37	118	0.118
Greenhouse	kg CO2	4	1.69	0.0156	0.0498	2.24	0.00427
Solid waste	kg	1.28	0.034	0.00393	0.000116	1.24	1.01E-05
Acidification	kg SO2	0.0632	0.0518	9.23E-05	0.000299	0.011	2.53E-05
Eutrophication	kg PO4	0.0036	0.00281	9.62E-06	3.09E-05	0.000744	2.64E-06
Summer smog	kg C2H4	0.0306	0.00784	2.33E-06	7.79E-06	0.0228	6.39E-07
Heavy metals	kg Pb	4.91E-06	2.75E-06	1.48E-09	4.67E-09	2.15E-06	4.05E-10
Ozone layer	kg CFC11	2.61E-07	1.57E-08	2.89E-13	9.14E-13	2.45E-07	7.93E-14
Carcinogens	kg B(a)P	1.15E-06	3.84E-09	2.48E-11	7.84E-11	1.15E-06	6.8E-12
Pesticides	kg act.subst	0	0	0	0	0	0

Table 4.66 Environmental impact in equivalent units for each impact category for the use phase of GPPS production

Impact category	Unit	Total	Electricity-Thai	Clear Shelf
Energy resources	MJ LHV	33.9	33.9	0
Greenhouse	kg CO2	1.23	1.23	$2.86E^{-4}$
Solid waste	kg	$7.29E^{-3}$	$2.89E^{-3}$	$4.4E^{-3}$
Acidification	kg SO2	$7.26E^{-3}$	$7.26E^{-3}$	$9.4E^{-9}$
Eutrophication	kg PO4	$7.57E^{-4}$	$7.57E^{-4}$	$1.56E^{-9}$
Summer smog	kg C2H4	$1.84E^{-4}$	$1.84E^{-4}$	$1.06E^{-9}$
Heavy metals	kg Pb	$1.16E^{-7}$	$1.16E^{-7}$	0
Ozone layer	kg CFC11	$7.18E^{-11}$	$2.28E^{-11}$	$4.9E^{-11}$
Carcinogens	kg B(a)P	$1.95E^{-9}$	$1.95E^{-9}$	$3.59E^{-14}$
Pesticides	kg act.subst	0	0	0

Table 4.67 Environmental impact in equivalent units for each impact category for raw material preparation process in the manufacturing phase of GPPS production

Impact category	Unit	Total	Styrene Monomer	Ethylbenzene	Naphtha	Peroxide	Electricity-Thai
Energy resources	MJ LHV	89.1	77.8	7.59	1.53	8.91E^{-1}	1.28
Greenhouse	kg CO2	1.69	1.26	3.19E^{-1}	1.02E^{-2}	4.89E^{-2}	4.63E^{-2}
Solid waste	kg	3.4E^{-2}	3.33E^{-2}	0	1.01E^{-4}	4.64E^{-4}	1.09E^{-4}
Acidification	kg SO2	5.18E^{-2}	5.05E^{-2}	5.49 E^{-4}	1.06E^{-4}	4.11E^{-4}	2.75E^{-4}
Eutrophication	kg PO4	2.81E^{-3}	2.69E^{-3}	4.62E^{-5}	1.15E^{-5}	2.99E^{-5}	2.86E^{-5}
Summer smog	kg C2H4	7.84E^{-3}	7.38E^{-3}	3.42E^{-4}	5.26E^{-6}	1.02E^{-4}	6.94E^{-6}
Heavy metals	kg Pb	2.75E^{-6}	2.2E^{-6}	5.76E^{-8}	1.07E^{-9}	4.84E^{-7}	4.4E^{-9}
Ozone layer	kg CFC11	1.57E^{-8}	0	0	0	1.57E^{-8}	8.61E^{-13}
Carcinogens	kg B(a)P	3.84E^{-9}	1.51E^{-9}	5.28E^{-10}	3.6E^{-12}	1.73E^{-9}	7.38E^{-11}
Pesticides	kg act.subst	0	0	0	0	0	0

Table 4.68 Environmental impact in equivalent units for each impact category for SM recovery process in the manufacturing phase of GPPS production

Impact category	Unit	Total	Electricity Thai	SM Recovery	Water Thai
Energy resources	MJ LHV	118	$4.21E^{-1}$	0	118
Greenhouse	kg CO2	2.24	$1.52E^{-2}$	0	2.22
Solid waste	kg	1.24	$3.59E^{-5}$	0	1.24
Acidification	kg SO2	$1.1E^{-2}$	$9.02E^{-5}$	$3.21E^{-6}$	$1.09E^{-2}$
Eutrophication	kg PO4	$7.44E^{-4}$	$9.41E^{-6}$	$5.97E^{-7}$	$7.34E^{-4}$
Summer smog	kg C2H4	$2.28E^{-2}$	$2.28E^{-6}$	$8.65E^{-4}$	$2.19E^{-2}$
Heavy metals	kg Pb	$2.15E^{-6}$	$1.45E^{-9}$	0	$2.15E^{-6}$
Heavy metals	kg Pb	$2.15E^{-6}$	$1.45E^{-9}$	0	$2.15E^{-6}$
Ozone layer	kg CFC11	$2.45E^{-7}$	$2.83E^{-13}$	0	$2.45E^{-7}$
Carcinogens	kg B(a)P	$1.15E^{-6}$	$2.43E^{-11}$	$9.15E^{-8}$	$1.06E^{-6}$
Pesticides	kg act.subst	0	0	0	0

Table 4.69 Environmental impact in equivalent units for each impact category for disposal phase of GPPS production

Impact category	Unit	Total	Landfill	Recycling
Energy resources	MJ LHV	-17.3	0	-17.3
Greenhouse	kg CO2	$-2.54E^{-1}$	0	$-2.54E^{-1}$
Solid waste	kg	$6.64E^{-1}$	$5.0E^{-1}$	$1.64E^{-1}$
Acidification	kg SO2	$-2.47E^{-3}$	0	$-2.47E^{-3}$
Eutrophication	kg PO4	$-4.1E^{-4}$	0	$-4.1E^{-4}$
Summer smog	kg C2H4	$-3.6E^{-4}$	0	$-3.6E^{-4}$
Heavy metals	kg Pb	$2.72E^{-6}$	$1.91E^{-7}$	$2.53E^{-6}$
Ozone layer	kg CFC11	$2.17E^{-7}$	0	$2.17E^{-7}$
Carcinogens	kg B(a)P	$1.72E^{-8}$	0	$1.72E^{-8}$
Pesticides	kg act.subst	0	0	0

Using Eco-indicator 99, the single score results show the same trend as the results assessed by using Eco-Indicator 95, except for resource depletion which is not included in Eco-Indicator 95. For damage assessment (Figure 4.42), the damages are mainly in the resources depletion and human health which resulted from depletion of fossil fuels, respiration of inorganic substances and climate change effect on human as shown in Figure 4.43. The impact assessment for various phases in the production of GPPS is shown in Figure 4.44. It can be seen that the environmental impact is mainly in the manufacturing phase and use phase (injection) which is similar to the results obtained by using Eco-indicator 95. Disposal phase also contributes the positive effect for the environment in decreasing of the extensive utilization of electricity generated from fossil fuels in the recycle process. Figure 4.44 reveals that the impact is in fossil fuel depletion and respiration of inorganics respectively. In manufacturing phase, Table 4.45 shows environmental impact is mostly in raw material preparation and SM recovery process. This is attributed to the use of styrene monomer, water and electricity in manufacturing and use phases, respectively, as shown in Figures 4.46, 4.47, and 4.48.

The comparison of the results obtained from Eco-indicator 95 and Eco-indicator 99 is shown in Figures 4.49 for each impact category. Although the percentages may be different but similar trend is clearly observed between these two impact assessment methods.

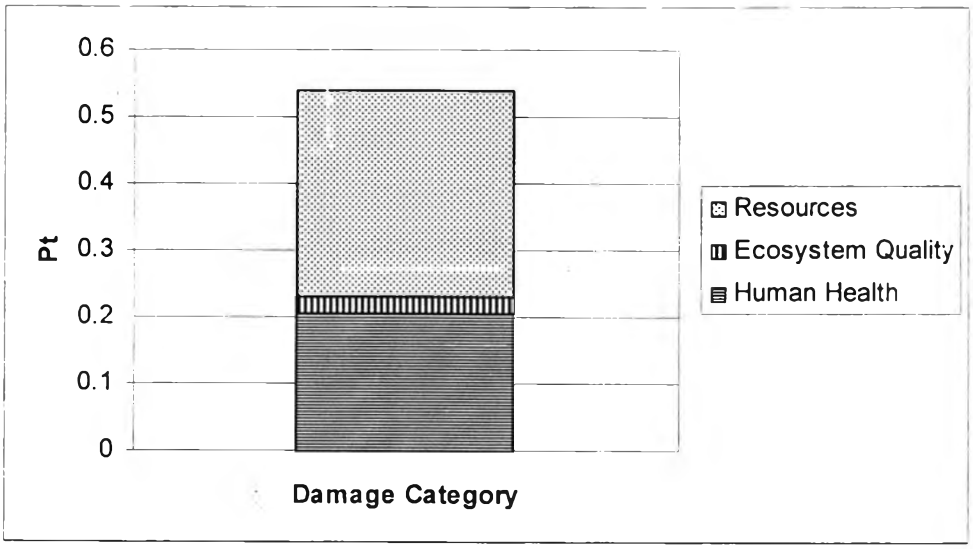

Figure 4.42 Damage assessment for the production of 1 kg GPPS by using Eco-indicator 99.

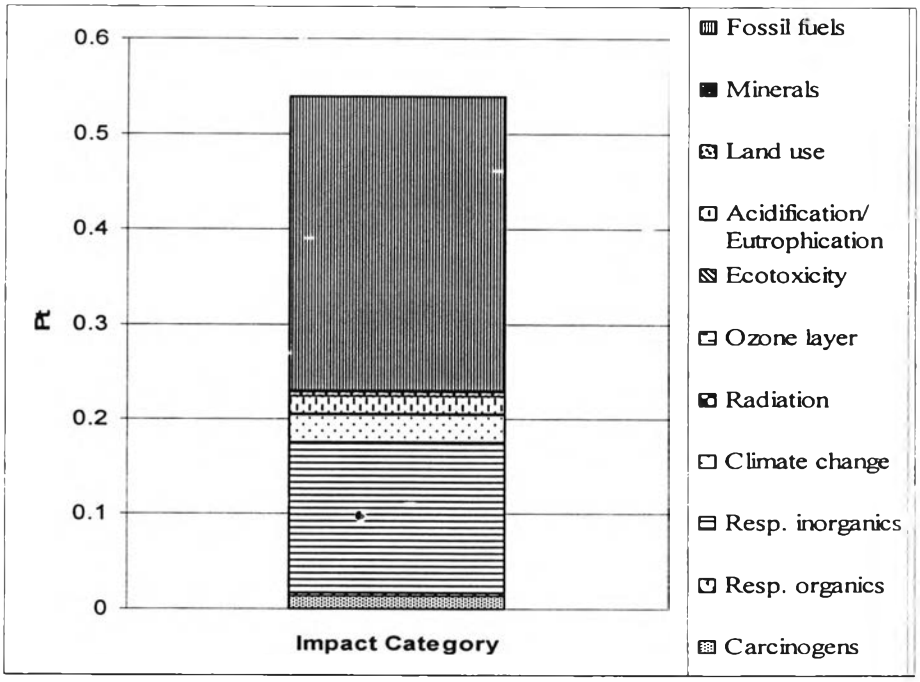

Figure 4.43 Impact assessment by category for the production of 1 kg GPPS by using Eco-indicator 99.

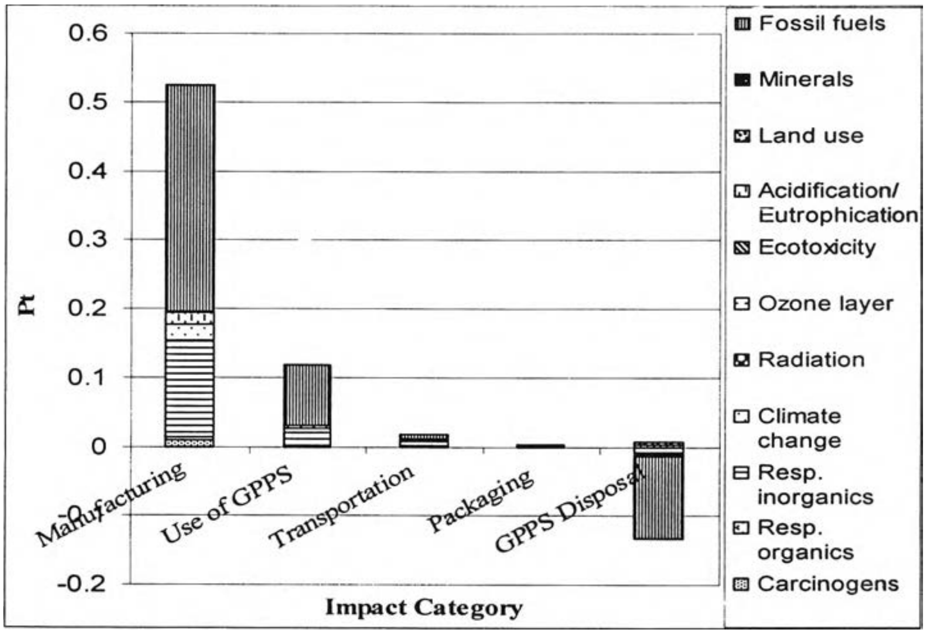

Figure 4.44 Impact assessment for each phase in the production of 1 kg GPPS by using Eco-indicator 99.

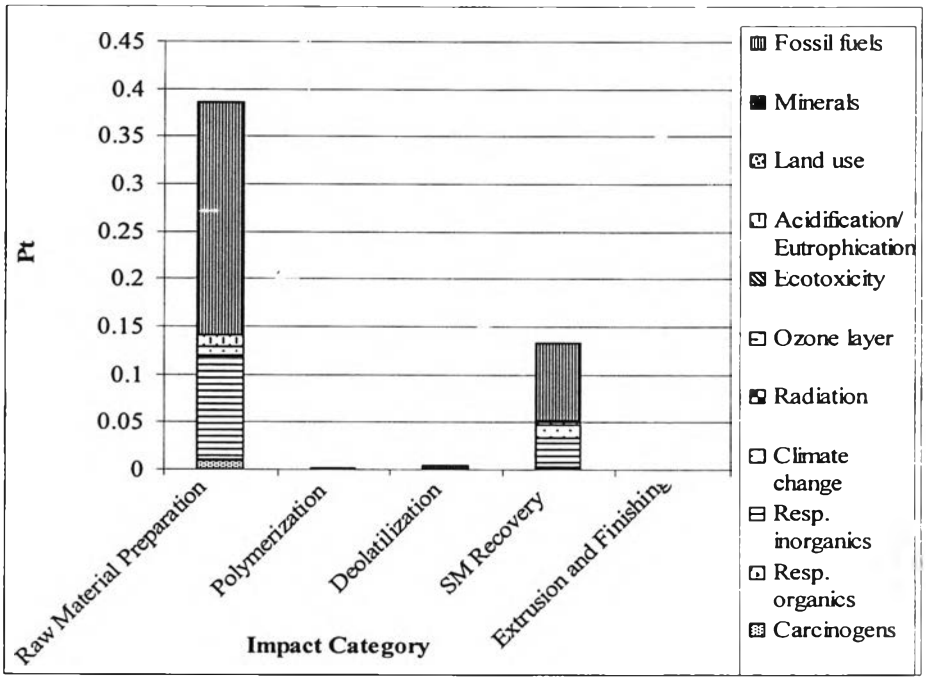

Figure 4.45 Impact assessment for each process in the manufacturing phase of 1 kg GPPS production by using Eco-indicator 99.

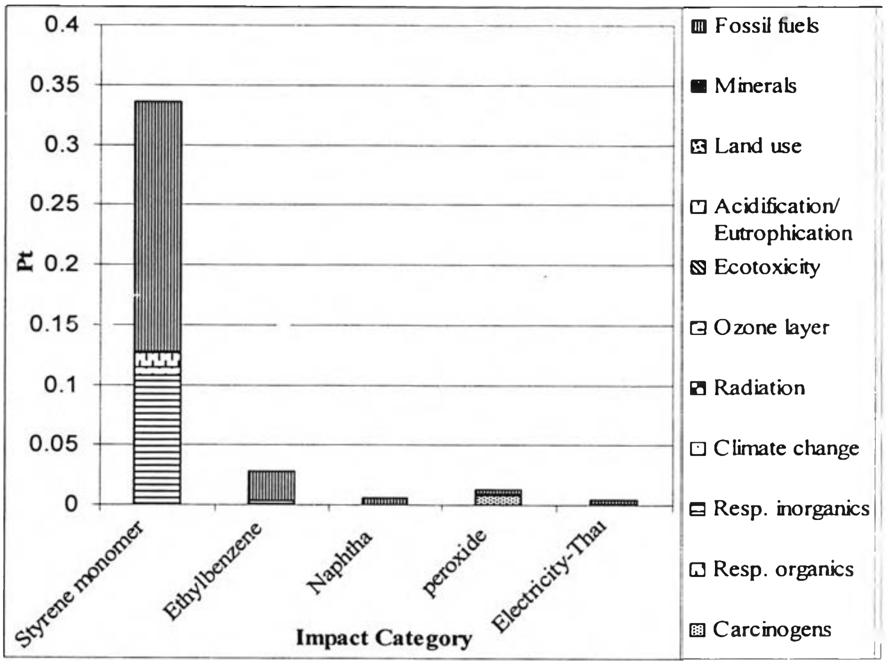

Figure 4.46 Impact assessment for raw material preparation process in the manufacturing phase of 1 kg GPPS production by using Eco-indicator 99.

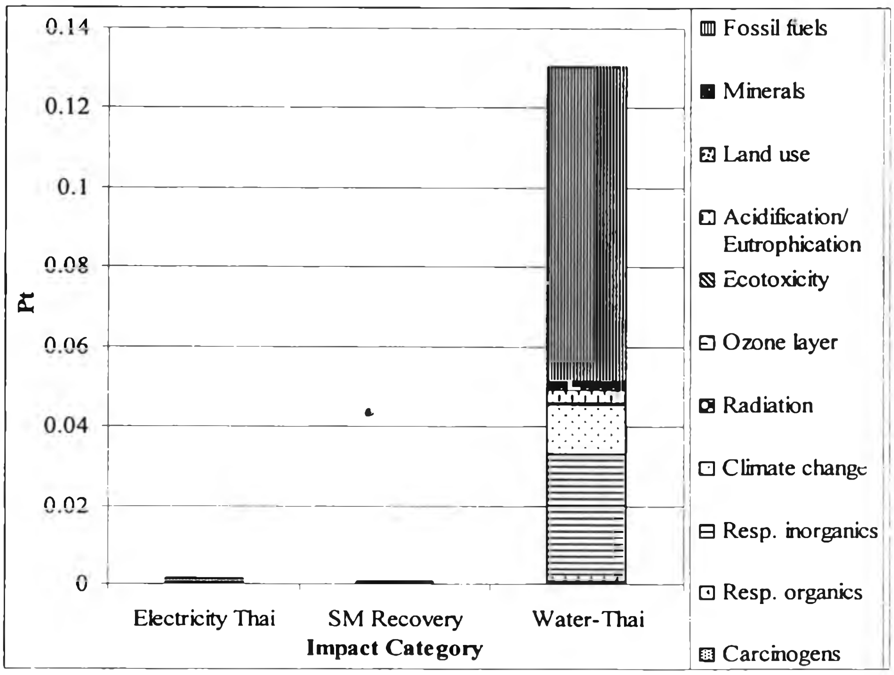

Figure 4.47 Impact assessment for SM recovery process in the manufacturing phase of 1 kg GPPS production by using Eco-indicator 99.

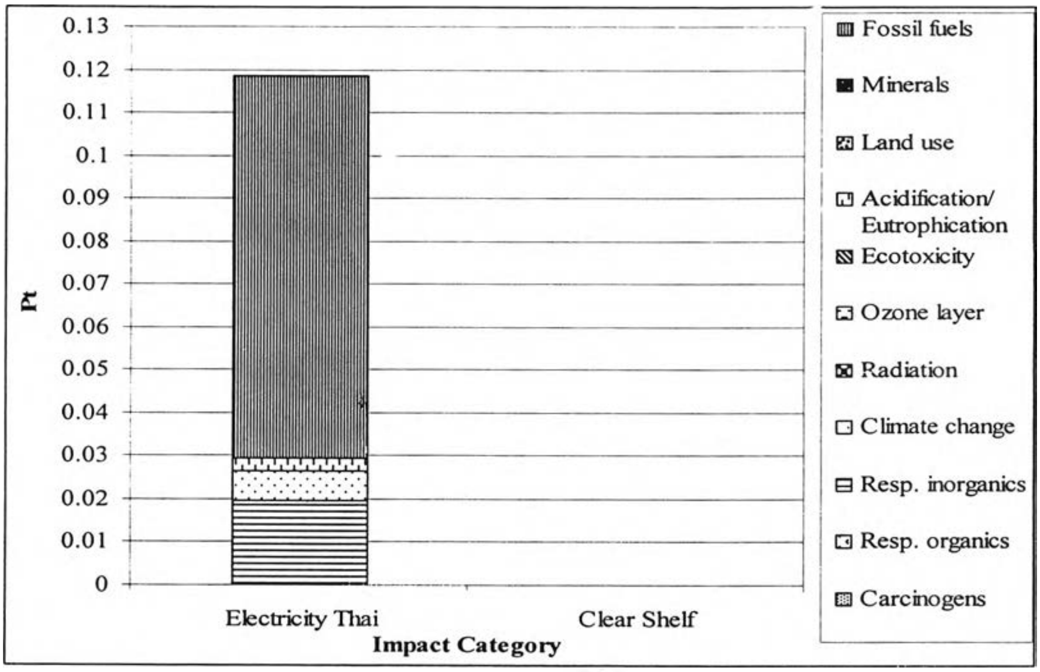

Figure 4.48 Impact assessment of use phase in the production of 1 kg GPPS by using Eco-indicator 99.

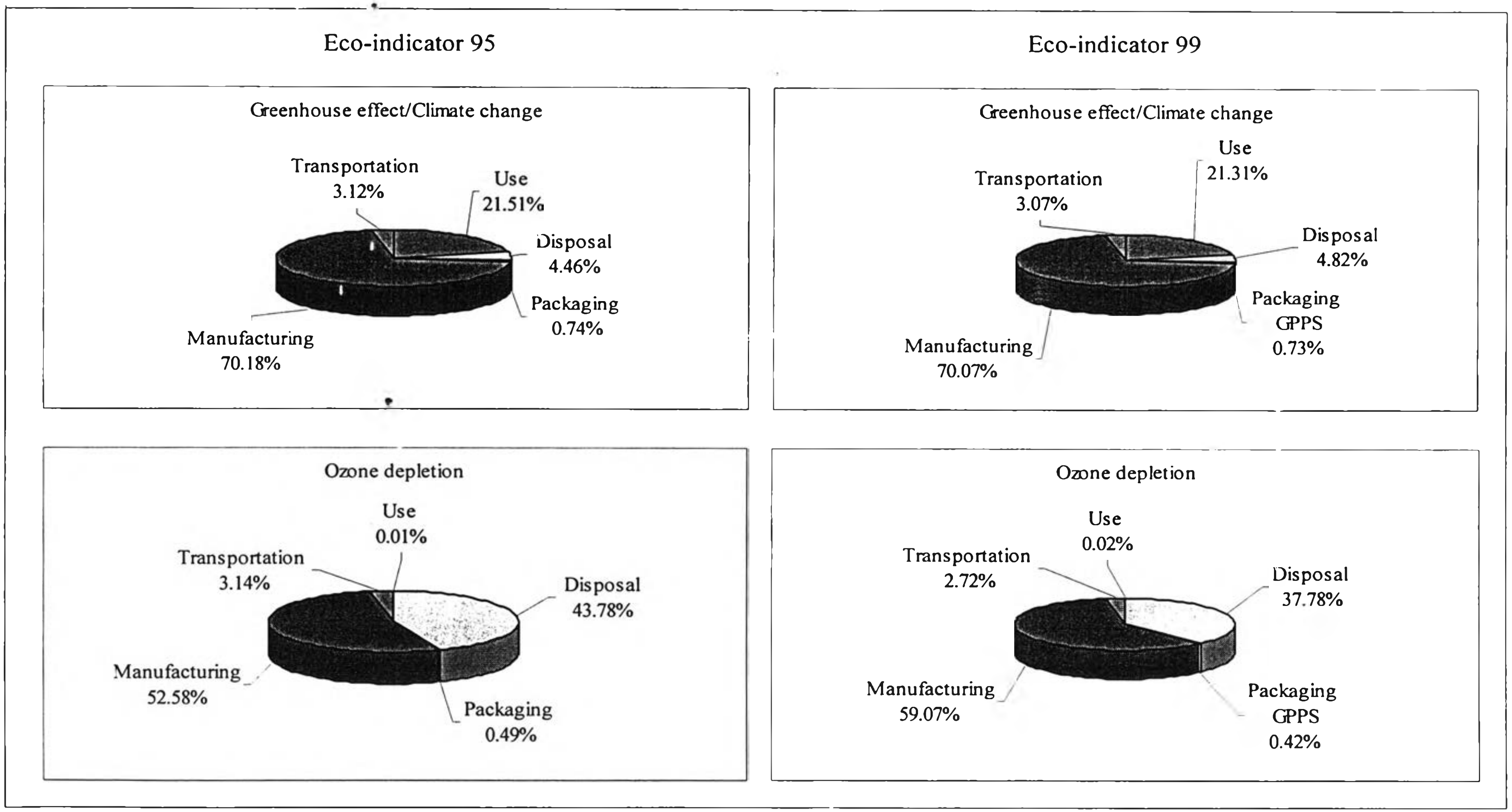

Figure 4.49 Comparison of the environmental impacts assessed by Eco-indicator 95 and Eco-indicator 99 for 1 kg GPPS.

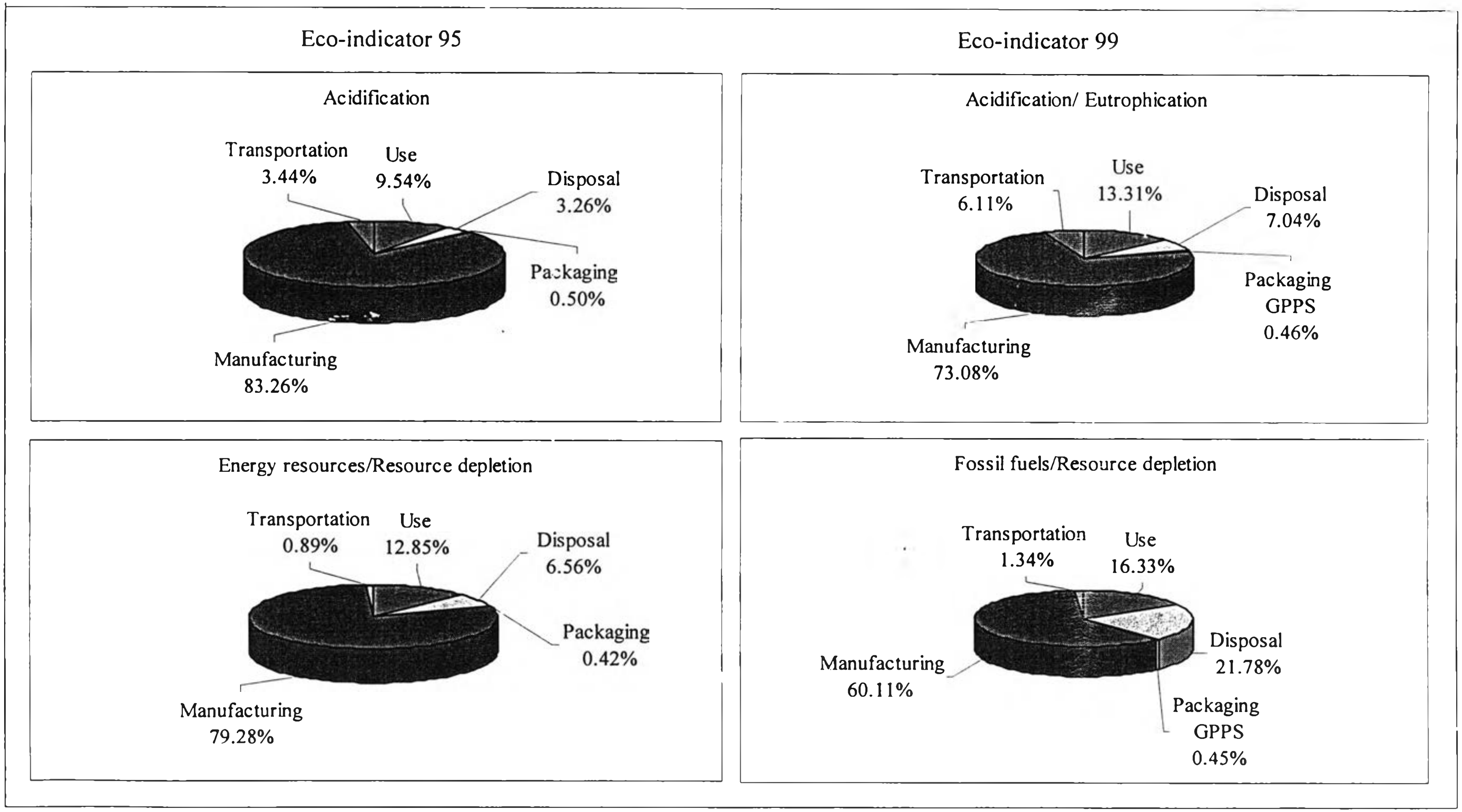

Figure 4.49 Comparison of the environmental impacts assessed by Eco-indicator 95 and Eco-indicator 99 for 1 kg GPPS (continued).

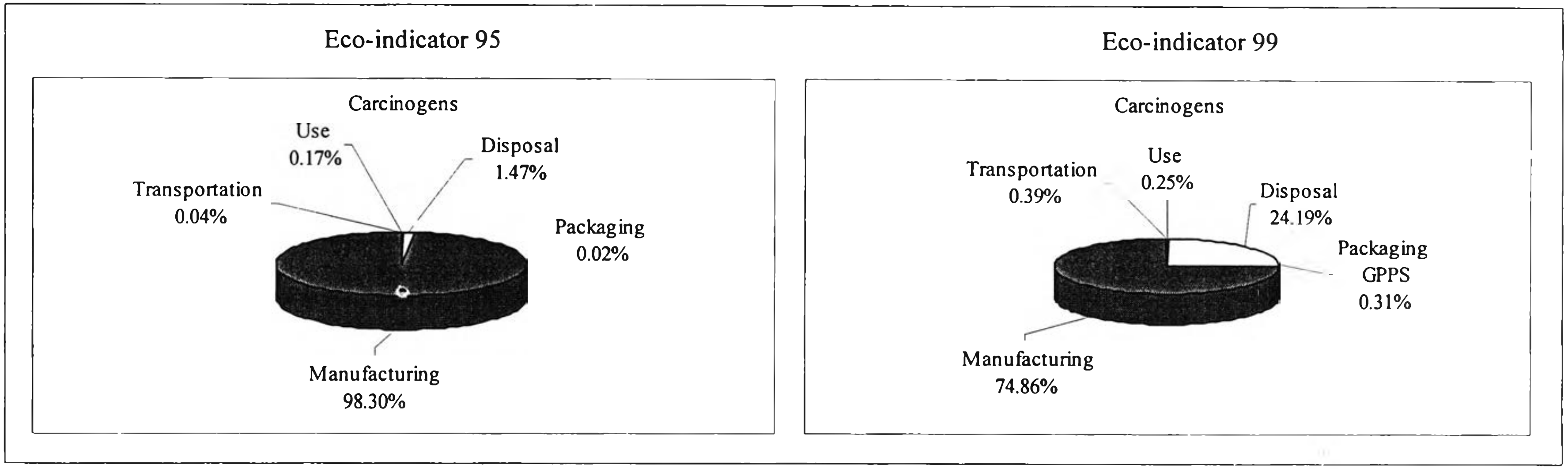

Figure 4.49 Comparison of the environmental impacts assessed by Eco-indicator 95 and Eco-indicator 99 for 1 kg GPPS (continued).

4.2.3 Environmental Impact Assessment of High Impact Polystyrene

The environmental impact assessment of 1 kg HIPS production by using Eco-indicator 95 and Eco-indicator 99 gives the similar results as seen in the production of 1 kg GPPS but slightly higher due to the polybutadiene rubber production. Using Eco-indicator 95, the overall results of the production of 1 kg HIPS shown in Figure 4.50 indicates that the environmental impacts mainly come from the raw material used in the manufacturing processes which is styrene monomer. Figure 4.51 reveals that acidification and summer smog formation are the major environmental impact categories of the overall HIPS process. The comparison of the environmental impact for all 5 phases of HIPS production is shown in Figure 4.52 illustrates that the manufacturing phase contributes most followed by the use phase (injection) and transportation whereas the contributions from packaging is shown to be negligible. Similar to GPPS, the disposal phase yields positive effect to the environment as indicated from minus value due to the recycle process that can reduce the use of materials in the manufacturing phase. In manufacturing phase, there are 5 processes as HIPS which the result in Figure 4.53 identifies raw material preparation process and SM recovery respectively. For raw material preparation process, Figures 4.54 shows that the environmental impact is essentially from styrene monomer and polybutadiene rubber of which their production contributes mainly in acidification and summer smog. In SM recovery process, the environmental impact is mainly in the production of water in Thailand which contributes to summer smog, acidification, and carcinogenic effect as illustrated in Figure 4.55. Figure 4.56 shows the environmental impact assessment for the use phase where the main contribution is from electricity in Thailand. Acidification, greenhouse gases, and eutrophication are the main impact categories resulted from the electricity production.

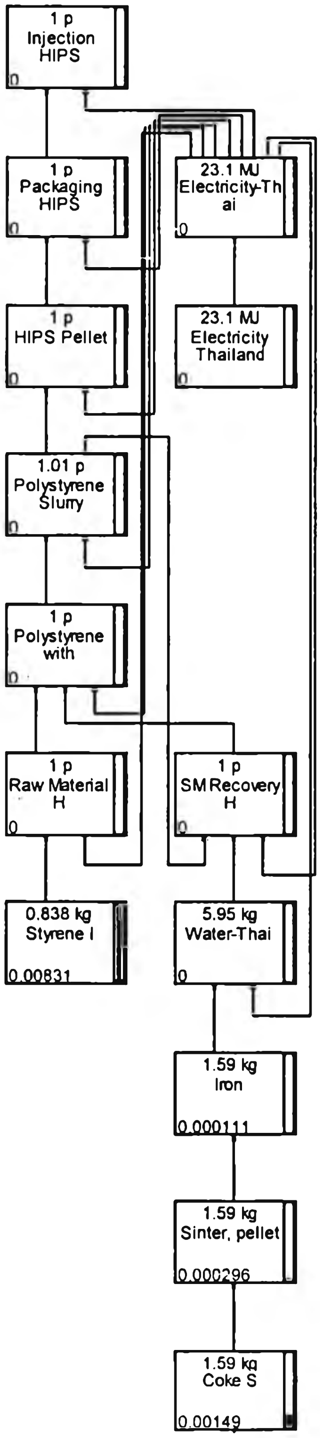

Figure 4.50 Overall results of the environmental impact assessment of the production of 1 kg High Impact Polystyrene (HIPS) obtained by using Eco-indicator 95 .

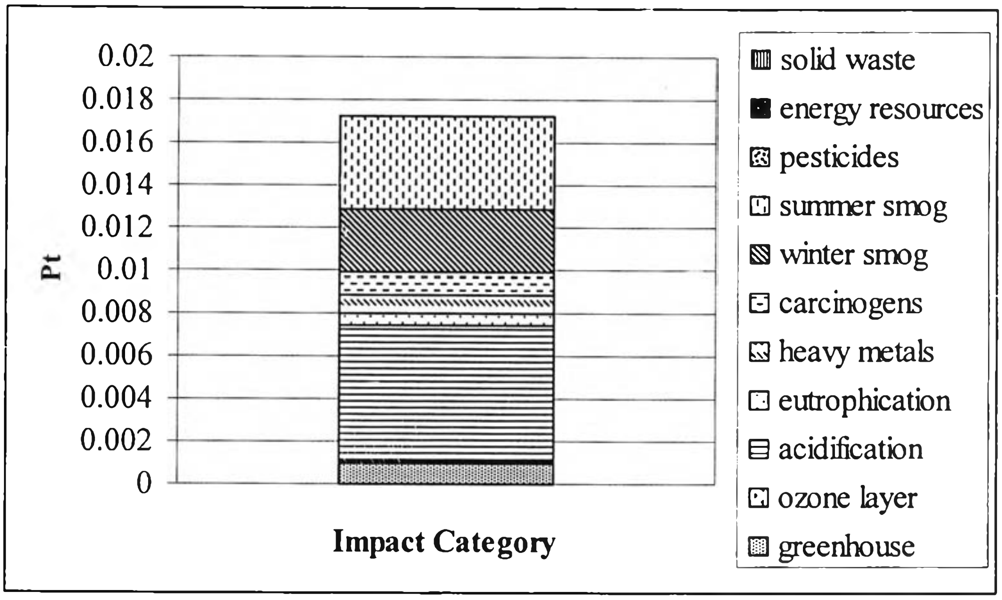

Figure 4.51 Environmental impact categories of 1 kg HIPS production obtained by using Eco-indicator 95.

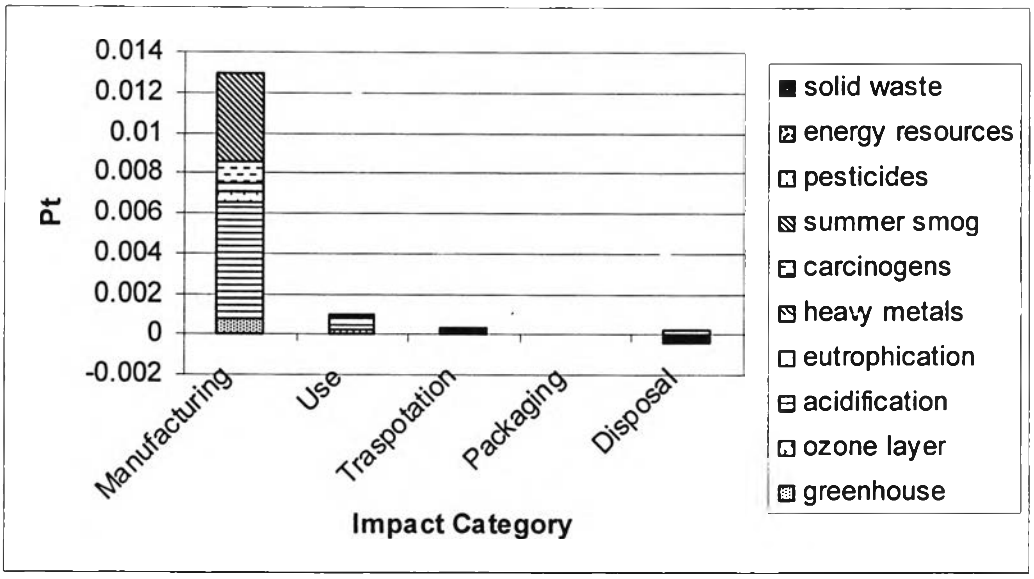

Figure 4.52 Environmental impact categories of each phase in the production of 1 kg HIPS obtained by Eco-indicator 95.

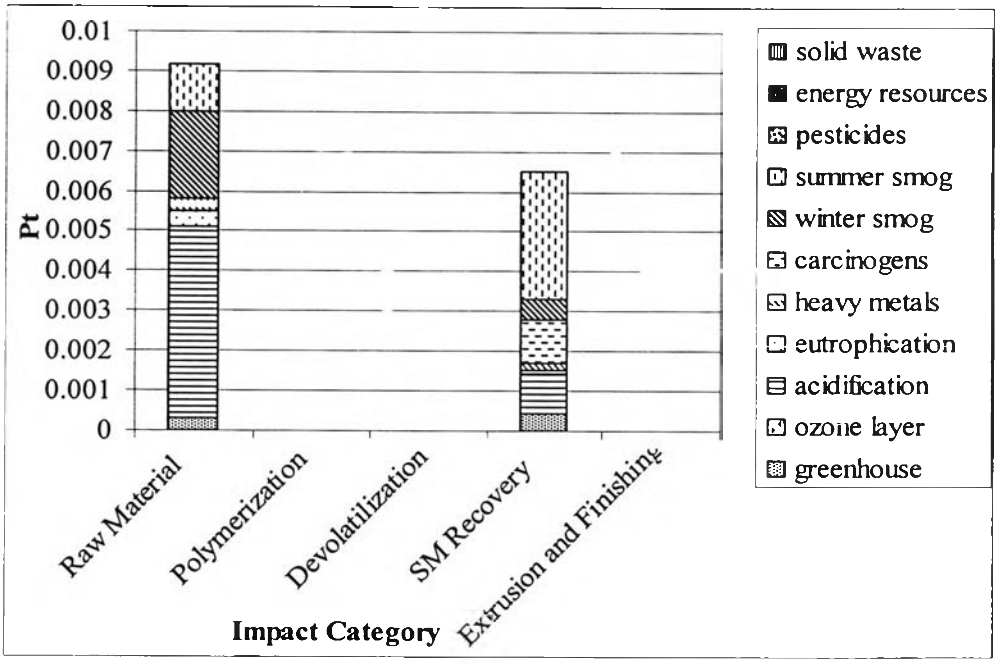

Figure 4.53 Environmental impact categories of each process in the manufacturing phase of 1 kg HIPS production obtained by using Eco-indicator 95.

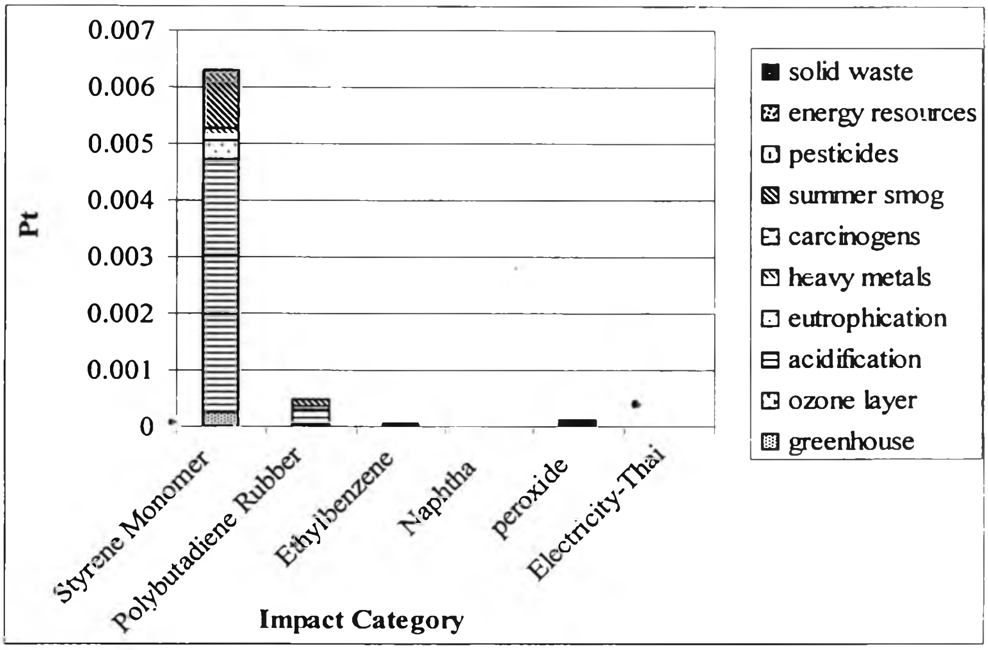

Figure 4.54 Environmental impact categories of raw material preparation process in the manufacturing phase of 1 kg HIPS production obtained by using Eco-indicator 95.

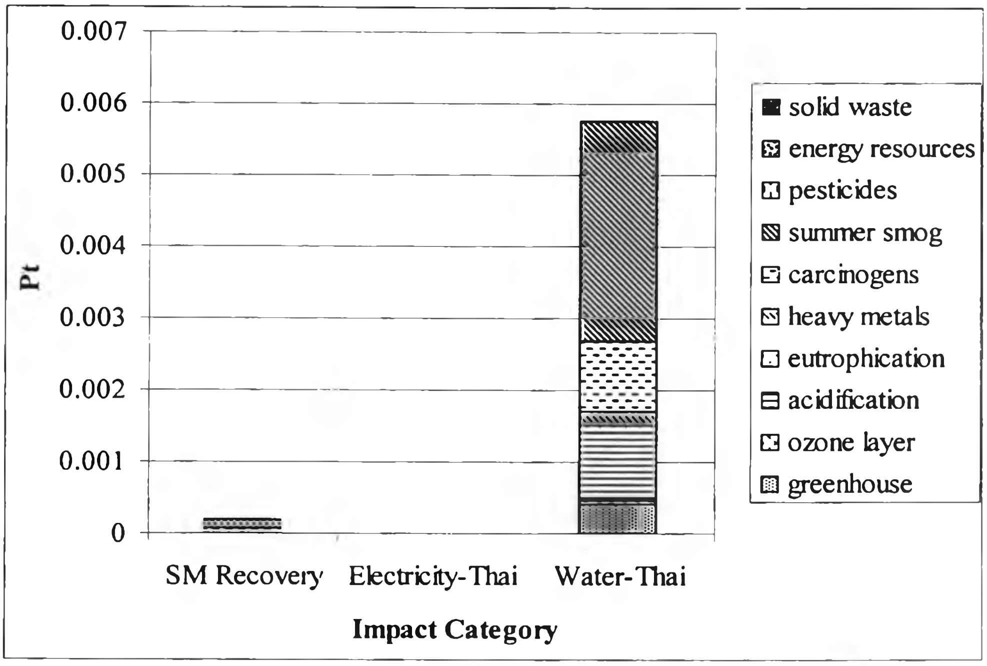

Figure 4.55 Environmental impact categories of SM recovery process in the manufacturing phase of 1 kg HIPS production obtained by using Eco-indicator 95.

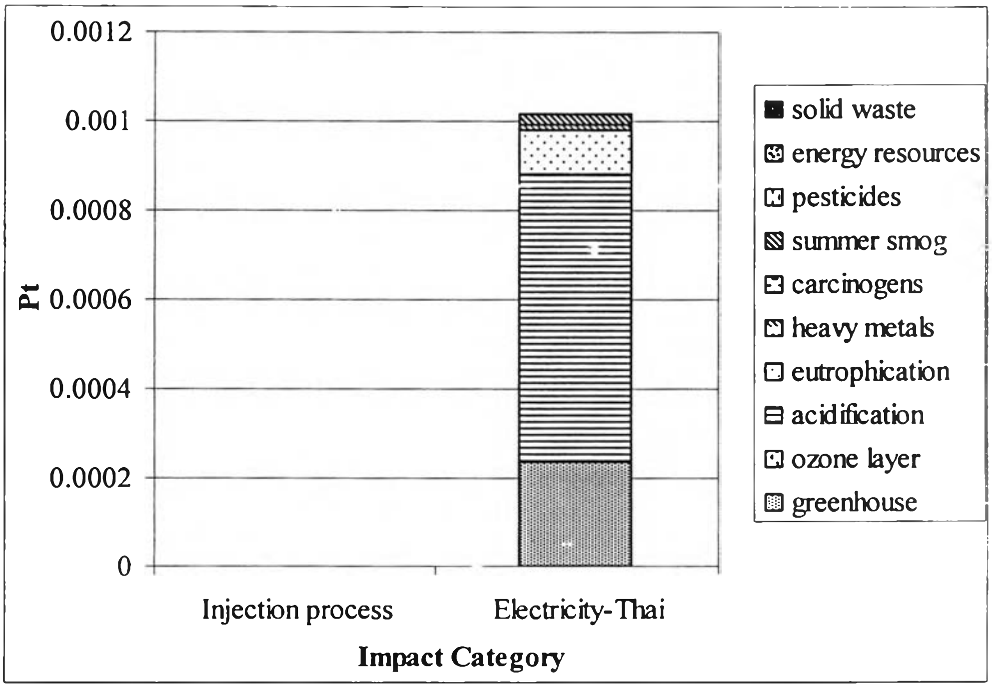

Figure 4.56 Environmental impact categories of the use phase in the production of 1 kg HIPS obtained by using Eco-indicator 95.

Table 4.70 shows the results of the environmental impact assessment using Eco-indicator 95 in terms of equivalent units for each impact category for the production of 1 kg HIPS. It can be seen that the production of 1 kg of HIPS utilizes energy resources equivalent to 231 MJ LHV and generates green house gases equivalent to 5.01 kg CO_2, solid wastes 1.97 kg, acidification equivalent to $7.23E^{-2}$ kg of SO_2, heavy metals $9.0E^{-6}$ kg of Pb equivalent, ozone layer depletion substances equivalent to $5.21E^{-7}$ kg of CFC11, and carcinogenic effect equivalent to $1.17E^{-6}$ kg of benzo(a)pyrene. Similar to PU and GPPS, energy is mostly consumed in the manufacturing phase (approximately 92%), especially in the production of styrene monomer. Greenhouse gases are generated mainly from manufacturing and use phases which account for 77% and 25%, respectively. Manufacturing phase also contributes most to the solid wastes and acidification being generated in the production of HIPS which contribute approximately 65% and 90%, respectively.

Tables 4.71 and 4.72 show the environmental impacts in equivalent units for the manufacturing phase and use phase, respectively. For manufacturing phase, the environmental impacts cause from raw material preparation process and SM recovery process. It can be obviously seen from the results shown in Tables 4.73 and 4.74 that styrene monomer contributes most in almost all impact categories followed by polybutadiene rubber in raw material preparation process. For SM recovery process, the production of water in Thailand contributes highest in almost all impact categories in. For use phase, electricity produced in Thailand and extensively used in injection process, has been shown to be the major contributor to all impact categories. For disposal phase, similar to GPPS, Table 4.75 shows the benefit for the environment in minus value in almost all impact categories.

Table 4.70 Environmental impact in equivalent units for each impact category for the production of 1 kg HIPS

Impact category	Unit	Total	Manufacturing	Use	Transportation	Packaging	Disposal
Energy resources	MJ LHV	231	212	33.9	1.99	$9.55E^{-2}$	-17.3
Greenhouse	kg CO2	5.01	3.86	1.23	$1.51E^{-1}$	$2.61E^{-2}$	$-2.54E^{-1}$
Solid waste	kg	1.97	1.28	$7.29E^{-3}$	$5.68E^{-5}$	$2.12E^{-2}$	$6.64E^{-1}$
Acidification	kg SO2	$7.23E^{-2}$	$6.5E^{-2}$	$7.26E^{-3}$	$2.42E^{-3}$	$8.88E^{-5}$	$-2.47E^{-3}$
Eutrophication	kg PO4	$4.42E^{-3}$	$3.76E^{-3}$	$7.57E^{-4}$	$3.04E^{-4}$	$7.18E^{-6}$	$-4.1E^{-4}$
Summer smog	kg C2H4	$3.14E^{-2}$	$3.13E^{-2}$	$1.84E^{-4}$	$2.48E^{-4}$	$-5.4E^{-5}$	$-3.6E^{-4}$
Heavy metals	kg Pb	$9.0E^{-6}$	$5.57E^{-6}$	$1.16E^{-7}$	$9.33E^{-8}$	$5.05E^{-7}$	$2.72E^{-6}$
Ozone layer	kg CFC11	$5.21E^{-7}$	$2.61E^{-7}$	$7.18E^{-11}$	$3.93E^{-8}$	$3.27E^{-9}$	$2.17E^{-7}$
Carcinogens	kg B(a)P	$1.17E^{-6}$	$1.15E^{-6}$	$1.95E^{-9}$	$1.19E^{-9}$	$-2.3E^{-9}$	$1.72E^{-8}$
Pesticides	kg act.subst	0	0	0	0	0	0

Table 4.71 Environmental impact in equivalent units for each impact category for the manufacturing phase of kg HIPS production

Impact category	Unit	Total	Raw Material	Polymerization	Devolatilization	Recovery SM	Extrusion and Finishing
Energy resources	MJ LHV	212	93.4	$1.54E^{-1}$	$4.88E^{-1}$	118	$4.22E^{-2}$
Greenhouse	kg CO2	3.86	1.61	$5.56E^{-3}$	$1.78E^{-2}$	2.23	$1.53E^{-3}$
Solid waste	kg	1.28	$3.86E^{-2}$	$3.9E^{-3}$	$4.15E^{-5}$	1.24	$3.59E^{-6}$
Acidification	kg SO2	$6.5E^{-2}$	$5.39E^{-2}$	$3.29E^{-5}$	$1.25E^{-4}$	$1.1E^{-2}$	$9.03E^{-6}$
Eutrophication	kg PO4	$3.76E^{-3}$	$3.0E^{-3}$	$3.43E^{-6}$	$1.44E^{-5}$	$7.39E^{-4}$	$9.42E^{-7}$
Summer smog	kg C2H4	$3.13E^{-2}$	$8.57E^{-3}$	$8.32E^{-7}$	$2.78E^{-6}$	$2.28E^{-2}$	$2.28E^{-7}$
Heavy metals	kg Pb	$5.57E^{-6}$	$3.41E^{-6}$	$5.28E^{-10}$	$1.67E^{-9}$	$2.15E^{-6}$	$1.45E^{-10}$
Ozone layer	kg CFC11	$2.61E^{-7}$	$1.66E^{-8}$	$1.03E^{-13}$	$3.27E^{-13}$	$2.45E^{-7}$	$2.83E^{-14}$
Carcinogens	kg B(a)P	$1.15E^{-6}$	$3.54E^{-9}$	$8.86E^{-12}$	$2.8E^{-11}$	$1.15E^{-6}$	$2.43E^{-12}$
Pesticides	kg act.subst	0	0	0	0	0	0

Table 4.72 Environmental impact in equivalent units for each impact category for the use phase of HIPS production

Impact category	Unit	Total	Side Air Duct	Electricity Thai
Energy resources	MJ LHV	33.9	0	33.9
Greenhouse	kg CO2	1.23	$2.86E^{-4}$	1.23
Solid waste	kg	$7.29E^{-3}$	$4.4E^{-3}$	$2.89E^{-3}$
Acidification	kg SO2	$7.26E^{-3}$	$9.4E^{-9}$	$7.26E^{-3}$
Eutrophication	kg PO4	$7.57E^{-4}$	$1.56E^{-9}$	$7.57E^{-4}$
Summer smog	kg C2H4	$1.84E^{-4}$	$1.06E^{-9}$	$1.84E^{-4}$
Heavy metals	kg Pb	$1.16E^{-7}$	0	$1.16E^{-7}$
Ozone layer	kg CFC11	$7.18E^{-11}$	$4.9E^{-11}$	$2.28E^{-11}$
Carcinogens	kg B(a)P	$1.95E^{-9}$	$3.59E^{-14}$	$1.95E^{-9}$
Pesticides	kg act.subst	0	0	0

Table 4.73 Environmental impact in equivalent units for each impact category for raw material preparation process in the manufacturing phase of HIPS production

Impact category	Unit	Total	Styrene Monomer	Ethylbenzene	Polybutadiene Rubber	Naphtha	Peroxide	Electricity-Thai
Energy resources	MJ LHV	93.4	77.7	2.7	10.2	1.42	$9.37E^{-1}$	$4.61E^{-1}$
Greenhouse	kg CO2	1.61	1.26	$1.13E^{-1}$	$1.56E^{-1}$	$9.54E^{-3}$	$5.14E^{-2}$	$1.67E^{-2}$
Solid waste	kg	$3.86E^{-2}$	$3.33E^{-2}$	0	$4.75E^{-3}$	$9.41E^{-5}$	$4.88E^{-4}$	$3.93E^{-5}$
Acidification	kg SO2	$5.39E^{-2}$	$5.04E^{-2}$	$1.95E^{-4}$	$2.67E^{-3}$	$9.87E^{-5}$	$4.32E^{-4}$	$9.88E^{-5}$
Eutrophication	kg PO4	$3.0E^{-3}$	$2.69E^{-3}$	$1.64E^{-5}$	$2.44E^{-4}$	$1.07E^{-5}$	$3.15E^{-5}$	$1.03E^{-5}$
Summer smog	kg C2H4	$8.57E^{-3}$	$7.38E^{-3}$	$1.22E^{-4}$	$9.57E^{-4}$	$4.9E^{-6}$	$1.07E^{-4}$	$2.5E^{-6}$
Heavy metals	kg Pb	$3.41E^{-6}$	$2.2E^{-6}$	$2.05E^{-8}$	$6.84E^{-7}$	$1.0E^{-9}$	$5.09E^{-7}$	$1.58E^{-9}$
Ozone layer	kg CFC11	$1.66E^{-8}$	0	0	0	0	$1.66E^{-8}$	$3.1E^{-13}$
Carcinogens	kg B(a)P	$3.54E^{-9}$	$1.5E^{-9}$	$1.88E^{-10}$	0	$3.35E^{-12}$	$1.82E^{-9}$	$2.66E^{-11}$
Pesticides	kg act.subst	0	0	0	0	0	0	0

Table 4.74 Environmental impact in equivalent units for each impact category for SM recovery process in the manufacturing phase of HIPS production

Impact category	Unit	Total	Electricity-Thai	SM Recovery	Water-Thai
Energy resources	MJ LHV	118	0.15	0	118
Greenhouse	kg CO2	2.23	$5.44E^{-3}$	0	2.22
Solid waste	kg	1.24	$1.28E^{-5}$	0	1.24
Acidification	kg SO2	$1.1E^{-2}$	$3.22E^{-5}$	$9.0E^{-6}$	$1.09E^{-2}$
Eutrophication	kg PO4	$7.39E^{-4}$	$3.36E^{-6}$	$1.67E^{-6}$	$7.34E^{-4}$
Summer smog	kg C2H4	$2.28E^{-2}$	$8.14E^{-7}$	$8.67E^{-4}$	$2.19E^{-2}$
Heavy metals	kg Pb	$2.15E^{-6}$	$5.16E^{-10}$	0	$2.15E^{-6}$
Ozone layer	kg CFC11	$2.45E^{-7}$	$1.01E^{-13}$	0	$2.45E^{-7}$
Carcinogens	kg B(a)P	$1.15E^{-6}$	$8.67E^{-12}$	$9.17E^{-8}$	$1.06E^{-6}$
Pesticides	kg act.subst	0	0	0	0

Table 4.75 Environmental impact in equivalent units for each impact category for disposal phase of HIPS production

Impact category	Unit	Total	Landfill	Recycling
Energy resources	MJ LHV	-17.3	0	-17.3
Greenhouse	kg CO2	$-2.54E^{-1}$	0	$-2.54E^{-1}$
Solid waste	kg	$6.64E^{-1}$	0.5	$1.64E^{-1}$
Acidification	kg SO2	$-2.47E^{-3}$	0	$-2.47E^{-3}$
Eutrophication	kg PO4	$-4.1E^{-4}$	0	$-4.1E^{-4}$
Summer smog	kg C2H4	$-3.6E^{-4}$	0	$-3.6E^{-4}$
Heavy metals	kg Pb	$2.72E^{-6}$	$1.91E^{-7}$	$2.53E^{-6}$
Ozone layer	kg CFC11	$2.17E^{-7}$	0	$2.17E^{-7}$
Carcinogens	kg B(a)P	$1.72E^{-8}$	0	$1.72E^{-8}$
Pesticides	kg act.subst	0	0	0

The results of the impact assessment of HIPS production using Eco-indicator 99 show the same trend as observed with GPPS. Figure 4.57 reveals that the damages are mainly in the resources depletion and human health which resulted from depletion of fossil fuels, respiration of inorganic substances and climate change effect on human as elaborated in Figure 4.58. The impact assessment for various phases in the production of HIPS is shown in Figure 4.59. The environmental impact is mainly in the manufacturing phase and use phase (injection). The recycle process in the disposal phase contributes the positive effect to the environment by decreasing the extensive utilization of electricity generated from fossil fuels. Figure 4.59 reveals that the impact is in fossil fuel depletion and respiration of inorganics respectively. In manufacturing phase, Table 4.60 shows that the major environmental impacts are in raw material preparation and SM recovery process. This is attributed to the use of styrene monomer, water and electricity in manufacturing and use phases, respectively, as shown in Figures 4.61, 4.62, and 4.63.

The comparison of the results obtained from Eco-indicator 95 and Eco-indicator 99 is shown in Figure 4.64 for each impact category. Although the percentages may be different but similar trend is clearly observed between these two impact assessment methods.

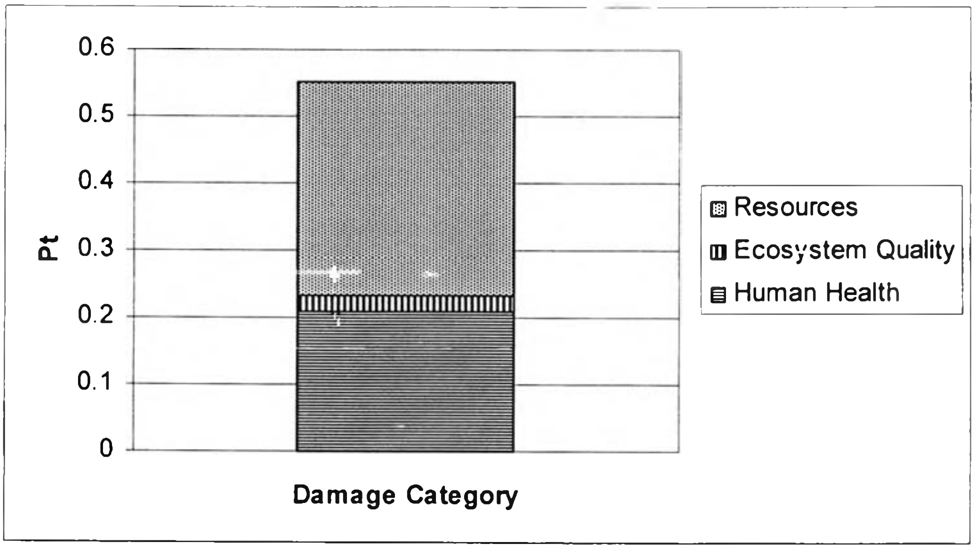

Figure 4.57 Damage assessment for the production of 1 kg HIPS by using Eco-indicator 99.

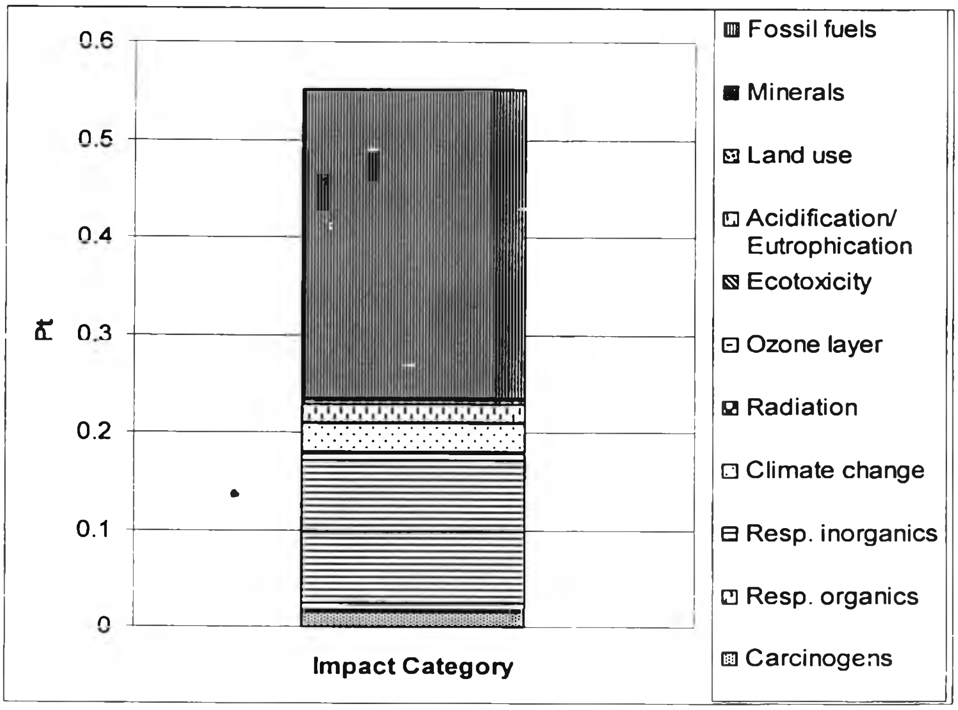

Figure 4.58 Impact assessment by category for the production of 1 kg HIPS by using Eco-indicator 99.

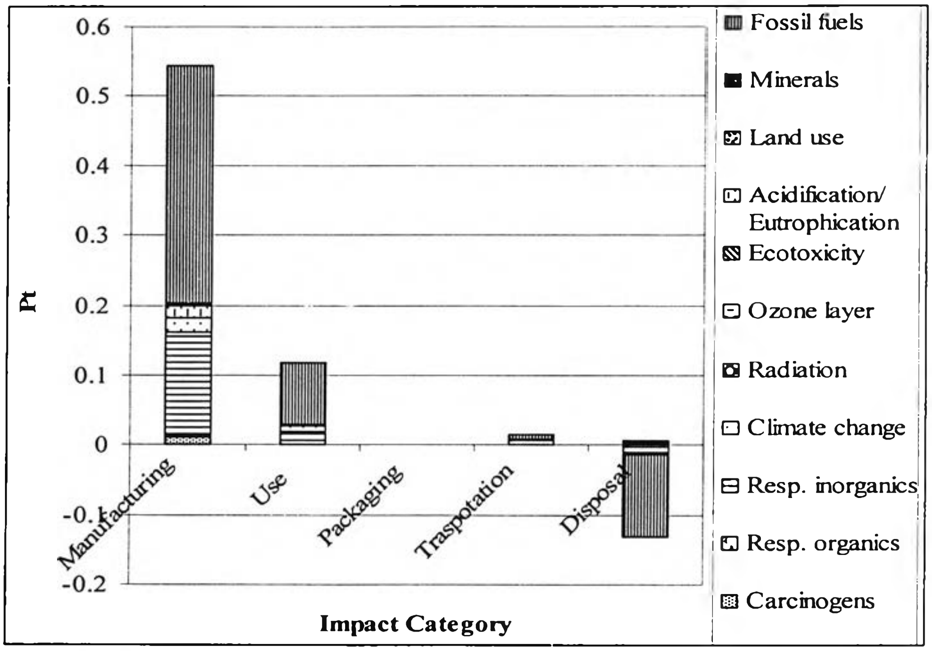

Figure 4.59 Impact assessment for each phase in the production of 1 kg HIPS by using Eco-indicator 99.

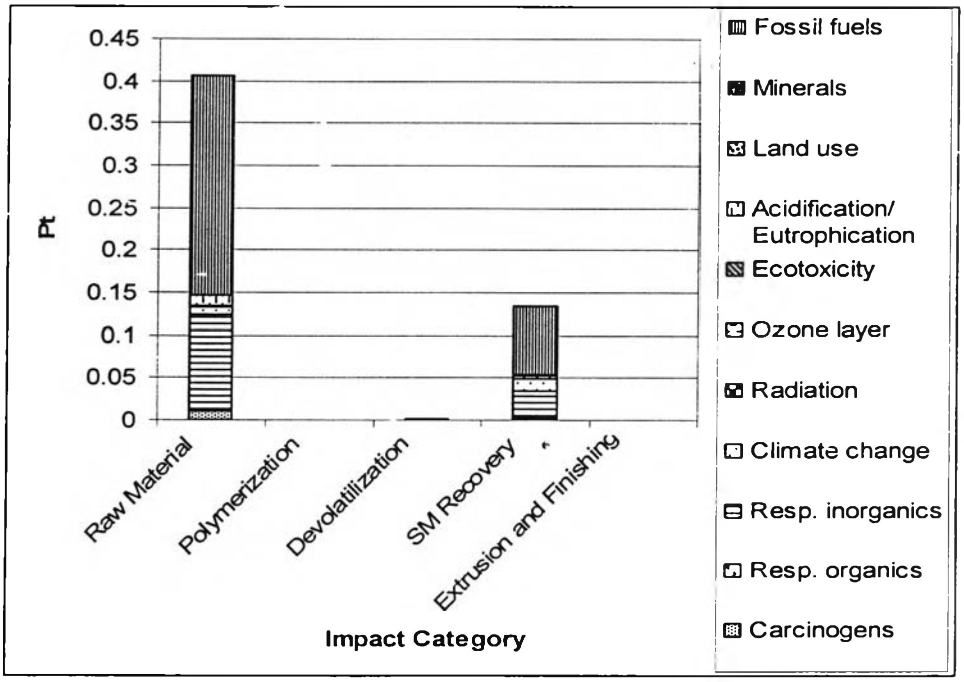

Figure 4.60 Impact assessment for each process in the manufacturing phase of 1 kg HIPS production by using Eco-indicator 99.

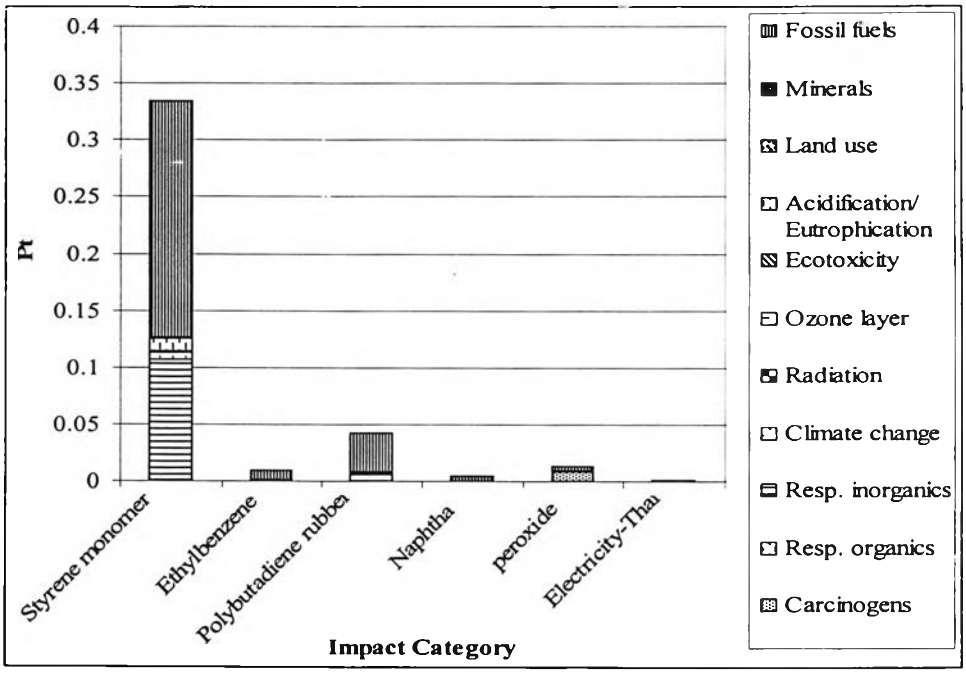

Figure 4.61 Impact assessment for raw material preparation process in the manufacturing phase of 1 kg HIPS production by using Eco-indicator 99.

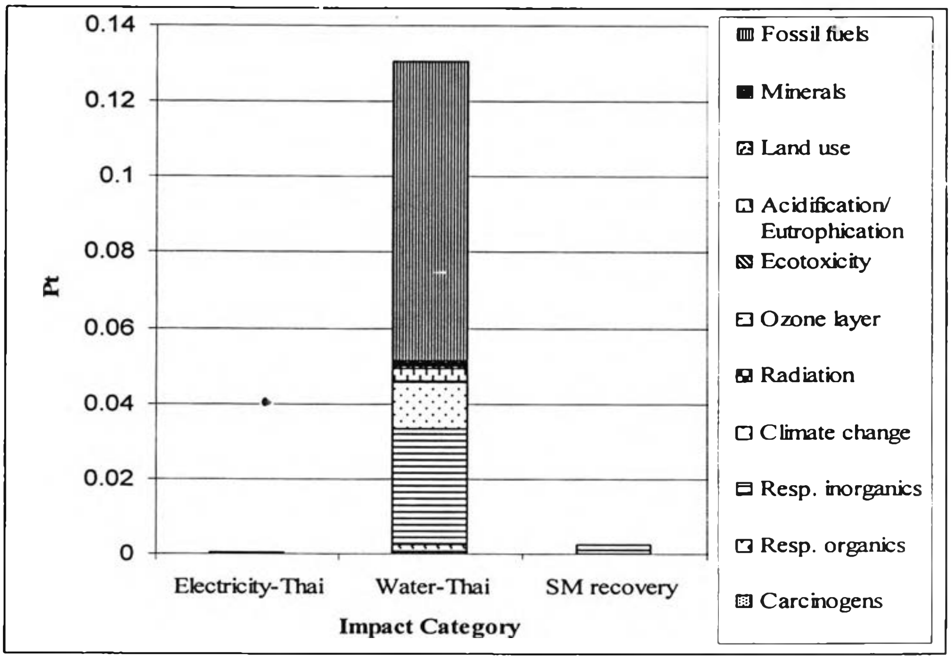

Figure 4.62 Impact assessment for SM recovery process in the manufacturing phase of 1 kg HIPS production by using Eco-indicator 99.

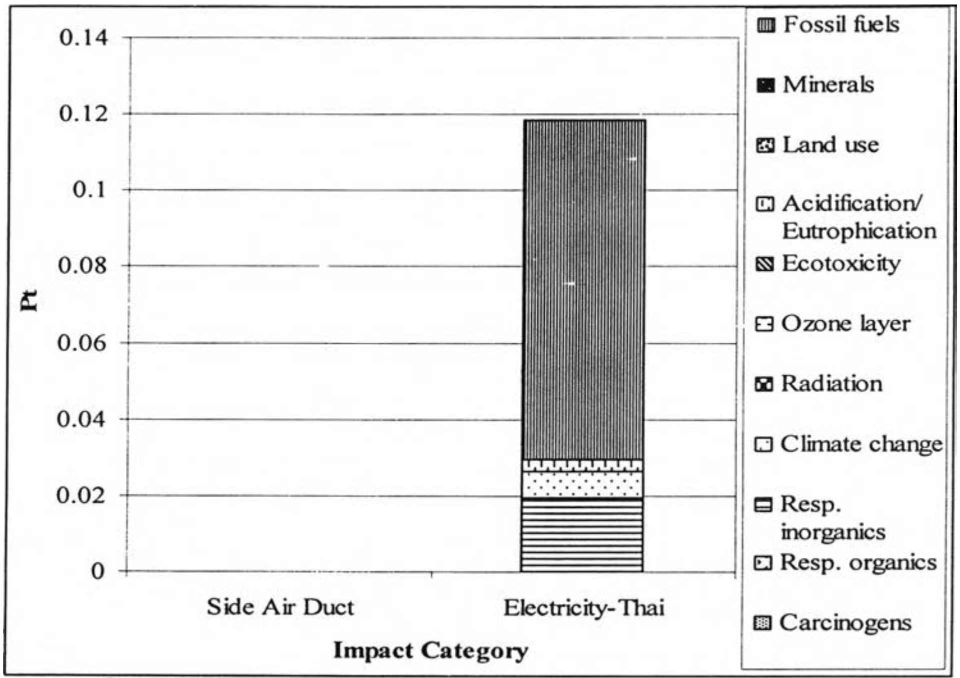

Figure 4.63 Impact assessment of use phase in the production of 1 kg HIPS by using Eco-indicator 99.

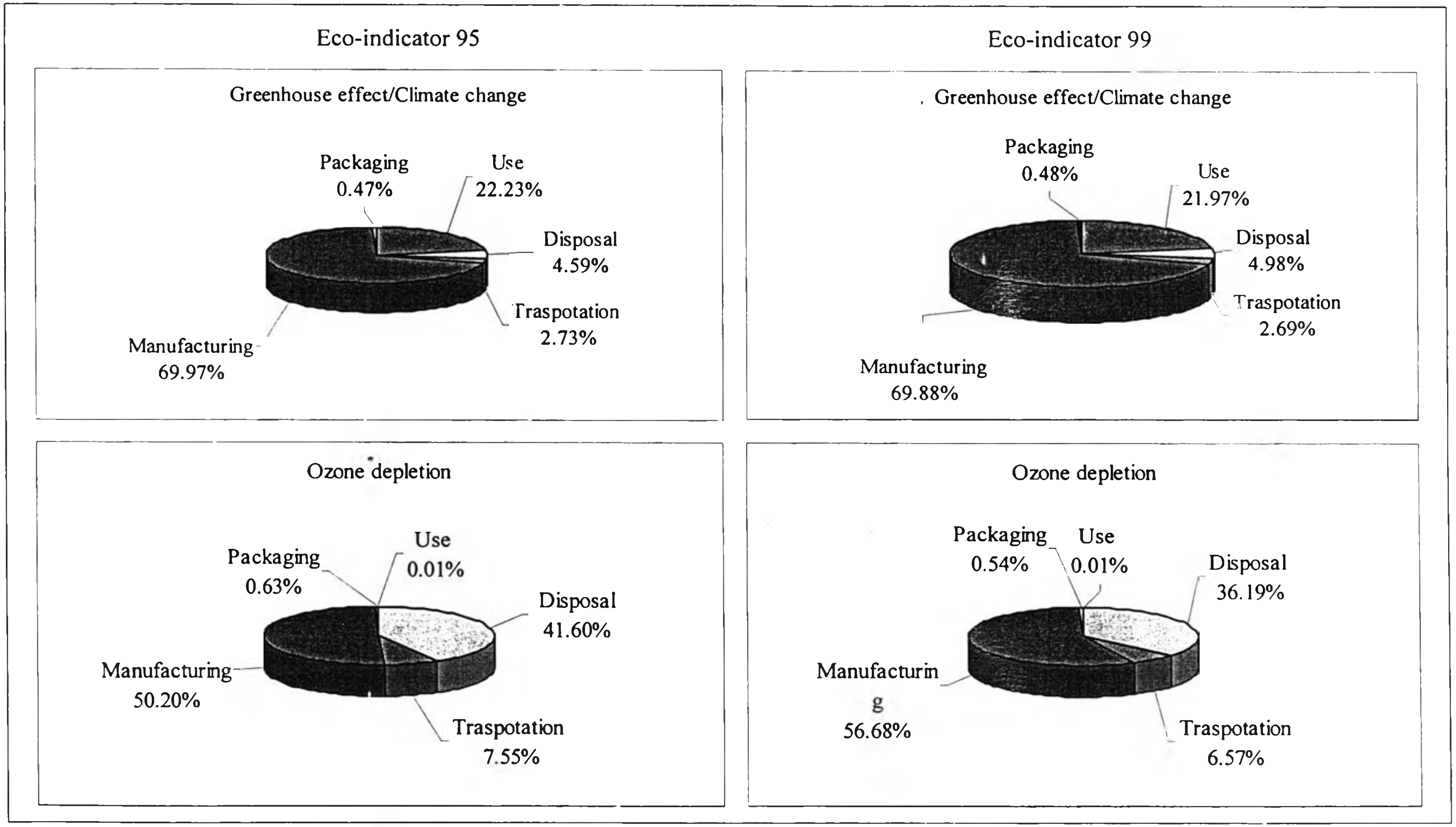

Figure 4.64 Comparison of the environmental impacts assessed by Eco-indicator 95 and Eco-indicator 99 for 1 kg HIPS.

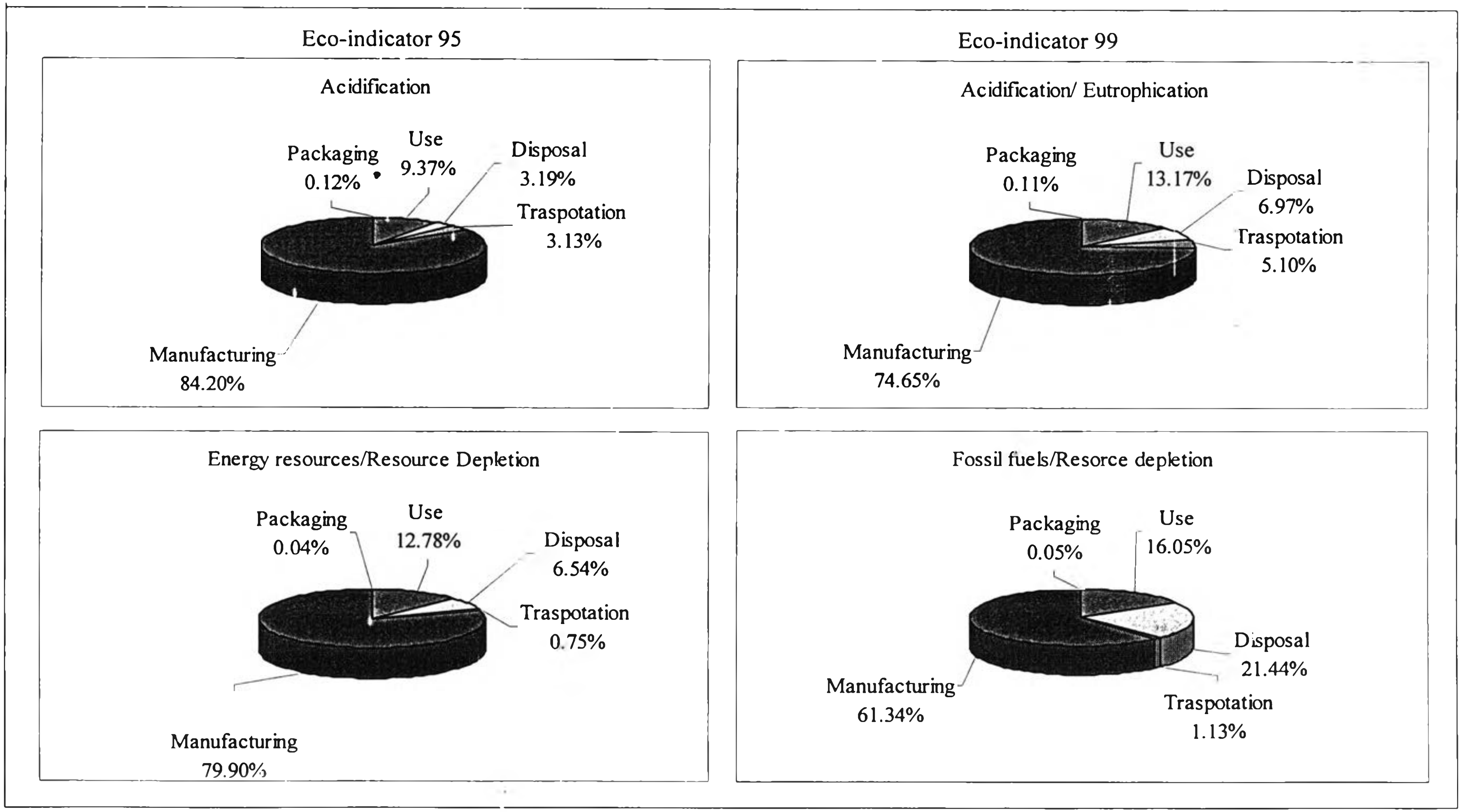

Figure 4.64 Comparison of the environmental impacts assessed by Eco-indicator 95 and Eco-indicator 99 for 1 kg HIPS (continued).

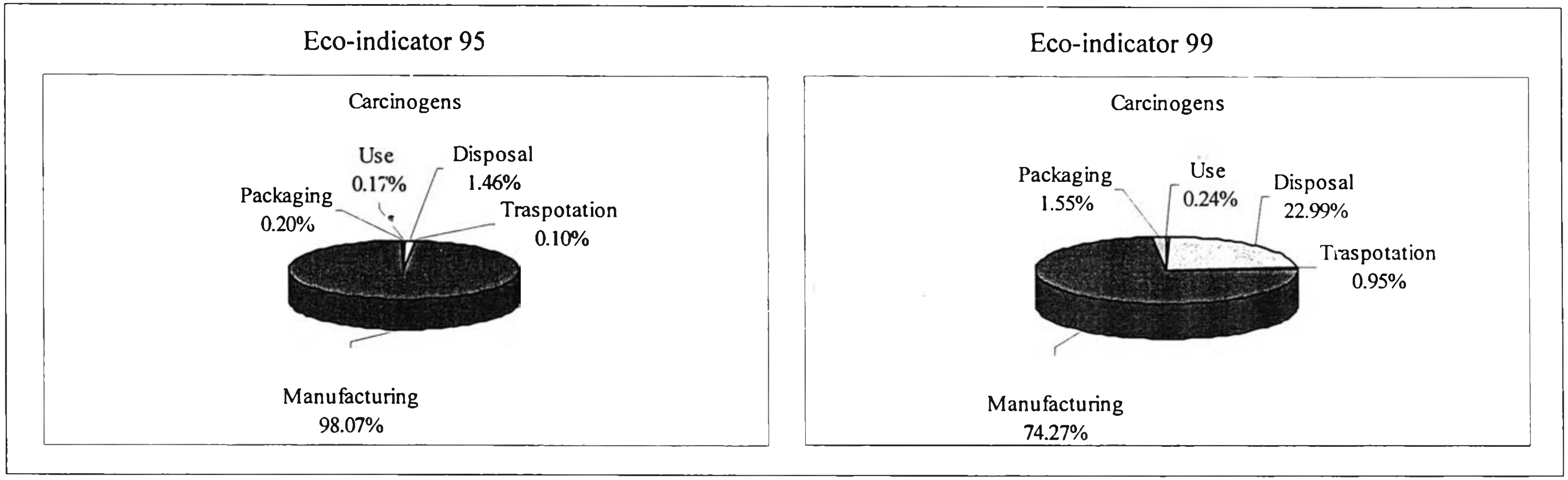

Figure 4.64 Comparison of the environmental impacts assessed by Eco-indicator 95 and Eco-indicator 99 for 1 kg HIPS (continued).

4.3 Comparison of the Life Cycle Assessment of Polyurethane Foam, General Purpose Polystyrene and High Impact Polystyrene

Figure 4.65 shows the comparison of the life cycle assessment (LCA) of the three polymers used in this study, PU foam, GPPS, and HIPS. It can be seen that the environmental impacts of HIPS and GPPS are nearly the same and are much higher than the impacts caused by the production of PU foam. The total impact of PU foam is approximately 1.5 times lower than that of HIPS. For all three polymers, the main impact is in fossil fuels followed by respiration of inorganics, climate change and acidification. For PU foam, carcinogens appear to be one of the important factors as well.

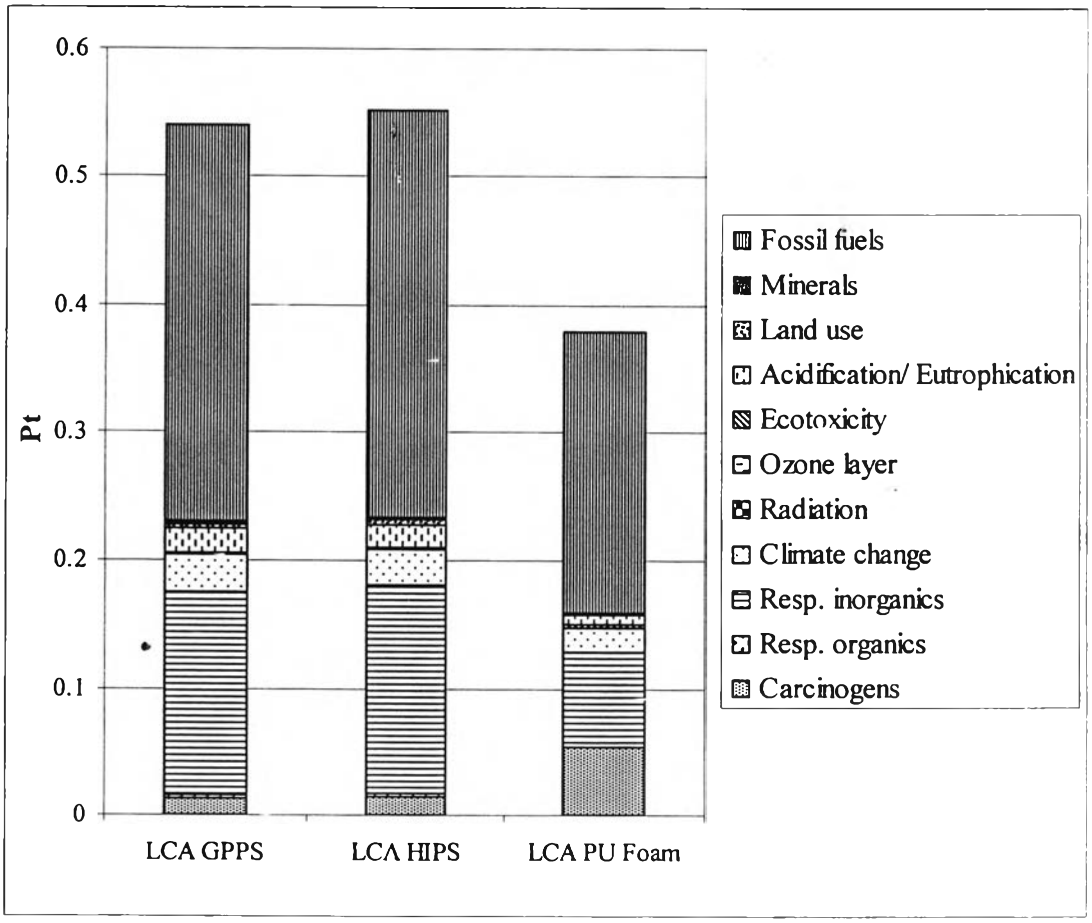

Figure 4.65 LCA comparison between PU foam, GPPS, and HIPS.

The comparison of life cycle assessment of PU foam, GPPS, and HIPS for each impact category is shown in Figure 4.66. This includes greenhouse effect, ozone layer depletion, acidification, carcinogens, and energy resources depletion. It can be seen from the figure that, for all three plastics, the most affected areas are in manufacturing and use phases which is quite common for the production of petrochemical products. In addition, it is clearly seen that, among the three plastics studied, PU foam contributes the least in all impact categories.

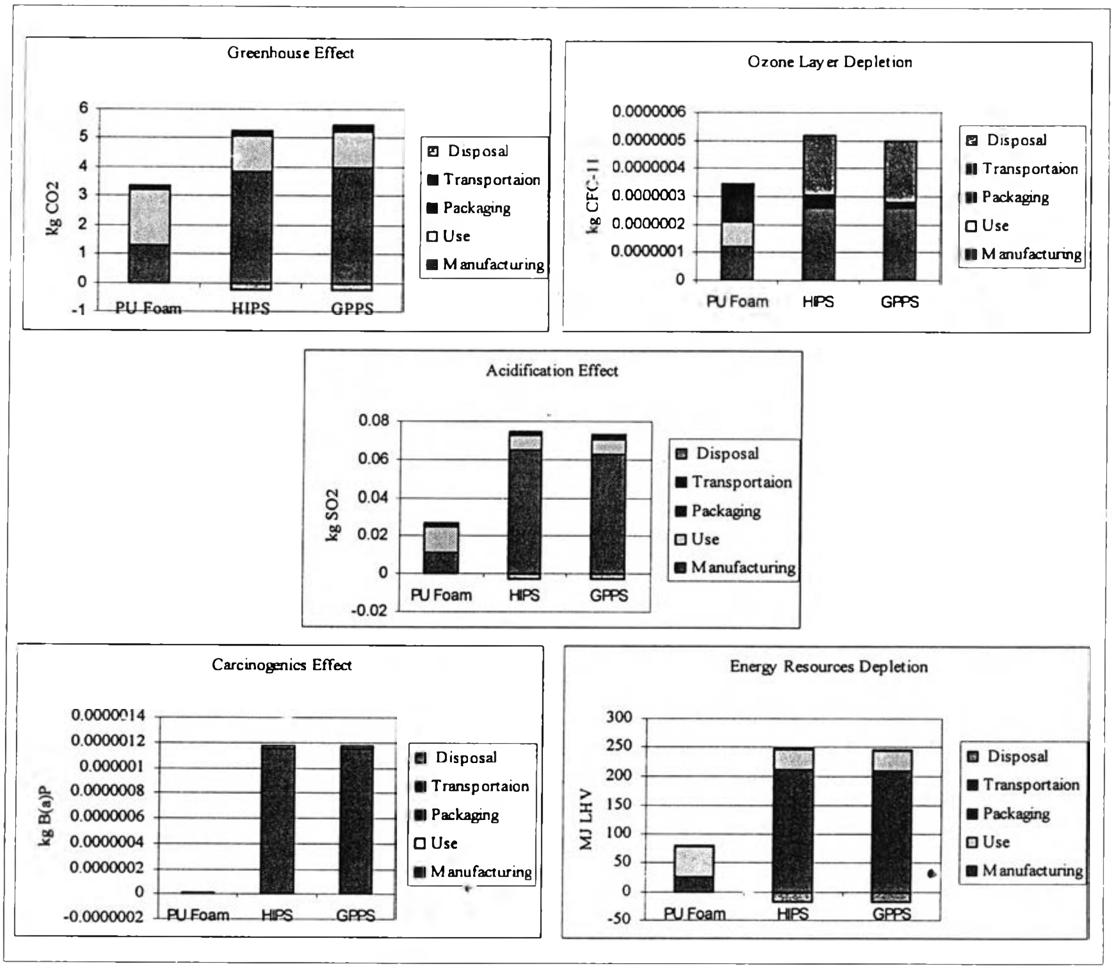

Figure 4.66 LCA comparison between PU foam, GPPS, and HIPS for various impact categories.

4.4 Suggestions for Improvement

In this section, suggestions for the improvements of the process based on the results obtained from LCA study are discussed for each plastic as follows.

4.4.1 Polyurethane Foam Production

From the LCA results, the environmental impacts of the production of PU foam are mainly from the chemicals used in the manufacturing and use phases. In particular, diphenylmethane diisocyanate or MDI used in injection process contributes most significantly. Therefore, the process can be improved if MDI can be replaced by a more environmental friendly substance. In this case, MDI can be easily replaced by toluene diisocyanate or TDI which is extensively used in the production of PU foam in other parts of the world. By substituting MDI with TDI and rerun the program using the same conditions, the results show that 15% reduction in the environmental impact of PU foam production can be achieved as shown in Figure 4.67.

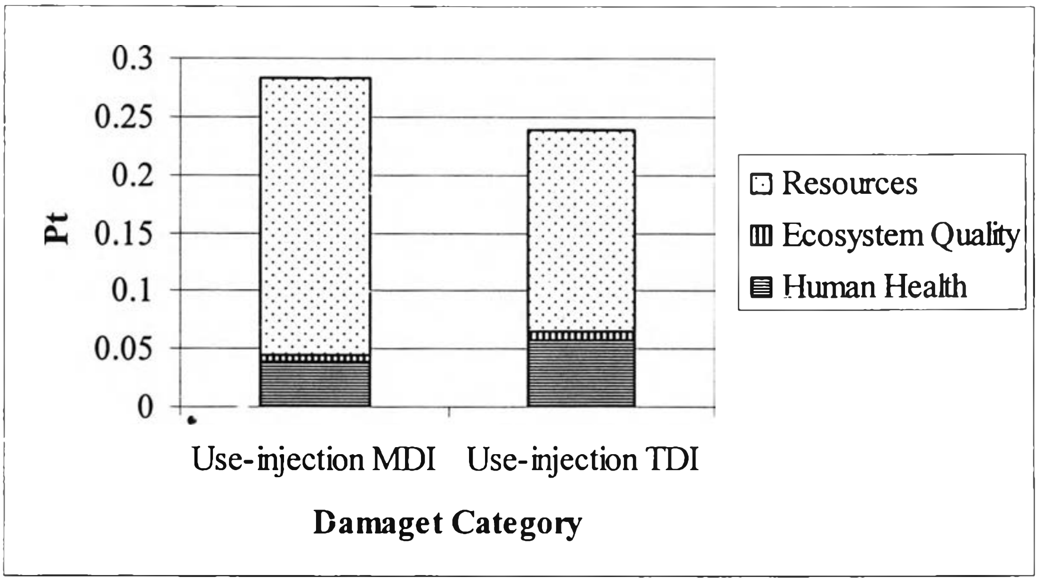

Figure 4.67 Comparison of the environmental impact in PU foam production using MDI versus TDI in the injection process.

4.4.2 General Purpose Polystyrene Production

The LCA results show that the environmental impact of the production of GPPS is mainly from chemicals and electricity used the manufacturing and use phases. For chemicals, the production of styrene monomer contributes most to the environmental impact and it is rather difficult to change this monomer as long as the current production technology is still being used to produce GPPS. In contrast, for electricity, reducing electricity consumption in the injection process could lead to lowered environmental impact. For injection process, Engineering Plastics Co., Ltd uses 2 injection machines, 450-ton and 350-ton, to produce clear shelf for refrigerators at the production of 4000 pieces/month. In many cases, although the 350-ton machine is capable of the work but the 450-ton machine is normally used instead. If the 350-ton injection machine is used to produce GPPS part instead of 450-ton machine, it is estimated that 22% decrease in the environmental loads could be achieved as shown in Figure 4.68.

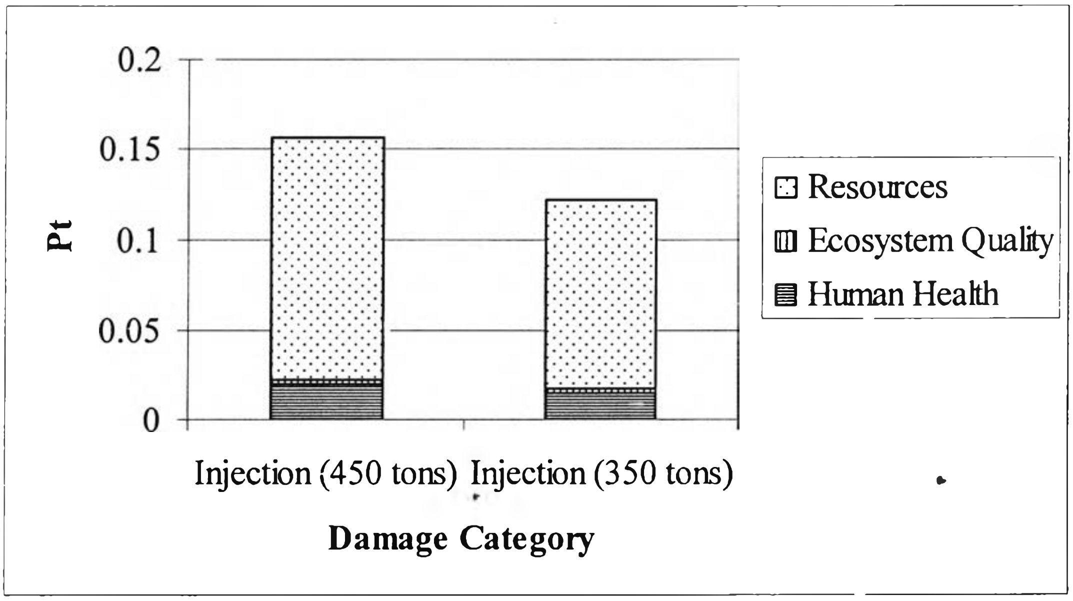

Figure 4.68 Comparison of the environmental impact of GPPS production by using 350-ton injection machine versus 450-ton injection machine in injection process.

4.4.3 Use of Cleaner Technology in the Production Process

Apart from chemicals used, energy consumption is the major source of the environmental impacts in the production of these plastics (PU foam, GPPS, and HIPS). New or emerging technologies such as cleaner technology (CT) and Eco-design can be used to improve the efficiency of energy utilization in the production process of these petrochemical products. The feasibility and appropriateness of the use of these environmental management tools should be conducted at the manufacturing level of the companies in the petrochemical industry.