CHAPTER IV
RESULTS AND DISCUSSION

4.1 End-of-life Management of Asphalt

End-of-life processes of asphalt in this study can be divided into three technologies (recycle/reuse/landfill) with four main processes of which are hot in-plant recycling, hot in-place recycling, cold in-place recycling (reuse) and landfill. Hot in-plant recycling and landfill will be included of dismantling and transportation processes in their burdens but hot in-place recycling and cold in-place recycling are not. Because these two latter processes already have dismantling roller included in their machine. Energy calculations for hot in-plant recycling, cold in-place recycling and landfill of WMA are as same as HMA except hot in-place recycling because the temperature use for heating aggregates and asphalt binder of HMA in hot in-place recycling is higher than the temperature use in WMA (20-30°C).

4.1.1 Dismantle

4.1.1.1 Basis of Calculations

Calculation of energy consumption for this process comes from Vidal *et al.* (2013) which studied on life cycle assessment of hot-mixed asphalt and zeolite-based warm-mixed asphalt with reclaimed asphalt pavement. When focus on construction and end-of-life section of their paper. It can be found that the equation for calculation of energy consumption with 64 L/hr fuel consumption of cold milling machine is as follow:

$$EC = \frac{64\frac{L}{hr}}{1} \times \frac{1km}{1.9\frac{km}{hr}} \times \frac{7m}{1.3m} \times \frac{0.05m}{0.05m} \times \frac{1}{Functional\ Unit}$$

$$= 181.38\ L \times \frac{1}{1000m \times 7m \times 0.05m \times 2.428\frac{ton}{m^3}} \times \text{LHV of diesel}$$

$$= 0.2134\ \frac{L}{ton} \times 35.94\ \frac{MJ(Diesel)}{L}$$

= 7.671 MJ/ton asphalt

4.1.1.2 Inventory Analysis

Table 4.1 shows the total input and output data from dismantle process of HMA and WMA (before calculation by SimaPro software) and energy consumption from the previous calculation. There are five assumptions for dismantle process as follow:

- Traveling speed is 1.9 km/h with full load of diesel engine.
- Effective width for milling machine is 1.3 m.
- Dismantle calculation data use only for hot in-plant recycling and landfill.
- No waste both residue and air emission in dismantle processes.
- Cold milling machine is as trade name "Wirtgen" model W 130 F / W 130 Fi (Writgen, G., 2011).

Table 4.1 Results of the inventory analysis of dismantle process

Input			**Output**		
Item	Quantity	Unit	Item	Quantity	Unit
Raw material			**Products**		
Reclaimed asphalt pavement	1000	kg	Asphalt binder + aggregate	1000	kg
Energy			**Waste**		
Milling roller	7.671	MJ	No waste		

4.1.2 Transportation

4.1.2.1 Basis of Calculations

Assume distances of trucks for transportation both recycling and landfill processes are similar at 50 km for forth trip (full load) and 50 km for back trip (empty load). The type of truck is weight of 16 tons and 10 wheels. Energy consumption of the truck is 0.2640 L/km (full load) and 0.2188 L/km (empty load) (MTEC, 2010).

4.1.2.2 Inventory analysis

Inventory data of transported RAP which present emissions based on one ton reclaimed asphalt pavement was showed in Table 4.2.

Table 4.2 Emissions from transportation of RAP (MTEC, 2010).

Transportation of RAP					
Input Inventory			**Output Inventory**		
Description	**Unit**	**Amount**	**Description**	**Unit**	**Amount**
Resource			**Product**		
Diesel	kg	0.693	Reclaim asphalt pavement	kg	1000
			Emission to air		
			Carbon dioxide (CO_2)	g	2172.5
			Carbon monoxide (CO)	g	7.445
			Nitrogen oxides (NO_x)	g	22.375
			Particulate matter (PM)	g	1.675
			Hydrocarbons (HC)	g	1.945
			Methane (CH_4)	g	0.045
			Benzene (C_2H_6)	g	0.0369
			Toluene (C_7H_8)	g	0.01555
			Xylene (C_8H_{10})	g	0.01555
			Non – methane volatile organic compounds (NMVOCs)	g	3.71
			Sulfur oxides (SO_x)	g	0.47
			Nitrous Oxide (N_2O)	g	0.085
			Cadmium	g	6.7E-06
			Copper	g	0.001135
			Chromium	g	3.34E-05
			Nickel	g	4.68E-05
			Selenium	g	6.7E-06
			Zinc	g	0.00067
			Lead	g	7.35E-08
			Mercury	g	1.34E-08

From inventory data of transported RAP that showed in Table 4.2. Thus, total diesel used for transported RAP is equal to:

$$Diesel\ use\ of\ full\ load = 0.2640\frac{L}{km} \times 0.84\frac{kg}{L}(Diesel) \times \frac{1000kg(RAP)}{1600kg\ (truck)} \times 50km$$

= 0.693 kg diesel (Full load)

$$Diesel\ use\ of\ no\ load = 0.2188\frac{L}{km} \times 0.84\frac{kg}{L}(Diesel) \times \frac{1000kg(RAP)}{1600kg\ (truck)} \times 50km$$

= 5.74×10^{-7} kg diesel (No load)

Energy consumption = 0.693 kg (Full load) + 5.74×10^{-7} kg (No load) × LHV of diesel

= 0.6930006 kg × 42.91 MJ/kg (Diesel)

= 29.717 MJ/ton asphalt

4.1.3 Hot in-plant recycling

4.1.3.1 Basis of calculations

The important data of hot in-plant recycling is the storage, crushing and screening data that come from Miliutenko *et al.* (2012), dismantle data comes from calculation of dismantle process (7.671MJ) and transportation of RAP data comes from calculation of transportation of RAP process (29.717 MJ). There are two assumptions for hot in-plant recycling processes as follow:

- No waste both residue and air emission in hot in-plant recycling process.
- RAP ratio of hot in-plant recycling process is 100% consisting of aggregate (94%) and bitumen (6%) (do not add virgin asphalt).
- Transport distance from RAP site to asphalt plant both HMA and WMA is 50 km.

4.1.3.2 Inventory analysis

Table 4.3 shows the total input and output data from hot in-plant process of HMA (before calculation by SimaPro software).

Table 4.3 Results of the inventory analysis of hot in-plant recycling

Input			**Output**		
Item	Quantity	Unit	Item	Quantity	Unit
Raw material			**Products**		
Reclaimed asphalt pavement	1000	kg	Asphalt binder + aggregate	1000	kg
Energy			**Waste**		
Storage, crushing, screening	25	MJ	No waste		
Dismantle	7.671	MJ			
Transportation (diesel)	29.717	MJ			

4.1.4 Hot in-place recycling

4.1.4.1 Basis of calculations

Calculation of energy consumption for hot in-place recycling process comes from Vidal et al. (2013) like dismantle process. Energy consumption with 55 L/hr fuel consumption of hot in-place recycling machine which uses only scarifying and paving sessions is as follow:

$$EC = \frac{55\frac{L}{hr}}{1} \times \frac{1km}{2\frac{km}{hr}} \times \frac{7m}{4.5m} \times \frac{0.05m}{0.05m} \times \frac{1}{Functional\ Unit}$$

$$= 42.778\ L \times \frac{1}{1000m \times 7m \times 0.05m \times 2.428\frac{ton}{m^3}} \times \text{LHV of diesel}$$

$$= 0.0566\ \frac{L}{ton} \times 35.94 \frac{MJ(Diesel)}{L}$$

= 2.0353 MJ/ton asphalt

4.1.4.2 Inventory analysis

Table 4.4 shows the total input and output data from hot in-place process of HMA (before calculation by SimaPro software) and energy consumption. Hot in-place recycling process has seven assumptions as follow:

- Propane is used for heating and mixing based on the study of Miliutenko et al (2012).
- Heat capacity of hot-mixed asphalt is **185.515** MJ/Ton asphalt used in energy calculation of asphalt heating.
- Traveling speed is 2 km/h with full load of diesel engine.
- Hot in-place recycling machine is as trade name "Wirtgen remixer 4500" (Writgen, G., 2011).
- Effective width for hot in-place recycling machine is 4.5 m.
- No waste both residue and air emission in hot in-place recycling process.
- RAP ratio of hot in-place recycling process is 100% consisting of aggregate (94%) and bitumen (6%) (do not add virgin asphalt)

Table 4.4 Results of the inventory analysis for hot in-place recycling of hot-mixed asphalt

Input			Output		
Item	**Quantity**	**Unit**	**Item**	**Quantity**	**Unit**
Raw material			**Products**		
Reclaimed asphalt pavement	1000	kg	Asphalt binder + aggregate	1000	kg
Energy			**Waste**		
Propane for Heating and mixing	500	MJ	No waste		
Diesel for Scarifying, paving	2.0353	MJ			

Energy consumption calculation of WMA for hot in-place recycling process is as same as the calculation for HMA but propane for heating and mixing data are different. Because WMA uses mixing temperature less than HMA, energy for heating and mixing should be reduced which was calculated by heat capacity value. Table 4.5 shows the total input and output data from hot in-place process of WMA.

- Energy for heating asphalt which calculates from "heat capacity" of warm-mixed asphalt is **166.992** MJ/Ton asphalt.

Table 4.5 Results of the inventory analysis for hot in-place recycling of warm-mixed asphalt

Input			**Output**		
Item	**Quantity**	**Unit**	**Item**	**Quantity**	**Unit**
Raw material			**Products**		
Reclaimed asphalt pavement	1000	kg	Asphalt binder + aggregate	1000	kg
Energy			**Waste**		
Propane for Heating and mixing	481.48	MJ	No waste		
Diesel for Scarifying, paving	2.0353	MJ			

4.1.5 Cold in-place recycling (Reuse)

4.1.5.1 Basis of calculations

Cold in-place recycling or reuse has no dismantling and transportation because this machine can mill surface of road and also immediately pave as base-course material. Therefore, we do not add impact from transportation into this reuse process. Calculation of energy consumption for this process comes from Vidal et al. (2013) like dismantle process. Energy consumption with 187 L/hr fuel consumption of cold in-place recycling machine is as follow:

$$EC = \frac{187\frac{L}{hr}}{1} \times \frac{1km}{2\frac{km}{hr}} \times \frac{7m}{2.2m} \times \frac{0.05m}{0.05m} \times \frac{1}{Functional\ Unit}$$

$$= 297.5\ L \times \frac{1}{1000m \times 7m \times 0.05m \times 2.428\frac{ton}{m^3}} \times \text{LHV of diesel}$$

$$= 0.3501\ \frac{L}{ton} \times 35.94\frac{MJ(Diesel)}{L}$$

$$= 13.8402\ \text{MJ/ton asphalt}$$

4.1.5.2 Inventory analysis

Table 4.6 shows the total input and output data from cold in-place process of HMA and WMA (before calculation by SimaPro software) which includes energy consumption data from the above calculation. Cold in-place process has five assumptions as follow:

- Traveling speed is 2 km/h with full load of diesel engine.
- Reuse machine is as trade name "Wirtgen" model WR 2200CR (Writgen, G., 2011).
- Effective width for cold in-place recycling machine is 2.2 m.
- No waste both residue and air emission in hot in-place recycling process.
- RAP ratio of cold in-place recycling process is 100% consisting of aggregate (94%) and bitumen (6%) (do not add virgin asphalt).

Table 4.6 Results of the inventory analysis of cold in-place recycling

Input			**Output**		
Item	**Quantity**	**Unit**	**Item**	**Quantity**	**Unit**
Raw material			**Products**		
Reclaimed asphalt pavement	1000	kg	Asphalt binder + aggregate	1000	kg
Energy			**Waste**		
Scarifying, paving, compaction	13.8402	MJ	No waste		

4.1.6 Landfill

4.1.6.1 Basis of calculations

The important data of landfill is dismantle data that comes from calculation of energy use in dismantle process (7.671MJ) and transportation of RAP (29.717 MJ). Landfill process has four assumptions as follow:

- Calculated impacts of landfill by using ETH-ESU 96 system processes from SimaPro 7 program.
- Transport distance from dismantling site to landfill site is about 50 km.
- No waste both residue and air emission in landfill process.
- RAP ratio of cold in-place recycling process is 100% consisting of aggregate (94%) and bitumen (6%) (do not add virgin asphalt)

4.1.6.2 Inventory analysis

Table 4.7 shows the total input and output data from landfill process of HMA and WMA (before calculation by SimaPro software)

Table 4.7 Results of the inventory analysis of landfill

Input			**Output**		
Item	Quantity	Unit	Item	Quantity	Unit
Raw material			**Products**		
Reclaimed asphalt pavement	1000	kg	Asphalt binder + aggregate	1000	kg
Energy			**Waste**		
Transportation (diesel)	29.717	MJ	No waste		
Dismantle	7.671	MJ			

4.1.7 Life cycle impact assessment of end-of-life

After LCI of HMA and WMA for end-of-life asphalt was completed, life cycle impact assessment (LCIA) could be analyzed based on one ton of asphalt for relevant impact categories, using both impact assessment model CML 2 baseline 2000 and Eco-Indicator 95. Figure 4.1 illustrates a simple process diagram of HMA and WMA, which can be divided into 4 main unit processes: asphalt production (raw material + production), transportation, pavement and end-of-life processes.

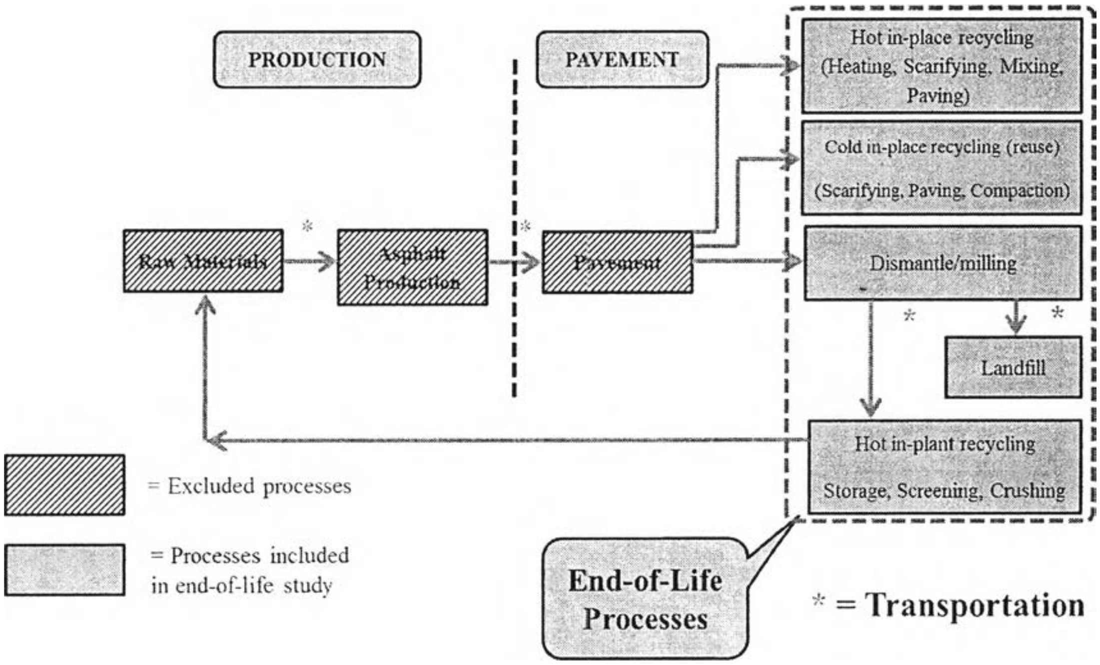

Figure 4.1 Simple process diagram of hot-mixed and warm-mixed asphalt production.

4.1.7.1 *HMA*

For energy resources usage, as seen in Figure 4.2, hot in-place recycling has the highest energy resource burdens from propane for heating and mixing (492.41 MJ LHV/ Ton of asphalt pavement) and avoided energy resource burdens from avoided asphalt production (– 443.47 MJ LHV / Ton of asphalt pavement). Cold in-place recycling and landfill have no avoided burden for energy resources.

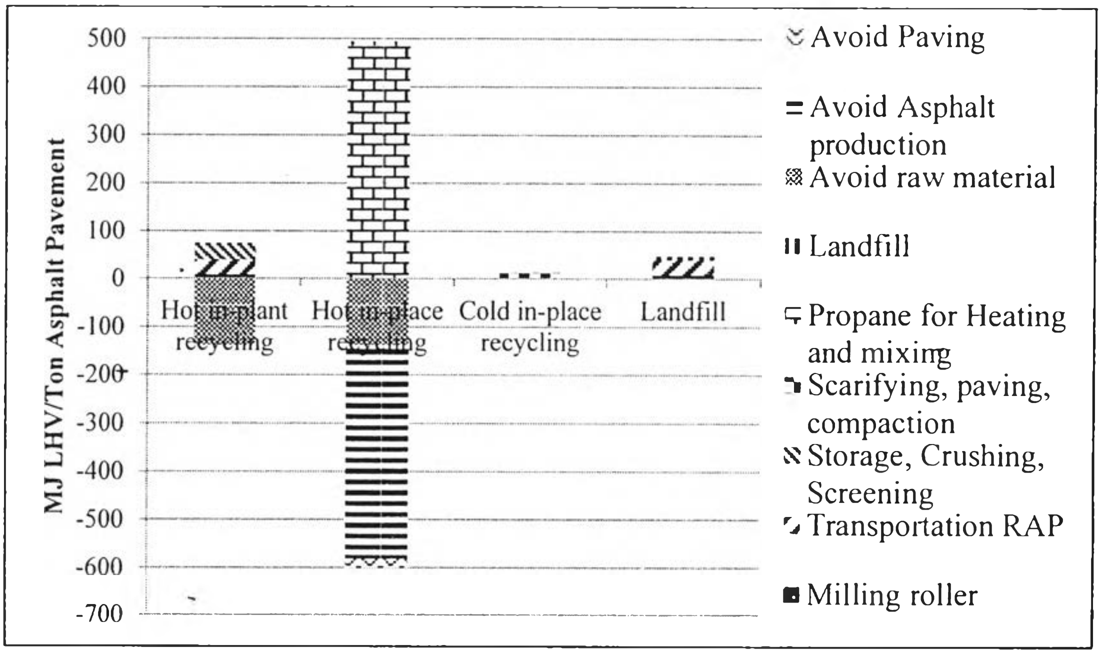

Figure 4.2 Energy resources usage only end-of-life sessions for each end-of-life process of hot-mixed asphalt by using Eco-Indicator 95 method.

It can be seen from Figure 4.3 that landfill has shown to be the highest energy resources usage which is equal to 47.66 MJ LHV/ Ton of asphalt pavement. The lowest energy resource usage is hot in-place recycling which is equal to – 105.62 MJ LHV / Ton of asphalt pavement. Because the most avoided burden of hot in-place recycling comes from avoided asphalt production. In contrast, landfill has no avoided burden. Moreover, it has burdens from milling roller, transportation RAP and landfill site.

For GHG emission impact, as seen in Figure 4.4, hot in-place recycling has the highest GHG emission burdens from propane for heating and mixing (34.44 kg CO_2 eq. / Ton of asphalt pavement) and avoided GHG emission burdens from avoided raw material (– 32.55 kg CO_2 eq. / Ton of asphalt pavement). But cold in-place recycling and landfill have no avoided burden GHG emission impact.

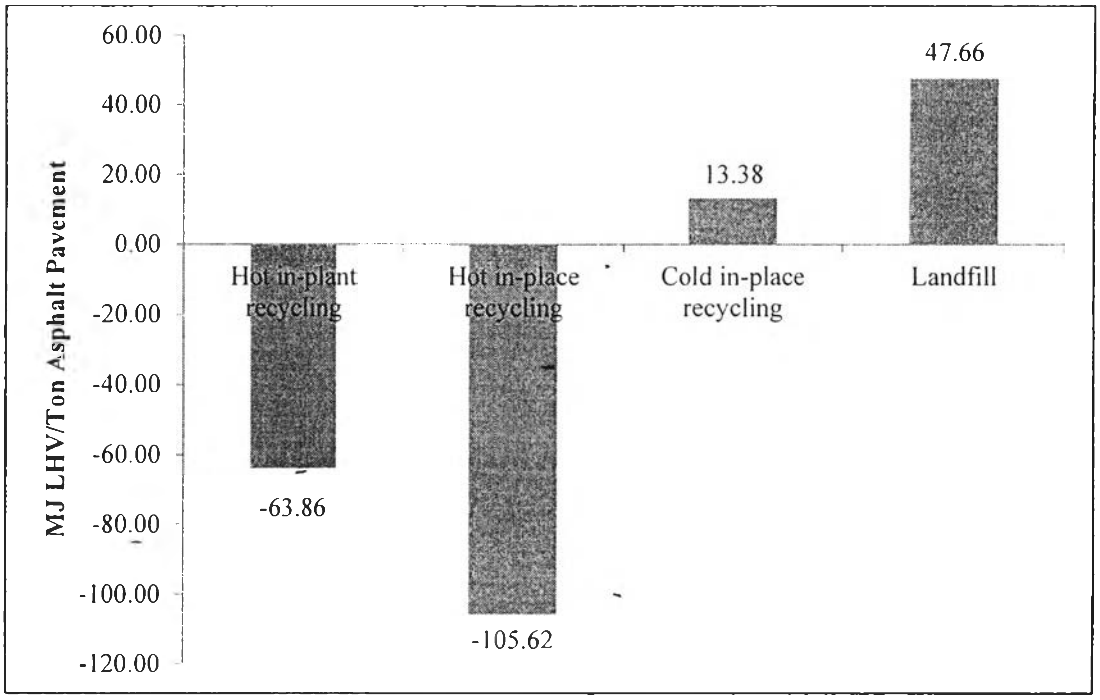

Figure 4.3 Net energy resources usage only end-of-life sessions for each end-of-life process of hot-mixed asphalt by using Eco-Indicator 95 method.

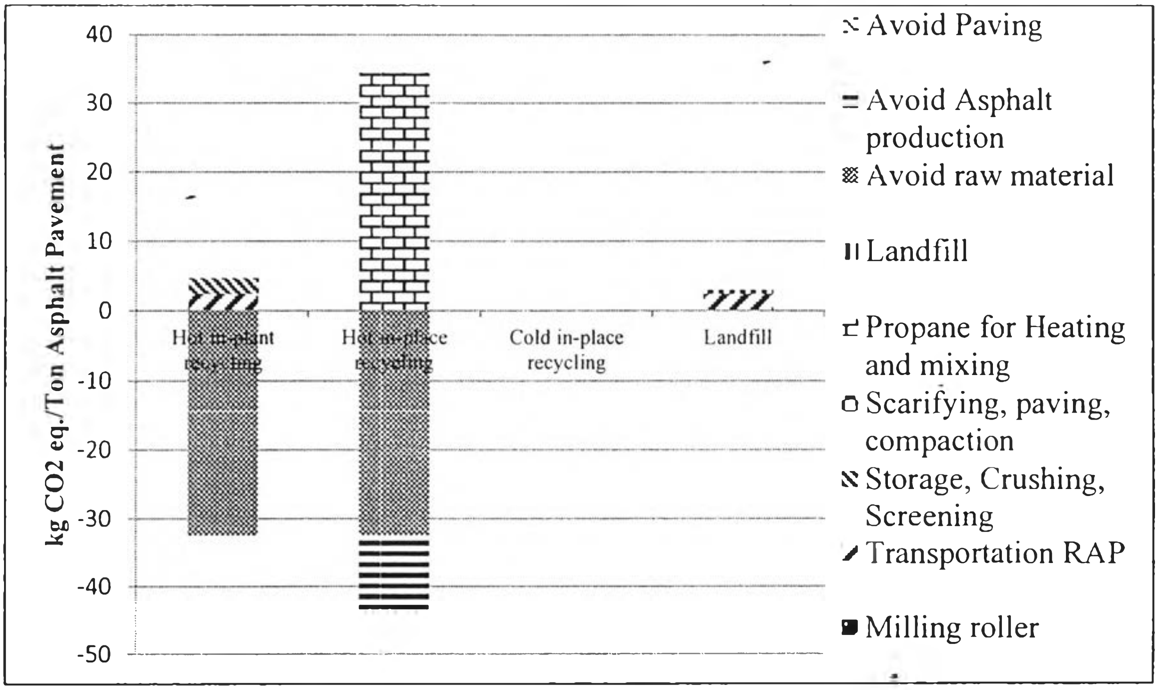

Figure 4.4 GWP only end-of-life sessions for each end-of-life process of hot-mixed asphalt by using CML 2 baseline 2000.

It can be seen from Figure 4.5 that landfill has shown to be the highest GHG emission which is equal to 2.99 kg CO_2 eq. / Ton of asphalt pavement. The lowest GHG emission is hot in-plant recycling which is equal to – 27.81 kg CO_2 eq. / Ton of asphalt pavement. Because the most avoided burden of hot in-place recycling comes from avoided raw material which is included feedstock GHG emission of bitumen (i.e., heavy fuel oil). By the way, GHG from asphalt production of hot in-plant recycling is 11.11 kg CO_2 eq. / Ton of asphalt pavement which lower than GHG emission from hot in-place recycling (34.44 kg CO_2 eq. / Ton of asphalt). In contrast, landfill has no avoided burden. Moreover, it has burdens from dismantling, transportation of RAP and landfill site.

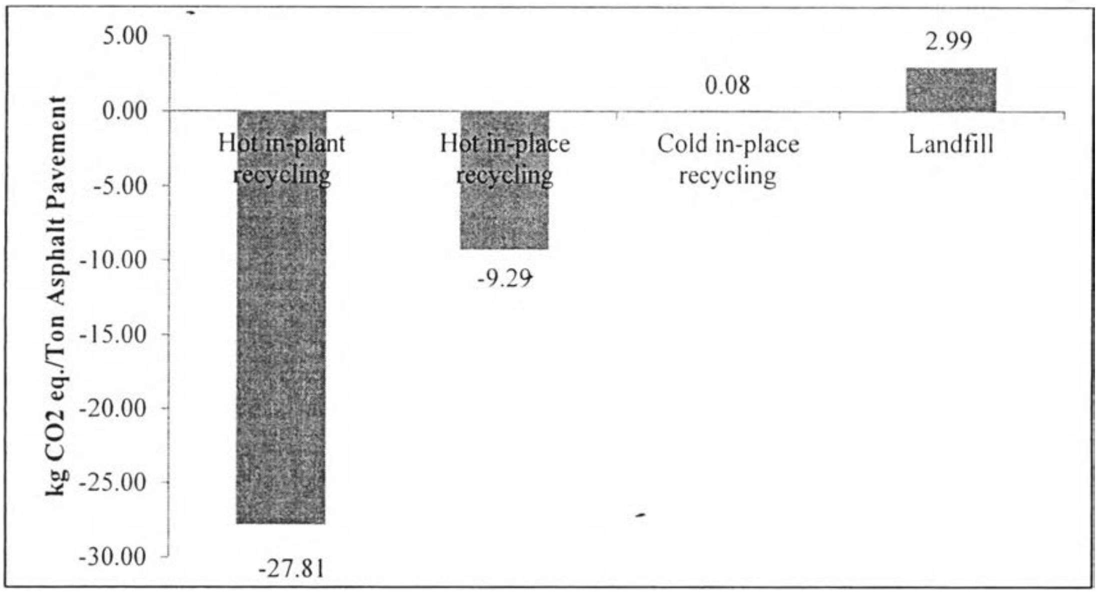

Figure 4.5 Net GWP only end-of-life sessions for each end-of-life process of hot-mixed asphalt by using CML 2 baseline 2000.

4.1.7.2 WMA

For energy resources usage, as seen in Figure 4.6, hot in-place recycling has the highest energy resource burdens from propane for heating and mixing (482.04 MJ LHV/ Ton of asphalt pavement) and avoided energy resource burdens from avoided asphalt production (– 420.12 MJ LHV / Ton of asphalt pavement). Cold in-place recycling and landfill have no avoided burden for energy resources.

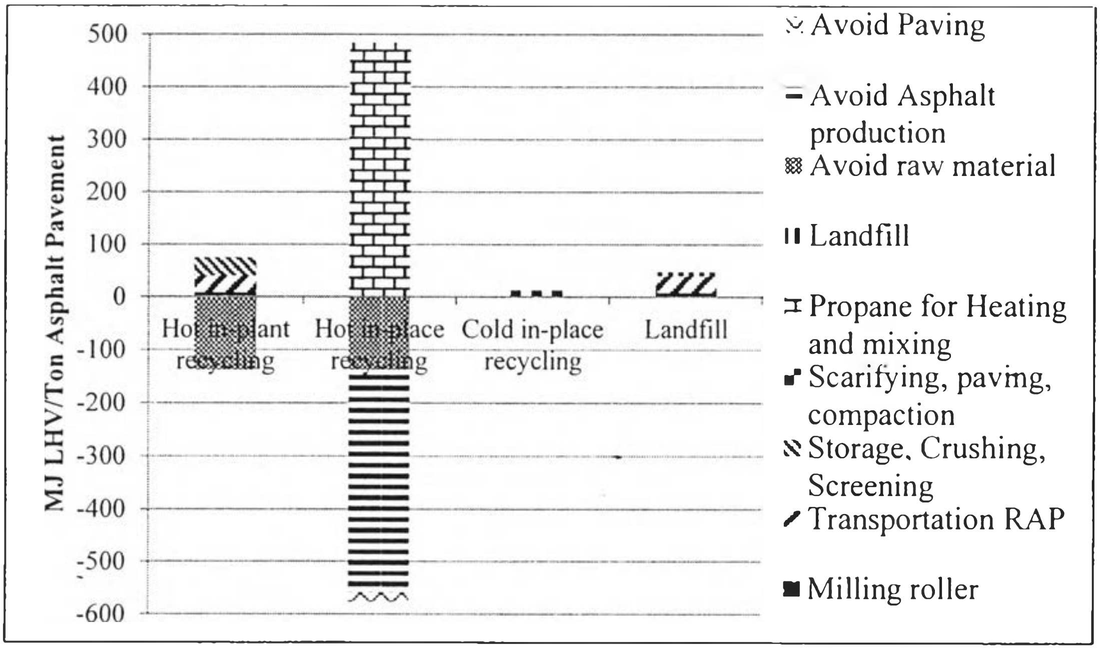

Figure 4.6 Energy resources usage only end-of-life sessions for each end-of-life process of warm-mixed asphalt by using Eco-Indicator 95 method.

It can be seen from figure 4.7 that landfill has shown to be the highest energy resources usage which is equal to 47.66 MJ LHV/ Ton of asphalt pavement. The lowest energy resource usage is hot in-place recycling which is equal to –92.36 MJ LHV / Ton of asphalt pavement. Because the most avoided burden of hot in-place recycling comes from avoided asphalt production. In contrast, landfill has no avoided burden. Moreover, it has burdens from milling roller, transportation RAP and landfill activities.

For GHG emission impact, as seen in Figure 4.8, hot in-place recycling has the highest GHG emission burdens from propane for heating and mixing (33.72 kg CO_2 eq. / Ton of asphalt pavement) and avoided GHG emission burdens from avoided raw material (– 31.77 kg CO_2 eq. / Ton of asphalt pavement). But cold in-place recycling and landfill have no avoided burden GHG emission impact.

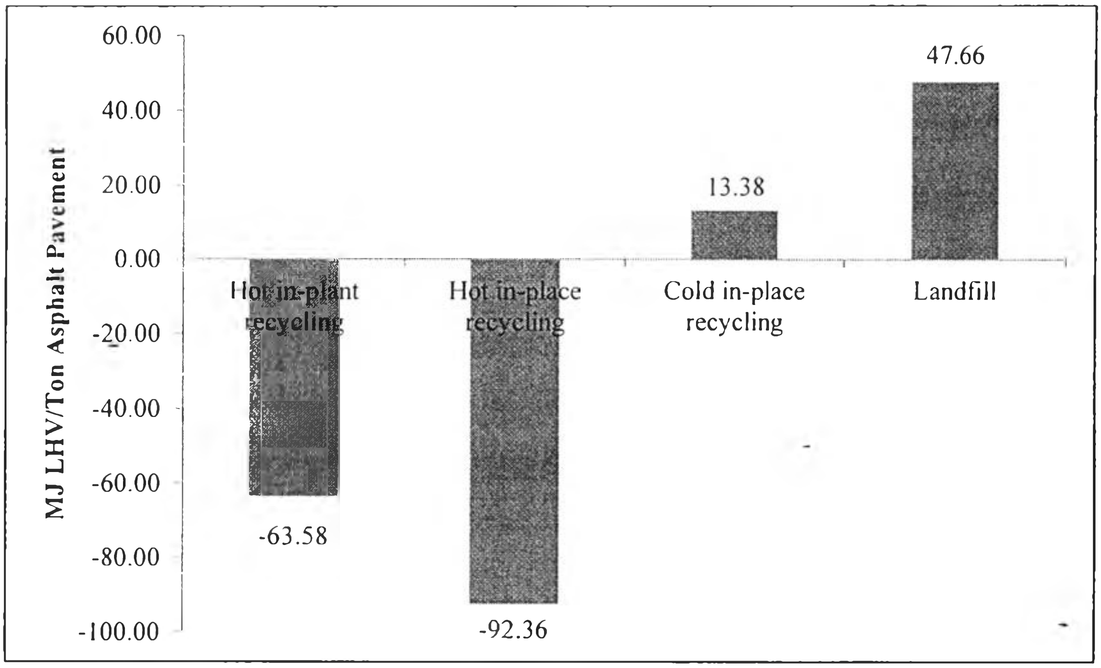

Figure 4.7 Net energy resources usage only end-of-life sessions for each end-of-life process of warm-mixed asphalt by using Eco-Indicator 95 method.

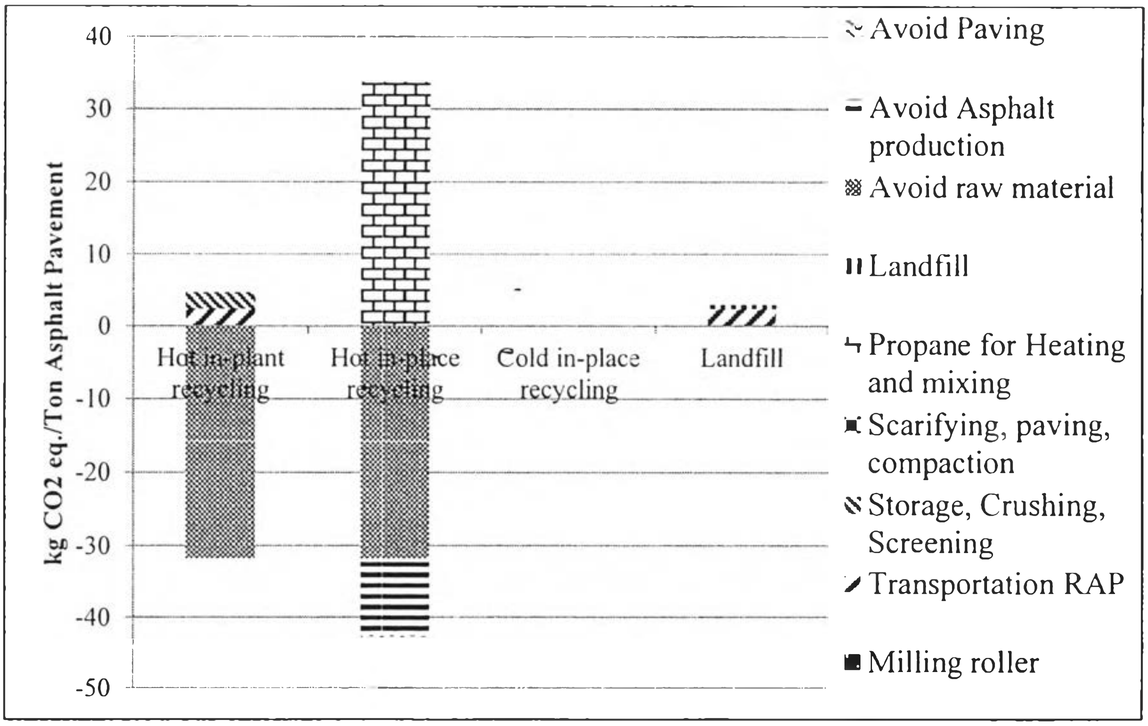

Figure 4.8 GWP only end-of-life sessions for each end-of-life process of warm-mixed asphalt by using CML 2 baseline 2000.

It can be seen from Figure 4.9 that landfill has shown to be the highest GHG emission which is equal to 2.99 kg CO_2 eq. / Ton of asphalt pavement. The lowest GHG emission is hot in-plant recycling which is equal to – 27.05 kg CO_2 eq. / Ton of asphalt pavement. Because the most avoided burden of hot in-place recycling comes from avoided raw material which is included feedstock GHG of bitumen (i.e., heavy fuel oil). By the way, GHG emission from asphalt production of hot in-plant recycling is 10.82 kg CO_2 eq. / Ton of asphalt pavement which lower than GHG emission from hot in-place recycling (33.72 kg CO_2 eq. / Ton of asphalt pavement). In contrast, landfill has no avoided burden. Moreover, it has burdens from milling roller, transportation RAP and landfill activities.

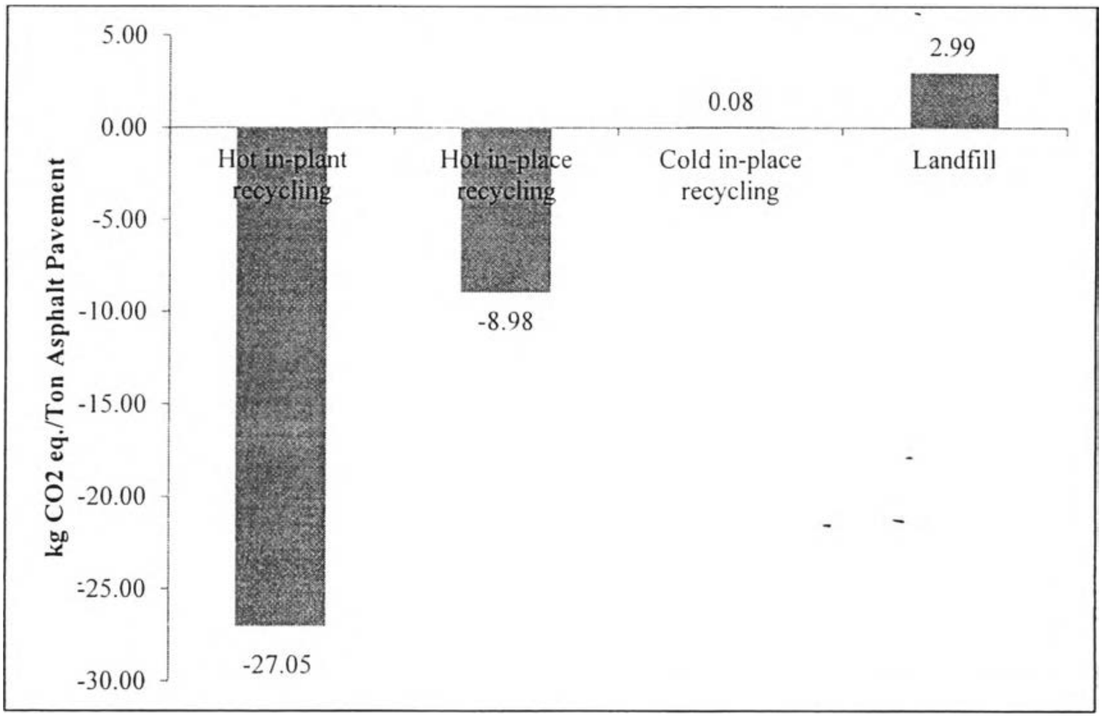

Figure 4.9 Net GWP only end-of-life sessions for each end-of-life process of warm-mixed asphalt by using CML 2 baseline 2000.

4.2 Whole life cycle assessment

4.2.1 Whole life cycle assessment of HMA

Figure 4.10 and 4.11 show whole life cycle energy resources usage for each end-of-life process and net whole life cycle of HMA respectively. Figure 4.11 can be seen that landfill has shown to be the highest energy resource usage which is equal to-731.55 MJ LHV/ Ton of asphalt pavement. The lowest energy resource is hot in-place recycling which is equal to 578.27 MJ LHV / Ton of asphalt as same as the result when focus only end-of-life sessions. Because inventory data for the other sessions of energy resources usage (raw material, production, transportation and pavement) that come from previous study are similar in every end-of-life process.

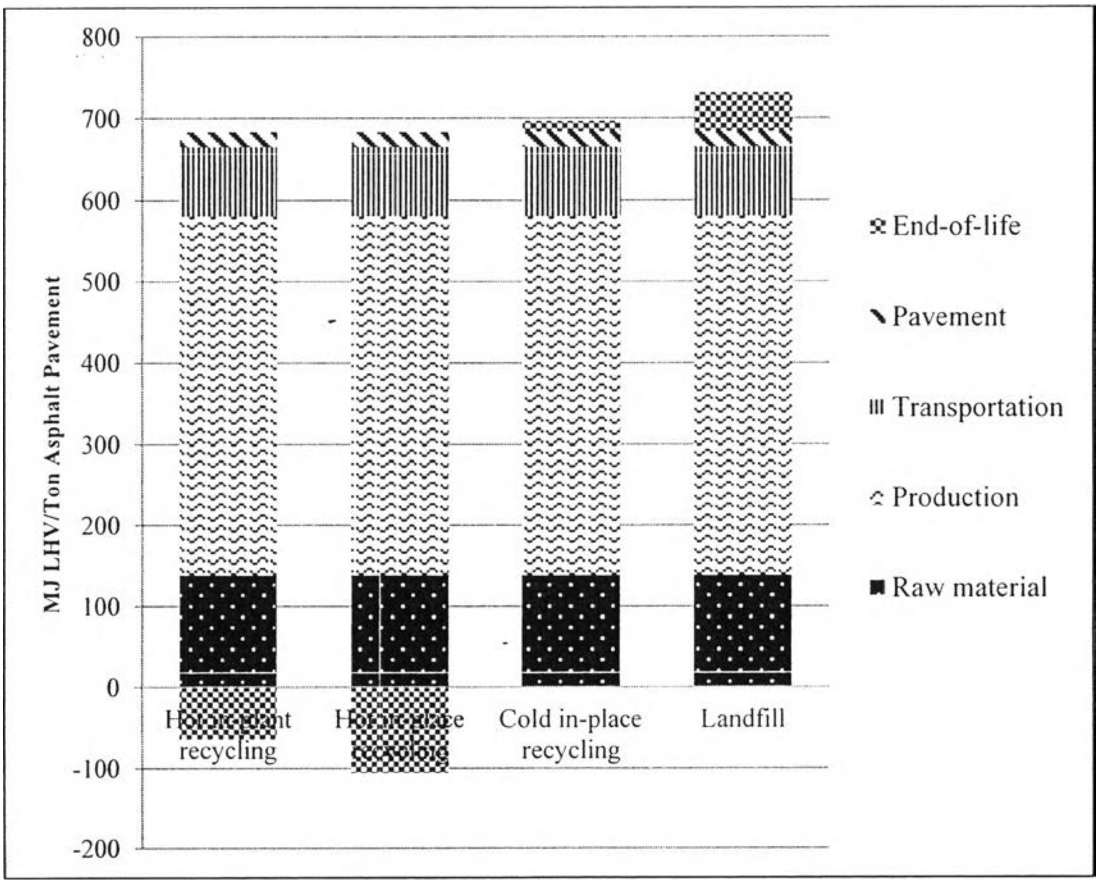

Figure 4.10 Whole life cycle energy resources usage for each end-of-life process of hot-mixed asphalt by using Eco-Indicator 95 method.

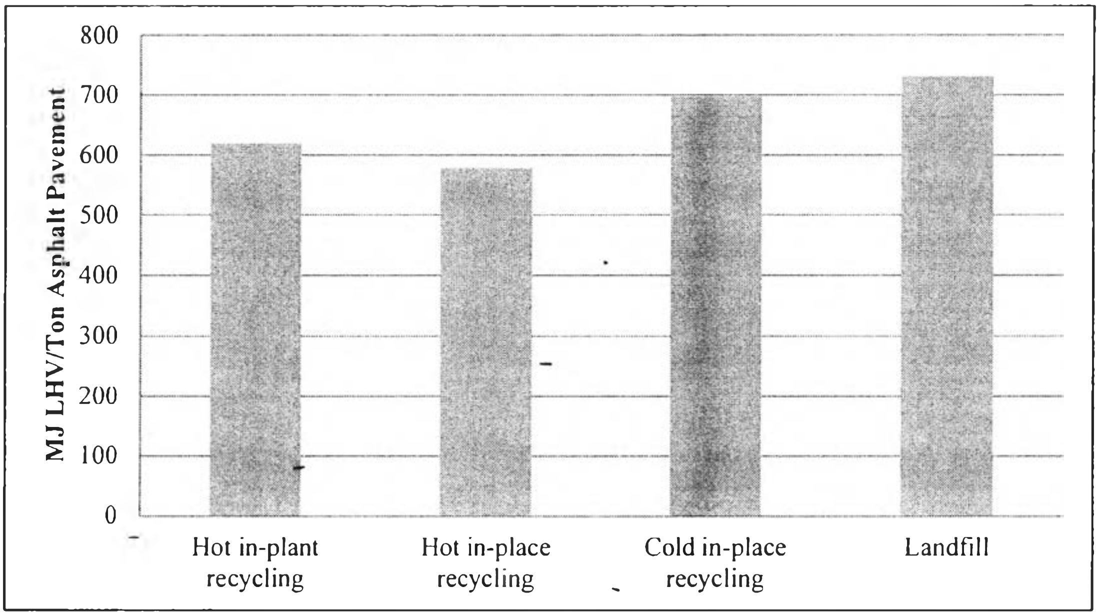

Figure 4.11 Net whole life cycle energy resources usage for each end-of-life process of hot-mixed asphalt by using Eco-Indicator 95 method.

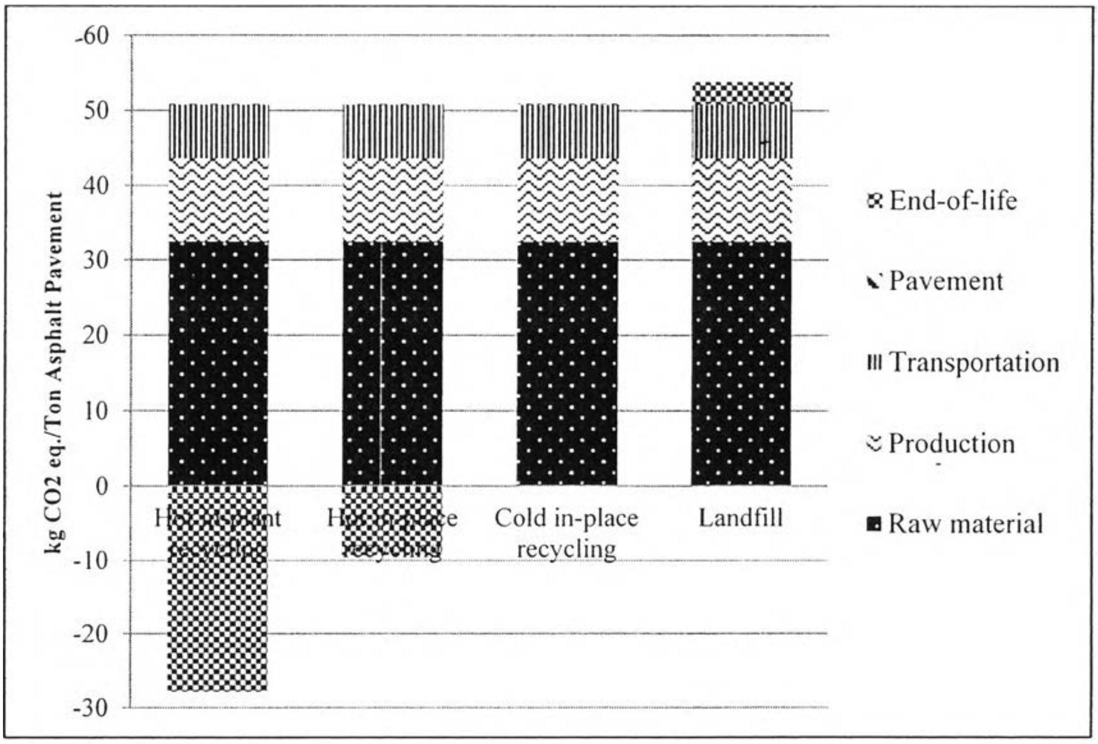

Figure 4.12 Whole life cycle GWP for each end-of-life process of hot-mixed asphalt by using CML 2 baseline 2000.

Figure 4.12 and 4.13 show whole life cycle GWP for each end-of-life process and net whole life cycle of HMA respectively. Figure 4.13 can be seen that landfill has shown to be the highest GHG emission which is equal to 53.88 kg CO_2 eq. / Ton of asphalt pavement. The lowest GHG emission is hot in-plant recycling which is equal to 23.09 kg CO_2 eq. / Ton of asphalt pavement as same as the result when focus only end-of-life sessions. Because inventory data for the other sessions of GHG emission (raw material, production, transportation and pavement) that come from previous study are similar in every end-of-life process.

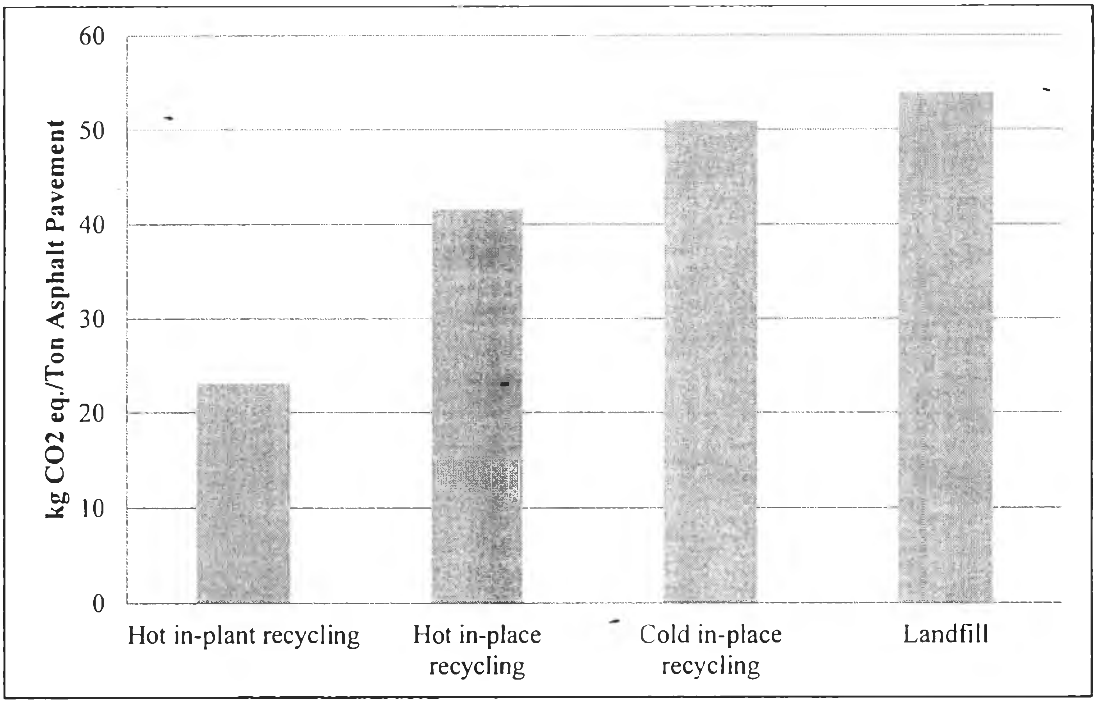

Figure 4.13 Net whole life cycle GWP for each end-of-life process of hot-mixed asphalt by using CML 2 baseline 2000.

4.2.2 Whole life cycle assessment of WMA

Figure 4.14 and 4.15 show whole life cycle energy resources usage for each end-of-life process and net whole life cycle of WMA respectively. Figure 4.15 can be seen that landfill has shown to be the highest energy resource usage which is equal to 709.22 MJ LHV/ Ton of asphalt pavement. The lowest energy resource is hot in-place recycling which is equal to 569.21 MJ LHV / Ton of asphalt pavement as same as the result when focus only end-of-life sessions. Because the inventory data for the other sessions of energy resources usage (raw material, production, transportation and pavement) that come from previous study (Leedilok. S., 2013) are similar in every end-of-life process.

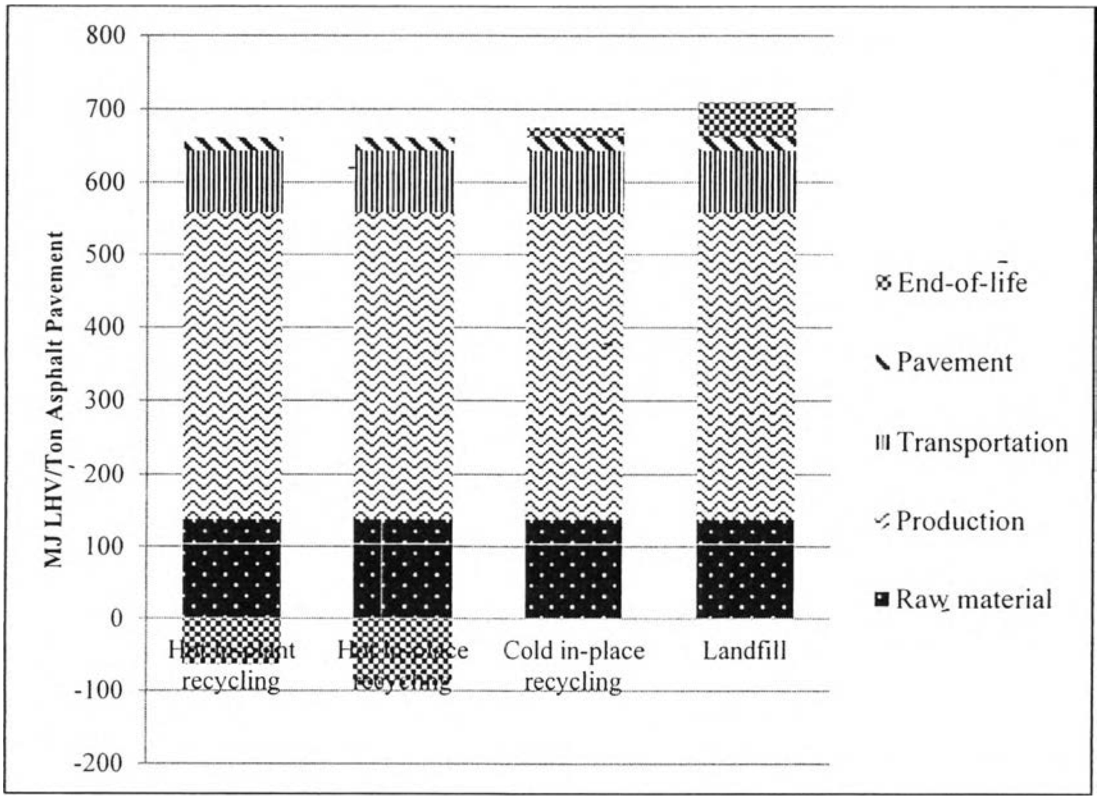

Figure 4.14 Whole life cycle energy resources usage for each end-of-life process of warm-mixed asphalt by using Eco-Indicator 95 method.

Figure 4.16 and 4.17 show whole life cycle GWP for each end-of-life process and net whole life cycle of WMA respectively. Figure 4.17 can be seen that landfill has shown to be the highest GHG emission which is equal to 52.84 kg CO_2 eq. / Ton of asphalt pavement. The lowest GHG emission is hot in-plant recycling which is equal to 22.80 kg CO_2 eq. / Ton of asphalt pavement as same as the result when focus only end-of-life sessions. Because the inventory data for the other sessions of GHG emission (raw material, production, transportation and pavement) that come from previous study (Leedilok, S., 2013) are similar in every end-of-life process.

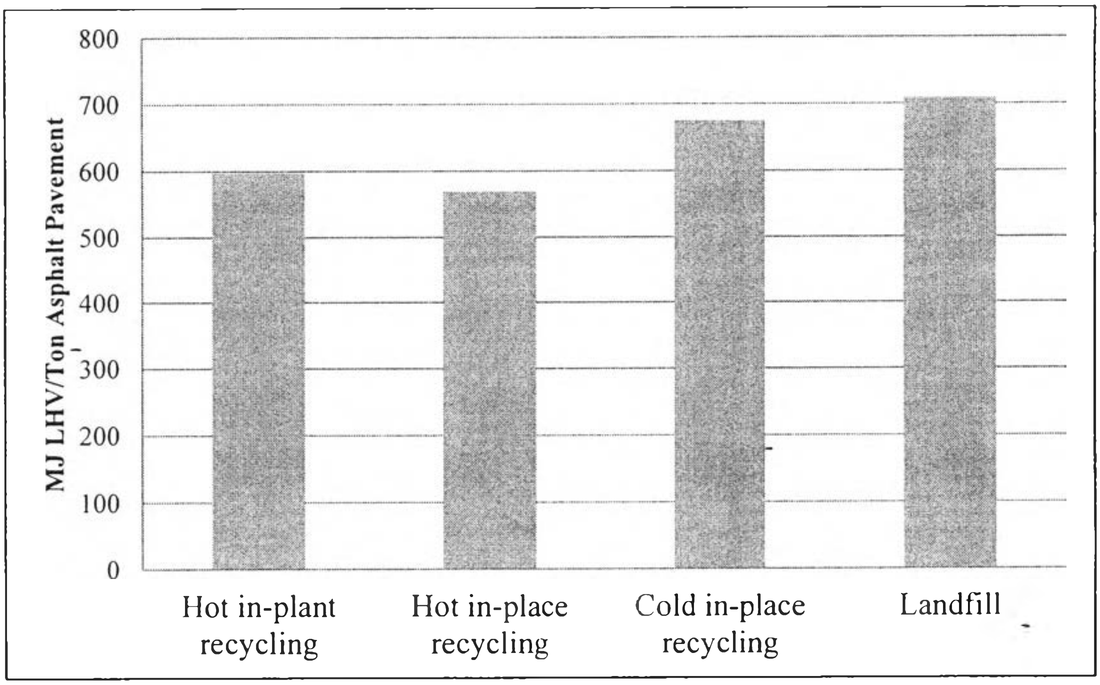

Figure 4.15 Net whole life cycle energy resources usage for each end-of-life process of warm-mixed asphalt by using Eco-Indicator 95 method.

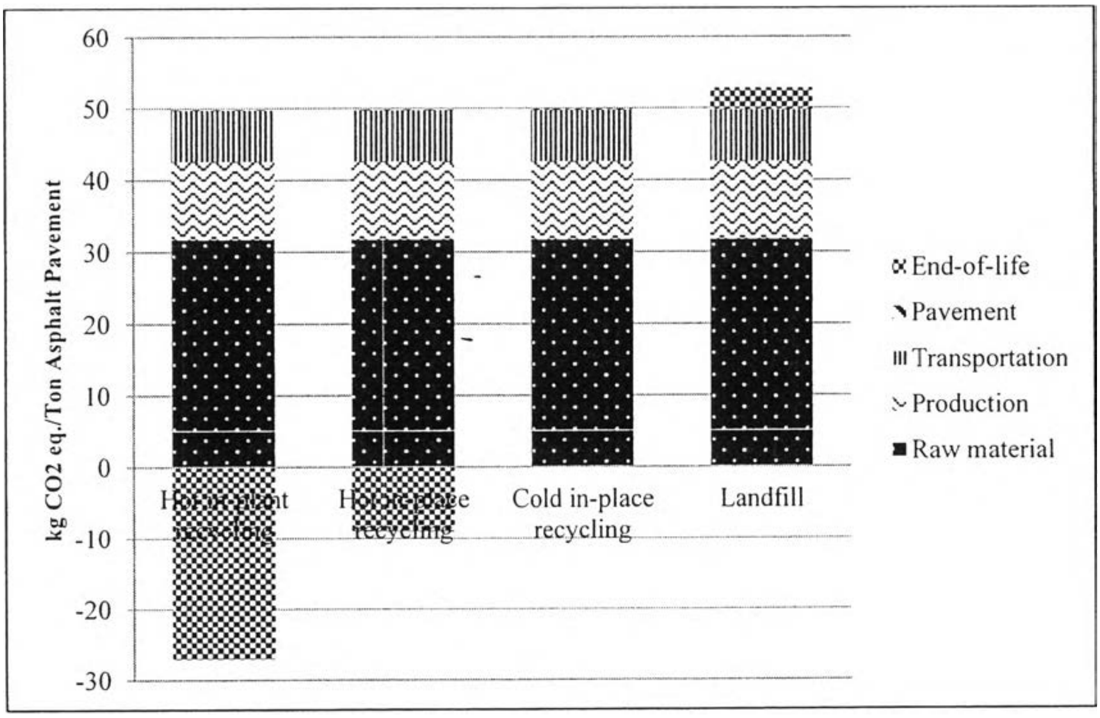

Figure 4.16 Whole life cycle GWP for each end-of-life process of warm-mixed asphalt by using CML 2 baseline 2000.

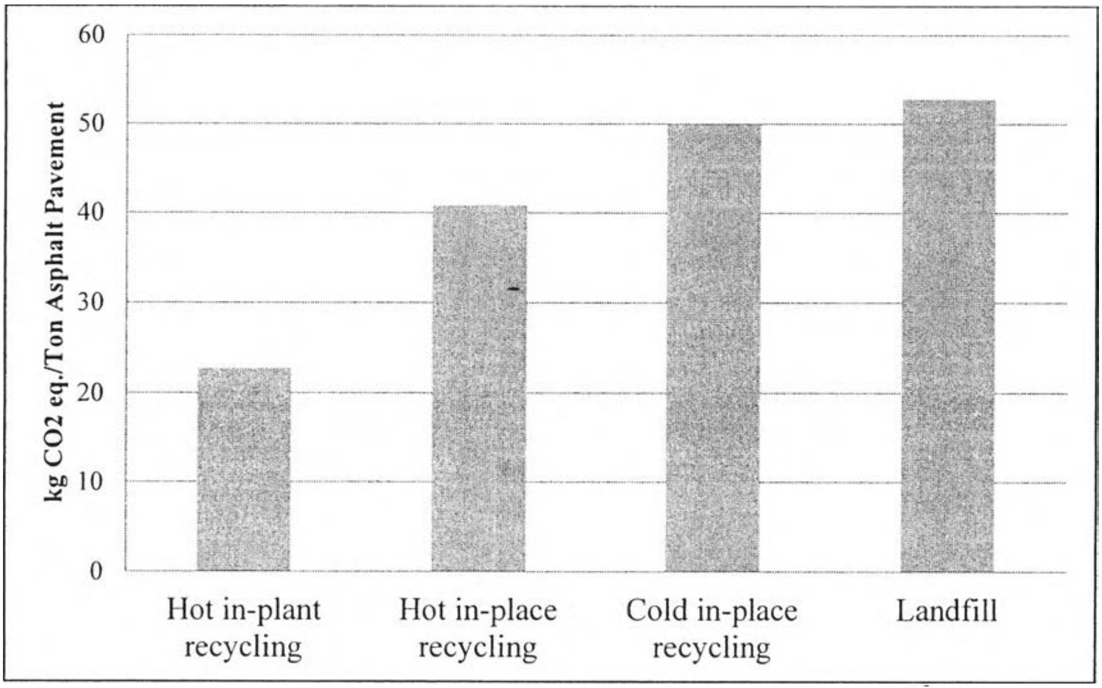

Figure 4.17 Net whole life cycle GWP for each end-of-life process of warm-mixed asphalt by using CML 2 baseline 2000.

4.3 Scenario analysis

Table 4.8 shows scenario analysis that was performed in order to find the best end-of-life process scenario which can mostly reduce energy consumption and GWP both of HMA and WMA by case 1 is business as usual case and case 2, 3 and 4 are the studied case.

Table 4.8 The scenarios for assessing end-of-life phase of asphalt production

Conditions/Scenarios	*1	2	3	4
Cold in-place recycling	90%	60%	50%	40%
Hot in-place recycling	1%	40%	25%	30%
Hot in-plant recycling	0%	0%	25%	30%
Landfill	9%	0%	0%	0%

* Business as usual case

4.3.1 Scenario analysis of HMA

Figure 4.18 and 4.19 show the energy resource usage in every stage for each scenario and net energy resources usage per ton of whole life cycle hot-mixed asphalt pavement respectively. It can be seen from Figure 4.19 that case 1 (BAU) is the highest energy impact among four cases of the studied scenarios which is equal to 699.17 MJ LHV/ Ton of asphalt pavement. While the lowest energy resource is case 4 (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) which is equal to 638.40 MJ LHV/ Ton of asphalt pavement. Because case 4 has the lowest ratio of cold in-place recycling but has the total ratio of hot in-place and hot in-plant recycling equal to 60% of which both hot in-place and hot in-plant recycling have the most avoided burdens that come from three avoided processes which are raw material, asphalt production and pavement.

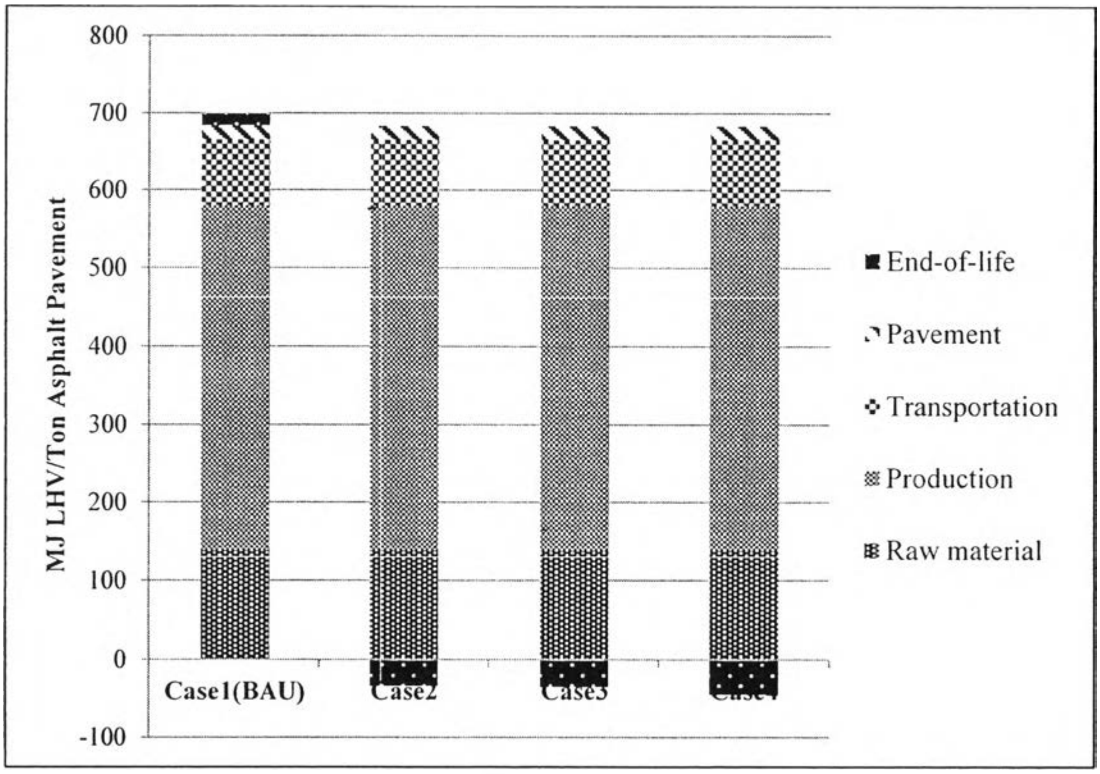

Figure 4.18 Energy resources usage in every stage of life cycle for each scenario of 1 ton of hot-mixed asphalt pavement by using Eco-Indicator 95 method.

Figure 4.20 shows the net energy resources usage compared between BAU case (case 1) and the best case of studied scenarios (case 4) per ton of whole life cycle of hot-mixed asphalt production. It can be seen from this figure that case 4 (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) shows the value of energy resources usage which has 8.69% reduction lower than BAU case (cold in-place recycling: landfill: hot in-place recycling = 90:9:1).

When comparisons of BAU case in a whole life cycle, the highest reduction of energy resources usage is case 4 followed by case 3 and case 2 (8.69%, 7.29% and 7.08% respectively).

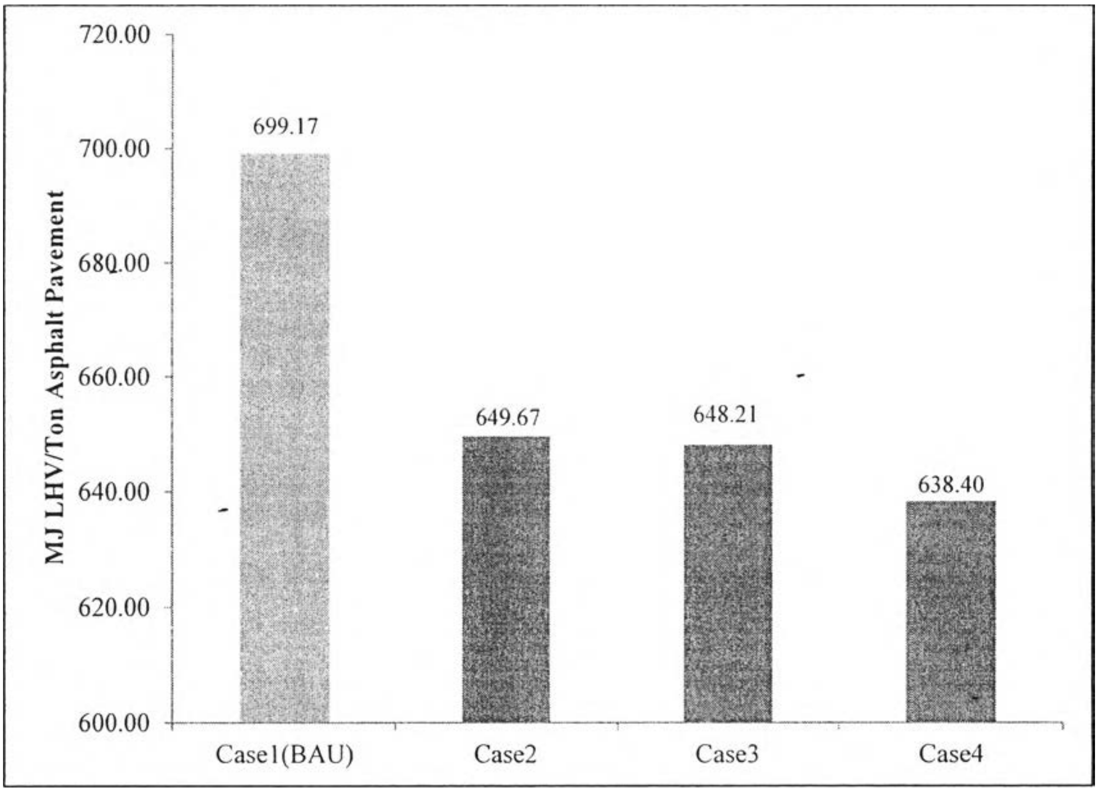

Figure 4.19 Net energy resources usage in every stage for each scenario of 1 ton of hot-mixed asphalt pavement by using Eco-Indicator 95 method.

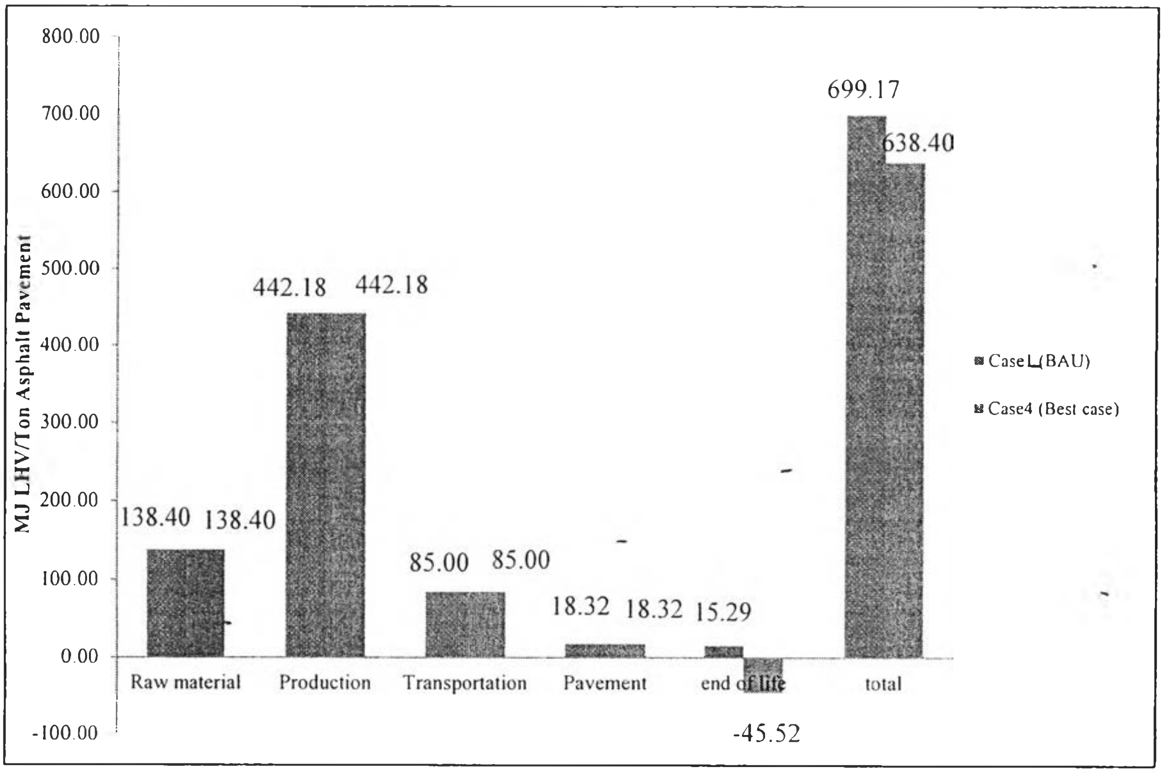

Figure 4.20 Net energy resources usage compare between case 1 (BAU) and the best case of studied scenarios (case 4) of 1 ton of hot-mixed asphalt pavement by using Eco-Indicator 95 method.

Figure 4.21 and 4.22 show the GWP in in every stage for each scenario and net GWP per ton of whole life cycle hot-mixed asphalt pavement respectively. It can be seen from Figure 4.22 that case 1 (BAU) is the highest GHG emission among four cases of studied scenarios which is equal to 51.14 kg CO_2 eq. / Ton of asphalt pavement. While the lowest GWP is case 4 (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) which is equal to 39.80 kg CO_2 eq. / Ton of asphalt pavement. Because case 4 has the lowest ratio of cold in-place recycling but the total ratio of hot in-place and hot in-plant recycling equal to 60% of which both hot in-place and hot in-plant recycling have the most avoided burdens that come from three avoided processes which are raw material, asphalt production and pavement.

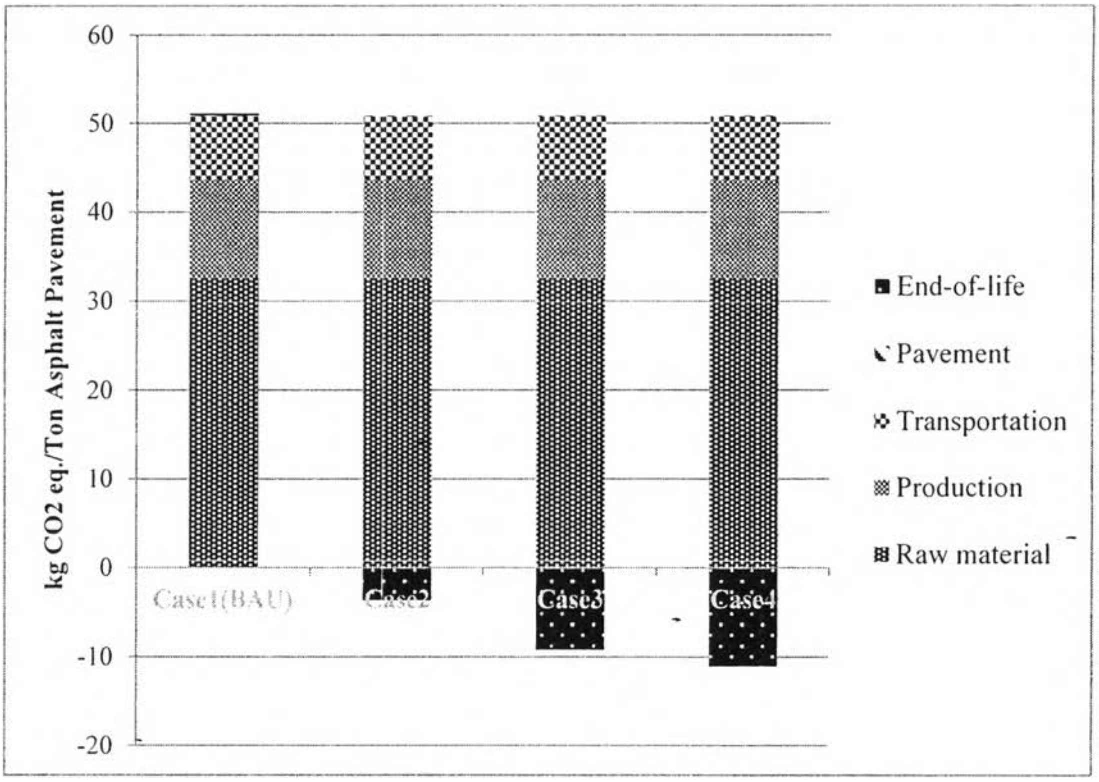

Figure 4.21 GWP in every stage of life cycle for each scenario of 1 ton of hot-mixed asphalt pavement by using CML 2 baseline 2000.

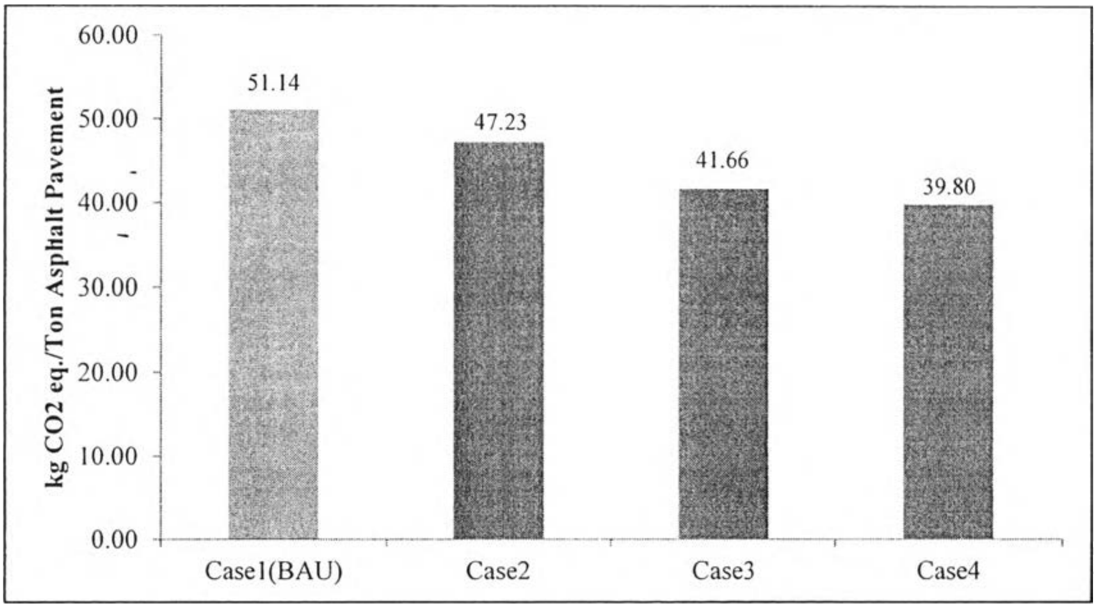

Figure 4.22 Net GWP in every stage for each scenario of 1 ton of hot-mixed asphalt pavement by using CML 2 baseline 2000.

Figure 4.23 shows the net GWP compared between BAU case (case 1) and the best case of studied scenarios (case 4) per ton of whole life cycle of hot-mixed asphalt pavement. It can be seen from this figure that case 4 (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) shows the value of GHG emission which has 22.17% reduction lower than BAU case (hot in-place recycling: landfill: cold in-place recycling = 1:9:90).

When comparisons of BAU case in a whole life cycle, the highest reduction of GHG emission is case 4 followed by case 3 and case 2 (22.17%, 18.54% and 7.65% respectively).

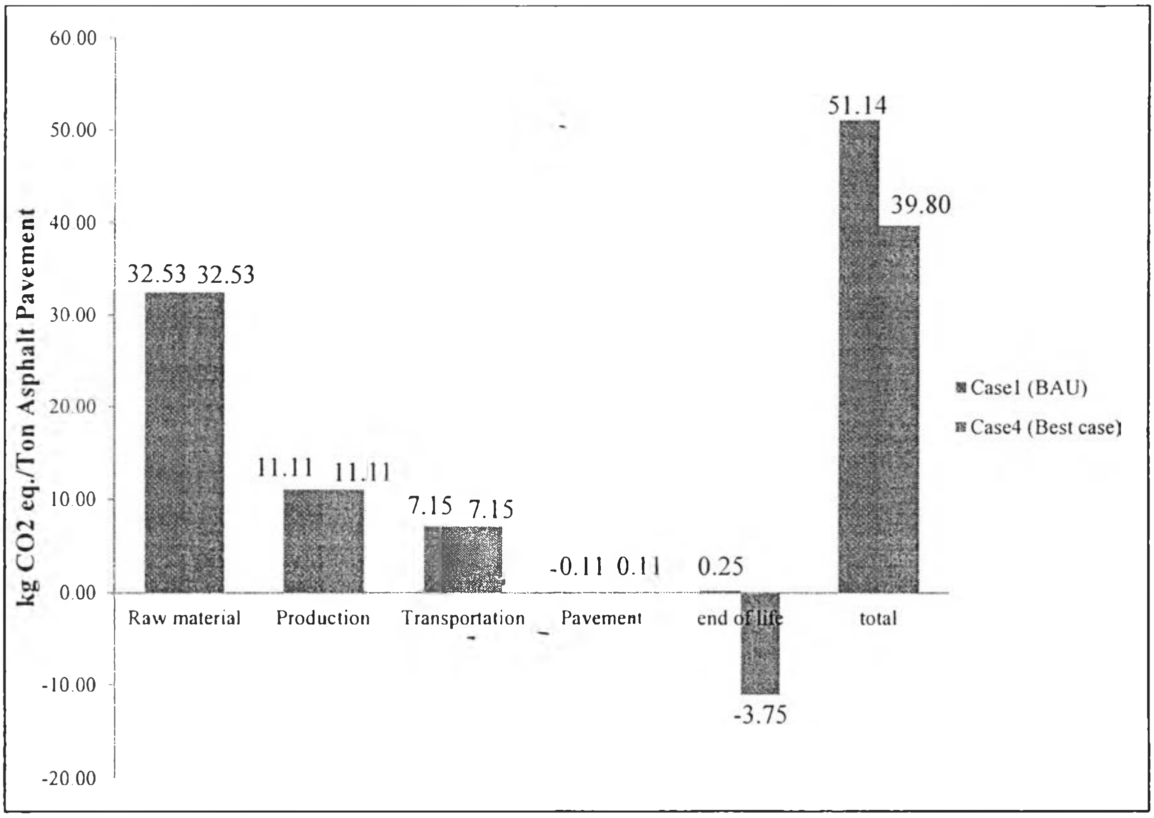

Figure 4.23 Net GWP compare between case 1 (BAU) and the best case of studied scenarios (case 4) of 1 ton of hot-mixed asphalt pavement by using CML 2 baseline 2000 method.

4.3.2 Scenario analysis of WMA

Figure 4.24 and 4.25 show the energy resource usage in every stage for each scenario and net energy resources usage per ton of whole life cycle warm-mixed asphalt pavement respectively. It can be seen from Figure 4.25 that case 1 (BAU) is the highest energy impact among four cases of the studied scenarios which is equal to 676.97 MJ LHV/ Ton of asphalt pavement. While the lowest energy resource is case 4 (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) which is equal to 620.13 MJ LHV/ Ton of asphalt pavement.

Because case 4 has the lowest ratio of cold in-place recycling but has the total ratio of hot in-place and hot in-plant recycling equal to 60% of which both hot in-place and hot in-plant recycling have the most avoided burdens that come from three avoided processes which are raw material, asphalt production and pavement.

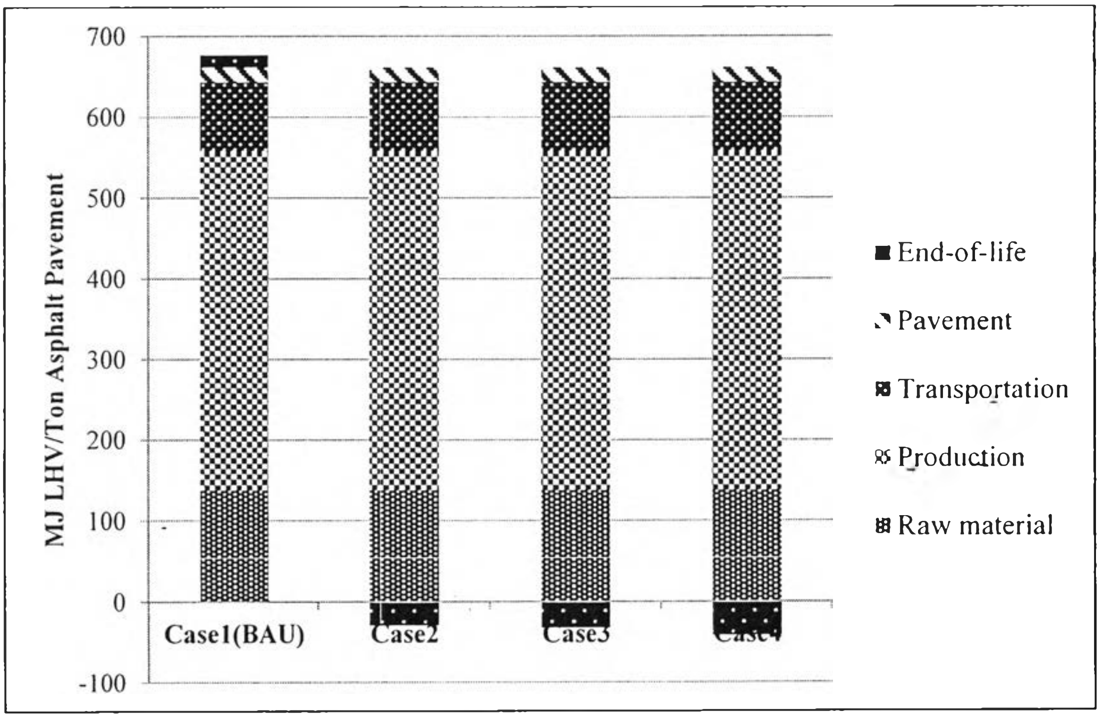

Figure 4.24 Energy resources usage in every stage of life cycle for each scenario of 1 ton of warm-mixed asphalt pavement by using Eco-Indicator 95 method.

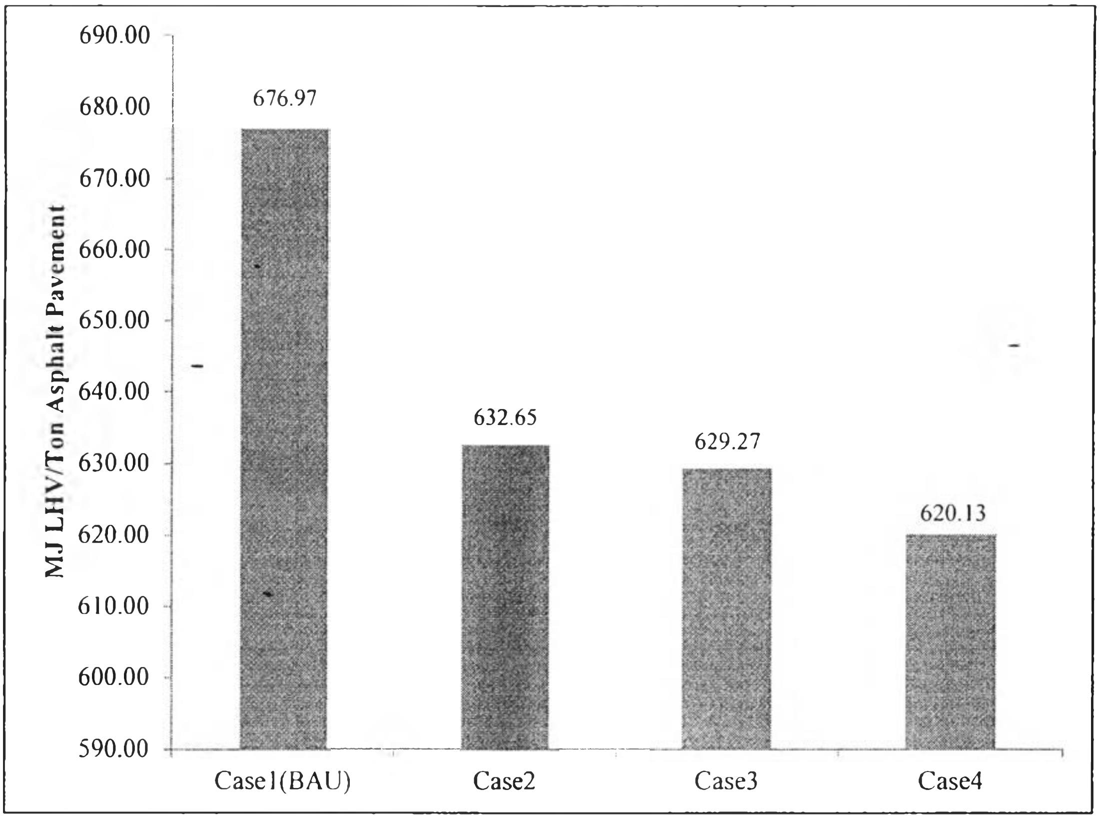

Figure 4.25 Net energy resources usage in every stage for each scenario of 1 ton of warm-mixed asphalt pavement by using Eco-Indicator 95 method.

Figure 4.26 shows the net energy resources usage compared between BAU case (case 1) and the best case of studied scenarios (case 4) per ton of whole life cycle of warm-mixed asphalt production. It can be seen from this figure that case 4 (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) shows the value of energy resources usage which has 8.40% reduction lower than BAU case (cold in-place recycling: landfill: hot in-place recycling = 90:9:1).

When comparisons of BAU case in a whole life cycle, the highest reduction of energy resources usage is case 4 followed by case 3 and case 2 (8.40%, 7.05% and 6.55% respectively).

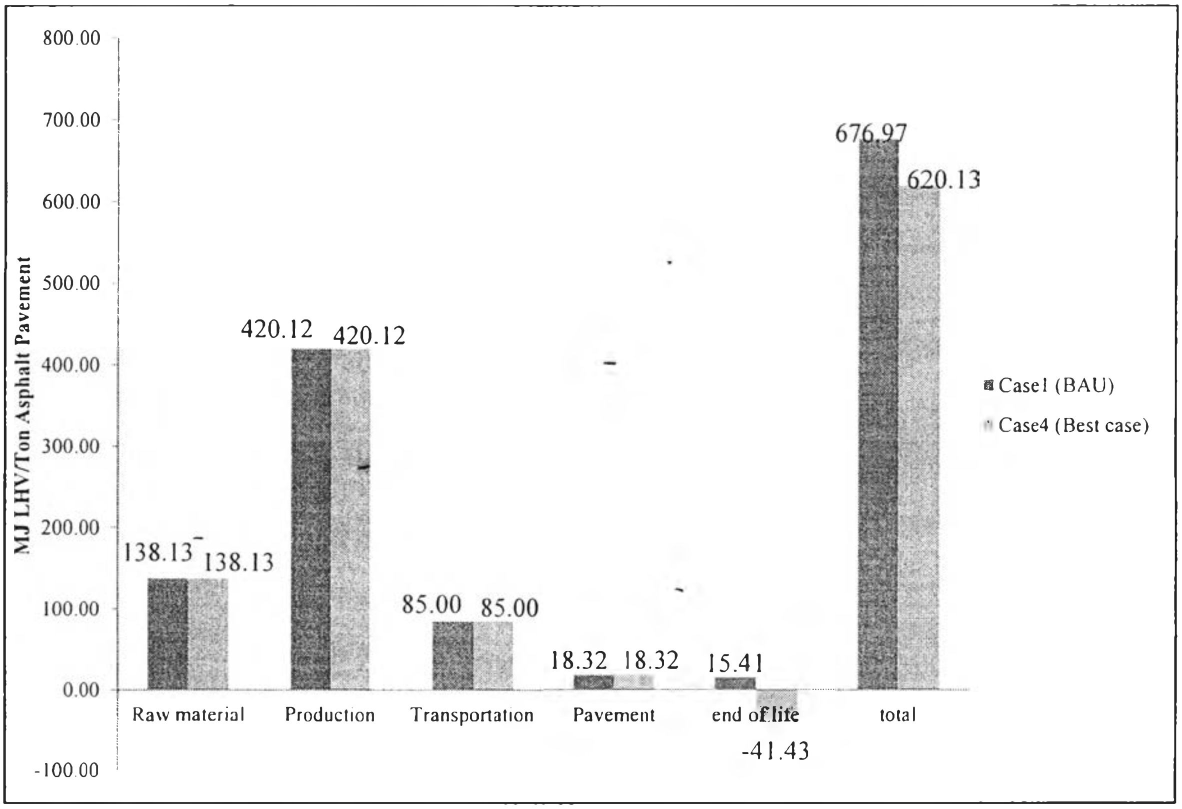

Figure 4.26 Net energy resources usage compare between case 1 (BAU) and the best case of studied scenarios (case 4) of 1 ton of warm-mixed asphalt pavement by using Eco-Indicator 95 method.

Figure 4.27 and 4.28 show the GWP in in every stage for each scenario and net GWP per ton of whole life cycle warm-mixed asphalt pavement respectively. It can be seen from Figure 4.22 that case 1 (BAU) is the highest GHG emission among four cases of studied scenarios which is equal to 50.10 kg CO_2 eq. / Ton of asphalt pavement. While the lowest GWP is case 4 (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) which is equal to 39.08 kg CO_2 eq. / Ton of asphalt pavement. Because case 4 has the lowest ratio of cold in-place recycling but the total ratio of hot in-place and hot in-plant recycling equal to 60% of which both hot in-place and hot in-plant recycling have the most avoided burdens that come from three avoided processes which are raw material, asphalt production and pavement.

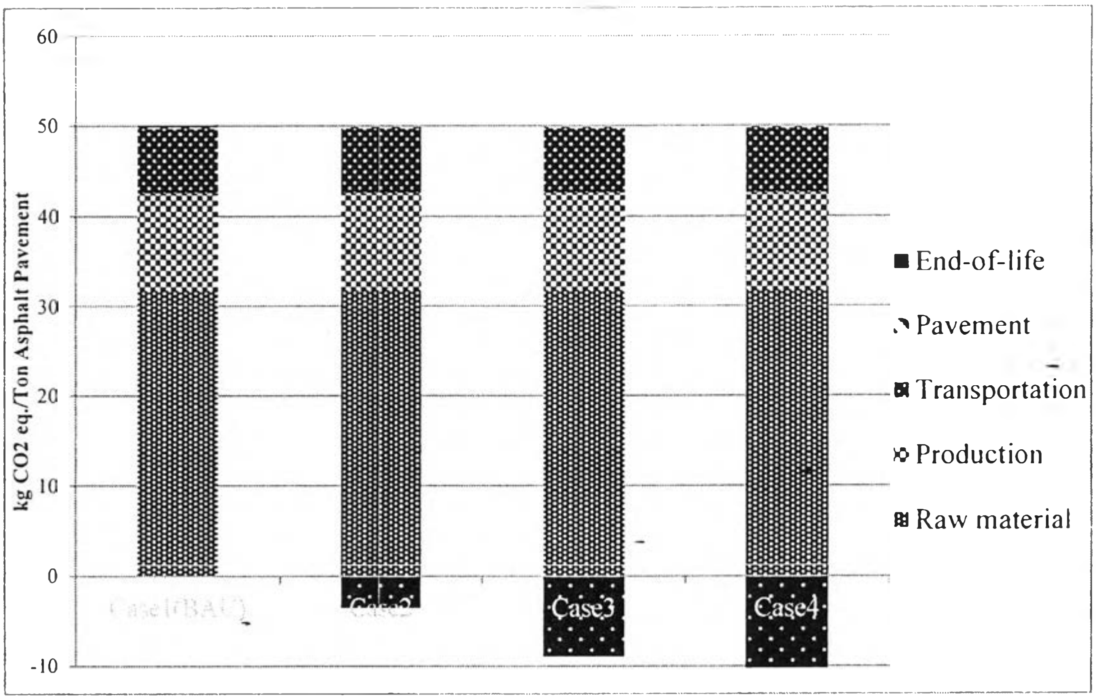

Figure 4.27 GWP in every stage of life cycle for each scenario of 1 ton of warm-mixed asphalt pavement by using CML 2 baseline 2000.

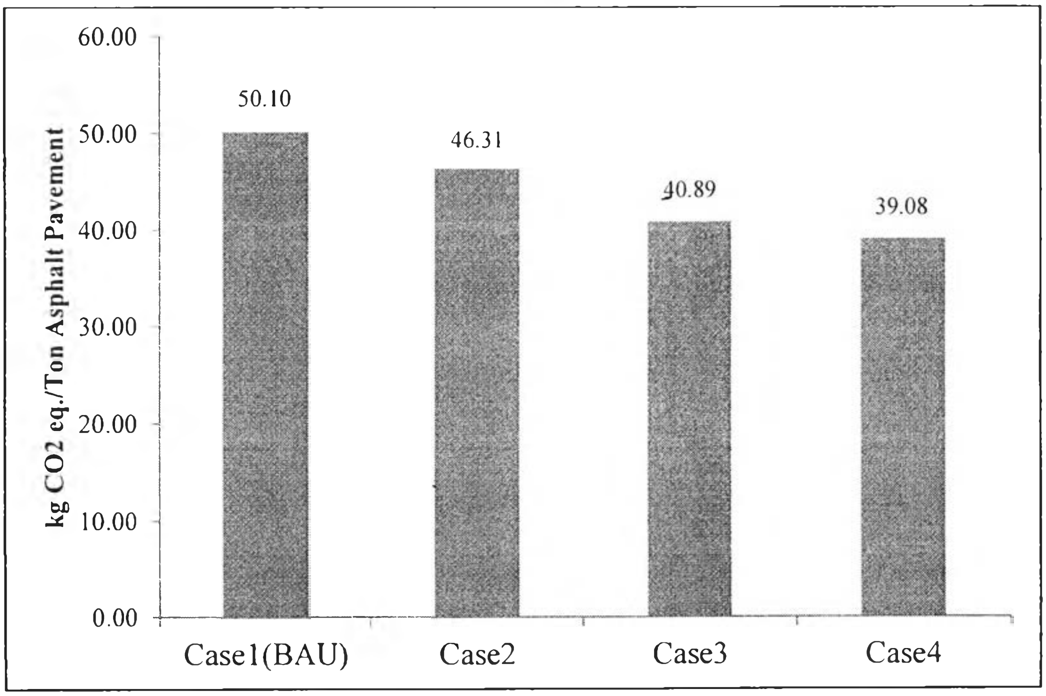

Figure 4.28 Net GWP in every stage for each scenario of 1 ton of warm-mixed asphalt pavement by using CML 2 baseline 2000.

Figure 4.29 shows the net GWP compared between BAU case (case 1) and the best case of studied scenarios (case 4) per ton of whole life cycle of hot-mixed asphalt pavement. It can be seen from this figure that case 4 (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) shows the value of GHG emission which has 22.00% reduction lower than BAU case (hot in-place recycling: landfill: cold in-place recycling = 1:9:90).

When comparisons of BAU case in a whole life cycle, the highest reduction of GHG emission is case 4 followed by case 3 and case 2 (22.00%, 18.38% and 7.56% respectively).

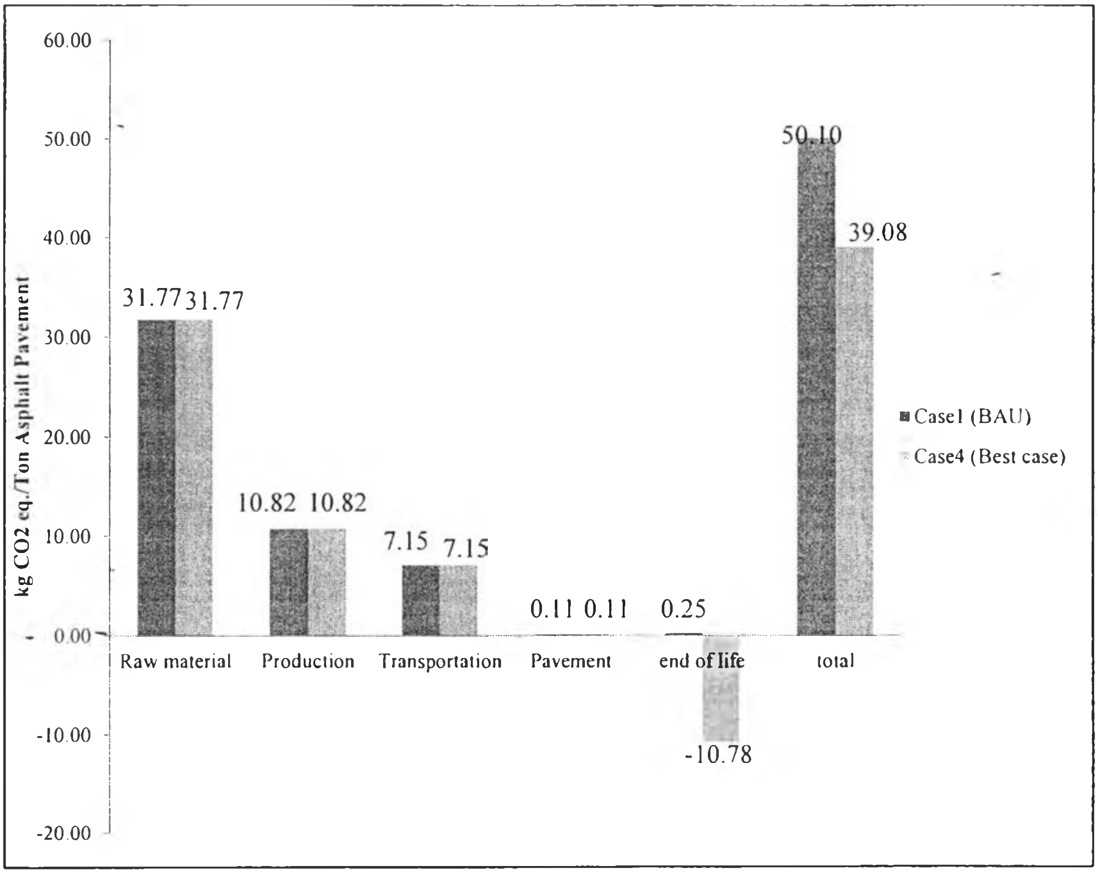

Figure 4.29 Net GWP compare between case 1 (BAU) and the best case of studied scenarios (case 4) of 1 ton of warm-mixed asphalt pavement by using CML 2 baseline 2000 method.

4.4 Comparison between HMA and WMA

It can be seen from Figure 4.30 that the avoided energy resource usage of hot in-place and hot in-plant recycling process of HMA is lower than WMA about 13.26 MJ LHV/ Ton of asphalt pavement and 0.28 MJ LHV/ Ton of asphalt pavement respectively. Because hot-mixed asphalt production consumes energy consumption and raw material more than warm-mixed asphalt production due to the high mixing temperature usage. Therefore, when asphalt production and raw material for HMA burdens are avoided, it will show the avoided burden more than WMA.

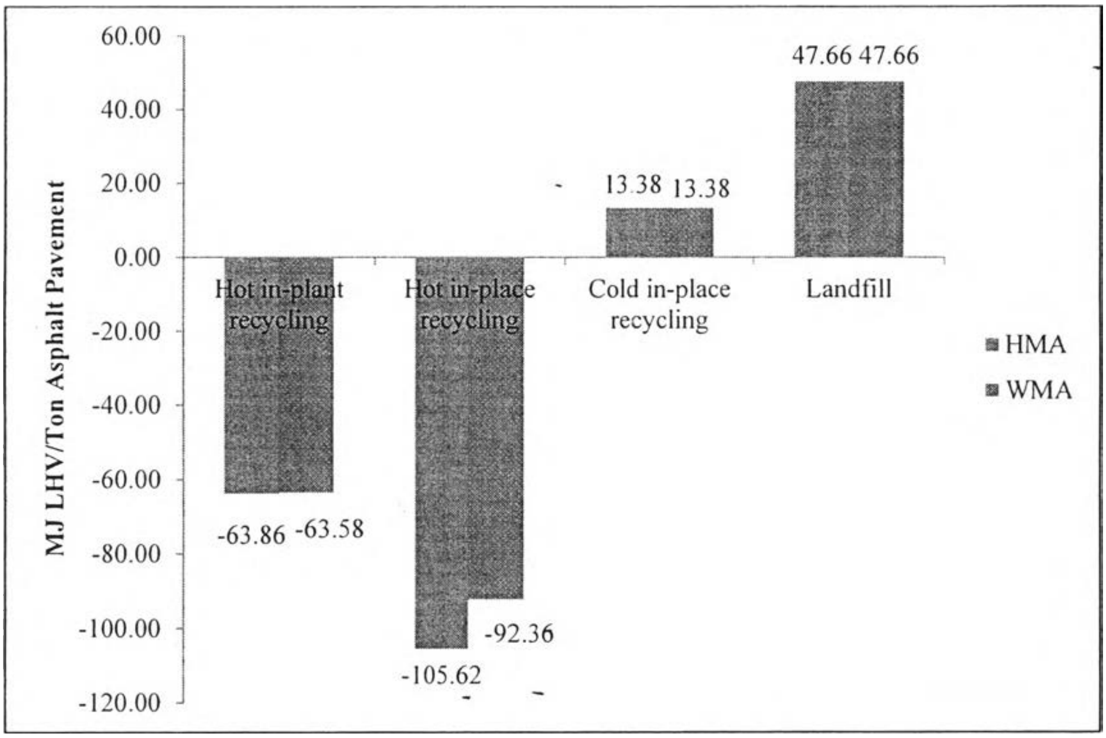

Figure 4.30 Comparison of net energy resource usage only end-of-life sessions for each end-of-life process between hot-mixed asphalt and warm-mixed asphalt by using Eco-Indicator 95 method.

It can be seen from Figure 4.31 that the avoided GWP of hot in-place and hot in-plant recycling process of HMA is lower than WMA about 0.31 kg CO_2 eq. / Ton of asphalt pavement and 0.76 kg CO_2 eq. / Ton of asphalt pavement respectively. Because hot-mixed asphalt production consumes energy consumption and raw material more than warm-mixed asphalt production due to the high mixing temperature usage. Therefore, when asphalt production and raw material for HMA burdens are avoided, it will show the avoided burden more than WMA.

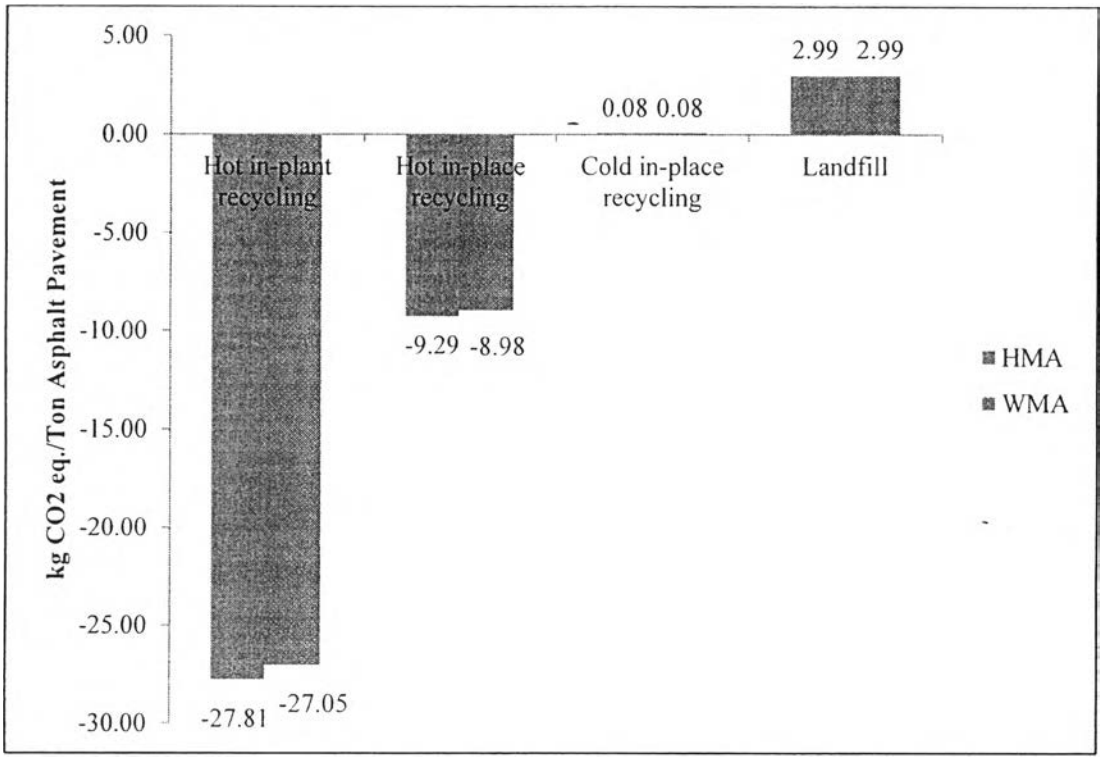

Figure 4.31 Comparison of net GWP only end-of-life sessions for each end-of-life process between hot-mixed asphalt and warm-mixed asphalt by using CML 2 baseline 2000.

Figure 4.32 and 4.33 show net energy resource usage and net GWP of whole life cycle of HMA and WMA in every end-of-life process, these two figures have shown the energy consumption usage and GHG emission of WMA 3-5% lower than HMA. Because hot-mixed asphalt production use temperature in terms of production, paving and recycling sessions higher than warm-mixed asphalt. However, HMA shows the benefit in term of end-of-life. Because the avoided burdens of end-of-life sessions of hot-mixed asphalt are avoided more than warm-mixed asphalt both energy consumption and GHG emission. Thus, the percent reduction is only 3-5%.

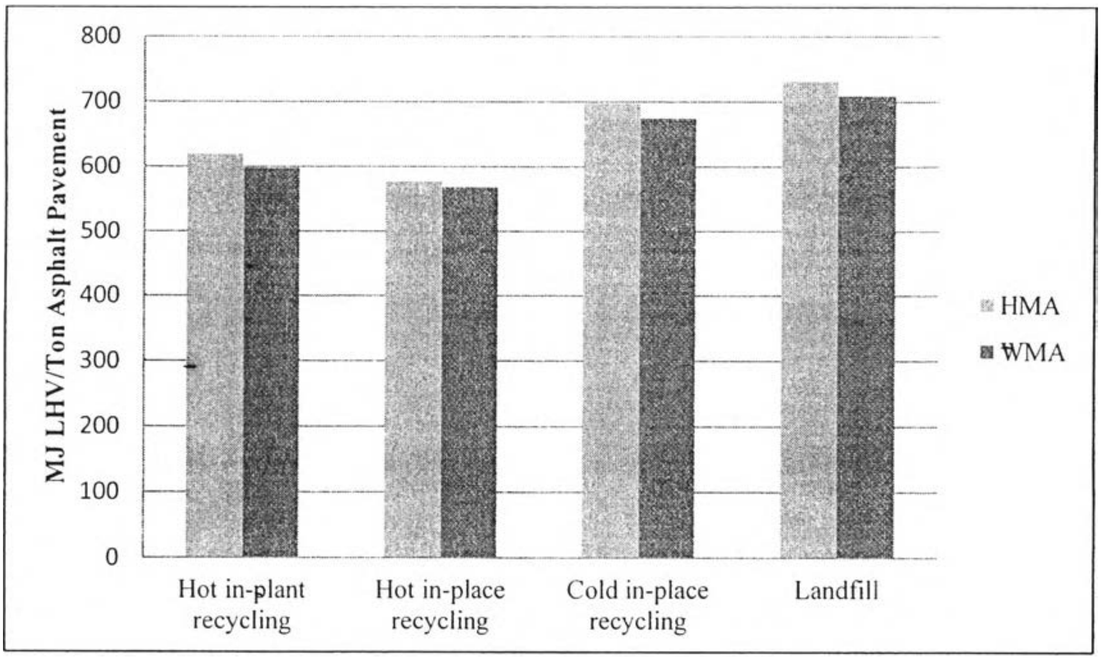

Figure 4.32 Comparison of whole life cycle energy resources usage for each end-of-life process between hot-mixed asphalt and warm-mixed asphalt by using Eco-Indicator 95 method.

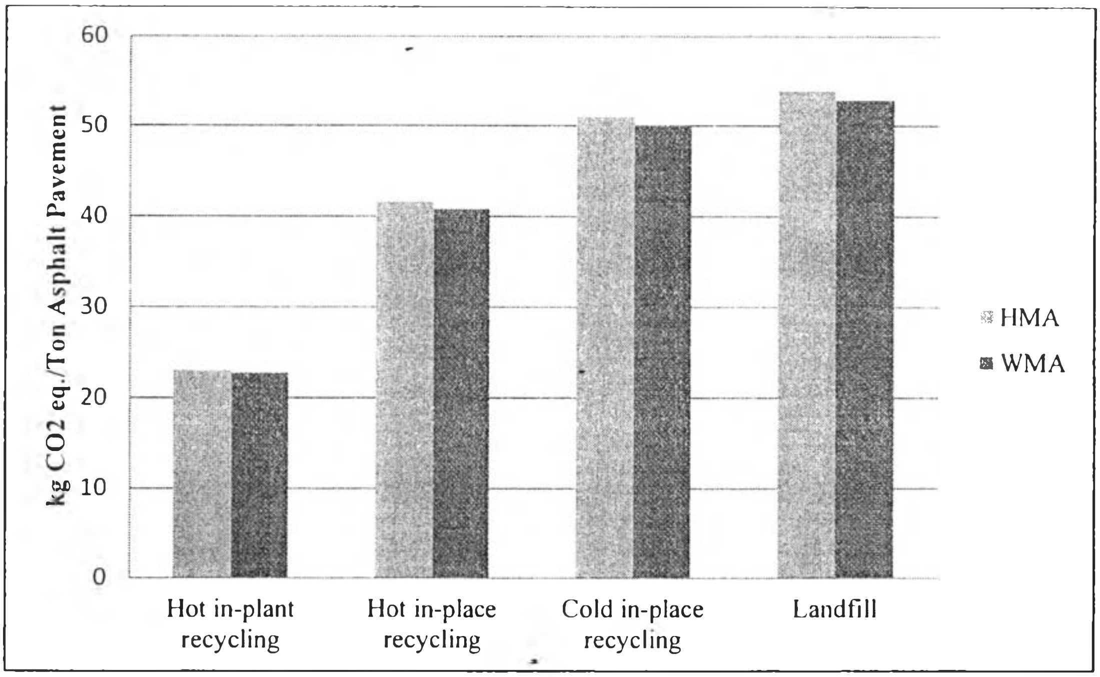

Figure 4.33 Comparison of whole life cycle GWP for each end-of-life process between hot-mixed asphalt and warm-mixed asphalt by using CML 2 baseline 2000.

Figure 4.34 and 4.35 show net energy resources usage and net GWP of studied scenario per ton of whole life cycle hot-mixed and warm-mixed asphalt pavement. These two figures have shown the energy consumption usage and GHG emission of WMA 3-5% lower than HMA. Because hot-mixed asphalt production use temperature in terms of production, paving and recycling sessions higher than warm-mixed asphalt. However, HMA shows the benefit in term of end-of-life. Because the avoided burdens of end-of-life sessions of hot-mixed asphalt are avoided more than warm-mixed asphalt both energy consumption and GHG emission. Thus, the percent reduction is only 3-5% as same as the result from Figure 4.32 and 4.33.

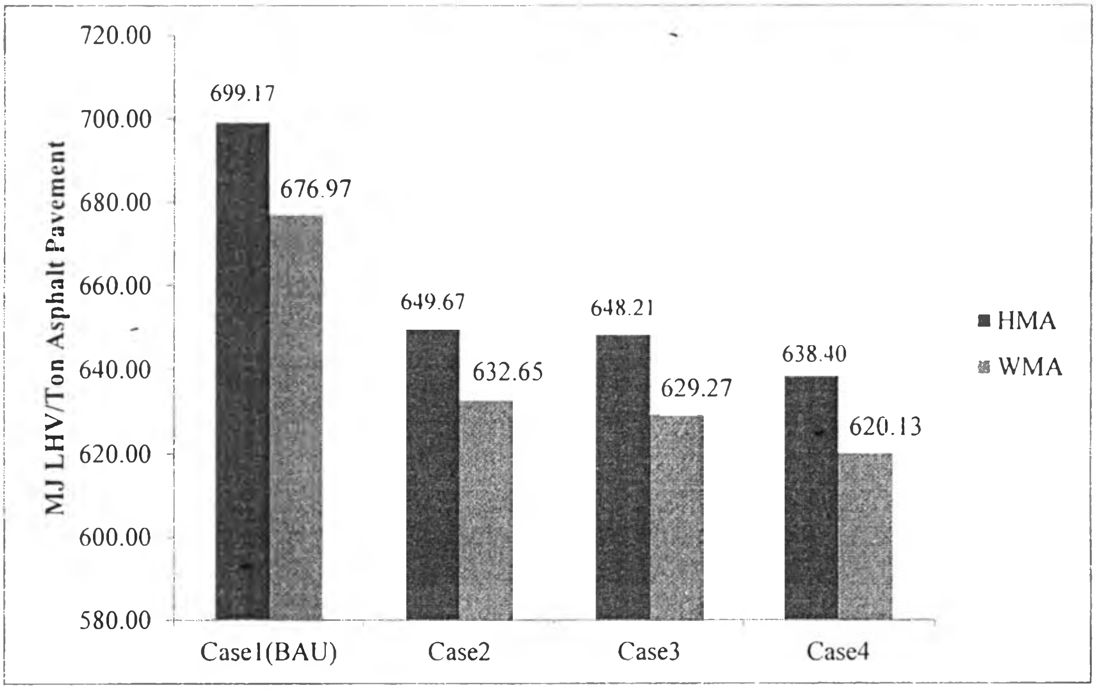

Figure 4.34 Comparison of net energy resources usage for each scenario of 1 ton of asphalt pavement between hot-mixed asphalt and warm-mixed asphalt by using Eco-Indicator 95 method.

If case 4 is uesd for calculation. According to Figure 4.34 and 4.35, energy consumption of hot-mixed asphalt and warm-mixed asphalt is 638.40 and 620.13 MJ LHV / Ton of asphalt pavement and GHG emission of hot-mixed asphalt and warm-mixed asphalt is 39.80 and 39.08 kg CO_2 eq./Ton asphalt pavement. One functional unit is 1 km length, 7 width and 5 cm thickness which equal to 849.8 ton hot-mixed asphalt and 848.05 ton warm-mixed asphalt. Thus. GHG emission and energy consumption usage of warm-mixed asphalt when compare with hot-mixd asphalt is decreased to 680.25 kg per functional unit and 16,611.07 MJ LHV per functional unit respectively.

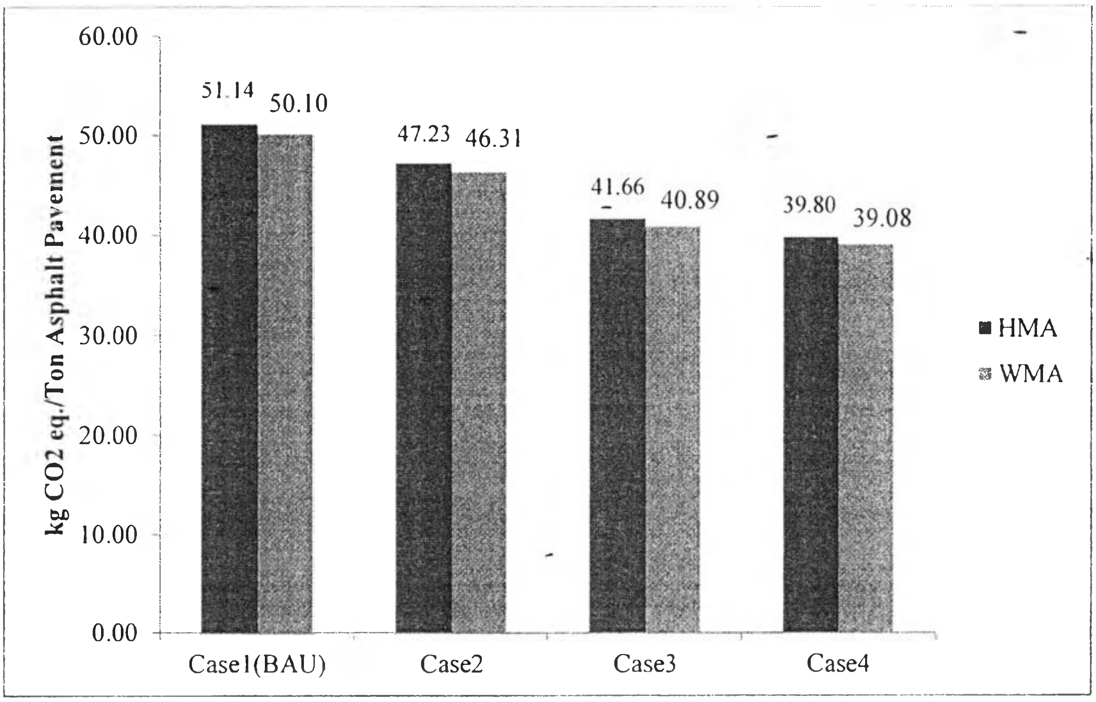

Figure 4.35 Comparison of net GWP for each scenario of 1 ton of asphalt pavement between hot-mixed asphalt and warm-mixed asphalt by using CML 2 baseline 2000.

Figure 4.36 shows whole life cycle energy resource usage compare between BAU case of HMA and the best case of studied scenarios of WMA per ton of asphalt pavement. It can be seen from this figure that the best case of WMA (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) shows 11.30% reduction of energy resources usage lower than BAU case of HMA (cold in-place recycling: landfill: hot in-place recycling = 90:9:1).

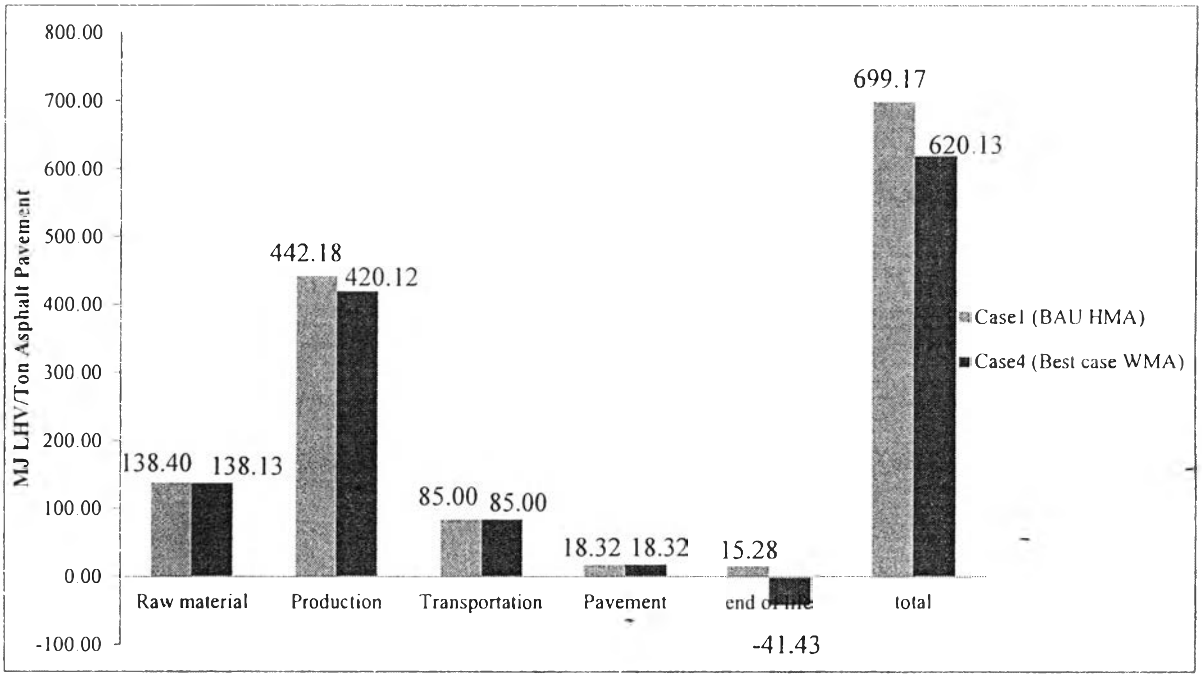

Figure 4.36 Comparison of net energy resources usage between case 1 (BAU) of hot-mixed asphalt and the best case of studied scenarios (case 4) of warm-mixed asphalt by using Eco-Indicator 95 method.

Figure 4.37 shows whole life cycle GWP compare between BAU case of HMA and the best case of studied scenarios of WMA per ton of asphalt pavement. It can be seen from this figure that the best case of WMA (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30) shows 23.58% reduction of energy resources usage lower than BAU case of HMA (cold in-place recycling: landfill: hot in-place recycling = 90:9:1).

Therefore, if the technology of asphalt production is changed from business as usual of hot-mixed asphalt (cold in-place recycling: landfill: hot in-place recycling = 90:9:1) to the best case of warm-mixed asphalt (cold in-place recycling: hot in-place recycling: hot in-plant recycling = 40:30:30). The benefit of 11% reduction for energy consumption usage and 23% for GHG emissions are gotten.

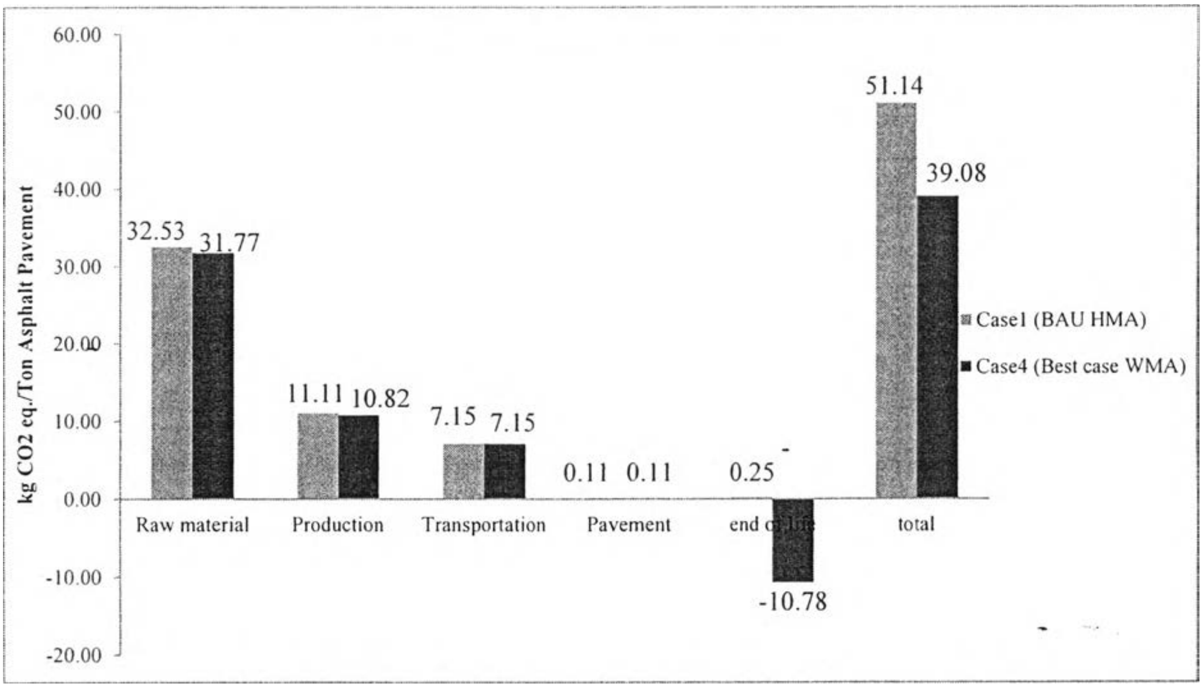

Figure 4.37 Comparison of net GWP between case 1 (BAU) of hot-mixed asphalt and the best case of studied scenarios (case 4) of 1 ton of warm-mixed asphalt by using CML 2 baseline 2000 method.