

# Life cycle assessment of single use thermoform boxes made from polystyrene (PS), polylactic acid, (PLA), and PLA/starch: cradle to consumer gate

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## Abstract

**Purpose** Currently, the bio-based plastics have been drawing considerable attention from the packaging industry as a sustainable solution for replacing petroleum-based plastics in order to reduce the accumulation of plastic waste in the environment. This work has benchmarked the environmental impact of bio-based against petroleum-based plastics for single use boxes. In this paper, the cradle to consumer gate environmental impact data of these boxes was calculated and reported as part 1. End-of-life options of both bio- and petroleum-based boxes are an important subject which will be further studied for part 2. The energy sources in this work

were taken from the Thailand energy database namely: Thai electricity grid mix (TEGM), Thai coal electricity (TCE), Thai natural gas combine cycle (TNGCC), and Thai coal integrated gasification combine cycle (TIGCC).

**Methods** The materials studied were polystyrene (PS) derived from petroleum, polylactic acid (PLA) derived from corn, and PLA/cassava starch blend (PLA/starch). The tray with lid (herein after called box) was processed in a plastic manufacturing in Thailand using cast sheet extrusion and then thermoforming techniques. The functional unit is specified as 10,000 units of 8.0×10.0×2.5 cm of PS, PLA, and PLA/starch boxes which weigh 447.60, 597.60, and 549.56 kg, respectively. Three impact categories; namely global warming potential including direct greenhouse gas, and indirect land use change (LUC) emissions, acidification, and photochemical ozone formation are investigated. Finally, the normalization results including and excluding LUC consideration were compared and reported.

**Results and discussion** The results from this study have shown that the total environmental impact including LUC emission of bio-based boxes were different when the various energy sources were supplied throughout the life cycle production stage. It can be seen that the PS box has lower environmental impact than PLA and PLA/starch boxes when TEGM, TCE, TNGCC, and TIGCC were used as energy supplied. LUC of renewable feedstocks, such as corn and cassava, were considered as the biggest impact of absolute scores of PLA and PLA/starch boxes. These results are consistent with Piemonte and Gironi (2010).

**Conclusions** PLA and PLA/starch boxes give a slightly higher environmental impact than the PS box by 1.59 and 1.09 times, respectively, when LUC was not accounted in the absolute scores and clean energy TIGCC was used throughout the life cycle.

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## 1 Introduction

Life cycle assessment (LCA) is a powerful tool used to compute environmental impact performance of materials, processes, and products. LCA has been used by research scientists and industrialists for product development and process improvement. It also can be used for making public policies and developing new marketing norms. In recent years, LCA has found application in various industries such as packaging, automobiles (Jeong et al. 2007), electronics (Andrae et al. 2004), constructions (Singh et al. 2011), textiles (Shen and Patel 2008), steels (Xing et al. 2008), and chemicals (Klopffer 2005). Plastics are important materials that are now widely used in packaging industries. The environmental impacts of both petroleum and bio-based plastics have been studied using LCA methodology to compare different applications such as trays (Madival et al. 2009), cups (Bohlmann 2004), bags (Khoo et al. 2010), and forks (Razza et al. 2009). Narayan (2004) reviewed the use of bio-based materials and reported that bio-based packaging is very attractive material and properly suitable for single use, short life and disposable packaging. Many LCA studied reported that bio-based plastics show better environment profiles than the conventional counterparts in term of energy requirement, greenhouse gas emission, and acidification. In bio-polymer production stages, the polymerization for polylactic acid (PLA) and the fermentation for polyhydroxyalkanoate (PHA) showed the significant impacts throughout the life cycle production (Vink et al. 2003, 2007, 2010; Bohlmann 2004; Groot and Boren 2010; Khoo et al. 2010; Suwanmanee et al. 2010).

Plastics consumption in Thailand exceeds 4.7 million tons per year with yearly increase in supply and demand (Plastic Intelligence Unit 2007). These plastics turn to solid waste after their end of life and will pollute in the environment for a long time as they are not degraded under natural environment. The developing and utilization of bio-based and biodegradable plastics such as PLA, PHA, and thermoplastic starch are a solution to solve this problem. PLA is one of the most promising bio-based plastics derived from renewable sugar-based material such as corn, cassava, or sugarcane (Smith 2005). It can be processed to form various useful plastic products with high economic potential for consumer applications, e.g., agricultural plastics, diapers, and electric appliances. Moreover, it also has been successfully thermoformed

into various packaging applications such as disposable or single use cups, trays, lids, and blister packaging (Lim et al. 2008). It was reported that around 70 % of PLA is used in packaging applications (Dornburg et al. 2006). However, the main disadvantages of PLA are its high price and unsatisfactory mechanical properties. Many works have studied the blending of PLA with degradable polymers such as starch (Chen et al. 2006; Huneault and Li 2007; Iovio et al. 2008; Wang et al. 2008; Yokensahachart and Yoksan 2011), polycaprolactone (Chen et al. 2003; Sarazin et al. 2008), polybutylene adipate-co-terephthalate (Ren et al. 2009; Signori et al. 2008), polybutylene succinate (Yokohara and Yamaguchi 2008), polyvinyl acetate (Gajria et al. 1996), polyethylene glycol (Sheth et al. 1997), polyhydroxybutyrate (Yu et al. 2006), and Mater-Bi (Fang and Hanna 2001; Ganjyal et al. 2007). Starch is another potentially useful raw material for bio-based plastics because of its natural abundance and low cost. It is a polysaccharide found in renewable resources or green plants as an energy store. The starch industry extracts and refines starch from seeds, roots, and tubers. However, it cannot be used alone as a packaging material because of its hydrophilic character, poor mechanical properties due to the thermal decomposition of starch before melting, and strong water absorption. Blending of PLA with starch is an effective way to reduce material cost and get a new material that has a good performance. PLA/starch blends have become attractive materials for single use or nondurable packaging and easy degradability in the environment (Avella et al. 2005; Leejarkpai et al. 2010). For packaging applications, starch is used for film, loose fill, and single-use tray (Shen and Patel 2008).

This study compared the environmental impact from cradle to consumer gate of polystyrene (PS) against PLA-based, PLA, and PLA/starch, boxes based on Thailand's energy database. Three impact categories, namely global warming potential (GWP) including direct greenhouse gas (GHG) and indirect land use change (LUC) emissions, acidification (AD), and photochemical ozone formation (PCOM), are chosen and investigated because they cover the important emissions from the production. These emissions resulted in the air pollutions which have been the main environmental effects in Thailand (Department of Energy Development and Promotion 2000). LUC emission is an interesting topic because it is expected that the use of renewable feedstocks for bio-based production is increasing in Thailand in the near future (National Innovation Agency 2008). However, there are not many works have been assessed the life cycle of bio-based plastics using LUC. The Thailand energy database, namely: Thai electricity grid mix (TEGM), Thai coal electricity (TCE), Thai natural

gas combine cycle (TNGCC), and Thai integrated gasification combine cycle (TIGCC) were used to assess the environmental impact of single use boxes. Natural gas (NG), crude oil, and coal are used as fuels to generate electricity for fuel fired power plants. TEGM was used as the energy supplied because it is available and presently used in Thailand. About 94 % of TEGM generation is from fossil fuel power plants. The largest contribution is from combined cycle power plants which accounted for 50 % of fossil fuel production. TCE is the steam power plant which uses coal (lignite) to produce steam and gives 38.23 % efficiency. TNGCC is the steam turbine and gas turbine power plant (a combined cycle power plant). It is the most efficient (48.27 %) fuel fired power plant in Thailand. TCE and TNGCC were of interest in this study because they have been available as electricity supplies in Thailand. Whereas, TIGCC was chosen since it could be the main energy supply for Thailand in the near future. The Department of Alternative Energy Development and Efficiency (2007) reported that the coal depletion in Thailand would occur 150 years; while crude oil and NG depletion will be around 17 and 34 years, respectively (Energy Policy and Planning Office 2003). Integrated gasification combined cycle technology is the combination of gasification, where the syngas is produced, with a combined-cycle system, where the syngas is cleanly burned, to generate the electricity. It is being considered as an important clean energy technology for the next generation of coal fired power plant. This advanced clean coal technology give high thermal efficiency of 50–60 % with lower air and solid emission, and always gives higher efficiency than conventional coal technology (Duke Energy 2007; Lee and Lee 2007; Varabuntoonvit 2008; Phumpradab et al. 2009).

## 2 Life cycle assessment

The most widely acceptable method to assess the environmental impacts of services and products is LCA. LCA is an important tool to quantify the potential environmental load during the product life cycle from cradle to gate or cradle to grave. The life cycle inventory data represents the various

emissions of energy and raw materials used. The study examines atmospheric emission such as CO, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, NO<sub>x</sub>, SO<sub>x</sub>, and nonmethane volatile organic compounds (NMVOC). The impact assessments used GWP including direct GHG and LUC emissions, AD, and PCOM. The normalization values were calculated according to the parameters of Thailand's annual emission inventory (Department of Energy Development and Promotion 2000; United Nations Statistics Division 2007). This study was carried out using the life cycle methodology in compliance with following standards:

- ISO 14040 (2006): Environmental management–life cycle assessment–life cycle assessment–principles and framework
- ISO 14044: (2006): Environmental management–life cycle assessment–life cycle assessment–requirement and guideline

### 2.1 LCA goal, scope, and functional unit

The goal of this work was to compare the environmental impact from cradle to consumer gate in the production of PS- and PLA-based boxes. In the base case, the electricity supplied throughout the life cycle production of PS- and PLA-based boxes was obtained from TEGM. In the energy scenario, TCE, TNGCC, and TIGCC were used as the energy supplied for PLA-based box production. The LCA scope starts with raw material extraction which included the extraction of crude oil and natural gas for PS tray and the extraction of corn and cassava for PLA-based boxes. It is followed by polymer pellet preparation and box forming. The distribution of the intermediate and finished product from the manufacturing to consumer was considered as the final step. The tray with lid (herein after called box) for all materials studied was processed using a thermoform technique. These boxes are used for serving dessert as shown in Fig. 1. The functional unit (FU) of the LCA is specified as 10,000 units of 8.0×10.0×2.5 cm of PS, PLA, and PLA/starch boxes which weigh 447.60, 597.60, and 549.56 kg, respectively. The density of the materials was determined using Ultracycrometer 1000 Version 2.12 Analyzer (Quantachrome Corporation) with target pressure of 10.00 psi, flow purge of 1.0 min, averaged run of five, and

**Fig. 1** Photographs of PS, PLA, and PLA/starch boxes



**Table 1** Characteristics of PS, PLA, and PLA/starch boxes

Characteristic	Weights of tray (kg) W×L×H: 8.0×10.0×2.5 cm	Density (kg/m <sup>3</sup> )	Mass load (kg)
PS	447.60	1.07×10 <sup>3</sup>	2.14×10 <sup>-2</sup>
PLA	597.60	1.31×10 <sup>3</sup>	2.62×10 <sup>-2</sup>
PLA/starch	549.56	1.33×10 <sup>3</sup>	2.66×10 <sup>-2</sup>

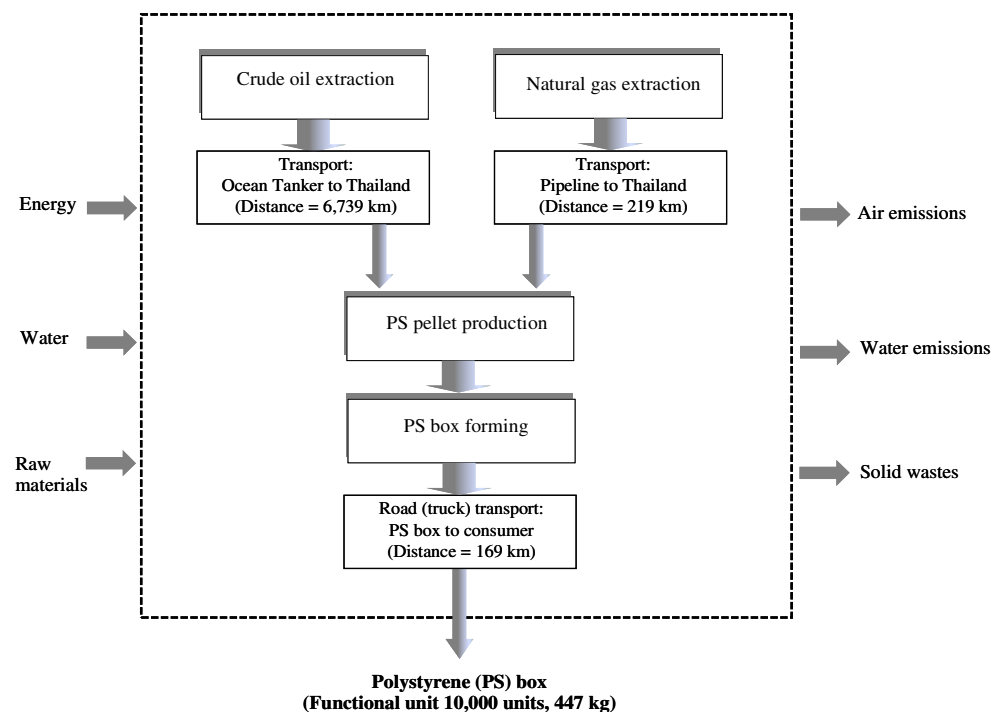
A one box with carrying capacity is 100 g

reported in Table 1. The total volume of all boxes is  $2.00 \times 10^{-4} \text{ m}^3$  per box. This study assumed that all materials have the same carrying capacity of 100.00 g. Therefore, the mass load of these boxes were calculated according to their dimension and density and reported as  $2.14 \times 10^{-2} \text{ kg/m}^3$  for PS box,  $2.62 \times 10^{-2} \text{ kg/m}^3$  for PLA box, and  $2.66 \times 10^{-2} \text{ kg/m}^3$  for PLA/starch box.

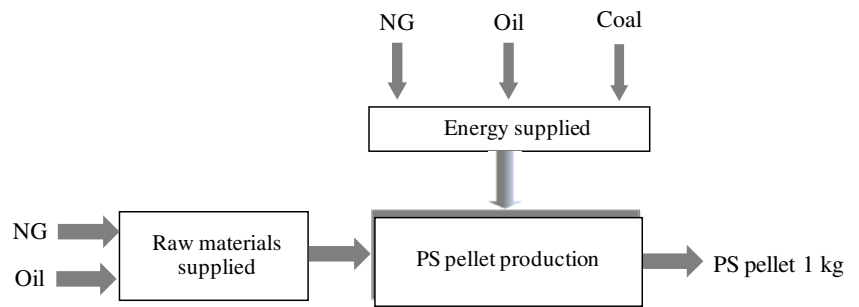
The LCA system boundary for the production of PS box begins with crude oil extraction in the Middle East and South SE Asian and shipping to Thailand via ocean tanker. NG was extracted and piped from the Gulf of Thailand (83.00 %) and Burma (17.00 %) as shown in Fig. 2. NG and crude oil were used as raw materials for styrene monomer which is then processed to PS pellets (Ecoinvent 1.01 database Switzerland). This study assumed that PS pellet and PS box production plants are located in the same area. Hence, the transportation activities between them are negligible. A flowchart showing the most relevant inputs used for manufacturing PS pellet is shown in Fig. 3. The thermoforming box was produced by a packaging

manufacturer in Thailand during 2010. About 0.97 kg of crude oil (lower heating value (LHV) 45.00 MJ/kg) and 0.71 kg of NG (LHV 54.00 MJ/kg) is required for the production of 1.00 kg of PS pellet (Ecoinvent 1.01 database Switzerland; Narita et al. 2002). Boxes were processed using cast sheet extrusion and then thermoforming in a plastic manufacturing plant in Rayong province, Thailand. The delivery distance for the PS box from the plastic manufacturing to the consumer in Bangkok is 169 km (Department of Highway 2010).

Nowadays, there are two world-class technologies available for the PLA manufacturing, namely Ingeo<sup>®</sup> of NatureWorks LLC (Vink et al. 2010) and Purac's PLA production (Groot and Boren 2010). This research work focused on studying LCA methodology using Ingeo<sup>®</sup> technology because PTT Global Chemical Public Company Limited, the largest chemical company in Thailand, announced the investment of US\$ 150 million supports NatureWorks. They planned to build the second Ingeo<sup>®</sup> PLA production plant in Thailand in 2015 (NatureWork LLC 2011). The system boundary from cradle to consumer gate for PLA box is shown in Fig. 4. The PLA pellet is produced from corn using current Ingeo<sup>®</sup> polylactide production technology. It starts with the corn production which is mainly situated in the North East of Thailand: Nakornsawan, Petchaboon, Nakornrachasima, Lopburi, and Sakaeo provinces. Corn growing includes inputs such as corn seed, fertilizer, pesticides, and fuel used by the farmers, land used, and excluding CO<sub>2</sub> absorption through the photosynthesis process (Ecoinvent 2.2 database Switzerland). After harvest, corn is transferred by truck for 244 km to the

**Fig. 2** The system boundary for PS box production

**Fig. 3** Flow chart showing the most relevant input and output for PS pellet production



PLA pellet production plant in Rayong province, East of Thailand. PLA pellet production was divided into four major steps: the conversion of corn into dextrose by wet milling, processing of dextrose into lactic acid by fermentation, conversion of lactic acid into lactide, and polymerization of lactide into polylactide. Finally, polylactide is extruded and cut to form pellet. The hypothesis of this study is that new fermentation technology is to be used and operated at significantly lower pH for the PLA pellet production. This technology reduces the use of chemicals, e.g., calcium hydroxide and sulfuric acid. The energy used in PLA pellet production was expressed in units of electricity. A flowchart showing PLA pellet production is shown in Fig. 5. The thermoformed box was produced in another plastic manufacturing plant nearby in Rayong. Finally, the PLA box is delivered to the consumer in Bangkok which estimated distance to be 169 km.

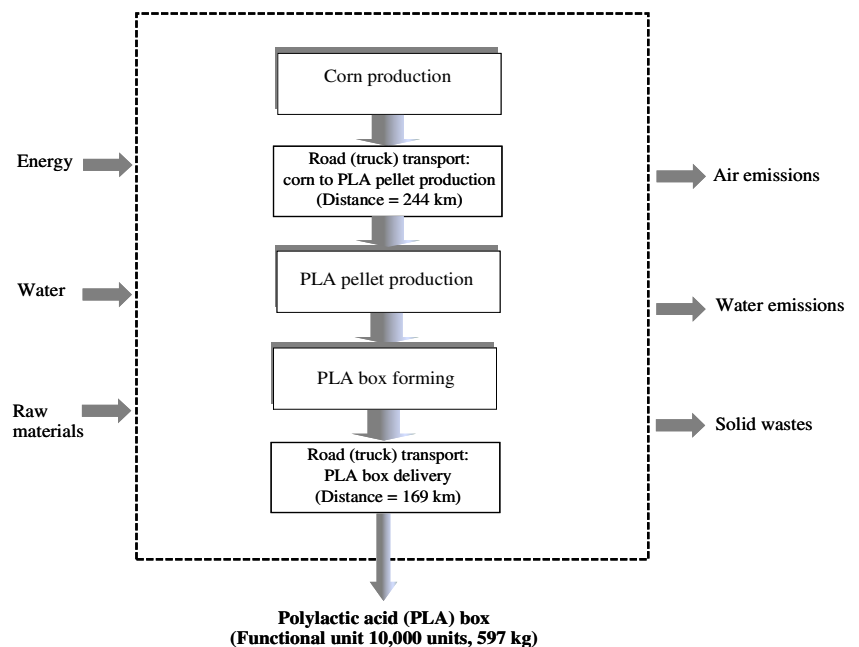
The system boundary from cradle to consumer gate for PLA/starch box is shown in Fig. 6. The PLA/starch box production starts with the cassava production which is mainly produced in the North East and East of Thailand:

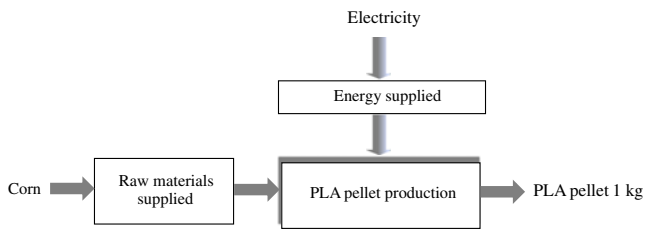
Nakornrachasima, Chanthaburi, Chachoengsao, and Chonburi provinces. Data for cassava plantation and cassava starch production in Thailand were reported by Silalertruksa and Gheewala (2009). It is assumed that the locations of cassava plantation and cassava starch production plant are in the same area. The average distance from cassava starch production plants to the PLA/starch pellet production plant in Rayong province is about 220 km. Finally, the PLA/starch box is formed and delivered to the consumer with the average distance of 169 km. TCE, TNGCC, and TIGCC were used as the electricity for PLA pellet, and cassava starch, and box production.

The assumptions of this LCA study were summarized as follows:

- In both transportation and production stages, the air emission of CO, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, NO<sub>x</sub>, SO<sub>x</sub>, and volatile organic compounds (VOC) are considered, mostly from energy requirements and partially from direct emissions.

**Fig. 4** The system boundary for PLA box production





**Fig. 5** Flow chart showing the most relevant input and output for PLA pellet production

- The impact assessments used GWP including direct GHG emissions and LUC based on the Intergovernmental Panel on Climate Change (2006). This paper considered LUC emissions with the assumption from land converted to cropland. Average value of 328.00 t of CO<sub>2</sub> equivalent per hectare of land converted to corn (Piemonte and Gironi 2011). The emission calculation for cropland change from corn to cassava is zero (Joint Graduate School of Energy and Environment 2010).
- The production of 1.00 kg corn and cassava required  $6.26 \times 10^{-1}$  and  $4.57 \times 10^{-1}$  m<sup>2</sup> of arable land, respectively.
- In the present study, VOC emission is represented in the function of NMVOC emission. The investigation based on Electricity Generating Authority of Thailand data in 2007. NG, crude oil, and coal were supplemented from the secondary source (ETH-ESU 1996; Varabuntoonvit 2008)

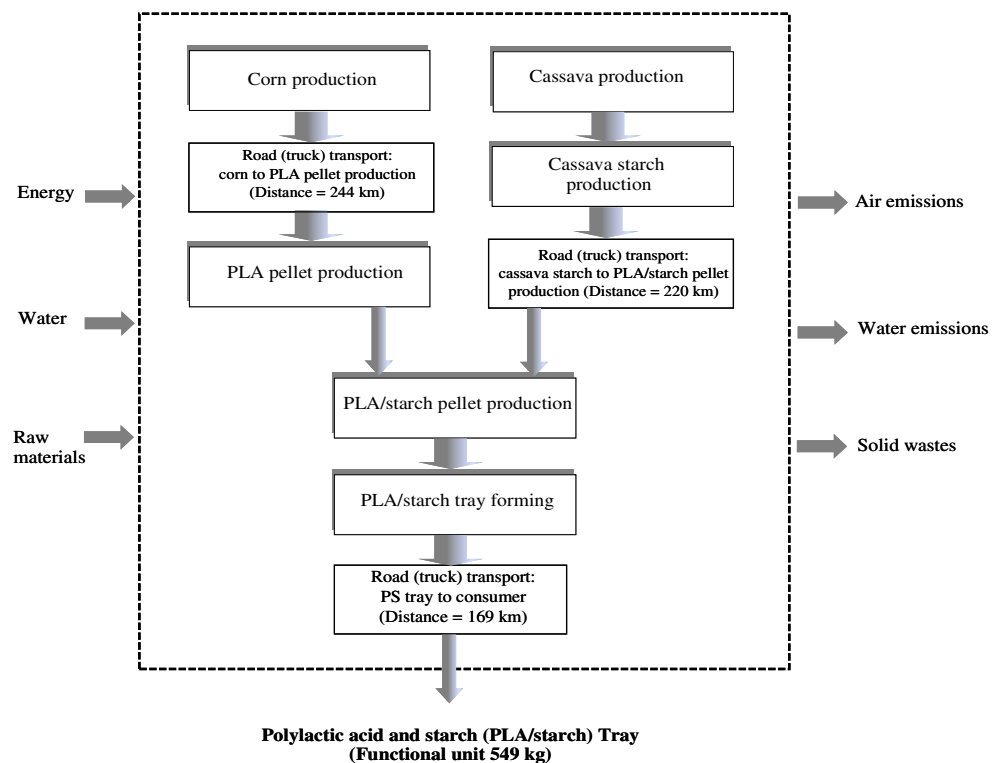
- Co-product from oil refinery (e.g., gasoline, diesel, LPG, long or short residue, kerosene, and Naphtha) and co-product from PLA pellet production (corn wet milling, e.g., corn gluten meal and corn oil) are not investigated in the system boundary.
- CO<sub>2</sub> emission arising from biomass carbon is excluded from the life cycle of products (PAS 2050 2008). Therefore, CO<sub>2</sub> absorption during photosynthesis is negligible.
- The average corn yields in Asia countries are about one–two of those of major corn producers. For example, yield in China is around 5 t/ha while the USA is around 10 t/ha (FAO 2006; OECD-FAO 2006).
- The LCI of box production data was provided by Polymer Chemistry Research Unit (MTEC, Thailand).

### 3 Results and discussion

#### 3.1 Life cycle inventory analysis

The database for the production of raw materials and energy sources are extracted from several research works and available databases. These data were used to evaluate and compare the life cycle environmental impact of PS- and PLA-based (PLA and PLA/starch) boxes. In the base case, boxes

**Fig. 6** The system boundary for PLA/starch box production



**Table 2** Energy requirements for the production of PS box

Description	Energy requirement
1. Fossil fuel extraction	
NG	11.34 MJ/kg NG
Crude oil	24.30 MJ/kg crude oil
2. PS pellet production	
NG, crude oil, and coal	39.75 MJ/ kg PS
3. PS box forming	
Electricity: TEGM	4.75 MJ/kg PS tray
4. Road (truck) transport	
PS box delivery to consumer	284.19 MJ/FU

were prepared using TEGM while TCE, TNGCC, and TIGCC were considered as energy scenario.

### 3.1.1 Life cycle inventory of PS box production

The LCI of PS box production has five major stages; raw material extraction, raw material transportation, PS pellet production, PS box forming, and PS box delivery to consumer as shown in Fig. 2. The energy requirements in each stage of PS box production, from cradle to factory gate, are evaluated in mega joules per unit and reported in Table 2. The energy requirement per kilogram for NG extraction is 11.34 MJ which gives LHV of 54.00 MJ/kg natural gas (Spath and Mann 2000a, b). Sheehan et al. (1998) reported that the energy requirement per kilogram crude oil extraction is 24.30 MJ which gives LHV 45.00 MJ/kg crude oil. The raw material input for producing 1.00 kg PS pellet was 46.38 MJ which is derived from 0.33 kg NG and 0.63 kg crude oil. The energy supplied for 1.00 kg PS pellet production was 39.75 MJ which is derived from 0.37 kg NG, 0.34 kg crude oil and 0.37 kg coal (Razza et al. 2009). Therefore, the total energy used for 1.00 kg PS pellet production is 86.13 MJ (46.38+39.75 MJ). This result agreed with the energy requirement (87.00 MJ) for the production of 1.00 kg PS pellet in Vink et al. (2010).

**Table 3** Air emission from fossil fuel extraction and transportation

Air emissions	NG		Crude oil	
	(kg/MJ)	(kg/FU)	(kg/MJ)	(kg/FU)
CO	$1.54 \times 10^{-8}$	$1.10 \times 10^{-2}$	$1.66 \times 10^{-5}$	$3.88 \times 10^{-1}$
CO <sub>2</sub>	$1.10 \times 10^{-3}$	$9.61 \times 10^1$	$9.33 \times 10^{-3}$	$2.18 \times 10^2$
CH <sub>4</sub>	$5.84 \times 10^{-8}$	$4.45 \times 10^{-2}$	$9.07 \times 10^{-5}$	$2.12 \times 10^0$
N <sub>2</sub> O	$3.45 \times 10^{-10}$	$2.57 \times 10^{-4}$	$6.62 \times 10^{-7}$	$1.54 \times 10^{-2}$
NO <sub>x</sub>	$3.79 \times 10^{-8}$	$2.87 \times 10^{-2}$	$9.18 \times 10^{-5}$	$2.14 \times 10^0$
SO <sub>x</sub>	$5.19 \times 10^{-8}$	$3.90 \times 10^{-2}$	$1.07 \times 10^{-5}$	$2.51 \times 10^{-1}$
NMVOC	$1.01 \times 10^{-8}$	$7.57 \times 10^{-3}$	$1.73 \times 10^{-4}$	$4.03 \times 10^0$

The energy for PS box forming was calculated as 4.75 MJ/kg PS tray from the energy consumption during sheet extrusion and thermoforming. The energy requirements for PS box delivery by a fully loaded (28 t) truck to the consumer was 284.19 MJ/FU.

Air emissions from fossil fuel extraction, energy supplied for PS box production and transportation are compiled in Tables 3, 4, and 5, respectively. For PS pellet production, air emissions from ocean tanker and pipeline for raw material transportation are sourced from the Ecoinvent 1.01 database Switzerland. For transportation, the NG is piped from Gulf of Thailand and Burma to Thailand for 219 km. The distance for crude oil shipping from Middle East Asia and South of Asia to Rayong province is estimated about 6,739 km. The average distance for boxes delivery from manufacturing to consumer is about 169 km.

### 3.1.2 Life cycle inventory of PLA box production

Figure 4 shows the five major stages of PLA box production including corn production, corn transportation, PLA pellet production, PLA box production, and PLA box delivery to consumer. The total energy used for PLA pellet and box production is the combination of 78.30 % NG, 0.70 % crude oil, and 21.00 % coal. The energy requirements in each stage from corn plantation to PLA box forming are compiled in Table 6. In corn plantation, the information on energy requirement was taken from the Ecoinvent 2.2 database Switzerland and reported as 4.31 MJ/kg corn. The energy used to produce 1.00 kg PLA pellet was calculated as 38.00 MJ/kg PLA. It was reported that 1.00 kg PLA pellet was derived from 1.54 kg corn (Vink et al. 2010; Khoo et al. 2010). Therefore, the total energy used for 1.00 kg PLA pellet production is 51.1 MJ ( $4.31 \times 1.54 + 38.00$  MJ). The energy requirement for PLA box forming was calculated as 2.42 MJ/kg PLA box. The energy requirement for transportation of corn was 640.19 MJ/FU and for PLA box was 379.42 MJ/FU.

The emissions to air from PLA box production, excluding the emissions from transportation, are calculated and

**Table 4** Air emissions from energy supplied for PS pellet production and box forming

Air emissions	PS pellet production <sup>a</sup>				PS box forming Electricity: TEGM (kg/FU)
	NG (kg/MJ)	Crude oil (kg/MJ)	Coal (kg/MJ)	Total (kg/FU)	
CO	$1.01 \times 10^{-6}$	$6.19 \times 10^{-5}$	$1.23 \times 10^{-7}$	$2.78 \times 10^{-2}$	$2.78 \times 10^{-2}$
CO <sub>2</sub>	$8.83 \times 10^{-3}$	$9.44 \times 10^{-3}$	$3.45 \times 10^{-4}$	$3.83 \times 10^1$	$3.83 \times 10^1$
CH <sub>4</sub>	$4.09 \times 10^{-6}$	$9.27 \times 10^{-5}$	$3.72 \times 10^{-7}$	$9.11 \times 10^{-3}$	$9.11 \times 10^{-3}$
N <sub>2</sub> O	$2.36 \times 10^{-8}$	$6.67 \times 10^{-7}$	$2.23 \times 10^{-9}$	$1.17 \times 10^{-3}$	$1.17 \times 10^{-3}$
NO <sub>x</sub>	$2.64 \times 10^{-6}$	$9.23 \times 10^{-5}$	$3.16 \times 10^{-7}$	$8.99 \times 10^{-2}$	$8.99 \times 10^{-2}$
SO <sub>x</sub>	$3.95 \times 10^{-6}$	$1.10 \times 10^{-5}$	$4.20 \times 10^{-7}$	$5.00 \times 10^{-4}$	$5.00 \times 10^{-4}$
NMVOOC	$6.96 \times 10^{-7}$	$1.76 \times 10^{-4}$	$7.06 \times 10^{-8}$	$1.45 \times 10^0$	$1.45 \times 10^0$

<sup>a</sup>Negligible combustion emissions from PS pellet production

recorded in Table 7. The inventory analysis of PLA transportation is presented in two stages including road corn transportation and PLA boxes delivery to consumer by a fully loaded 28 t truck. The total air emissions from energy supplied for transportation of PLA box, from corn plantation to consumer gate, are evaluated and reported as shown in Table 8. The comparison of the total air emissions of PLA box production using TEGM (base case), TCE, TNGCC, and TIGCC as electricity sources were evaluated and compared as shown in Table 9.

### 3.1.3 Life cycle inventory of PLA/starch box production

The PLA/starch box production is divided into seven major stages; including corn and cassava plantation, cassava starch production, corn and cassava starch transportation, PLA pellet production, PLA/starch pellet production, PLA/starch box production, and PLA/starch box delivery to consumer. Figure 6 shows the system boundary for PLA/starch box production. The energy requirements for PLA/starch box production, from cradle to consumer gate, are shown in Table 10. In the cassava plantation stage, the energy requirement for producing 1.00 kg cassava was taken from Silalertruksa and Gheewala (2009) and reported as 0.53 MJ. The energy used for producing 1.00 kg cassava

starch is 2.72 MJ derived from electricity, water, and chemicals consumption. It was assumed that PLA/starch pellet and box forming are processed in the same plastic manufacturing in Rayong province. The energy requirement for these processes was calculated as 5.01 MJ/kg PLA/starch box. The amounts of energy used for corn and cassava starch transportation were calculated to be 105.63 and 40.89 MJ/FU, respectively. The energy requirement for PLA/starch box delivery was 93.05 MJ/FU for 169 km road transportation.

The air emissions of PLA/starch box production, excluding the emission from transportation, are calculated and recorded as shown in Table 11. The LCI of transportation during PLA/starch box production is presented in three stages; including road (truck) transportation of corn to PLA pellet production plant, cassava starch to PLA/starch pellet production plant, and delivery of PLA/starch boxes to consumer, as shown in Table 12. In this work, it was assumed that PLA and PLA/starch pellet production plants are in the same area, Rayong province. The other energy scenarios: TCE, TNGCC, and TIGCC were also considered in this work. The comparison of the total air emissions of PLA/starch box production, from cradle to consumer gate, using TEGM (base case), TCE, TNGCC, and TIGCC as electricity sources were evaluated and compared as shown in Table 13.

**Table 5** Air emissions from energy supplied for transportation of PS box

Air emissions	NG pipeline (distance=219 km)		Oil shipment (distance=6,739 km)		PS box delivery (distance=169 km) kg/FU
	kg/MJ	kg/FU	kg/tkm	kg/FU	
CO	$9.96 \times 10^{-7}$	$2.04 \times 10^{-2}$	$1.82 \times 10^{-4}$	$9.46 \times 10^{-2}$	$2.17 \times 10^{-3}$
CO <sub>2</sub>	$7.73 \times 10^{-3}$	$1.59 \times 10^2$	$1.97 \times 10^{-1}$	$1.02 \times 10^2$	$1.60 \times 10^0$
CH <sub>4</sub>	$4.03 \times 10^{-6}$	$8.27 \times 10^{-2}$	$1.06 \times 10^{-4}$	$5.48 \times 10^{-2}$	$2.00 \times 10^{-2}$
N <sub>2</sub> O	$2.32 \times 10^{-8}$	$4.77 \times 10^{-4}$	$1.97 \times 10^{-5}$	$1.02 \times 10^{-2}$	$3.06 \times 10^{-5}$
NO <sub>x</sub>	$2.60 \times 10^{-6}$	$5.33 \times 10^{-2}$	$3.02 \times 10^{-3}$	$1.57 \times 10^0$	$8.12 \times 10^{-3}$
SO <sub>x</sub>	$3.53 \times 10^{-6}$	$7.24 \times 10^{-2}$	$0.00 \times 10^0$	$0.00 \times 10^0$	$0.00 \times 10^0$
NMVOOC	$6.86 \times 10^{-7}$	$1.41 \times 10^{-2}$	$1.26 \times 10^{-4}$	$6.55 \times 10^{-2}$	$7.58 \times 10^{-12}$



**Table 6** Energy requirements for the production of PLA box

Description	Energy requirement
1. Corn plantation	
Diesel and chemicals	4.31 MJ/kg corn
2. PLA pellet production	
Electricity: TEGM	38.00 MJ/ kg PLA
3. PLA box forming	
Electricity	2.42 MJ/kg PLA box
4. Road (truck) transport	
Corn to PLA pellet production plant	640.19 MJ/FU
PLA box delivery to consumer	379.42 MJ/FU

### 3.2 Life cycle impact assessment results: life cycle of box production

The impact assessment is an important step in the LCA frame work (ISO 14040 2006) for evaluating the environmental impact based on the inventory results of the study. Three impact categories, namely GWP accounting direct GHG and indirect LUC emissions, AD, and PCOM, were chosen in this work as they cover the important emission from the production. The calculation is based on The Environmental Design of Industrial Product 2003 method (Hauschild and Potting 2005). These three impacts corresponded with the emissions from LCI results of PS- and PLA-based, PLA and PLA/starch boxes. Emissions of CO, CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O and LUC are the main cause of GWP whereas emissions of SO<sub>x</sub> and NO<sub>x</sub> are the main cause of AD (Tan and Khoo 2005). Furthermore, PCOM is caused mainly by the emissions of CO, CH<sub>4</sub>, NO<sub>x</sub>, and NMVOC (Ross and Evans 2003).

#### 3.2.1 Characterization

TEGM was used as the energy supplied for the production of petroleum and PLA-based boxes in base case. According to the FU, 10,000 units, 532.67 kg of PS pellet, 569.80 kg of PLA pellet, and 431.76 kg of PLA

pellet and 185.04 kg of cassava starch were required for manufacturing PS, PLA and PLA/starch boxes respectively. Figure 7 showed the GWP comparison of PS, PLA, and PLA/starch box productions. The total GWP of PS box production ( $5.00 \times 10^2$  kg CO<sub>2</sub> equivalent per FU) is the lowest, followed by PLA box production ( $1.75 \times 10^4$  kg CO<sub>2</sub> equivalent per FU), and PLA/starch box production ( $2.43 \times 10^4$  kg CO<sub>2</sub> equivalent per FU). For PS box production, it can be observed that raw materials extraction, NG, and crude oil, and the box forming stages generated high GWP. These stages contributed 91.81 % of total kg CO<sub>2</sub> equivalent per FU whereas PS box forming and delivery exhibited low GWP impact by 8.19 %. In PLA box production, LUC emission is the most significant GWP effect which contributed  $1.43 \times 10^4$  kg CO<sub>2</sub> equivalent per FU and can be translated to 81.81 % of total positive values of GHG emissions. This effect increases the total GHG emissions for PLA box production by 4.5 times. For PLA/starch box production, LUC emission from corn and cassava are the highest contribution to GWP, which are 36.47 and 54.80 % of total GWP, respectively. Comparison in total GWP between PLA and PLA/starch boxes revealed that the proportional usage of cassava starch by 30 % in the PLA/starch pellet production step could increase GHG emissions. This result leads to the increasing of GWP by 38.79 %, which accounts for  $6.80 \times 10^3$  kg CO<sub>2</sub> equivalent per FU. This result is similar to the observation of Piemonte and Gironi (2011) during a study of environmental impact of petroleum, PE, and bio-based, Master-Bi, shopping bag. From Fig. 7, it can be concluded that transportation by truck makes a slight contribution to GWP for PS, PLA, and PLA/starch boxes.

Figure 8 showed the total AD impact of PS, PLA, and PLA/starch box production. It can be seen that the highest total AD impact was 7.82 m<sup>2</sup> UES per FU for PLA box, followed by 5.36 m<sup>2</sup> UES per FU for PLA/starch box and the lowest AD impact was 2.57 m<sup>2</sup> UES per FU for PS box production. It was found that the

**Table 7** Air emissions from energy supplied for the production of PLA box

Air emissions	Corn plantation		PLA pellet production		PLA box forming	
	(kg/kg)	(kg/FU)	(kg/kg)	(kg/FU)	(kg/kg)	(kg/FU)
CO	$5.12 \times 10^{-4}$	$3.75 \times 10^{-1}$	$2.62 \times 10^{-3}$	$1.82 \times 10^0$	$3.73 \times 10^{-5}$	$1.67 \times 10^{-2}$
CO <sub>2</sub>	$4.38 \times 10^{-1}$	$3.05 \times 10^2$	$3.60 \times 10^0$	$2.51 \times 10^3$	$5.13 \times 10^{-2}$	$2.30 \times 10^1$
CH <sub>4</sub>	$6.13 \times 10^{-3}$	$4.28 \times 10^{-1}$	$8.56 \times 10^{-4}$	$5.97 \times 10^{-1}$	$1.22 \times 10^{-5}$	$5.46 \times 10^{-3}$
N <sub>2</sub> O	$1.40 \times 10^{-4}$	$9.75 \times 10^{-1}$	$1.10 \times 10^{-4}$	$7.66 \times 10^{-2}$	$1.57 \times 10^{-6}$	$7.01 \times 10^{-4}$
NO <sub>x</sub>	$2.03 \times 10^{-3}$	$1.42 \times 10^0$	$8.45 \times 10^{-3}$	$5.89 \times 10^0$	$1.20 \times 10^{-4}$	$5.39 \times 10^{-2}$
SO <sub>x</sub>	$1.14 \times 10^{-3}$	$7.94 \times 10^{-1}$	$4.70 \times 10^{-5}$	$3.28 \times 10^{-2}$	$6.71 \times 10^{-7}$	$3.00 \times 10^{-4}$
NMVOC	$2.82 \times 10^{-4}$	$1.97 \times 10^{-2}$	$1.36 \times 10^{-1}$	$9.49 \times 10^1$	$1.94 \times 10^{-3}$	$8.68 \times 10^{-1}$

**Table 8** Air emissions from energy supplied for transportation of corn and PLA box

Air emissions	Corn transportation (kg/FU) Distance=244 km	PLA box delivery (kg/FU) Distance=169 km
CO	$4.88 \times 10^{-3}$	$2.89 \times 10^{-3}$
CO <sub>2</sub>	$3.60 \times 10^0$	$2.13 \times 10^0$
CH <sub>4</sub>	$4.51 \times 10^{-2}$	$2.67 \times 10^{-2}$
N <sub>2</sub> O	$6.89 \times 10^{-5}$	$4.09 \times 10^{-5}$
NO <sub>x</sub>	$1.83 \times 10^{-2}$	$1.08 \times 10^{-2}$
SO <sub>x</sub>	$0.00 \times 10^0$	$0.00 \times 10^0$
NMVOC	$1.71 \times 10^{-11}$	$1.01 \times 10^{-11}$

emissions of SO<sub>x</sub> and NO<sub>x</sub> from crude oil extraction and PS pellet production stages show a dramatic effect on total AD impact of PS box production. They contributed 57.99 and 35.48 % of total impact, respectively. Whereas, the emission of 3.22 % from NG extraction and 0.27 % from box delivery stages only slightly affect the total AD impact of PS box production. For PLA and PLA/starch boxes, the emission from electricity use in PLA pellet production stage is the main cause accounting for 65.53 and 61.79 % of total impact, respectively. The emission from the plantation stages for PLA and PLA/starch box production generated the AD impact of 33.55 and 32.98 %, respectively. No significant effect from AD emission was observed in box forming, intermediate transportation and box delivery stages. The AD emission from raw material preparations, NG and crude oil extraction, was 1.57 m<sup>2</sup> UES for PS box production. This value is  $1.05 \times 10^0$  m<sup>2</sup> UES and  $1.94 \times 10^{-01}$  m<sup>2</sup> UES lower than those from material preparation, corn and cassava plantations, of PLA and PLA/starch box production, respectively. This indicated that the raw material preparation stage of PS box production gives lower impact than those of PLA and PLA/starch box production, which were 40.06 and 10.97 %, respectively.

Figure 9 showed total PCOM on PS, PLA, and PLA/starch box production. The results show that total PCOM of PLA box production is  $6.71 \times 10^{-3}$  person × ppm × h per FU which is  $6.02 \times 10^{-3}$  and  $2.25 \times 10^{-3}$  person × ppm × h per FU higher than PLA/starch box and PS box production,

**Table 9** Total air emissions from the production of PLA box in the base case and energy scenarios

Emissions parameters	Base case (kg/FU)	Energy scenarios (kg/FU)		
	TEGM	TCE	TNGCC	TIGCC
CO	$2.21 \times 10^0$	$1.53 \times 10^0$	$1.73 \times 10^0$	$5.84 \times 10^{-1}$
CO <sub>2</sub>	$2.85 \times 10^3$	$3.98 \times 10^3$	$2.27 \times 10^3$	$6.12 \times 10^2$
CH <sub>4</sub>	$1.10 \times 10^0$	$5.37 \times 10^{-1}$	$7.80 \times 10^{-1}$	$5.71 \times 10^{-1}$
N <sub>2</sub> O	$1.05 \times 10^0$	$1.03 \times 10^0$	$6.71 \times 10^0$	$9.84 \times 10^{-1}$
NO <sub>x</sub>	$7.40 \times 10^0$	$6.35 \times 10^0$	$7.11 \times 10^0$	$2.15 \times 10^0$
SO <sub>x</sub>	$8.27 \times 10^{-1}$	$7.94 \times 10^{-1}$	$9.74 \times 10^{-1}$	$7.98 \times 10^{-1}$
NMVOC	$9.60 \times 10^1$	$2.09 \times 10^2$	$4.05 \times 10^{-1}$	$1.16 \times 10^{+1}$

**Table 10** Energy requirements for the production of PLA/starch box

Description	Energy requirement
1. Corn plantation	
Diesel and chemicals	4.31 MJ/kg corn
2. Cassava plantation	
Diesel and chemicals	0.53 MJ/kg cassava
3. PLA pellet production	
Electricity: TEGM	38.00 MJ/ kg PLA
4. Cassava starch production	
Electricity, water, and chemicals	2.72 MJ/ kg cassava starch
5. PLA/starch pellet production and box forming	
Electricity: TEGM	5.01 MJ/kg PLA/starch box
6. Road (truck) transport	
Corn to PLA pellet production plant	105.63 MJ/FU
Cassava starch to PLA pellet production plant	40.89 MJ/FU
PLA/starch box delivery to consumer	93.05 MJ/FU

respectively. It is clearly seen that PLA box production exhibited the highest PCOM impact which is calculated to be 33.54 and 89.60 % higher than PLA/starch and PS box production, respectively. For PLA and PLA/starch boxes, the PLA pellet production stage gives a significant effect on total PCOM which was 95.83 and 93.12 % of total impact, respectively. The plantation stages give very low PCOM impact on PLA and PLA/starch box production, which in total are 3.21 and 3.57 %, respectively. However, box forming, intermediate transportation, and box delivery show no PCOM effect on box production. For PS box production, the total PCOM effect is very low and primarily comes from crude oil extraction, followed by PS pellet production and box forming. The PCOM summation from these three stages is 99.02 % of total PCOM and very small PCOM effect is observed in the NG extraction and box delivery stages.

### 3.2.2 Normalization

Thailand national annual emission data (Department of Energy Development and Promotion 2000; United Nations

**Table 11** Air emissions from energy supplied for the production of PLA/starch box

Air emissions	Corn and cassava plantations			PLA pellet and cassava starch productions			PLA/starch box forming	
	Corn (kg/kg)	Cassava (kg/kg)	Total (kg/FU)	PLA pellet (kg/kg)	cassava starch (kg/kg)	Total (kg/FU)	(kg/kg)	(kg/FU)
CO	$5.12 \times 10^{-4}$	$9.04 \times 10^{-5}$	$3.01 \times 10^{-1}$	$2.62 \times 10^{-3}$	$8.47 \times 10^{-5}$	$1.19 \times 10^0$	$4.22 \times 10^{-5}$	$2.32 \times 10^{-2}$
CO <sub>2</sub>	$4.38 \times 10^{-1}$	$2.86 \times 10^{-2}$	$2.14 \times 10^2$	$3.60 \times 10^0$	$1.79 \times 10^{-1}$	$1.66 \times 10^3$	$5.81 \times 10^{-2}$	$3.19 \times 10^1$
CH <sub>4</sub>	$6.13 \times 10^{-3}$	$3.89 \times 10^{-5}$	$2.99 \times 10^{-1}$	$8.56 \times 10^{-4}$	$3.25 \times 10^{-5}$	$3.92 \times 10^{-1}$	$1.38 \times 10^{-5}$	$7.59 \times 10^{-3}$
N <sub>2</sub> O	$1.40 \times 10^{-4}$	$3.05 \times 10^{-6}$	$6.06 \times 10^{-1}$	$1.10 \times 10^{-4}$	$3.56 \times 10^{-6}$	$5.01 \times 10^{-2}$	$1.77 \times 10^{-6}$	$9.73 \times 10^{-4}$
NO <sub>x</sub>	$2.03 \times 10^{-3}$	$1.48 \times 10^{-4}$	$1.01 \times 10^0$	$8.45 \times 10^{-3}$	$5.29 \times 10^{-4}$	$3.90 \times 10^0$	$1.36 \times 10^{-4}$	$7.49 \times 10^{-2}$
SO <sub>x</sub>	$1.14 \times 10^{-3}$	$1.90 \times 10^{-5}$	$5.08 \times 10^{-1}$	$4.70 \times 10^{-5}$	$3.33 \times 10^{-4}$	$8.27 \times 10^{-2}$	$7.58 \times 10^{-7}$	$4.17 \times 10^{-4}$
NM VOC	$2.82 \times 10^{-4}$	$8.52 \times 10^{-5}$	$1.98 \times 10^{-1}$	$1.36 \times 10^{-1}$	$4.38 \times 10^{-3}$	$6.21 \times 10^1$	$2.19 \times 10^{-3}$	$1.21 \times 10^0$

Statistics Division 2007) and Thailand population in 2007, 63,038,247 persons, from Department of Provincial Administration (2007) were used to calculate the normalized references adjusted for Thailand as compiled in Table 14. The absolute normalized score (absolute score) including and excluding LUC emissions from cradle to consumer gate of PS- and PLA-based boxes were shown in Figs. 10 and 11, respectively. It can be seen from Fig. 10 that PLA/starch box production shows the highest absolute score, followed by PLA and PS box production. GWP was the main cause of total impact accounting as 48.27 % for PS box and 73.48–97.83 % for PLA-based boxes and it was not affected by changing the energy supply. It is interesting to note that LUC contributed the high absolute score greater than 81.81 % of total GWP impact. In all types of energy supply, the addition of 30 % cassava starch in the PLA/starch box increased the absolute score by 10.63–31.50 % of PLA box.

In the first energy scenario, TCE was investigated as energy supplied in placed of TEGM. For PLA box production, the absolute score was slightly increased by 3.77 % when TCE was used. This is because there were higher emissions from the electricity generation used in PLA pellet

production and box-forming stages. TCE used only coal as the power source which contributes higher emissions than using a combination of NG, crude oil, and coal in TEGM. However, both TEGM and TCE showed higher PCOM impact than that of TNGCC and TIGCC because coal produces high CO, CH<sub>4</sub>, NO<sub>x</sub>, and NMVOC emissions. The absolute score of PLA/starch showed an increase by 14.47 %, compared to score of PLA/starch in base case. This is because of higher emissions from electricity used in both cassava starch and PLA pellet production stages. It was also found that the production of PLA and PLA/starch boxes have 22.90 and 30.11 times higher impact than that of PS box in the base case.

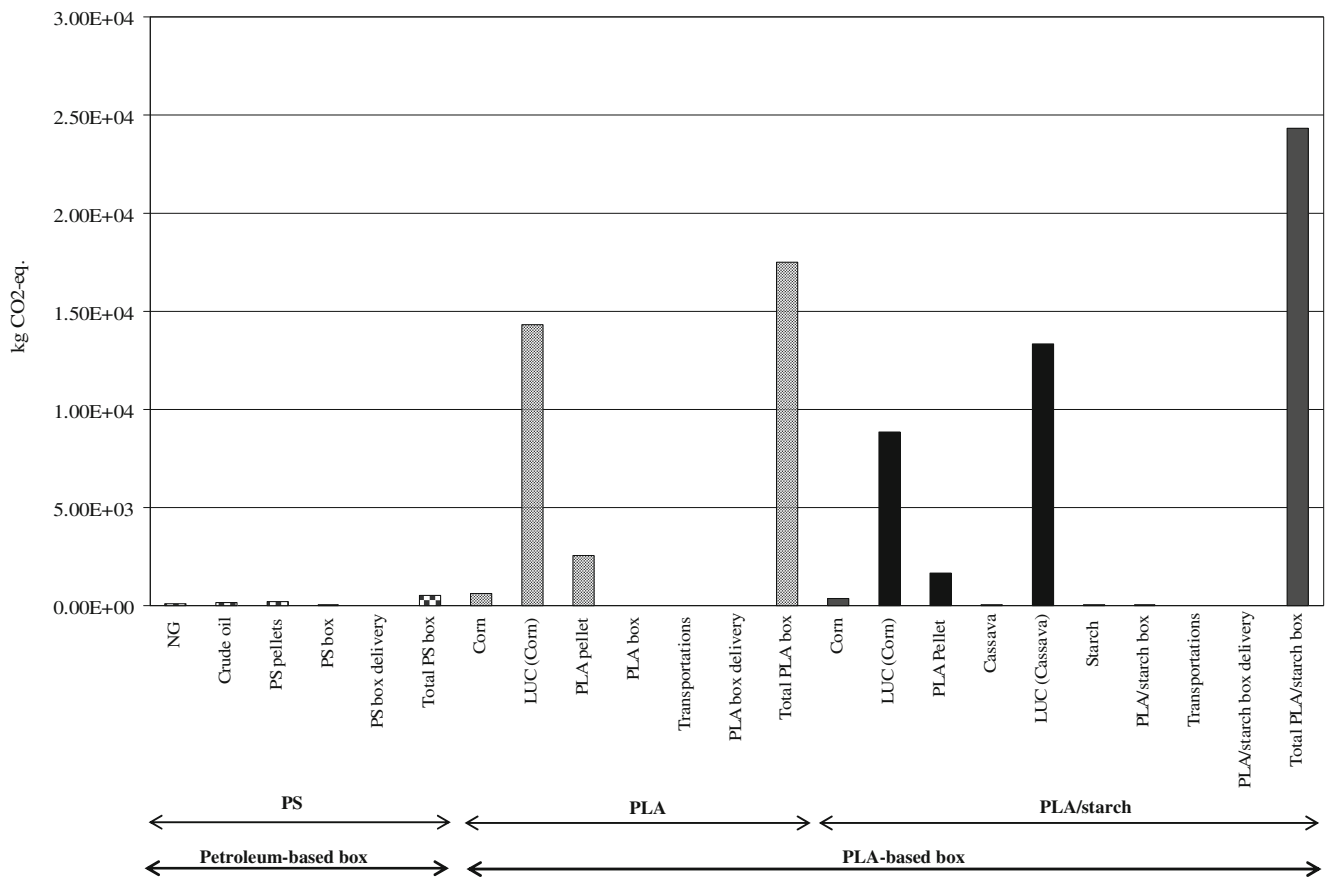
In the second energy scenario, TNGCC was used as energy supplied replace of TEGM. TNGCC use only NG which is a cleaner energy source than using the combination of NG, crude oil, and coal in TEGM. This is because NG releases lower emissions than crude oil and coal. It is interesting to note that there were some emissions from pipeline transportation from NG sources, Burma and Gulf of Thailand, to TNGCC plant in Thailand. These results lead to the reduction of absolute score of both PLA-based boxes, PLA and PLA/starch, by 7.36–24.15 % when TNGCC was supplied. It can be concluded that TNGCC gives more

**Table 12** Air emissions from energy supplied for transportation of corn, cassava starch and PLA/starch box

Air emissions	Corn transportation (kg/FU)	Cassava starch transportation (kg/FU)	PLA/starch box delivery (kg/FU)
	Distance=244 km	Distance=220 km	Distance=169 km
CO	$3.02 \times 10^{-3}$	$1.17 \times 10^{-3}$	$2.66 \times 10^{-3}$
CO <sub>2</sub>	$2.23 \times 10^0$	$8.62 \times 10^{-1}$	$1.96 \times 10^0$
CH <sub>4</sub>	$2.79 \times 10^{-2}$	$1.08 \times 10^{-2}$	$2.46 \times 10^{-2}$
N <sub>2</sub> O	$0.00 \times 10^0$	$0.00 \times 10^0$	$3.76 \times 10^{-5}$
NO <sub>x</sub>	$1.13 \times 10^{-2}$	$4.38 \times 10^{-3}$	$9.97 \times 10^{-3}$
SO <sub>x</sub>	$0.00 \times 10^0$	$0.00 \times 10^0$	$0.00 \times 10^0$
NM VOC	$1.06 \times 10^{-11}$	$4.09 \times 10^{-12}$	$9.31 \times 10^{-12}$

**Table 13** Total air emissions from the production of PLA/starch box in the base case and energy scenarios

Emissions parameters	Base case (kg/FU)	Energy scenarios (kg/FU)		
	TEGM	TCE	TNGCC	TIGCC
CO	$1.52 \times 10^0$	$1.08 \times 10^0$	$2.07 \times 10^0$	$4.52 \times 10^{-1}$
CO <sub>2</sub>	$1.91 \times 10^3$	$2.65 \times 10^3$	$2.78 \times 10^3$	$2.36 \times 10^2$
CH <sub>4</sub>	$7.50 \times 10^{-1}$	$3.77 \times 10^{-1}$	$7.98 \times 10^{-1}$	$3.53 \times 10^{-1}$
N <sub>2</sub> O	$6.57 \times 10^{-1}$	$6.45 \times 10^{-1}$	$6.11 \times 10^{-1}$	$6.06 \times 10^{-1}$
NO <sub>x</sub>	$5.01 \times 10^0$	$4.32 \times 10^0$	$8.37 \times 10^0$	$1.09 \times 10^{-1}$
SO <sub>x</sub>	$5.91 \times 10^{-1}$	$5.69 \times 10^{-1}$	$8.03 \times 10^{-1}$	$5.69 \times 10^{-1}$
NM VOC	$6.35 \times 10^1$	$1.38 \times 10^2$	$4.29 \times 10^{-1}$	$4.37 \times 10^{-1}$



**Fig. 7** Global warming potential (GWP) results from cradle to consumer gate in the base case

environmental friendly impact than TEGM for PLA-based box production. However, the absolute scores of PLA and PLA/starch in this energy scenario are higher than the score of PS box in base case by 17.45 and 23.85 times, respectively.

The third energy scenario of this work was the consideration of using TIGCC as the energy source to replace TEGM. The absolute scores of both PLA-based boxes, PLA and PLA/starch, were reduced by 12.59–33.00 % when TIGCC was used. This is due to the advanced technology of TIGCC which exhibited high thermal efficiency and very low air emissions of CO, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, NO<sub>x</sub>, SO<sub>x</sub>, and NMVOC during product production. Furthermore, no emissions from coal shipping, from mine to TIGCC plant, were considered because the power plant is located at the mine site in Thailand. The results indicated that the production of PLA and PLA/starch boxes give higher environmental impact than that of PS box in the base case by 15.42 and 22.51 times, respectively.

When LUC was considered, it is clearly seen that TNGCC and TIGCC exhibited more environmental friendly impact than TEGM and TCE for PLA-based box

production. It can be concluded that TIGCC is the most suitable energy supply, followed by TNGCC, for PLA-based box production in Thailand. Whereas, TCE showed the worst results which corresponds to the work study by Khoo et al. (2010), who reported that the environmental impact of PHA bio-bag production is about five times greater than that from PP bag when coal based electricity was used as the power supply. However, PS box production in base case exhibited the friendliest product as it contributed lowest impact.

When LUC was not considered, the absolute score of all PLA-based boxes are significantly reduced as shown in Fig. 11. PCOM was the main cause of total impact accounting as 52.54–60.96 % for PLA-based boxes when TEGM and TCE were supplied. The reduction of absolute score of PLA-based boxes was observed by 63.19–63.44 % when TNGCC was supplied. It can be concluded that TNGCC gives more environmental friendly impact than TEGM for PLA-based box production. However, the absolute scores of PLA and PLA/starch in this energy scenario are higher than that of PS box in base case by 2.45 and 3.65 times, respectively. Interestingly, the absolute scores of PLA-based boxes were significantly reduced by 83.54–83.99 % when TIGCC

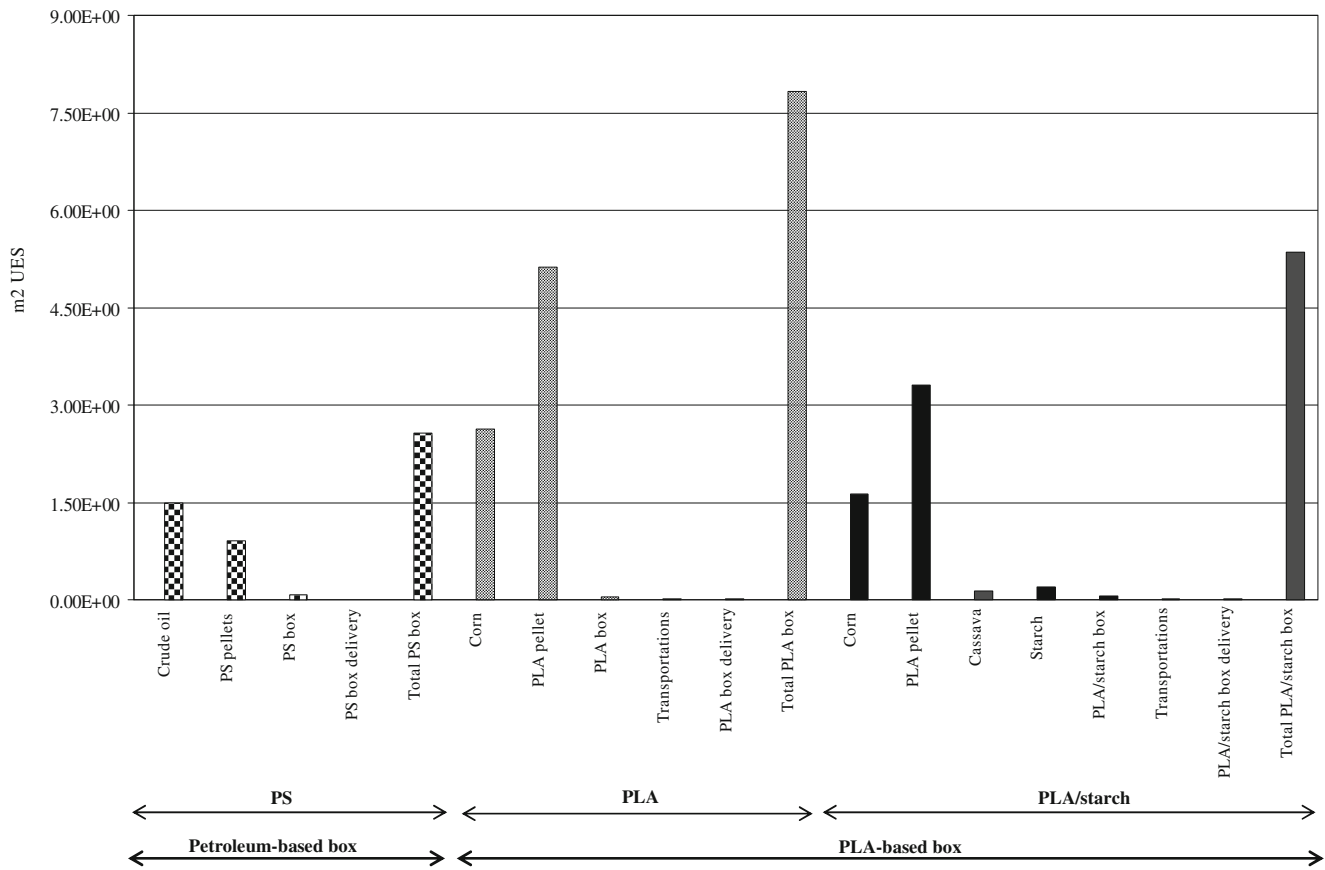


Fig. 8 Acidification (AD) results from cradle to consumer gate in the base case

was used. Obtained results indicated that the production of PLA and PLA/starch boxes give slightly higher environmental impact than that of PS box in the base case by 1.59 and 1.09 times, respectively.

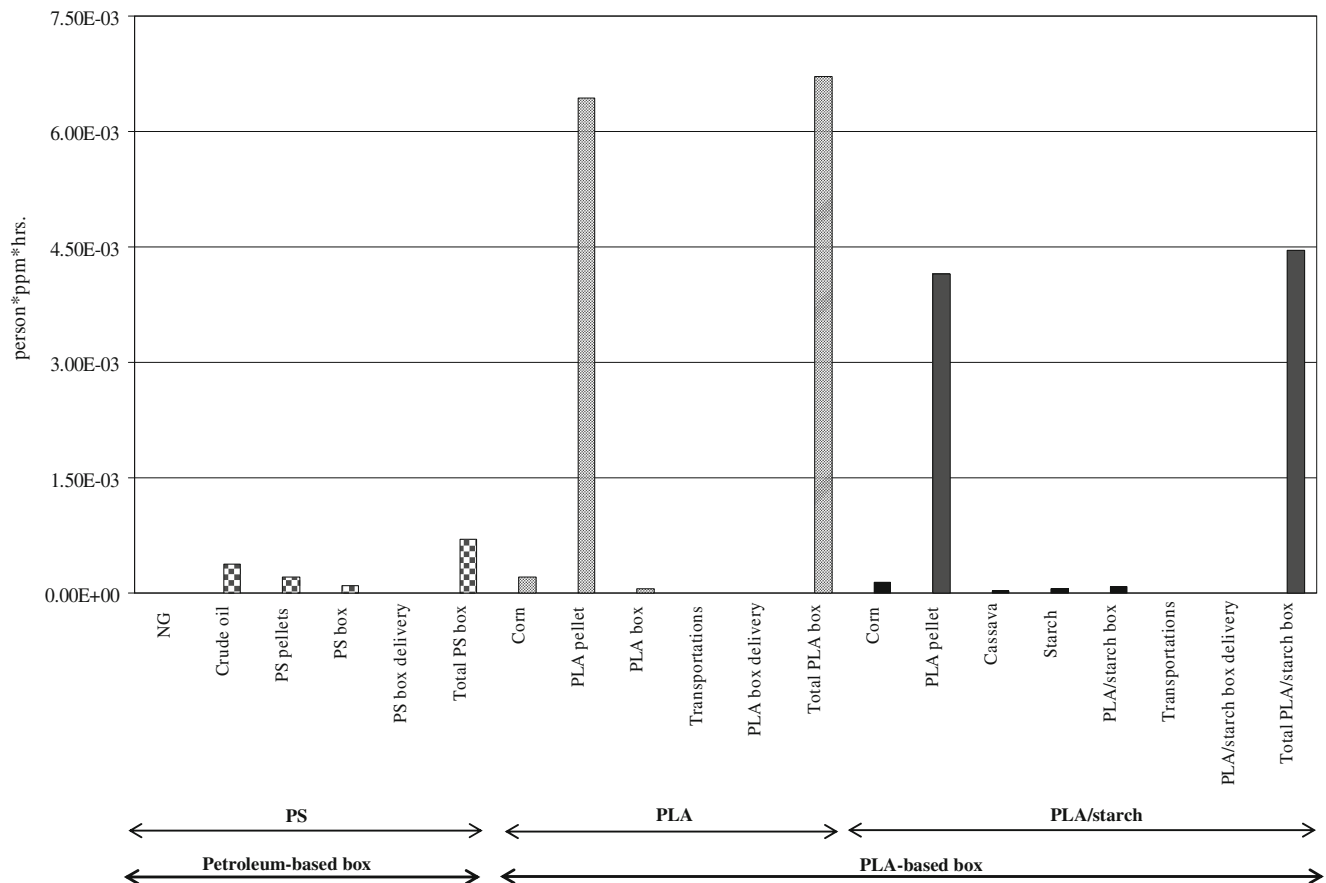
**4 Conclusions**

This study considered the LCA of PS and PLA-based box production in Thailand. Environmental impacts including and excluding LUC emissions were investigated in a life cycle perspective from cradle to consumer gate. In the base case, the absolute scores of PLA and PLA/starch box productions, using TEGM, are 23.01 and 25.75 times higher than PS box production. It is indicated that the production of PS box exhibits lower environmental impact than the production of PLA-based boxes. In the energy scenarios part, the absolute scores of PLA-based boxes were different when the various energy scenario sources, TCE, TNGCC, and TIGCC, were supplied throughout the life cycle production stage.

The impact of PLA and PLA/starch boxes are 22.90 and 30.11 times greater than that of PS box in base case when TCE was supplied throughout the life cycle production

stage. Moreover, the absolute score was slightly increased by 3.77 % for PLA box production while it was moderately increased by 14.77 % for PLA/starch box production when TCE was supplied replacing TEGM. These results indicated that TCE is not suitable for PLA-based box productions in Thailand. In the energy scenario where TNGCC was supplied as power energy, PLA and PLA/starch exhibited higher absolute score than PS box in base case by 17.45 and 23.85 times, respectively. Nevertheless, TNGCC showed higher absolute scores than TEGM in base case for both PLA and PLA/starch box productions by 24.15 and 7.36 %, respectively. When TIGCC was used throughout the life cycle production, PLA and PLA/starch box production have higher environmental impact than that of PS box production in base case by 15.42 and 22.51 times, respectively. In addition, TIGCC is the most appropriate energy scenario as it can reduce environmental impact of PLA-based box production. The absolute scores of PLA-based box production were reduced when TEGM was replaced TIGCC by 12.59–33.00 %.

The environmental impact of PS box production is better than PLA-based box production when TEGM, TCE, TNGCC, and TIGCC were supplied as power energies. Obtained results showed that the production of PLA and



**Fig. 9** Photochemical ozone (PCOM) results from cradle to consumer gate in the base case

PLA/starch boxes has GWP impact by 72.65–97.10 % of total absolute score. This is because LUC emission from corn and cassava were the main contribution to GWP impact by 81.81–91.28 %.

PLA and PLA/starch box production is more environmental friendly than PS box production when indirect LUC emission was not accounted in the absolute scores and TIGCC was supplied. The latest case, the absolute score of PLA and PLA/starch box production give slightly higher impact than PS box production by 1.59 and 1.09 times, respectively. It can be concluded that TIGCC is the most appropriate energy scenario as it can reduce environmental impact of PLA-based box production.

**Table 14** Normalized references adjusted for Thailand

Impact category	Normalized references
Global warming	2,459.00 (CO <sub>2</sub> equivalent/capita/year)
Acidification	25.70 (UES m <sup>2</sup> /capita/year)
Ozone photochemical formation	$5.92 \times 10^{-3}$ (person ppm h/capita/year)

## 5 Recommendations and perspectives

The results of this work give the environmental profile for PLA-based box production in comparison with PS box production. The results obtained are only applicable in Thailand since all data was obtained from Thailand's database except crude oil extraction and corn plantation are from secondary sources. When LUC was considered, from cradle to consumer gate environmental, impact of PLA-based boxes was higher than that of PS box in all types of energy study. However, cradle to grave of PLA-based box production is an important subject and needs to be further studied. The environmental impact of PLA-based box production could be reduced when suitable waste treatment is applied. When LUC was not considered, TIGCC was found to be the most appropriate energy for PLA-based box production in term of environmental impact assessment. Moreover, it will become the most significant energy source in Thailand because the coal depletion will occur in around 150 years or sooner. While the depletions of crude oil and NG are 17 and 34 years, respectively (Energy Policy and Planning Office 2003). This leads to a shortage of raw materials supplied for the production of TEGM and TNGCC in the near future.

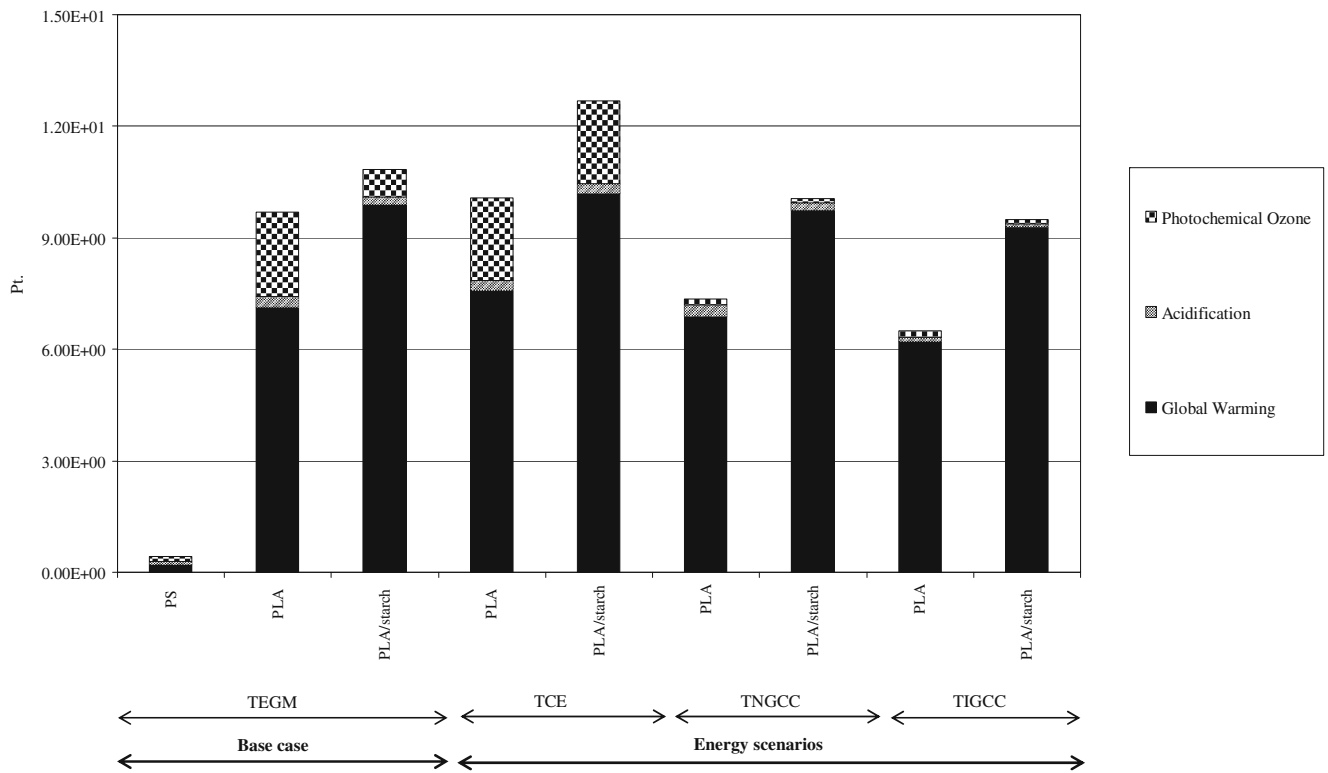


Fig. 10 Absolute normalized score including LUC emission from cradle to consumer gate in the base case and energy scenarios

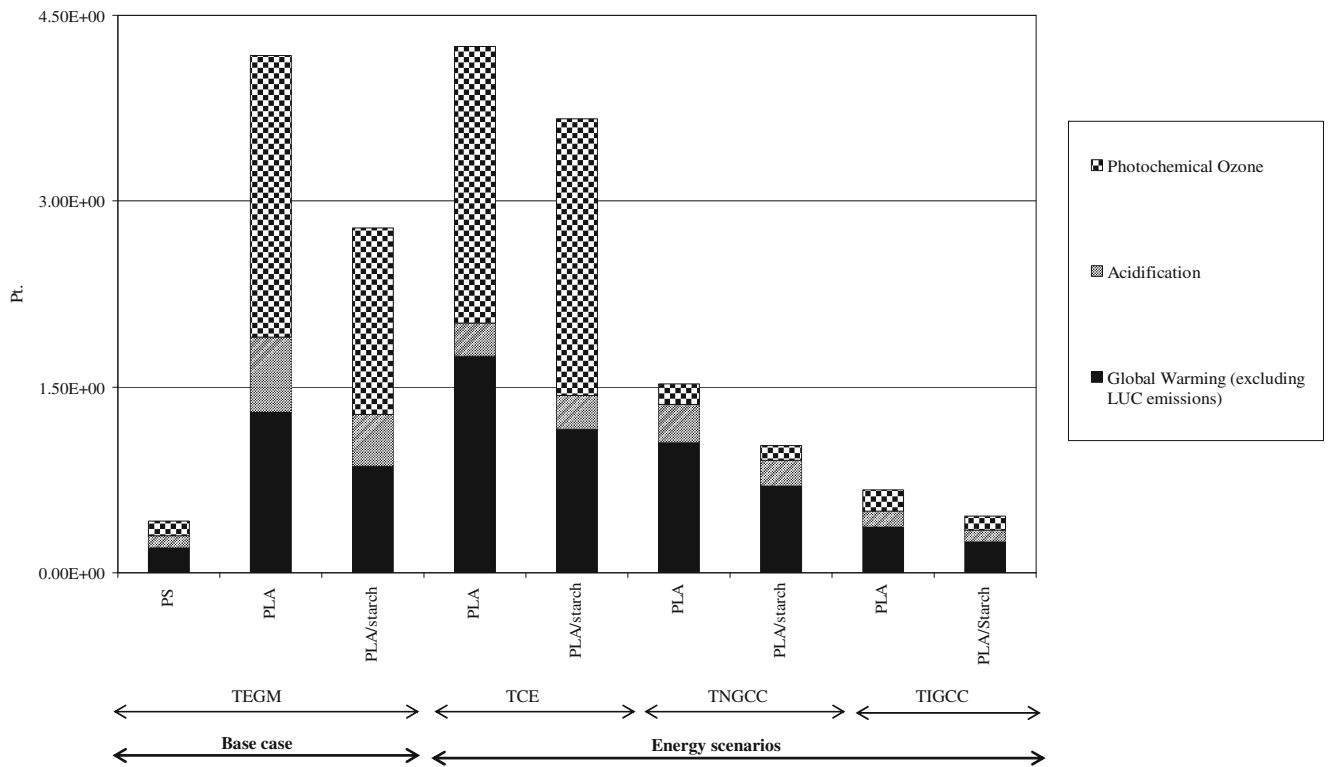


Fig. 11 Absolute normalized score excluding LUC emission from cradle to consumer gate in the base case and energy scenarios

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