

Life Cycle Economic and Environmental Implications of Pristine High Density Polyethylene and Alternative Materials in Drainage Pipe Applications

Long Nguyen¹ · Grace Y. Hsuan¹ · Sabrina Spatari¹

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Abstract A life cycle assessment (LCA) and cost analysis were conducted to compare the environmental and economic performance of nanocomposite polymers that use pristine and recycled high density polyethylene (HDPE) polymer with pristine, and pristine/recycled HDPE polymeric materials in drainage pipe. We evaluate three performance metrics; (a) non-renewable energy consumption (NRE); (b) greenhouse gas (GHG) emissions; and (c) production costs of the three pipe material alternatives. Original life cycle inventory data for the production of nanoclay from the mineral Montmorillonite were collected for this case study in the United States. Life cycle inventory models were developed for the cradle-to-gate production of drainage pipe used in highway construction that consider the sensitivity of model parameter inputs on the life cycle impact and cost results for the three material options. The GHG emissions for the nanoclay composite pipe are 54 % lower than those for pristine HDPE pipe, and 16 % lower than those for pristine/recycle HDPE pipe. With a slight difference in GHG emissions between the pristine/recycled and nanoclay composite, the production of nanoclay does not introduce a significant environmental burden to the pipe material. On average, the pristine HDPE pipe is 13 and 17 % higher in cost than the pristine/recycled HDPE and nanoclay composite pipes, respectively. Results of the LCA and cost analysis support using recycled HDPE as a substitute for pristine HDPE due to its low energy requirements and production costs. The uncertainty in

GHG emissions of manufacturing pristine HDPE causes the largest variation of GHG emissions in nanoclay composite pipe (+3/−2 %). The production cost of the nanocomposite pipe is most influenced by the energy cost of PCR-HDPE (+25/−11 %). Our study suggests that a nanocomposite design that replaces part of the pristine HDPE with recycled HDPE and nanoclay reduces certain environmental risks and material cost of corrugated pipe.

Keywords Nanocomposite · Life cycle assessment (LCA) · Greenhouse gas (GHG) emissions · Green plastic · High density polyethylene alternatives recycled plastic

Introduction

The production supply chain of high density polyethylene (HDPE) uses and consumes vast quantities of fossil energy (i.e. crude oil and natural gas), and those consumed resources emit large volumes of greenhouse gases (GHG) to the atmosphere. The Energy Information Administration (EIA) states that the energy consumed to produce one ton of HDPE is 30 and 34 % higher than that of polypropylene and polyvinylchloride, respectively [1]. Moreover, global annual demand for ethylene, whose production consumes 4.9 EJ of energy, is 103 Mt; 58 % of which is used to make high density polyethylene. As a result, the energy needed for HDPE production is 2.8 EJ, which is responsible for 240 million metric tons of atmospheric CO₂ emissions per year [1]. In the past decade, HDPE has become a widely used polymeric engineering material that has been adopted in different industries, including in the construction of landfill liners, power and telecom cable conduits, sewage and drainage pipe, and automotive fuel tanks [2–5]. Researchers have investigated the environmental impacts

✉ Long Nguyen
lkn25@drexel.edu

¹ Civil, Architectural and Environmental Engineering, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA

of using HDPE in pipe applications [3, 6–8] and automotive applications [4, 9–11] using life cycle assessments (LCA). Lloyd and Lave [12] emphasized the advantages of reducing the unit weight of those products due to the low density of the polymer compared to more traditional materials such as steel and concrete. However, the high energy required to extract and process crude oil to produce HDPE contributes to global climate change [9, 10]. Recent research has been carried out on alternative feedstocks for polymer production such as recycled polymer, biobased (i.e. sugarcane, agricultural materials) and biodegradable (food source for the bacteria in the disposal environment) materials [10, 12–15]. Replacing pristine HDPE with recycled HDPE (PCR-HDPE) (partially or completely) could be a favorable alternative because post-consumer recycled plastics use obsolete resources and potentially consume less energy to re-process compared to pristine (virgin or primary) materials, and they may also lower the production costs.

Plastics' manufacturers began to explore and use recycled plastic solid waste (PSW) in the early 1980s [16]. PSW recycling techniques for various plastics such as polyethylene (PE) and polyvinyl chloride (PVC) have been described by numerous research studies [16–18]. Recycling and recovery methods are classified into four routes: re-extrusion, mechanical, chemical and energy recovery [18]. In 2011, the US Environmental Protection Agency [19] reported that Americans generate about 389 million tons of municipal solid waste (MSW), among which 35 % (87 million tons) was recycled and composted. PSW represents 10 % of the total MSW stream (39.3 million tons). A large portion of the PSW (82.7 %) was disposed in landfills and the remainder was managed through recycling (6.7 %), energy recovery in waste-to-energy (WTE) facilities (9.9 %), or transformed to alternative fuel in cement production (0.7 %) [19]. The recycled HDPE made up 8–10 wt % of recycled plastics from 2008 to 2011. According to Themelis et al. [19], the recycling rate of plastics increased by 21 % over these 3 years. Among several available recycling methods, mechanical recycling is said to be the most widely used technique in the plastic recycling industry [13, 16, 18]. This method begins with separation of the polymer from its associated contaminants followed by its reprocessing to the useable polymer by melt extrusion [13, 20–22].

Blends of pristine/post-consumer HDPE materials have been used previously in the drainage pipe industry [23]. The Plastics Pipe Institution has been supporting research to improve the performance of recycled pipe [24]. According to a report from the Association of Postconsumer Plastic Recyclers (APR) in 2013 [25], 28 % of recycled HDPE is used to make pipe in the US. Another report from APR showed that this number increased to

35 % in 2014 [26]. This statistic shows recycled plastics are in high demand by pipe manufacturers. The challenge of using PCR-plastics in products, particularly in building and infrastructure materials, is maintaining the required and equivalent mechanical performance of the pristine plastics [13]. La Mantia [27] and Pattankul et al. [28] found that the tensile strength and elastic modulus of recycled HDPE were higher than that of pristine HDPE but its elongation at break was significantly lower due to reprocessing. Nanomaterials blended with polymer are one avenue for enhancing mechanical properties and reducing manufacturing costs. Analysis by Roes and colleagues shows that the life cycle costs of the automotive applications can be reduced by between 3 and 6 % when using nanocomposite [10]. An additional small percentage of organically modified clays were shown experimentally to enhance physical and mechanical properties of polymers such as stress cracking resistance and fire-retardant properties [29–32]. Due to these benefits, nanoclay can be employed to compensate for the mechanical performance (e.g. strength, stiffness) lost from the use of PCR-HDPE [20]. Commercially available nanoclay is manufactured by chemically modified, montmorillonite (MMT), which can be directly blended with polymer. The chemical modification converts the hydrophilic MMT to be compatible with the HDPE matrix by altering the surface chemistry of MMT to become organophilic. Studies have identified that such treatment requires the most energy in the manufacturing procedure of nanoclay [10, 32, 33]. Roes et al. [10] investigated the life cycle impacts (i.e. eutrophication, acidification, global warming potential, etc.) and cost of polypropylene (PP)/layered silicate nanocomposite from cradle-to-gate in three applications: packaging film, agricultural film and automotive panels. They found that the nanocomposites have environmental and economic benefits in agricultural film and automotive panel end uses. Lloyd and Lave [12] used LCA to evaluate the environmental and financial aspects of a clay-polypropylene nanocomposite in manufacturing motor vehicle panels and compared it with steel and aluminum. Their results suggested that adding organoclays to polymer is very promising for reducing the energy consumption and GHG emissions of the polymer. The mechanical and physical properties of polymeric nanocomposite are substantially improved with a low content of nanoclay (3–6 wt%) [32]. Hsuan et al. [34] also blended 3 and 6 wt% of nanoclay in an HDPE matrix to evaluate the stress crack resistance of the nanocomposite. These findings suggest an improvement in mechanical properties at relatively low nanoclay concentration, which could be economically feasible for commercial production of pipe materials used in civil engineering infrastructure. Examination of the production cost and environmental performance of polymer nanocomposites in the 4–6 %

range is necessary to evaluate their commercial feasibility as sustainable substitutes for the pristine polymer. Therefore, the objective of this paper is to apply LCA and cost analysis to evaluate the production of drainage pipes in highway applications using 47 wt% HDPE/6 wt% nanoclay blended with 47 wt% PCR-HDPE (nanoclay HDPE/PCR), and compare the material with 100 wt% pristine HDPE and 50 wt% pristine HDPE blended with 50 wt% PCR-HDPE (HDPE/PCR).

Methodology

Life Cycle Assessment (LCA) Fundamentals

LCA systematically evaluates the environmental burden of a product system using sequential material balances at each stage in the product life cycle from the extraction of feedstocks to the production of a final product (pipe). The LCA framework is outlined in ISO 14040 [35]. When comparing the formulations of pristine HDPE, HDPE/PCR and nanoclay HDPE/PCR (they were assumed to meet the same functional requirements), the boundary system selection is from cradle-to-pipe exit gate. A life cycle inventory (LCI) analysis was undertaken that audited energy and resource inputs for each life cycle process using the software, GaBi 6.0 and SimaPro 8.0 [36, 37]. For the processes from GaBi 6.0, this study employed select metrics from the Tool for the Reduction and Assessment of Chemical and other environmental impacts (TRACI 2.1) developed by the United States Environmental Protection [38], which sources the 100-year global warming potential (GWP100) metric from Intergovernmental Panel on Climate Change (IPCC). Non-renewable energy is estimated based on a metric in the GaBi database [36], which sums all non-renewable energy inputs across the life cycle. For the processes from DataSmart LCI database, this study used the ReCIpe midpoint method, which is based on the method published by ecoinvent version 2.0, to evaluate non-renewable energy whereas GWP is also evaluated based on the 100-year impact factor proposed by IPCC. This study considered the lower heating value for non-renewable energy in both methods.

Goal Definition and Scoping

The design life of a drainage pipe is at least 50 years and could be up to 100 years [39–41]. For this reason, our study needed to evaluate a pipe material that maintains mechanical properties, minimizes life cycle costs, and reduces the risk of failure over a 50–100-year service life. In addition, the material needs to be produced at low cost to be competitive with alternative pipe materials, consume

less energy, and reduce possible health and safety risks during manufacturing compared to the traditional concrete, steel and polyvinyl chloride (PVC). As a result, HDPE was selected to be the pipe material in our study. Drainage pipe made from HDPE could be and has been engineered using post-consumer recycled HDPE [24]. However, both pristine and PCR-blended pipe are subjected to the slow crack growth (SCG), which is the main cause of failure in extruded HDPE and recycled pipe [42, 43]. According to Na and his colleagues, the presence of a small amount of nanoclay would enhance the stress crack resistance because the nanoclay particles, which have a unique two-dimensional geometry, act as obstructions to crack propagation [44]. We conducted this analysis to understand whether these alternative materials have environmental and economic merit for civil engineering infrastructure.

The goal of the study was to conduct prospective LCA and cost analysis of pipe made from nanoclay HDPE/PCR. The results were then compared with two materials: pristine HDPE and HDPE/PCR for environmental and cost advantages/disadvantages. The functional unit was defined as a 24-in diameter by 20-ft length pipe, the size of commercially manufactured corrugated HDPE pipe for highway drainage. The mass of such pipe based on pristine polymer is 226 lbs (103 kg) [45]. The mass of the HDPE/PCR and nanoclay HDPE/PCR pipe is discussed in “[Estimating Mass Change Using Mechanical Properties](#)” section. The function of highway drainage pipe is to convey and discharge storm water that flows within and along the highway right-of-way as well as under large parking lots. The alternative pipes in this study were assumed to perform the same function with the same geometry. Regarding the service lifetime, Na et al. [44] conducted a test to obtain the failure time and then used the J-integral numerical method to investigate the long-term performance of recycled and nanocomposite materials. The J-integral value has been used to characterize the strain energy release rate associated with the crack growth for a nonlinear elastic–plastic material [46]. The authors found that the addition of nanoclay in a recycled blend could extend the failure time of a polymer-based material. Therefore, it is reasonable to assume that the service lifetime of a nanoclay HDPE/PCR pipe can be the same or longer than that of a pristine HDPE pipe. For an optimistic cost analysis, the nanoclay content used throughout our study was set according to the most expensive HDPE nanocomposite among three levels of nanoclay contents: 2, 4, and 6 wt% [34]. The production cost of 6 wt% nanocomposite is the highest (see “[Cost of Pristine HDPE, HDPE/PCR and Nanoclay HDPE/PCR Pipes](#)” section) and thus is used for the analysis. Since this study investigates nanocomposite products that are still undergoing research, a comprehensive study on all environmental impacts and costs for the service lifetime was

not possible. However, the outcomes from this study can be used to guide the selection of environmentally preferable pipe materials, including materials still undergoing research prior to commercial scale production. This paper builds on prior research on prospective polymer-nanoclay composites; Roes et al. [10] and Schrijvers et al. [9] also studied the materials that were still in the R&D phase. The authors acknowledge that missing in-use and service lifetime data could make the assessment subject to substantial uncertainty.

The Life Cycle System Boundary

The LCA framework begins with the extraction of raw materials and ends with the creation of plastic pipe; therefore, the scope of the present study is referred to as cradle-to-gate LCA [13]. The production cost was the sum of the material, energy and pipe extrusion costs.

- For pristine HDPE, the cradle-to-gate LCA includes (1) extracting crude oil; (2) transporting crude oil to crude oil refinery by train or pipeline; (3) Refining oil to separate naphtha; (4) transporting naphtha to steam cracking by pipeline; (5) cracking naphtha to produce ethylene; (6) transporting ethylene to the polymerization plant by pipeline; (7) polymerizing HDPE; (8) pelletizing HDPE; (9) transporting polymer resin pellets to pipe manufacturer sites; and (10) manufacturing pipe.
- For the HDPE/PCR, the system boundary consists of (1) steps 1–8 above for pristine HDPE; (2) collecting and processing recycled resin; (3) transporting HDPE resin and PCR-HDPE to pipe manufacturers; and (4) manufacturing pipe.
- For the nanoclay HDPE/PCR, the system boundary consists of (1) steps 1–8 described in pristine HDPE boundary; (2) collecting and processing recycled resin; (3) mining and processing clay materials to nanoclay production; (4) transporting HDPE resin, PCR-HDPE and nanoclay master-batch to pipe manufacturers; and (5) manufacturing pipe.

Finally, this paper evaluates the sensitivity in life cycle GHG emissions and production cost of the nanoclay HDPE/PCR with respect to select uncertain model parameters that are expected to exhibit variability. Uncertain parameters consisting of the price of materials, processing energy (based on different technology) and diverse source-to-destination points were factored into upper and lower bound sensitivity estimation of the cost and environmental LCIA metrics. Scenario 1 (upper bound) and scenario 2 (lower bound) consist of the high and low values of energy consumption or cost assessment, respectively. Based on the range established in two scenarios, a single-variable sensitivity analysis was used to examine the parametric variability [47, 48].

Estimating Mass Change Using Mechanical Properties

The mass of a product importantly influences life cycle energy consumption and production costs [9, 10, 12]. With the introduction of alternative materials having unique material properties for a given product system, the mass of a new product is expected to vary. Thus, product mass can be used to compare different material properties because the mass of the material can be reduced while maintaining the required mechanical design properties for a given application. For examples, Roes et al. [10] and Schrijvers et al. [9] evaluated the mass reduction when substituting nanocomposite for conventional polymers in agricultural films. Lloyd and Lave [12] estimated the mass change of an automotive panel when replacing steel with aluminum and polypropylene nanocomposite. In our study, a corrugated pipe made from pristine HDPE is replaced with pristine HDPE blended with different weight percentages of nanoclay and recycled HDPE or by recycled HDPE, which can result in pipe mass changes. Roes et al. [10], Shrivijers et al. [9] and Lloyd and Lave [12] incorporated physical properties of materials along with functional unit definitions described in the ISO standards [35] to determine product mass changes that affect reference flows among plastic alternatives. These studies defined the material indices based on required performance properties of a specific product function (i.e. panel, column, plate etc.). The material indices are set on three parameters (a) Young's modulus (E); (b) tensile strength (σ); and (c) density (ρ) [49]. For corrugated pipes with the same geometric profile, the pipe stiffness is governed by the material modulus [35]. For a thermosetting plastic, it is impossible to define the Young's modulus due to the nonlinearity of the true stress–strain curve. Therefore, the elastic modulus was used in this study and this property was determined by the elastic–plastic model described in Na et al. [50]. Na and his colleagues also indicated that the mechanical properties of semi-crystalline polymer are generally governed by crystallinity. Therefore, crystallinity was used in our study rather than density.

The material index (M) with ratio of elastic modulus and crystallinity is used to evaluate the mass of pipe made from different materials. As the material index increases, the quantity of material, which is required to fulfill the same performance, reduces. This change in mass is calculated based on Eq. (1):

$$\text{Changes in Mass (\%)} = \left[\frac{\frac{\text{Elastic Modulus}}{\text{Crystallinity}} [\text{Conventional}]}{\frac{\text{Elastic Modulus}}{\text{Crystallinity}} [\text{Alternative}]} - 1 \right] \times 100 \quad (1)$$

Applying the mass reduction to the functional units based on pristine HDPE yields the mass of the products made with HDPE/PCR and nanoclay HDPE/PCR. Using Eq. (1), the mass savings of 20-foot HDPE/PCR and nanoclay HDPE/PCR pipes are 2.1 and 19.5 % less than pristine HDPE pipe, respectively. Table 1 summarizes the improvement in elastic modulus when PCR-HDPE and nanoclay are used. This improvement increases the material indices of HDPE/PCR and nanoclay HDPE/PCR and thus decreases the material used [10].

Inventory Data and Analysis

GaBi 6.0 database [36], DataSmart LCI database [51] together with public literature were used to develop the life cycle inventory. The LCI of the U.S electricity grid mix, pipeline transportation, and fuel used to operate trucks and train were collected from the databases. Major assumptions and relevant data are described in section “Major Assumptions and Data Sources”.

Pristine HDPE

Crude oil input for the production of 1 kg pristine HDPE was derived from the plastic to petrol ratio, which was provided in a study conducted by Nordell [52]. Nordell estimated 0.72 kg of crude oil is required to make 1 kg of pristine PE. The process energy and emissions of the ethylene production were obtained from the DataSmart LCI database [36, 51]. Since the database aggregates the input/output data for the crude oil-to-ethylene process, we subtracted the crude oil process data from the crude oil-to-ethylene process data in order to obtain the data for the ethylene production. As a result, the energy input for ethylene production by steam cracking, 14 MJ/kg of ethylene, aligns with the estimates from previous studies: 20 MJ/kg of ethylene from Vlachopoulos’s report [53], 25–40 MJ/kg of ethylene from Gielen et al. [54], 21 MJ/kg of ethylene from Bowen’s presentation [55]. Ren et al. [56] reported the energy consumption for different naphtha steam cracking technologies: 22–25 MJ/kg of ethylene from Technip [57], 21 MJ/kg of ethylene from ABB Lummus [57], 21 MJ/kg of ethylene from Linde AG [57], and 20–25 MJ/kg of ethylene from Stone and Webster [57].

For HDPE polymerization, the LCI presented challenges in data collection and modeling for slurry-phase and gas-phase polymerizations. The process data of the polymerization were assumed to be 5.5 MJ/kg for slurry-phase polymerization and 3.1 MJ/kg for gas-phase polymerization based on data from the IEA [1]. Also Vlachopoulos [53] estimated the energy consumption for slurry-phase polymerization to be 5 MJ/kg of polymer. In our study, the average value of these two estimates, 5.2 MJ/kg of polymer, was used for the slurry-phase polymerization. The energy input and GHG emissions for each process in the production of pristine HDPE are described in “Life Cycle Energy and GHG Emissions of 1 kg of pristine HDPE, PCR-HDPE and Nanoclay” section.

PCR-HDPE

The process data for the mechanical recycling route were obtained from published literature. According to the information from literature and personal communication with Envision Plastics, ~2.5 kg of plastic wastes are needed to produce 0.30 kg of PE (~ 10 %) [16, 21]. The energy consumption and environmental burden of processing plastic waste are only allocated to the 10 % PE. The sorting process at material recovery facilities (MRFs) were taken from the Franklin Associates’ report [22]. The energy input for compacting, baling, and sorting processes were obtained from Perugini et al. [21]. At the post-consumer recovery facilities (PRFs), the reprocessing procedure of recycled plastics consists of grinding, washing and pelletizing. The energy consumption for these gate-to-gate segments were adapted from Hubler et al. [14]. The energy input and GHG emissions for each process in the production of PCR-HDPE are described in “Life Cycle Energy and GHG Emissions of 1 kg of Pristine HDPE, PCR-HDPE and Nanoclay” section.

Nanoclay

For nanoclay production, an average of 0.84 kg Bentonite is required to produce 1 kg of nanoclay (see Table 6). The process data were provided by Nanocor Corporation [33], except for the energy consumed in the organic modification

Table 1 Estimated mass reduction based on material index

Material	Crystallinity (%)	Elastic modulus (MPa)	Material index (M)	Primary mass reduction (%)	Mass of 20-ft pipe (kg)
Pristine HDPE	67.2	869	12.9		103
HDPE/PCR	68.8 ^a	909 ^c	13.2	–2.1	101
Nanoclay HDPE/PCR	67.9 ^b	1091 ^d	16.1	–19.5	82

a, b, c, d Na et al. [50, 90]

process which was taken from Roes et al. [10]. The total energy input in our study, 44–51 MJ/kg of nanoclay, aligns with estimates from other studies such as 73 MJ/kg of nanoclay from Shrijvers et al. [9], 40 MJ/kg of nanoclay from Joshi's study [58], and 70 MJ/kg of nanoclay from Roes et al. [10]. The energy inputs and GHG emissions for each process in the production of nanoclay are described in "Life Cycle Energy and GHG Emissions of 1 kg of pristine HDPE, PCR-HDPE and Nanoclay" section.

Transportation

Crude oil is transported by train or pipeline, which depends on the infrastructure availability. All transportation legs utilized diesel commercial trucks or trains, with the distances determined from Google Maps [59]. Their LCI was taken from GaBi 6.0 [36]. While more efficient routes might be found given additional analytical inputs or using proprietary transportation resources (e.g. ports, terminals), the values used are sufficient for the purposes of this study. The transportation unit cost of different modes was obtained from literature [60–65] and listed in Table 2.

Pipe Extrusion

The Eastern region electricity grid mix, developed by PE International [36], was assumed as input to pipe extrusion given that pipe manufacture in the region is located in Swedesboro, New Jersey.

The costs for an extrusion line was estimated to range from \$0.04–\$1.27 per kg of plastic depending on the type of extruded products [10, 66]. The data from both Rauwendaal [66] and Roes et al. [10] were reliable since they were collected from industrial plants. Therefore, the average value of their estimates, \$0.65/kg or polymer, was used in our study.

Major Assumptions and Data Sources

Major assumptions regarding the system boundary, electricity grid mix and material processing are stated in Table 3. The relevant references for the processing data and material/processing costs are presented in Tables 4 and

5, respectively. The references for inputs of each gate-to-gate segment in the life cycle of HDPE, PCR-HDPE and nanoclay are presented in Tables 7, 8 and 9.

Pristine HDPE

The feedstock material for HDPE can be crude oil or natural gas while the most commonly used is crude oil [10, 53]. In the U.S, crude oil was usually obtained from six states including Alaska, California, New Mexico, North Dakota, Oklahoma and Texas. Texas produced 35 % of the crude oil in the US and became the largest crude oil supplier in 2013 [67]. In addition to these domestic oil resources, the U.S also imported crude oil from many countries from around the world, including Canada, Mexico, Qatar, Iraq, etc. According to the US Energy Information Administration, 32 % of the imported crude oil was from Canada in 2013 [68]. Therefore, Alberta (Canada) and Baytown (TX) were selected as the crude oil bays in this study. Our analysis assumed crude oil was transported by pipeline between the oil facilities within the state of Texas. For the crude oil imported from Canada, Frittelli et al. [69] stated that rail transportation of crude oil from Canada increased more than 20-fold since 2011. As a result, crude oil was transported by train from the Canadian crude oil bays to the Exxon Mobile oil refinery located at Baytown (TX) in order to separate naphtha. This hydrocarbon was then converted to light olefins such as ethylene, propylene and other products [70]. Next, Naphtha was transported from the oil refinery to a nearby petrochemical complex by pipeline. The ExxonMobil™ petrochemical complex (Houston, TX) is located 40 miles (64 km) from the ExxonMobil™ oil refinery (Baytown, TX) [71]. At a steam cracker unit of the petrochemical complex, naphtha was cracked into ethylene by the steam cracking method [70]. Then, ethylene entered the ExxonMobil™ polymerization plant by pipeline. The polymerization plant normally stays within the petrochemical complex. As such, the transport distance by pipeline was neglected in our study. At the polymerization plants, ethylene was compressed, cooled and converted to high density polyethylene (HDPE) at the reactors [72]. There are two common types of polymerization techniques: (1) slurry phase polymerization in which ethylene is polymerized in solution with the addition of Phillips Cr/Silica catalyst [73, 74]. This process requires temperatures of 85–110 °C and pressures of 30–45 bar [75], and (2) gas phase polymerization in which ethylene is in gaseous state during polymerization [1]. The gas phase polymerization, which was the most widely licensed and used polyethylene process in the world, operates at temperatures of 70–115 °C and pressures of 20–30 bar using a trimethylaluminum-silica catalyst [76]. After polymerization, appropriate amounts of antioxidants

Table 2 Energy unit cost of various transportation modes

	Unit cost	Transportation cost
Pipeline	[USD/gallon-mile]	0.040 ^a
Train	[USD/tonne-mile]	0.029 ^b
Truck	[USD/tonne-mile]	0.278 ^b

^a Ref. [91]

^b Refs. [60–62]

Table 3 Major assumptions and system boundaries

	Pristine HDPE	PCR-HDPE	Nanoclay
Feedstock production	Crude oil is transported by train from Alberta (Canada) to oil refinery in Baytown, TX (2500 miles (4000 km))	Recycled plastics is transported by truck from sources to the material recovery facilities (MRFs)	The excavation process has been done by 500 kW excavator operated by US diesel
	Diesel train (1000 ton total capacity) transport used with US diesel	Bailed plastic waste was transported by truck to the PE reprocessing plant (envision plastics)	Sodium bentonite (Na-bentonite) is transported by train from Wyoming to Mississippi
		Farthest MRFs are located in California [2600 miles (4200 km)]	
		Nearest MRFs are located in North Carolina [100 miles (160 km)]	
	Crude oil is transported by pipelines within Texas	The average traveling distance of incoming waste is 500 miles (800 km) by truck	The traveling distance is 1600 miles (2580 km)
	The traveling distance was assumed to be 62 miles (100 km)		
Pipeline: the average utilization ratio was calculated to be 28 %	Diesel truck (34–40 ton total capacity) transport used with U.S diesel	Diesel train (1000 ton total capacity) transport used with U.S diesel	
Electricity grid mix in Western Region	Electricity grid mix in Eastern Region	Electricity grid mix in Western Region	
The traveling distance of Naptha from oil refinery to petrochemical complex was assumed to be 40 miles (64 km)			
Material production			The nanocomposite contains 50 % nanoclay and 50 % HDPE resin carrier
	Electricity grid mix used in Eastern region	Electricity grid mix used in Eastern region	Electricity grid mix used in Western region
Pipe Formation	Single-screw extruder	Single-screw extruder	Twin-screw extruder
	Pristine HDPE pellets were transported to the pipe manufacturer by train	PCR-HDPE pellets were transported to the pipe manufacturer by train	Nanoclay masterbatch pellets were transported to the pipe manufacturer by train
	Electricity grid mix used in Eastern region	Electricity grid mix used in Eastern region	Electricity grid mix used in Eastern region

Table 4 Data for energy consumption of each material are obtained from literature

Processes	Sources
Crude oil extraction and production	[36, 51, 77]
Steam cracking	[36, 51, 56, 77]
PCR-HDPE	[14, 21, 22]
Nanoclay	[10, 33, 51]
Transportation by train	[36]
Transportation by truck	[36]
Transportation by pipeline	[36]

Table 5 Material and energy cost references

Materials/energy	Sources
Crude oil	[92]
Plastic waste	[93]
Bentonite	[94]
Maleic anhydride	[95]
Dimethyl dehydrogenated tallow	[96]
Electricity	[97]
Extrusion	[10, 66]

and stabilizers were added to the polymer puff for pelletization to be shipped by train to the pipe production sites, which is located in Swedesboro, New Jersey. The cradle-to-gate system diagram for pristine HDPE is shown in Fig. 1.

Post-consumer Recycled HDPE

Postconsumer HDPE was collected and separated with other post-consumer waste and plastics at material recovery facilities (MRFs). According to Franklin Associates

[77], the average travel distance of incoming materials was estimated to be ~500 miles (800 km). There are 1323 MRFs across the U.S: 561 residential type MRFs and 760 non-residential type MRFs [78]. They were classified into single-stream and dual stream MRFs. Single-stream MRFs process only one type of material, either fiber (paper and paperboard) or non-fiber (all other materials) [22]. Dual stream MRFs separate glass, plastic and metal out from the non-fiber materials. The sorting operations can range from manual sorting to highly mechanical systems, which use magnets, air classifiers, optical sorters etc. [77]. MRF technology levels for non-fiber lines were classified into four categories (1) level 1 has only manual separation with conveyor or balers; (2) level 2 involves the additional use of magnetic separators; (3) level 3 involves other separator technology such as eddy current, air classifier, trommels and an integrated sort system; and (4) level 4 has the additional use of computer- assisted technology [77]. According to Berenyi from Government Advisory Associates, 49 % of the MRFs have level 3 sorting technology [79]. The process energy data for the level 3 sorting technology was obtained from the Franklin Associate HDPE postconsumer report [22]. After plastics were sorted, postconsumer plastics were bailed and transported by truck to the plastic recovery facility (PRF), namely Envision Plastics. According to Envision Plastics, the mixed plastic bales were collected from MRFs across the US The farthest and nearest MRFs from Envision Plastics are located in California [2600 miles (4200 km)] and North Carolina [100 miles (160 km)], respectively. At PRF, mixed plastic bales were broken and sorted into

Polyethylene (PE) and other plastics. The PE was reprocessed by grinding, washing and pelletizing. The PCR-HDPE pellets were then transported by train to the pipe production site located in Swedesboro, New Jersey. The cradle-to-gate system diagram for PCR-HDPE is shown in Fig. 2.

Nanoclay Production

The nanoclay material, Nanomer[®] 1.44P, was provided in the form of a master batch by Nanocor. Nanoclay production begins with the raw clay (Sodium Bentonite (Na-Bentonite)) ready to be shipped by train from the based clays (Wyoming) to the nanoclay manufacturing plants in Mississippi (1600 miles (2580 km). Montmorillonite (MMT), which is the major constituent of Na-Bentonite, is used to produce nanoclays [32]. MMT belongs to the smectite group of clay, which consists of two tetrahedral sheets with sodium cations (1 nm apart) and one edge-shared octahedral sheet with aluminum hydroxide [80], which are held together by Van der Waals forces. As indicated in prior studies [32, 80], the purity of the clay can affect the final nanocomposite properties. Therefore, the centrifugation technique is used to eliminate as many impurities as possible such as amorphouse silica, calcite, kaolin etc. [32]. One important consequence of the charged nature of the MMT is that it is highly hydrophilic, which is incompatible with polyethylene. This results in the replacement of sodium cations by organic cations, namely dimethyle-dehydrogenated tallow ammonium, in the “organic modification” process before synthesizing

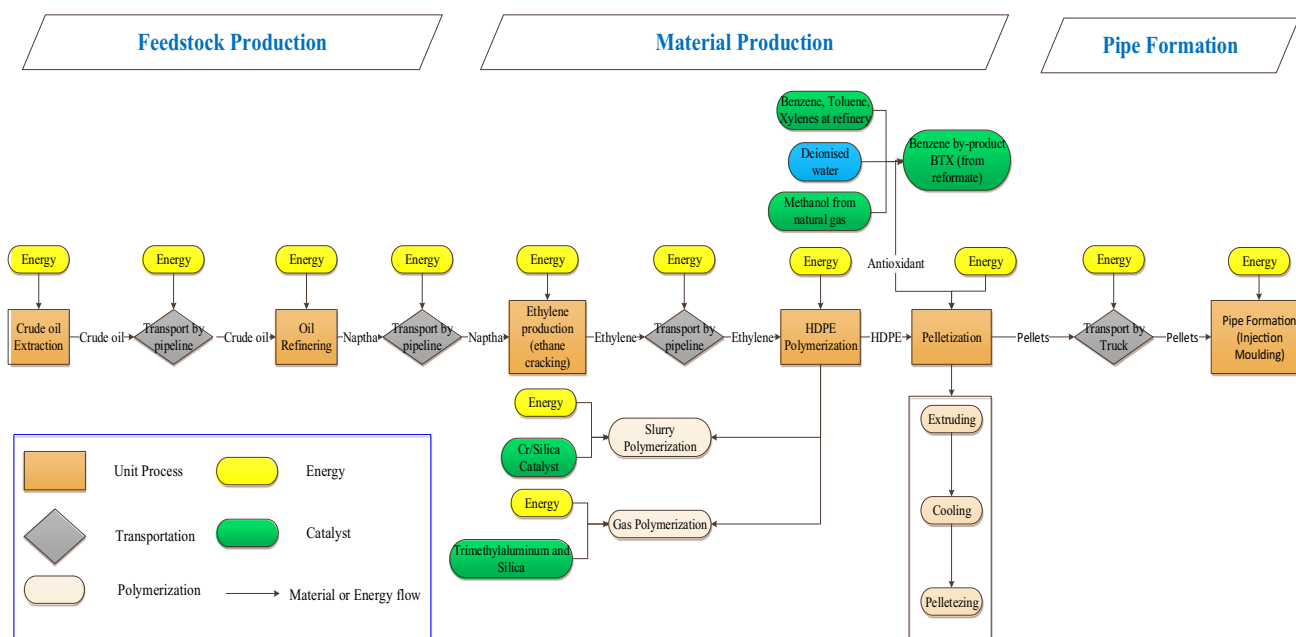


Fig. 1 Cradle-to-gate system diagram of 1 kg of pristine HDPE

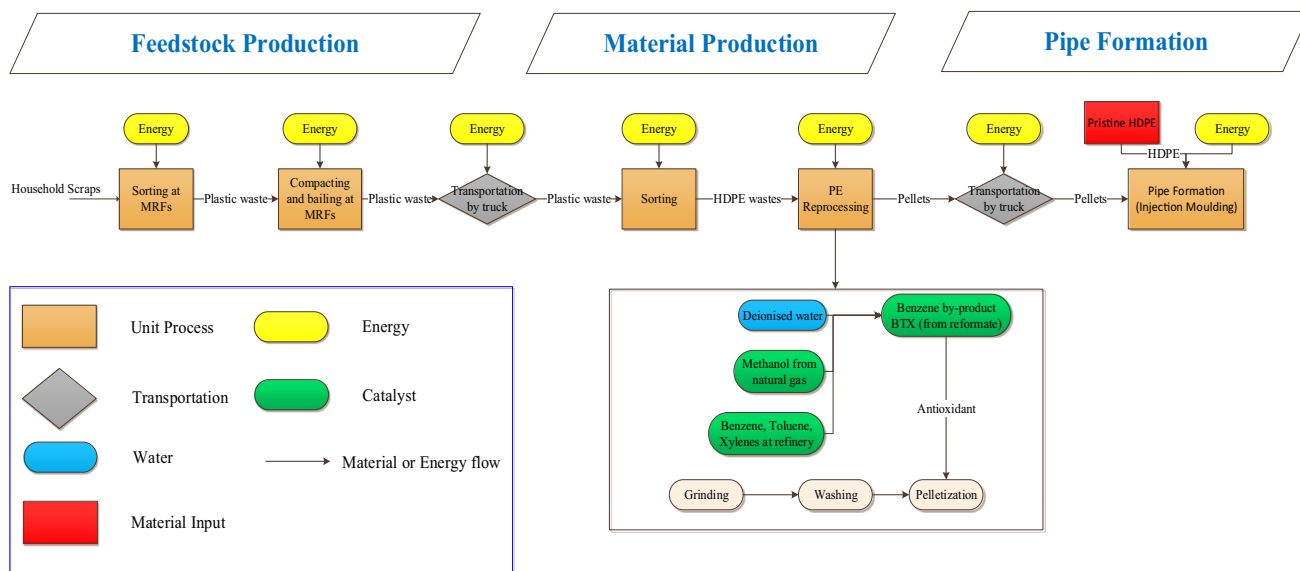


Fig. 2 Cradle-to-gate system diagram of 1 kg of PCR-HDPE

polymer/clay nanocomposites [34, 80]. The cation replacement transforms the surface properties of clay layers from hydrophilic to organophilic, which is compatible with the HDPE matrix. In addition, the interlayer space is widened, which enables polymer chains to migrate between the clay layers more easily. There are three methods for manufacturing polymer clay nanocomposites (1) in situ polymerization, in which a polymer precursor is inserted in between clay layers. The layered silicate platelets are expanded into the matrix by polymerization; (2) solution exfoliation, in which clays are swelled and dispersed into a polymer solution by solvent, and (3) melt intercalation, a procedure that applies intercalation and exfoliation of layered silicates in polymeric matrices during melting. Zeng et al. [81] stated that the most economically viable and straightforward approach is the melt intercalation method. While the blending is taking place in a twin screw extruder, a commonly used compatibilizer, maleic hydride modified polymers (MAP), is added to promote complete nanoclay dispersion. Finally, the master-batch product is dried and then pelletized. The master-batch product, which is provided by Nanocor, contains 50 % nanoclay and 50 % HDPE carrier resin [33]. The nanoclay pellets were then transported by train to the pipe production site located in Swedesboro, New Jersey. The cradle-to-gate system diagram for nanoclay is show in Fig. 3.

Uncertainties in Greenhouse Gas Emissions and Production Cost

A single variable sensitivity analysis was conducted to identify important parameters that contribute to variability in LCIA result metrics (GHG emissions and cost) in the life

cycle of the pipe materials. In the analysis, a single parameter was varied at the upper and lower bound uncertainty range (see Table 6 for parameter ranges and assumptions) while others were held constant at the average values.

Pristine HDPE

For the production of pristine HDPE, the crude oil was transported by either train or pipeline from two oil bays (Alberta or Baytown) to the oil refinery located in Baytown, Texas. Therefore, the energy demand varied with the transportation distance and mode. Scenario 1 contains the high energy inputs, which were derived from the longer transportation distance (Alberta, Canada to Baytown, TX) using the high energy-consuming transportation mode (train). In contrast, scenario 2 consisted of the lower energy inputs derived from the shorter transportation distance (within Baytown, Texas) and the low energy-consuming transportation mode (pipeline). Additionally, as described in “Pristine HDPE” section, the slurry-phase polymerization consumed more energy than that of the gas-phase polymerization. Therefore, the slurry-phase and gas-phase polymerizations were classified into scenarios 1 and 2 respectively.

PCR-HDPE

For the production of PCR-HDPE, the energy input of all processes relies on the material efficiency and transportation, which is dependent on the distance from Envision Plastics to the nearest and farthest MRFs. The transportation distance governs the energy difference between two scenarios since truck is the common mode. In this study,

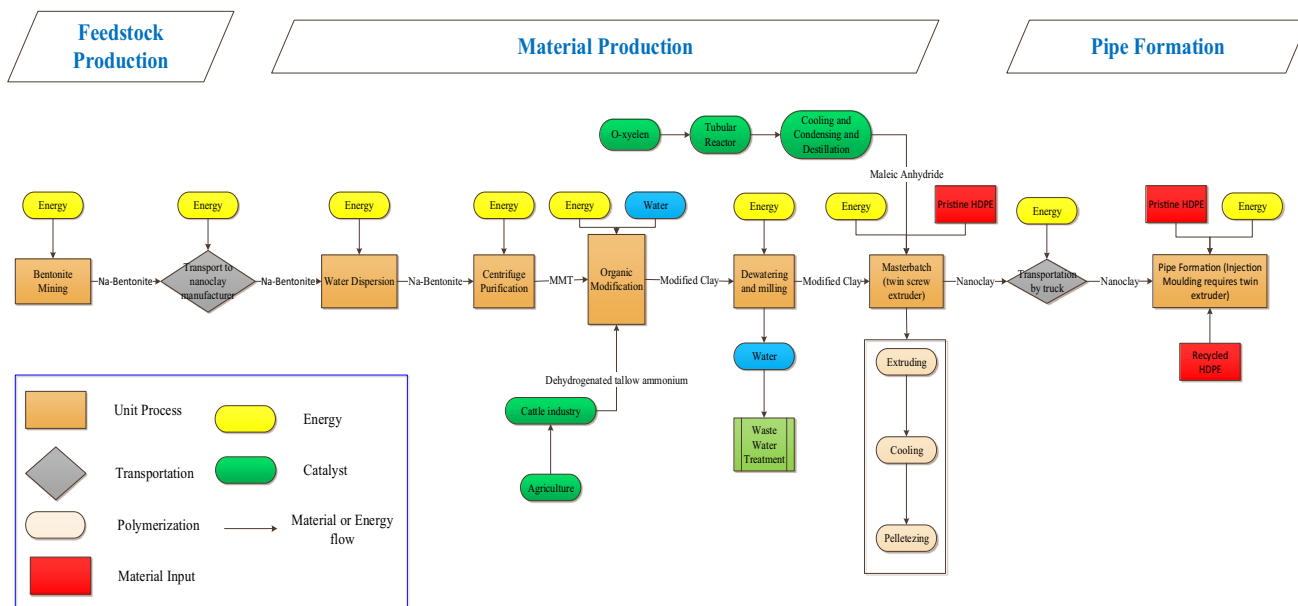


Fig. 3 Cradle-to-gate system diagram of 1 kg of Nanoclay

Table 6 Summary of model parameters for pristine HDPE, PCR-HDPE and nanoclay productions

Scenario parameters	Scenario 1	Scenario 2	Comments
<i>Key parameters contributes to the scenario analysis for GHG emissions</i>			
Pristine HDPE production	–		
Transport distance [km]: crude oil from bays to oil refinery	4000	100	<i>Scenario 1</i> Train from Alberta, Canada to Baytown, Texas oil refinery (4000 km), derived from Google Maps [59] <i>Scenario 2</i> Pipeline (100 km), derived from Google Maps [59]
HDPE polymerization [MJ/kg HDPE]	5.28	3.14	<i>Scenario 1</i> Slurry polymerization [1] <i>Scenario 2</i> Gas polymerization [1]
PCR-HDPE production	–		
Transport distance (km): plastics waste from MRFs to PRF	3.26	0.23	<i>Scenario 1</i> Truck from California (Farthest) to North Carolina (~4200 km), derived from Google Maps [59] <i>Scenario 2</i> Truck within North Carolina (Nearest) (~160 km), derived from Google Maps [59]
Efficiency of sorting (%)	90	75	<i>Scenario 1</i> Efficiency of an optical sorter obtained from a report prepared by Patrick Engineering [83]. <i>Scenario 2</i> Efficiency of a level 2 sorter from Perugini et al. [21]
Efficiency of reprocessing (%)	88	60	<i>Scenario 1</i> Efficiency of mechanical recycling system from Perugini et al. [21] <i>Scenario 2</i> Efficiency of mechanical recycling system from BIO Intelligence Service [82]
Energy from pristine HDPE production (MJ/kg HDPE)	71.4	68.1	<i>Scenario 1</i> Low value of pristine HDPE production <i>Scenario 2</i> High value of pristine HDPE production
Nanoclay production	–		
Energy from pristine HDPE production (MJ/kg HDPE)	71.4	68.1	<i>Scenario 1</i> High value of pristine HDPE production <i>Scenario 2</i> Low value of pristine HDPE production
<i>Key parameters contributes to the scenario analysis for production cost</i>			
Pristine HDPE production	–		
Crude oil (\$/kg crude oil)	0.45	0.34	<i>Scenario 1</i> Maximum crude oil price obtained from Index Mundi [92] <i>Scenario 2</i> Minimum crude oil price obtained from Index Mundi [92]

Table 6 continued

Electricity (\$/kg HDPE)	1.6	1.48	<i>Scenario 1</i> Electricity consumed in scenario 1 of pristine HDPE production <i>Scenario 2</i> Electricity consumed in scenario 2 of pristine HDPE production
Transportation diesel (\$/kg HDPE)	0.15	0.14	<i>Scenario 1</i> Diesel consumed in scenario 1 of pristine HDPE production <i>Scenario 2</i> Diesel consumed in scenario 2 of pristine HDPE production
PCR-HDPE production	–		
Plastic waste (\$/kg PSW)	0.02	0.01	<i>Scenario 1</i> Maximum plastic waste price reported by Kantchev [93] <i>Scenario 2</i> Minimum plastic waste price reported by Kantchev [93]
Electricity (\$/kg PCR-HDPE)	0.11	0.1	<i>Scenario 1</i> Electricity consumed in scenario 1 of PCR-HDPE production <i>Scenario 2</i> Electricity consumed in scenario 2 of PCR-HDPE production
Transportation diesel (\$/kg PCR-HDPE)	2.15	0.43	<i>Scenario 1</i> Diesel consumed in scenario 1 of PCR-HDPE production <i>Scenario 2</i> Diesel consumed in scenario 2 of PCR-HDPE production
Nanoclay production	–		
Bentonite clay (\$/kg clay)	0.07	0.06	<i>Scenario 1</i> Maximum clay price reported in USGS survey [94] <i>Scenario 2</i> Minimum clay price reported in USGS survey [94]
Maleic anhydride (compatibilizer) (\$/kg compatibilizer)	1.78	1.73	<i>Scenario 1</i> Maximum maleic anhydride price reported by Tecnon OrbiChem [95] <i>Scenario 2</i> Minimum maleic anhydride price reported by Tecnon OrbiChem [95]
Electricity (\$/kg HDPE)	1.6	1.48	<i>Scenario 1</i> Electricity consumed in scenario 1 of pristine HDPE production <i>Scenario 2</i> Electricity consumed in scenario 2 of pristine HDPE production
Transportation diesel (\$/kg HDPE)	0.15	0.14	<i>Scenario 1</i> Diesel consumed in scenario 1 of pristine HDPE production <i>Scenario 2</i> Diesel consumed in scenario 2 of pristine HDPE production

the minimum material efficiency of sorting and reprocessing were 75 and 60 %, which were reported in Perugini et al. [21] and BIO Intelligence Service [82] respectively. Perugini and colleagues considered a level-2 sorter, which is described in “Post-consumer Recycled HDPE” section. The maximum sorting efficiency was based on the efficiency of an optical sorter, which can achieve a maximum efficiency rate of 90 % based on data from Patrick Engineering and partners [83]. Regarding the maximum efficient rate of reprocessing, this study used the value reported in Perugini et al. [21], which is 88 %. As a result, the ranges for efficiency of sorting and reprocessing stages are 75–90 % and 60–88 %, respectively.

Nanoclay

It is important to determine how much Na-Bentonite clay is needed to produce 1 kg of nanoclay. The amount of Bentonite per kg nanoclay varies with MMT content. Previous

studies have reported different MMT content in Na-Bentonite [84, 85], showing a range by mass between 59 and 95 %. For that reason, the amount of MMT purified from Bentonite also fluctuates. Table 7 shows the amount of Na-Bentonite clay needed to produce 1 kg of MMT associated with different levels of MMT contents. The MMT is then organically modified and exfoliated into polymer matrix to produce nanoclay. At this stage, MMT is no longer the main component of nanoclay masterbatch due to the presence of pristine HDPE (approximately 50 %wt). Therefore, it requires less than 1 kg of MMT to produce 1 kg of nanoclay. According to Roes et al. [10], forming 1 kg of nanoclay requires 0.65 kg of MMT. Due to the lower demand of MMT, the amount of Na-Bentonite clay, required to make 1 kg of nanoclay, decreases accordingly (Table 7).

For the uncertainty analysis, scenario 1 includes the energy consumption corresponding to Na-Bentonite clay with lower MMT content and the higher energy to manufacture pristine HDPE. Scenario 2 contains the lower values of these parameters.

Table 7 Bentonite (with different MMT content) is needed for the production of 1 kg nanoclay

	Low	Average	High
MMT content in 1 kg of Na-bentonite clay (kg)	0.95	0.77	0.59
Bentonite needed to produce 1 kg MMT (kg)	1.05	1.30	1.69
MMT needed to produce 1 kg nanoclay (kg)	0.65		
Bentonite needed to produce 1 kg nanoclay (kg)	0.68	0.84	1.1

Production Cost

Scenarios 1 and 2 comprise the higher and lower prices per kg of HDPE, PCR-HDPE and nanoclay. In addition, scenarios 1 and 2 also include the high and low energy costs respectively, which were derived from energy consumption estimated in the LCA. Sources for feedstock and energy costs can be found in Table 5.

Results: Life Cycle Impact Assessment

This section presents results non-renewable energy input, GHG emissions, and cost for pristine HDPE, PCR-HDPE and nanoclay materials and for corrugated pipe made from pristine HDPE, HDPE/PCR and nanoclay HDPE/PCR.

Life Cycle Energy and GHG Emissions

Life Cycle Energy and GHG Emissions of 1 kg of Pristine HDPE, PCR-HDPE and Nanoclay

Pristine HDPE requires the highest input of energy among the three materials at 64 MJ/kg of pristine HDPE. This is mainly because of the high energy input required to extract

and refine crude oil. The extraction and refining of oil takes up 52 % of the total energy used to manufacture pristine HDPE. For the GHG emissions, the pristine HDPE is the second highest at 2.5 kg CO₂/kg of pristine HDPE (Table 8).

PCR-HDPE consumes the lowest energy, at 7.7 MJ/kg of PCR-HDPE as well as the lowest GHG emissions of 1.2 kg CO₂/kg of PCR-HDPE. The grinding and pelletizing processes consume 35 % of the total energy consumption (Table 9). In addition, the average travel distance of incoming PSW was assumed to be 500 miles (800 km) in this study, which could lead to an overestimate in energy consumption from transportation. A more accurate investigation could vary the results of the GHG emissions generated from transportation to capture the range of expected GHG emissions.

Nanoclay was the second highest energy consumer with 47 MJ/kg of nanoclay; however, on a unit basis it generates the largest GHG emissions at 3.2 kg CO₂/kg of nanoclay compared to the pristine HDPE and PCR-HDPE. The material production stage consumes more than 90 % of the total energy consumed in the nanoclay production, mainly due to the organic modification process, 19 MJ/kg of clay (Table 10).

Table 8 Life cycle energy and GHG emissions for the production of 1 kg of pristine HDPE

Processes	References	Energy input (MJ/kg)	High(+)/low(-)	GHG emission (kg CO ₂ /kg)	High(+)/low(-)
Crude oil extraction and production	Crude oil mix [36, 51] ^a	33	0/0	0.54	0/0
Transport crude oil from crude oil bays to oil refinery to extract naphtha	Diesel train [36] ^b	0.56	+0.56/−0.56	3.9×10^{-2}	+0.04/−0.039
Oil refinery	Petroleum production coproduct [36, 51] ^c	6.4	0/0	0.46	0/0
Transport naphtha from oil refinery to steam cracker at a petrochemical complex by pipeline	Pipeline [36] ^d	0.0036	0/0	4×10^{-4}	0/0
Ethylene (ethane cracking)	Ethylene [36, 51] ^c	14	0/0	0.2	0/0
Transport ethylene to polymerization plant by pipeline	Pipeline [36] ^f	0.005	0/0	0.001	0/0
HDPE polymerization	[1, 53]	4.2	+1.04/−1.07	0.67	+0.22/−0.17
Extrusion and pelletization	Plastic extrusion profile [36] ^e	3.2	0/0	0.48	0/0
Transport pellets to pipe manufacture by train	Diesel train [36] ^h	1.7	0/0	0.13	0/0
Antioxidant (1000 ppm)-	Benzene [36, 51] ⁱ	0.07	0/0	0.001	0/0
Total		64		2.5	

^{a, c, e, i} The data for these processes were developed in USEI by adopting the American industrial data

^e The data for these processes were developed in GaBi 6.0 by adopting the American industrial data

^{d, f} The data for this processes were developed in Gabi 6.0 by adopting the global industrial data

^{b, h} Train production, end-of-life treatment of the train and upstream processes for fuel production (e.g. exploration and production of fuels, refinery, transport) are not included in the data set. The upstream profile of diesel, which is used to operate train, is developed based on the US data

Table 9 Life cycle energy and GHG emissions for the production of 1 kg of PCR-HDPE

Processes	References	Energy input (MJ/kg)	High(+)/low(-)	GHG emission (kg CO ₂ /kg)	High(+)/low(-)
Transporting household scraps to MRFs by truck	Truck [36] ^a	1.2	0/0	0.082	0/0
Sorting at MRFs (electricity)	[22]	0.6	+0.07/-0.1	0.12	0/0
Compacting and bailing at MRFs (electricity)	[21]	0.16	+0.02/-0.03	0.025	0/0
Transportation (from MRFs to envision plastics at North Carolina)	Truck [36] ^a	1.8	+1.5/-1.5	0.12	+0.11/-0.11
Sorting	[21]				
Diesel		0.14	+0.01/-0.01	0.07	+0.01/-0.01
Electricity		0.21	+0.02/-0.02	0.032	+0.003/-0.003
PE reprocessing					
Washing	[14]	0.25	+0.06/-0.04	0.05	+0.01/-0.01
Grinding	[14]	0.78	+0.21/-0.11	0.16	+0.04/-0.03
Extruding and pelletizing	[14]	2.2	+0.6/-0.3	0.3	+0.1/-0.0
Transport pellets to pipe manufacturing	Truck [36] ^b	0.29	0/0	0.21	0/0
Antioxidant (1000 ppm)	Benzene [51] ^c	0.01	0/0	0.008	0/0
Total		7.7		1.2	

^{a, b} Truck production, end-of-life treatment of the truck and the fuel supply chain (emissions of exploration, refinery, transportation etc.) are not included in the data set. The upstream profile of diesel, which is used to operate train, is developed based on the US data

^c The data for these processes were developed in USEI by adopting the American industrial data

Table 10 Life cycle energy and GHG emissions for the production of 1 kg of nanoclay

Processes	References	Energy input (MJ/kg)	High(+)/low(-)	GHG emission (kg CO ₂ /kg)	High(+)/low(-)
Bentonite extraction	Excavator and truck transport ^a	0.22	+0.07/-0.04	0.015	+0.005/-0.003
Transport by train	Rail transport [36] ^b	0.84	+0.26/-0.16	0.063	+0.02/-0.012
Water dispersion	[33]	0.086	+0.024/-0.016	0.014	+0.004/-0.003
Centrifuge purification	[33]	0.30	+0.09/-0.057	0.048	+0.014/-0.009
Organic modification (electricity)	[10]	19	+5.7/-3.5	2.9	+0.9/-0.56
Dewatering/drying (electricity)	[33]	0.20	+0.058/-0.038	0.032	+0.01/-0.006
Milling (electricity)	[33]	0.40	+0.12/-0.077	0.064	+0.019/-0.012
Transport pellets to pipe manufacturer	Truck [36] ^c	1.2	0/0	0.087	0/0
Dimethyl dehydrogenated tallow	Ammonium salt [36] ^d	3.8	0/0	0.33	0/0
Maleic Anhydride (compatibilizer, 3000 ppm)	Maleic anhydride [36, 51] ^e	0.12	0/0	0.02	0/0
Master batch (50 % nanoclay + 50 % HDPE)		47		3.2	

^{a, c} The data for these processes were developed in USEI by adopting the American industrial data

^d The data for these processes were developed in Gabi 6.0 by adopting the German industrial data

^{b, e} Truck and train productions, end-of-life treatment of the truck/train and the fuel supply chain (emissions of exploration, refinery, transportation etc.) are not included in the data set. The upstream profile of diesel, which is used to operate truck/train, is developed based on the U.S data

Fig. 4 Life cycle energy for the production of 20-foot pristine HDPE, HDPE/PCR and nanoclay HDPE/PCR pipes (at average value). *Main bars* represent average values, *error bars* represent high and low values

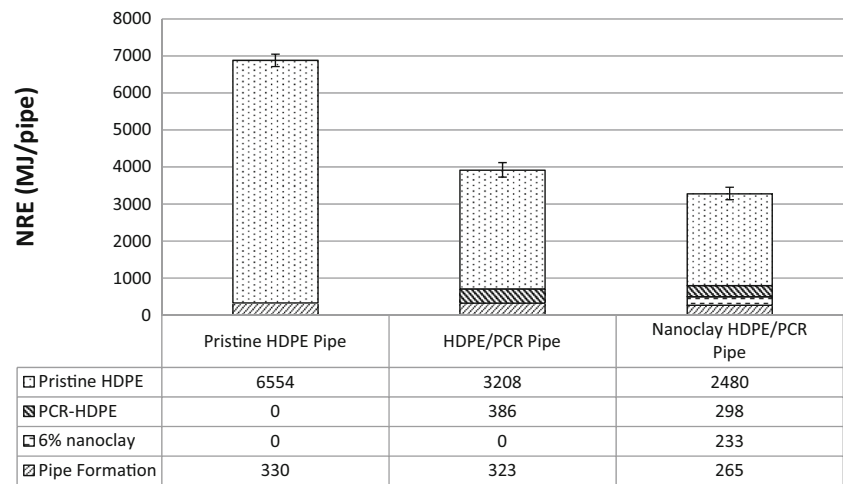
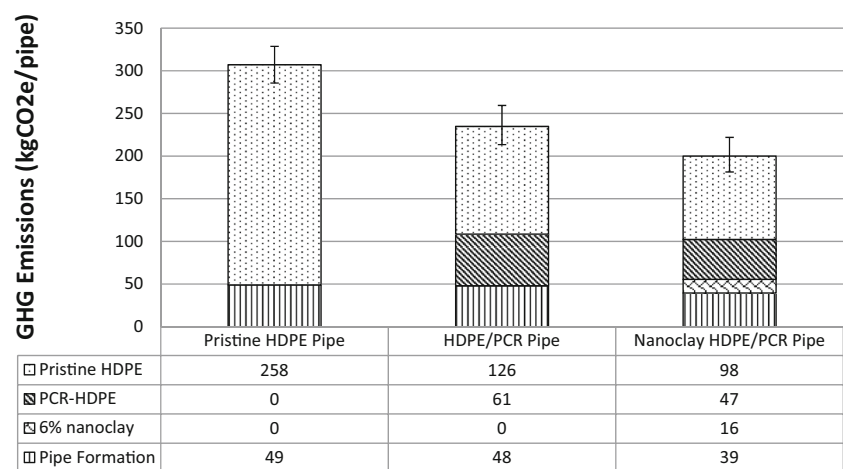


Fig. 5 Life cycle GHG emission for the production of 20-foot HDPE, HDPE/PCR and nanoclay HDPE/PCR pipes. *Main bars* represent average values, *error bars* represent high and low values



Life Cycle Energy and GHG Emissions of Pristine HDPE, HDPE/PCR and Nanoclay HDPE/PCR Pipes

Pristine HDPE pipe generates the largest GHG emissions and consumes the most energy compared to HDPE/PCR and nanoclay HDPE/PCR pipes (Figs. 4, 5). On average, the pristine HDPE pipe consumes 42 % more energy than HDPE/PCR and 52 % more energy than nanoclay HDPE/PCR pipes (Fig. 4; Table 14). The main source for the GHG emissions of pristine HDPE pipe comes from the production of pristine HDPE (95 %). The production of pristine HDPE also makes up a large portion of total GHG emissions produced from HDPE/PCR and nanoclay HDPE/PCR pipe manufacturing, 81 and 75 % respectively (Table 14).

PCR-HDPE contributes much less to the total energy input and GHG emissions than does pristine HDPE for both HDPE/PCR and nanoclay HDPE/PCR pipes. In these two pipes, PCR-HDPE contributes 9–10 % and 23–26 % to the energy consumption and GHG emissions, respectively

(Table 14). Both HDPE/PCR and nanoclay HDPE/PCR pipes require slightly different levels of energy input. The addition of nanoclay in HDPE/PCR pipe decreases the energy consumption and GHG emissions by around 16 % compared to the HDPE/PCR pipe (Figs. 4, 5). This is due to the fact that the mass of the nanocomposite pipe is lighter. The 6 wt% of nanoclay is a high concentration for polyethylene nanocomposite. Thus, the impact of nanoclay on energy consumption and GHG emissions will be even smaller at a lower nanoclay weight percentage.

Production Cost

Cost of Components 1 kg of Pristine HDPE, PCR-HDPE and Nanoclay

Pristine HDPE is the second most expensive component; its price ranges between \$1.6 and 1.8/kg. The price of PCR-HDPE is the least expensive ranging between \$0.6 and 2.3/kg. The nanoclay price ranges from \$6.4 to 6.6/kg, which is

Table 11 Production cost of 1 kg of pristine HDPE, PCR-HDPE and nanoclay

	Unit/kg	Average	High(+)/low(-)
Material cost (HDPE)	\$/kg	0.29	+0.03/−0.05
Material cost (PCR-HDPE)	\$/kg	0.03	+0.01/−0.01
Material cost (nanoclay)	\$/kg	5.5	+0.04/−0.03
Energy cost (HDPE) ^a	\$/kg	1.3	+0.03/−0.03
Energy cost (PCR-HDPE) ^a	\$/kg	1.05	+1.2/−0.54
Energy cost (nanoclay) ^a	\$/kg	1.03	+0.05/−0.07
Production cost (\$/1 kg of material)			
HDPE	\$/kg	1.6	+0.06/−0.07
PCR-HDPE	\$/kg	1.1	+2.3/−0.55
Nanoclay	\$/kg	6.5	+0.1/−0.1
<i>Production cost (\$/1 kg of material)</i>			
HDPE	\$/kg	1.6	+0.06/−0.07
PCR-HDPE	\$/kg	1.1	+2.3/−0.55
Nanoclay	\$/kg	6.5	+0.1/−0.1

^a Derived from the transport and processing energy

Table 12 Production cost of nanocomposite with 2, 4 and 6 wt% nanoclay

	Unit cost (\$/kg)	2-wt% nanocomposite [cost (\$)/(weight fraction (%))]	4-wt% nanocomposite [cost (\$)/(weight fraction (%))]	6-wt% nanocomposite [cost (\$)/(weight fraction (%))]
<i>20-foot nanoclay HDPE/PCR pipe</i>				
HDPE	1.6	64/(49)	63/(48)	62/(47)
PCR-HDPE	1.1	45/(49)	44/(48)	43/(47)
Nanoclay	6.5	11/(2)	22/(4)	32/(6)
Extrusion	0.65	54	54	54
Production cost (\$/pipe)		173	182	190

Costs by material input and extrusion are included

the highest of all three materials (Table 11). The energy cost contributes more to the total cost of these materials, except for nanoclay (Table 11).

Cost of Pristine HDPE, HDPE/PCR and Nanoclay HDPE/PCR Pipes

The nanoclay wt% in our study was determined based on the highest production cost of the nanocomposite. The HDPE nanocomposite with 6-wt% nanoclay is the most expensive (Table 12).

The production cost of pristine HDPE pipe is \$230/pipe, which is 13 and 17 % higher than HDPE/PCR and nanoclay HDPE/PCR pipes, respectively (Fig. 6). Furthermore, the production cost of pristine HDPE contributes 40 and 32 % to the production cost of HDPE/PCR and nanoclay HDPE/PCR pipes, respectively (Table 15). For these alternative pipes, PCR-HDPE contributes 22–28 % of the production cost. Although nanoclay is more expensive than the other two components, it only constitutes a small

fraction in weight (6-wt%) of nanoclay HDPE/PCR and thus contributes only ~17% to the production cost of the nanocomposite pipe (Table 15). The extrusion cost also plays a significant role in the production cost of all pipes since it contributes 28–33 % of the production cost.

Sensitivity Analysis

Life Cycle GHG Emissions

The ranges of GHG emissions of three material components are presented in Tables 7, 8 and 9. The high, low and average (base) GHG emissions of the production for pristine HDPE, HDPE/PCR and nanoclay HDPE/PCR pipes are described in Table 14. The results of the sensitivity analysis for HDPE, PCR-HDPE, and nanoclay parameter inputs on the nanocomposite pipe’s GHG emissions are presented in Fig. 7.

The manufacturing of pristine HDPE has the greatest influence on the average (base) GHG emissions of nanoclay

Fig. 6 Production cost of 20-foot pristine HDPE, nanoclay HDPE/PCR and HDPE/PCR pipes. *Main bars* represent average values, *error bars* represent high and low values

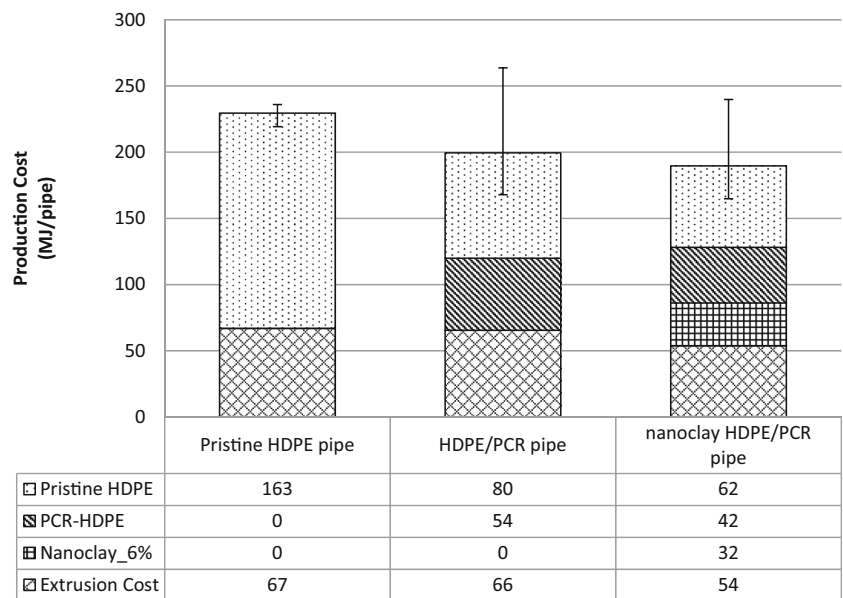
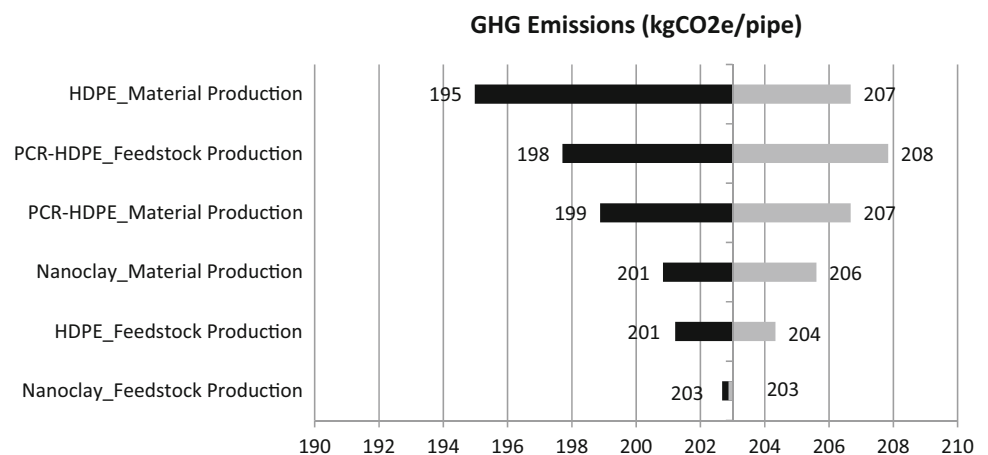


Fig. 7 Sensitivity analysis of GHG emissions of HDPE, PCR-HDPE and nanoclay in the nanoclay HDPE/PCR. The tornado diagram shows that GHG emissions are most sensitive to the material production stage of pristine HDPE and least sensitive to the material production stage of PCR-HDPE. An increase in GHG emissions sensitivity is shown in 50 % gray; and a decrease in GHG emissions sensitivity is shown in black



HDPE/PCR pipe, which is 200 kg CO₂ e/kg (Fig. 7; Table 14). This manufacturing stage can impose a variation in the base GHG emissions by +4/−6 kg CO₂ e/kg (+3/−2 %). This variation was mainly due to the different polymerization techniques, which consumes various levels of energy.

The feedstock production phase of recycled plastic has the second-largest impact on the base GHG emissions of the nanocomposite pipe since it can cause the base value to vary by +5/−4 kg CO₂ e/kg (+2.3/−1.8 %). These results from the large waste collecting radius of MRFs considered in our study, which led to a large variation in transportation energy consumption.

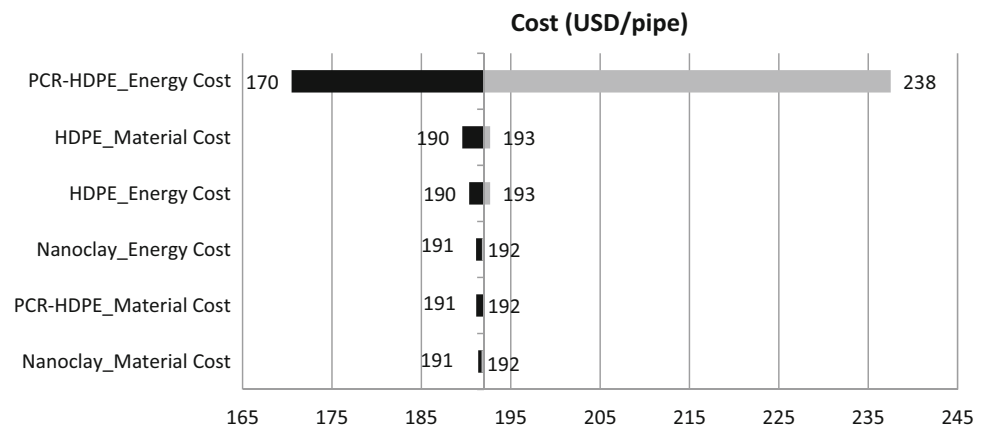
The clay mining process has the least effect on the GHG of nanoclay HDPE/PCR pipe because the entire reprocessing procedure consumes minimal energy (Fig. 7). The

results of the sensitivity analysis indicate the important contribution of polyethylene to the overall GHG emissions of the nanocomposite.

Production Cost

Sensitivity analysis results (Fig. 8) show that a variation in the energy cost for collecting, baling, transporting and reprocessing recycled PE can lead to the most adverse or positive effect on the production cost of nanoclay HDPE/PCR pipe. The variation in energy cost of PCR-HDPE (\$170–\$238/pipe), mainly due to transportation by truck, can change the average cost of the nanocomposite pipe by +\$47/−\$21/kg (+25/−11 %), whereas all the other

Fig. 8 Sensitivity analysis of cost of each component in the nanoclay HDPE/PCR. The tornado diagram shows that cost is most sensitive to energy cost of PCR-HDPE. An increase in cost is shown in 50 % gray; and a decrease in cost sensitivity is shown in black



parameters may cause variation in the nanoclay HDPE/PCR pipe cost by ≤ 1 % of the average.

Discussion: Life Cycle Interpretation

Life Cycle Assessment

The mass of pipe influences the life cycle energy and GHG emissions of pristine HDPE and alternative pipe. The material indices, which were derived from physical properties [49], were adopted in other studies [9, 10, 12] to estimate the decrease in weight of nanocomposite products. These studies used the elastic modulus and density values from a variety of literature to calculate weight reduction whereas our study used the crystallinity and elastic modulus obtained from our research team.

Our study evaluated the energy consumption per kg of pristine HDPE to be 62–65 MJ. This estimate agrees with a study by CSIRO [86] in which the author reported the energy consumption for PE production to be 75–103 MJ/kg of PE. The average GHG emissions of pristine HDPE in our study are 24 % higher than the estimate in Brogaard et al. [87] and 8 % higher than in Franklin Associate's report [77]. Brogaard et al. [87], Franklin Associates and CSIRO [22, 86, 87] found that the production of pristine HDPE had a major impact on the GHG emissions of its associated products. This results from the high embodied energy and emissions used in the feedstock stage of plastic manufacturing. Their finding resonates with our analysis; however, the overall discrepancy between their study and ours comes from the data collection methods and the quality of background information of various datasets. Whereas Brogaard and colleagues [87] collected and organized the GHG emissions of pristine HDPE from 26 different datasets, Franklin Associates [22] collected the process data from the manufacturing plants across the US.

Further, Brogaard et al. [87] and Franklin Associates [22] also evaluated the environmental burden and energy demand for recycling polyethylene, respectively. Compared to Brogaard's study, the average GHG emissions of PCR-HDPE in our study, 1.4 kg CO₂/kg of PCR-HDPE, is 62 % higher. The average energy consumption for HDPE/PCR presented in our study is 32 % higher than the energy estimate in Franklin Associate's report,

The environmental impacts of nanoclay production were derived from the energy input provided by Nanocor Inc. [33]. The average GHG emissions in our study compare well with prior research by Roes et al. [10], Joshi et al. [58] and Schrijvers et al. [9]. These earlier studies derived the energy consumption and GHG emissions to produce nanoclay from European databases. Utilizing the results from these studies, the highest and lowest GHG emissions per kg of nanoclay are 3.6 and 1.5 kg CO₂ e, respectively.

The system boundary, transportation modes and distances in our analysis were specified by precise locations in the US based on polymerization facilities and pipe extrusion manufacturing facilities, unlike the study by Franklin Associates, which assumed general distances and transportation modes. In their work, Franklin Associates apportioned crude oil transportation requirements among ocean tankers (from Alaska to the lower 48 states), pipelines and barges (domestic transportation of crude oil), whereas our study assumed rail (from Canada) and pipeline (in the US) as the primary transportation modes for crude oil. In Franklin Associates' report, the foreign and domestic crude oil supply data were outdated since they were obtained in 2003. The current supply data in our study were expected to change the logistics and its relative energy demand.

Our analysis obtained the process data for HDPE from the GaBi 6.0 and DataSmart LCI databases (e.g. the energy inputs and GHG emissions for crude oil production and naphtha steam cracking). The environmental modules for

these processes were developed according to the energy conditions in the United States. Natural gas is the main feedstock used to produce ethylene in the US. Therefore, the energy consumption and GHG emissions from the feedstock stage (mainly processing raw natural gas) of polyethylene production are expected to be different than the current results. Review of literature (Table 13) presents different estimates of three performance metrics for the production of HDPE, PCR-HDPE and nanoclay, as compared with our results.

Our study emphasizes that the substitution of pristine HDPE by PCR-HDPE significantly improves the environmental performance and production cost of corrugated drainage pipe. Approximately 43 % of the energy inputs and 15 % production cost are reduced by decreasing to 50 wt% pristine HDPE. The use of conventional plastics has been a great concern because of the high energy requirements during their feedstock production stage. Our study agreed with many previous studies [4, 7, 9, 10, 14] that the extraction and production of crude oil demands a great amount of energy and thus significantly contributes to environmental impacts, specifically GHG emissions. To mitigate these resource and environmental damages, it is important to research and find potential substitution for conventional plastics. Those alternatives should not only fulfill the performance level requirements (comparable with pristine HDPE), they should maintain competitive production costs while addressing environmental goals.

Production Cost

The production cost of pristine HDPE pipe is the highest compared to the other two pipe systems. The production cost of the pristine HDPE pipe varies from \$220 to \$236. The selling price of a pristine HDPE pipe, as quoted from commercial data, is approximately \$15.9/ft [88]. In other words, it costs \$318/20-ft pipe. It is reasonable to assume that a pipe manufacturer would set the selling price of a pipe to at least 30 % higher than the production cost. Under this assumption, the average selling price would be approximately \$299/20-ft pipe or \$15/ft in our study. This estimate is in line with that reported by Pluimer [88]. The authors believe that the result of this study would vary depending on logistics.

The use of PCR-HDPE in the pipe decreases the production cost by an average of 15 %, compared to the pristine HDPE pipe. Similarly, the substitution of pristine HDPE by nanocomposite reduces the pipe cost by 17 %. However, this trend did not appear in the upper bound; the production cost of the recycled material pipe could exceed the cost of the pristine HDPE pipe, which defeats the purpose of reducing cost (Table 15). This issue can be explained by the sensitivity analysis results. In fact, the uncertainty in energy cost for PCR-HDPE was shown to be the largest impact on the production cost of nanoclay HDPE/PCR. This is due to a large variation in transportation distance by truck (597–3107 miles (960–5000 km)).

Table 13 Comparison of different studies concerning the energy inputs, GHG emissions and cost of pristine HDPE, PCR-HDPE and nanoclay

	Energy inputs (MJ/kg)	GHG emissions (kg CO ₂ e/kg)	Cost (USD/kg) ^a
<i>HDPE</i>			
This study	68–71	2.8–3.3	1.6–1.8
Roes et al. [10]	50	–	–
Brogaard [87]	–	0.7–3.1	–
Franklin Associates [77]	84 ^b	2.3 ^c	–
Ambrose [86]	75–103		
<i>PCR-HDPE</i>			
This study	7.7–11	1.4–1.6	0.6–2.3
Franklin Associates [22]	5.8	–	–
Brogaard [87]	–	0.21–0.53	–
<i>Nanoclay</i>			
This study	48–55	3.2–4.2	6.5–6.7
Roes et al. [10]	70	3.6	6.9–15.7
Schrijvers et al. [9]	73	3.2	–
Joshi [58]	40	1.5	–

^a Material cost

^b Energy inputs include the production of extracting crude oil (46.84 MJ/kg), refining petroleum products (3.63 MJ/kg), producing ethylene (17.7 MJ/kg), and producing HDPE (15.5 MJ/kg)

^c GHG emissions include the production of extracting crude oil (0.0064 kg CO₂ e/kg), refining petroleum products (1.127 kg CO₂ e/kg), producing ethylene (1.25 kg CO₂/kg), and producing HDPE (2.43 × 10⁻⁴ kg CO₂/kg)

This transport mode was estimated to be the most expensive mode compared with other transport means (e.g. train, pipeline). In our study, the transportation energy for three materials was strongly dependent on the locations of resources and plants. Because of that, the transportation energy consumption and cost could vary with different scenarios.

Interpretation of Study Results

Regarding the performance of buried pipe, it is not only dependent on pipe's mechanical properties but also it relies on the uniformly well-compacted soil surrounding the pipe. Soft soil or compacted soil on one side will allow for deformation, which could lead to collapse or buckling of the pipe [40]. Therefore, proper installation in which equipment is needed to excavate a trench and lift the pipe in place is critical to the service life of the pipe. These steps would result in energy consumption and GHG emissions released from the excavated soil. On top of that, there are energy consumption, GHG emissions and costs associated with the frequent repair of failed joints, replacement of collapsed pipe resulting from erosion during service. At the end of a pipe's life, energy consumption and emissions result from a number of activities such as soil excavating, pipe transporting, pipe recycling, and energy recovering or landfilling. In some cases, study of the end of life of drainage pipes could be ignored if they were left beneath the ground after being disconnected from the network [89]. Further research should incorporate the in-use and end of life (i.e. pipe is recycled or landfilled) data to accomplish a cradle-to-grave life cycle study.

Conclusion

This LCA study shows that the nanocomposite material decreases GWP and production cost. The long term stress cracking resistance of this material was also shown to be similar to or greater than its fossil counterpart as noted by Na and colleagues [44], who used the J-integral method to predict the fracture behavior of nanocomposites. The GHG emissions of nanoclay HDPE/PCR decrease significantly due to the minimal dependence on the crude oil extraction and processing stages. From this research, the pipe, which is made from nanocomposite, was evaluated to be lighter than the conventional material. This will reduce the labor cost and the energy consumed during installation and transportation. For these reasons, this alternative holds great promise to pipe investors for replacing conventional polymers. However, the in-use data are still missing since the investigated nanocomposite in this study is still under research, which leads to the difficulty of justifying the use

of this material in industry. Although nanoclay HDPE/PCR is still in its infancy, research and development is ongoing to enhance its quality with the intention of replacing conventional polyethylene in producing non-pressure drainage pipe. The results show the resource, environmental, and economic tradeoffs when replacing HDPE resin by recycled plastics and adding small fractions of nanoclay to enhance the mechanical properties of polymeric nanocomposite pipe. From an economic point of view, the substitution of pristine resin with nanoclay (small fraction) and recycled plastic in pipe reduced the production cost. The production cost of the HDPE/PCR and nanoclay HDPE/PCR pipes is 12–17 % less than that of the pristine HDPE pipe. This study concludes that the use of recycled HDPE and nanoclay have clear environmental and economic advantages over pristine HDPE because a large portion of the energy consumed to produce the crude oil is avoided, which reduces the GHG emissions and mitigates the energy cost of the feedstock production. Results of the sensitivity analysis suggest that a wide range of energy cost of PCR-HDPE can incur significant variability in the total cost of the nanocomposite. This is caused by a large variation in transportation distance by truck. Results of the energy cost (process and transport) may be quite different in regions due to the change in the upstream profile of the supplying electricity grid. This study shows the minimal impacts of nanoclay on the production cost of nanocomposite. In order to estimate the GHG emissions of the recycled plastics, the distance of the incoming plastic waste was assumed based on the responses of a few MRFs 500 miles (800 km). Future work should further investigate a variety of MRFs in order to better estimate the radius of incoming waste materials, especially plastic waste. The results from this study are a preliminary step to shed a light to a more holistic green polymer research for drainage pipe applications.

Future Work

Our research included a sensitivity analysis, to characterize upper and lower bounds of environmental LCIA and cost metrics; however, such an analysis could be improved with a full analysis of uncertainty using Monte Carlo sampling techniques, whereby additional data would be collected to characterize the variability in life cycle processes. In our ongoing research we are aggregated data sets that can be resampled using Monte Carlo simulation to produce stochastic LCIA metrics. By employing probabilistic methods, better confidence intervals on cost and environmental metrics for each pathway can be generated, which would then increase the value of a life cycle study.

This study assesses only GHG emissions and NRE for the production phase of pipe (cradle-to-gate). Wang et al. [39] noted that pipe materials and their lifespan affect stormwater runoff quality and land imperviousness. Through this lens, Wang et al. [39] relates the environmental problems of stormwater runoff, such as disturbance to aquatic ecosystems and adverse impacts on human health, commercial and recreational activities to pipe material selection and design. Furthermore, the polluted runoff is sometimes discharged directly to the ocean with little to no treatment. As a result, future researches may include evaluation of LCIA metrics relevant to the in-use and disposal of a drainage infrastructure system such as

eutrophication, acidification, human toxicity, freshwater aquatic ecotoxicity and marine aquatic ecotoxicity.

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Appendix

See Tables 14 and 15.

Table 14 Life cycle energy and GHG emissions for the production of (1) 20-foot pristine HDPE pipe, (2) 20-foot HDPE/PCR pipe and (3) 20-foot nanoclay HDPE/PCR pipe

	Amount per kg of resin	Life cycle energy (MJ per HDPE pipe)		Life cycle GHG emissions (kg CO ₂ e per HDPE pipe)	
		Average	High (+)/low (–)	Average	High (+)/low (–)
Percentage of pristine HDPE	1	6554	+168/–168	258	+22/–22
Percentage of PCR-HDPE	0	0	0	0	0
Percentage of nanoclay	0	0	0	0	0
Pipe extrusion		330	0	49	0
Total		6883		307	

	Amount per kg of resin	Life cycle energy (MJ per HDPE/PCR pipe)		Life cycle GHG emissions (kg CO ₂ e per HDPE/PCR pipe)	
		Average	High (+)/low (–)	Average	High (+)/low (–)
Percentage of Pristine HDPE	0.50	3208	+82/–82	126.4	+ 11/–11
Percentage of PCR-HDPE	0.50	386	+121/–107	61	+14/–11
Percentage of Nanoclay	0	0.0	0	0	0
Pipe extrusion		323	0	48	0
Total		3917		235	

	Amount per kg of resin	Life cycle energy (MJ per nanoclay HDPE/PCR pipe)		Life cycle GHG emissions (kg CO ₂ e per nanoclay HDPE/PCR pipe)	
		Average	High (+)/low (–)	Average	High (+)/low (–)
Percentage of pristine HDPE	0.47	2480	+63/–63	98	+8.1/–8.1
Percentage of PCR-HDPE	0.47	298	+93/–83	47	+10.8/–8.5
Percentage of nanoclay	0.06	233	+20/–14	16	+2.9/–2.0
Pipe extrusion		265	0	40	0
Total		3276		200	

Table 15 Production cost of (1) 20-foot pristine HDPE pipe, (2) 20-foot HDPE/PCR pipe and (3) 20-foot nanoclay HDPE/PCR pipe

	Pristine HDPE pipe [cost \$]/(percentage (%))	HDPE/PCR pipe [cost \$]/(percentage (%))	Nanoclay HDPE/PCR pipe [cost \$]/(percentage (%))
Pristine HDPE	163/(71)	80/(40)	62/(32)
PCR-HDPE	0	54/(27)	43/(22)
nanoclay_6 %	0	0	32/(17)
Extrusion cost	67/(29)	66/(33)	54/(28)
Average	230	200	190
High (+)/low (–)	+6.4/–10	+64/–31	+50/–25

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