Energy Efficiency Evaluation in Petrochemicals Industry

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Abstract

Energy efficiency (EE) improvement is a crucial issue in a world suffers from threats of escalated depletion of energy nonrenewable resources. In the highly intensive energy consumption industries such as petro-chemical industries, more realistic modeling of energy efficiency is of a paramount importance. Building such models and thereby indicators for energy efficiency enables concerned firms to work out their plans for continuous improvement of the efficiency of energy utilization. In the presented work, a methodology, based on the concept of embodied product energy (EPE), is proposed for evaluation of energy efficiency. Accordingly, a baseline can be set for compliance with international energy management systems (EnMS) requirements like those of ISO 50001, or for self-declaration and benchmarking. For the purpose of validation of obtained expressions, a case study in petrochemicals industry is introduced. Using the proposed model, a main energy efficiency of 20.76 % was calculated for a certain polyethylene (PE) grade in the manufacturing unit of the additive and pelletizing unit (APU) in the polyethylene plant under study.

Keywords
Energy Efficiency, Embodied Product Energy, Intrinsic Energy, Energy Management System, Petrochemicals

1. Introduction

Energy demand is continuously increasing in the 21st century and despite the existing global efforts to replace the fossil fuel energy sources with renewable energy sources, there are a lot of barriers that make the fossil fuel continue as the major energy sources at least in the next twenty years. Energy sources based on fossil fuel is the main cause of greenhouse gases emissions that have the ultimate effect on climate change (IEA 2010). International Energy Agency (IEA) presented an analysis to show how to mitigate the threat of climate change. The analysis is based on having two scenarios for the trend of energy-related CO_2 emissions, the baseline scenario where it is expected to have about double quantity of CO_2 emission (57 Gt annually) in 2050 relative to that of 2010. The other scenario known as BLUE Map scenario propose that the CO_2 emissions in 2050 shall be (14 Gt) about half of the quantity recorded in 2010. The BLUE Map scenario is based on the contribution of energy efficiency improvement which may contribute by around 38% of all other expected contributions including carbon capture and storage (CCS) technologies, renewable energy, nuclear energy, power generation efficiency, and fuel switching (Wu 2012). In this context, energy efficiency became the focus of many researches and it is addressed in different end-use sectors including industry, transport, and buildings. Energy efficiency becomes one of the crucial issues in any manufacturing system especially in heavy industry where huge amount of energy is consumed which in turn results in huge amount of CO2 emissions.

1.1 Literature Review

The importance of energy efficiency (EE) is referred to its potential to rationalization of energy sources consumption which has an impact on sustainability and securing the future energy demand in addition to reducing the greenhouse gas emissions (IEA 2014). There are many researches that discuss the energy efficiency definitions and propose several models and methodologies for energy efficiency evaluation accompanied by different EE indicators. Some examples are indicated briefly in this section. However, the proposed methodology in this paper is amenable for practical applications where a baseline can be set for compliance with energy management system (EnMS) requirements like those of ISO 50001, or for self-declaration and benchmarking.

Energy efficiency may be measured by a ratio between the useful output of a process and the energy input into that process. This simple measure is broadly used and the related research of “What is energy efficiency? Concepts, indicators and methodological issues,” early published by Patterson in 1996 was cited by many researcher like De la Rue du Can et al. 2010 and Thiede 2012 where a number of methodological issues and indicators for energy efficiency evaluation were discussed to address how to define the useful output and energy input for a certain process so that energy efficiency can be improved. In such work, all the relevant indicators are categorized into four groups that is including thermodynamic, physical-thermodynamic, economic-thermodynamic, and economic indicators.

Hierarchical-indicator comparison (HIC) was introduced by Song et al. 2014 for evaluating energy efficiency in industry. In this method, the energy efficiency evaluation at the plant level is targeted. Specific energy efficiency indicators are selected and divided into two levels. Level-1 indicators are considered for whole plant whereas level-2 indicators are considered for certain production process or facility within the plant. In order to describe the HIC method, it was applied to certain chemical industry which is purified terephthalic acid (PTA) where four indicators are defined for level-1 group including (i) Comprehensive Energy Consumption per Unit Product of PTA, (ii) Comparable Energy Consumption per Unit Product of PTA, (iii) Energy Efficiency Index of PTA Plant, and (iv) Comprehensive Energy Consumption per Unit Value-added of PTA Plant.

Another method used in the public policy well known as American Energy Star Program is Stochastic Frontier Analysis (SFA) method. A parametric/ statistical approach was presented by Boyd 2005 that can provide a measure for energy efficiency gap for a certain company where the difference between best and average practice is monitored. The proposed approach of Boyd et al. 2008, was based on plant-level data and applies stochastic frontier regression analysis to get the energy intensity for a group of plants. Energy Star industrial energy performance indicator (EPI) is one of the application for SFA. Systematic effects, inefficiency, and random error are the three components of energy intensity proposed in stochastic frontier regression analysis method.

The approach of data envelopment analysis is also introduced with regard to energy efficiency evaluation. One of these approaches is to analyze the efficiency of electric power generation especially the operational performance of thermal power plants. This method was used in efficiency assessment for power plants in Turkey (Sarica and Or 2007) and in Taiwan as well (Liu et al. 2010). The data envelopment analysis is used to compare between organizational units performance, when each has multiple inputs and outputs, by using a technique based on linear programming.

2. Embodied Product Energy Framework

The approach of embodied product energy (EPE) is used in the present work for the purpose of energy efficiency evaluation like the work of Seow et al. 2011 and 2013 which was applied in manufacturing of products. In the present work, the EPE model is modified to be applicable in continuous processes industries like chemicals, oil and gas, steel, cement, etc. for the purpose of better utilization of the model in such industrial processes.

The framework for modeling energy consumption based on a product viewpoint in manufacturing system was introduced by Seow and Rahimifard 2011, where a discrete event simulation was used to establish EPE. Three viewpoints of energy flow modeling were considered based on plant, process, or product. This approach was based on product viewpoint while the energy consumption at the plant level and process level were used for calculating the amount of energy consumed to manufacture a unit product.

EPE can be expressed as $\sum EPE = \sum DE + \sum IE$ where DE is direct energy and IE is indirect energy. DE was further described by the sum of theoretical energy (TE) and auxiliary energy (AE). The use of the term "theoretical energy" may lead to some conflict while the main concern is to differentiate between required energy and consumed energy so that a classification of manufacturing processes is introduced before reforming the new definitions that could be used in EPE framework to avoid any conflict raised from previous definitions.

2.1 Classification of Manufacturing Processes

Any manufacturing industry consists of certain basic components that can be described as a whole plant or several plants where each plant consists of some production units or sections each has a certain processing action by applying a series of manufacturing processes. It is proposed that manufacturing processes can be classified into three classes, the pre-preparation processes, the main processes, and the post-preparation processes as described in Figure 1.

The pre-preparation processes are the processes that required to prepare the inputs including raw materials and any required additives to be ready to enter the main processes. It may include material handling, heating, cooling, flow regulating, chemical activation, chemical treatment, and etc. where no transformation of the inputs towards the final product of the production unit happens. The main processes include the processes that is responsible for the transformation of the inputs' properties into the final product properties. This transformation may include transforming the physical properties and shaping e.g. from gas into solid or from powder into pellets, from pellets into sheets and so on. The post-preparation processes include the processes required for preparing the final product of a certain plant or production unit after the main transformation processes to make the final product ready to be provided to its users. These post-preparation processes may include product material handling, heat exchange, drying, and so on.

Both pre-preparation and post-preparation processes can be considered as auxiliary processes along with some other auxiliary processes attached to main processes. Hence, the energy efficiency can be treated at different level as energy efficiency for the main processes, energy efficiency for the auxiliary processes, energy efficiency for the whole plant or production, and in some cases can be for several pants of certain company or organization. The energy efficiency can be aggregated at different level as required so that a measure for energy efficiency is developed for benchmark for operation or for improvement of the design of certain manufacturing processes. The proposed methodology is introduced for having such a measure at certain aggregation level.

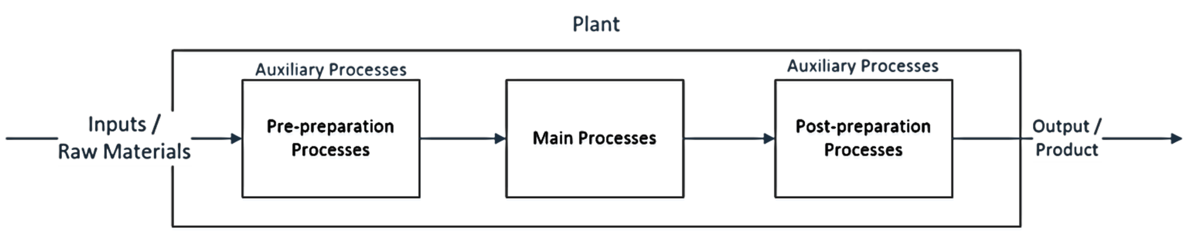

Figure 1. Classification of Manufacturing Processes within a Plant

At the plant level, there are other components rather than the manufacturing processes where certain amount of energy is consumed, they are the indirect energy components. The indirect energy components are those energy consumers which do not directly affect the production of certain product whereas are essentially without which the production cannot be accomplished such as lighting, ventilation, and air conditioning.

2.2 EPE Calculations

In the present work, EPE is calculated according to Equation (1) such that;

$$EPE_i = ME_i + AE_i + IE_i \qquad (1)$$

Where; EPE_i is Embodied Product Energy, ME_i is Main Energy, AE_i is Auxiliary Energy, and IE_i is Indirect Energy.

The terms of the right hand side of Equation (1) are representing the energy required to produce a unit of product i. Main Energy ($\boldsymbol{ME_i}$) is the intrinsic energy required by the main manufacturing processes where the input material is transformed from its original state to its final state of the product where any other processes which are essentially contributing in the transformation will be a part of auxiliary energy. At the product level, intrinsic energy to produce a unit of product i representing summation of the minimum amount of energy required by the main manufacturing processes to produce a certain product based on the theories of chemistry, physics, thermodynamics, and etc. without considering any losses that are already found in real situations. Auxiliary Energy ($\boldsymbol{AE_i}$) is the minimum energy required by auxiliary processes and can be calculated at the process level for all auxiliary processes based on the theories of chemistry, physics, thermodynamics, and etc. where can be further aggregated at the product level. Indirect Energy ($\boldsymbol{IE_i}$) is the minimum required energy of all other indirect energy components within a manufacturing facility which has no direct relation with the manufacturing processes, typical examples for IE are lighting and air conditioning and ventilation. It is usually considered at the plant level and can be evaluated in such a way that contribute to produce a unit of product i. Embodied Product Energy ($\boldsymbol{EPE_i}$) is only defined at the product level to introduce the minimum energy enclosed in a unit product and represented by the summation of intrinsic energy or main energy, auxiliary energy, and indirect energy components that contribute in the production of a unit of product i.

3. Energy Efficiency Evaluation

The energy efficiency shall be evaluated using Equation (2) as follows;

$$EE_i = \eta_i = \frac{EPE_i}{TEC_i} \qquad (2)$$

Where; EE_i or $\eta_i$is Energy Efficiency, EPE_i is Embodied Product Energy, TEC_i is Total Actual Energy Consumed. Total Actual Energy Consumed ($\boldsymbol{TEC_i}$) is the actual energy consumed by all manufacturing processes and indirect energy components to produce a unit of product i. It is defined at both plant and process levels and preferably measured but can be partly estimated in some cases where there is no available sub-meters. The term $\boldsymbol{TEC_i}$ can be further described as:

$$TEC_i = MEC_i + AEC_i + IEC_i \qquad (3)$$

Where; MEC_i is Main Energy Consumed, AEC_i is Auxiliary Energy Consumed, and IEC_i is Indirect Energy Consumed representing the energy consumed to produce a unit of product i by all main manufacturing processes, all auxiliary manufacturing processes, and all indirect energy components respectively.
In some practical cases where the auxiliary energy and indirect energy may be considered out of concern under some assumptions, another indicator for energy efficiency can be introduced for simplicity and applicability which is MEE_i representing energy efficiency of the main processes involved in producing one unit of product i and can be expressed as shown by Equation (4).

$$MEE_i = \frac{ME_i}{MEC_i} \qquad (4)$$

3.1 EE Evaluation Methodology

The methodology can be introduced by six steps, the first step is where the product under consideration should be specified as indicated in Figure 2 where (i) is the product identifier for which intrinsic and required energy shall be calculated and actual consumed energy shall be monitored and measured. The second step is to analyze the manufacturing facility in order to identify all the manufacturing processes required to produce product (i) this could be done by drawing a schematic diagram for energy flow that state and indicate all these processes. Once such a schematic diagram is accomplished, a classification for the manufacturing processes into main processes and auxiliary processes is required taking into consideration that auxiliary processes include both pre-preparation and post-preparation processes to easily identify main energy and auxiliary energy as per the definitions of the different parameters of equation (1).

The core of the methodology is the development of intrinsic energy equations based on the theories of physics, chemistry, and thermodynamics. It appears in the step “3” where a potential research effort initiative is proposed for both scientists and practitioners to develop an intrinsic energy equation or required energy equation for each process in the energy flow diagram. The equations should be based on theories however empirical equations could be accepted in some cases where theoretical equations are considered somehow difficult. Some intrinsic energy equations are presented later in the case study to communicate the idea and validate the methodology. Intrinsic energy equations should be introduced to all main manufacturing processes to calculate ME where required energy equations for auxiliary manufacturing processes and indirect energy components may be subjected to some assumptions for the purpose of ease of implementation accordingly.

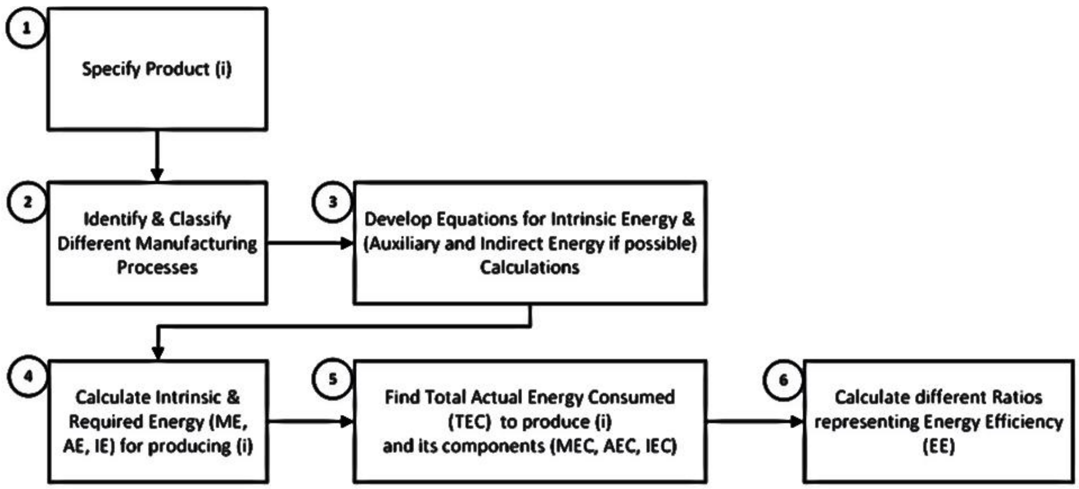

Figure 2. Main Steps of Energy Efficiency Evaluation Methodology

In step "4" of the methodology the calculations of intrinsic energy and required energy using the developed equations take place so that EPE can be found using equation (1). In step "5" records are collected for measurement of actual energy consumption for all the identified main and auxiliary manufacturing processes and indirect energy components so that TEC and its components can be found and verified using equation (2). In step "6" the energy efficiency is calculated according to equations (3) and (4).

4. Application of EE Evaluation in Petrochemicals Industry

For the purpose of explanation and validation of the proposed methodology, it is applied in petrochemicals industry as an example of the heavy industry and intensive energy consumer. The additive and pelletizing unit (APU) in a polyethylene plant was chosen for the methodology to be applied. Polyethylene (PE) is the raw material for many plastic industries where PE products are classified as low density (LDPE), linear low density (LLDPE), and high density (HDPE) and each class has different grades identified by the values of density and melt index for each. In APU, the virgin polyethylene powder from the polymerization unit is received and blended with special additives for extrusion and then pelletization. The product of APU is the polyethylene pellets which are pneumatically conveyed to storage system and product blending unit before being ready for bagging.

In order to apply the energy efficiency evaluation methodology, the APU unit is described according to the developed energy flow diagram shown in Figure 3 illustrating all the points of energy consumption in APU. The thirteen points from point (1) to (13) are considered as pre-preparation processes and the accompanied required energy is classified as auxiliary energy. Through these thirteen points, PE powder is received and mixed by certain additives then moved to the extruder. Point (14) is the extruder which is the first point of the main processes where the PE powder is transferred to PE melt and this is the first point where required energy is classified as main energy. However, other four points (14a) to (14d) demonstrate auxiliary energy attached to the main energy point (14). Point (15) is the second point of the main energy points where the rest of PE powder is transferred into PE melt and the molten PE became homogeneous melt ready for pelletizing; while the two points (15a and 15b) are classified as auxiliary energy points attached with that main energy point (15). Point (16); the third main energy point is under-water cutter where the PE melt is transferred into PE pellets. The two points (20) and (21) are considered as auxiliary energy points attached with the main energy point (16) while other six points (17, 18, 19, 22, 23, and 24) are auxiliary energy points of post-preparation processes where PE pellets are dried, classified, and then conveyed till reaching the storage. Table 1 summarizes the classifications of energy consumption points in such a way that differentiates main energy from auxiliary energy as required by the EE evaluation model.

Table 1. Classifications of Energy Consumption Points

Process Classification	Energy Consumption Points
Main Processes	Points 14, 15, 16
Auxiliary attached with Main Processes	Points 14a, 14b, 14c,14d, 15a, 15b, 20, 21
Auxiliary for Pre-preparation Processes	Points 1 to 13
Auxiliary for Post-preparation Processes	Points 17, 18, 19, 22, 23, 24

The steps of energy efficiency evaluation methodology shown in Figure 2 will be applied to APU plant so that the energy efficiency of such plant can be evaluated. The product is specified as polyethylene pellets and then the manufacturing processes are classified into main and auxiliary processes as illustrated in Table 1. There are some points of indirect energy consumption in APU plant which include lighting inside the extruder house in addition to lighting, air conditioning and ventilation in the APU control room. The energy consumed by the control system dedicated to APU plant is also considered as indirect energy consumption point.

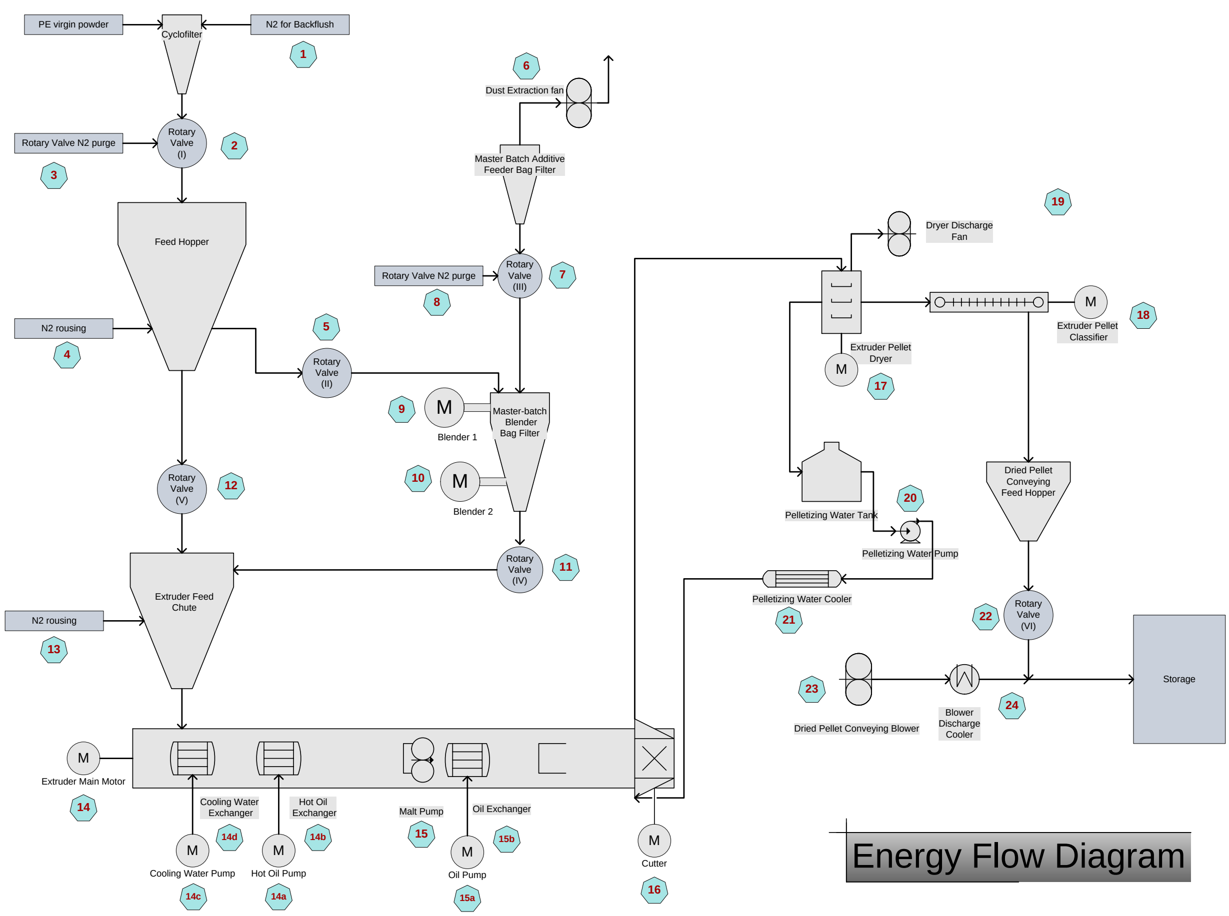

Figure 3. Points of Energy Consumption in APU Plant

4.1 Intrinsic Energy Equations

Here, it is required to develop equations based on physics and thermodynamics principles to express the intrinsic energy of those main manufacturing processes of the APU plant. The main processes include the extruder main function where the PE powder will be melted, pumped, and then pelletized. The power required in those points (14, 15, 16) indicated in Figure 3 to transfer PE powder into molten PE is the summation of power for raising temperature, power for melting, power for pumping molten polyethylene, and power for pelletizing as expressed in equations (5) to (8) and summarized in Figure 4. Once an expression for those required power, the required energy can be derived by multiplying the power by the working hours or specific energy consumption by dividing the power by the flow rate so than energy per unit product can be found.

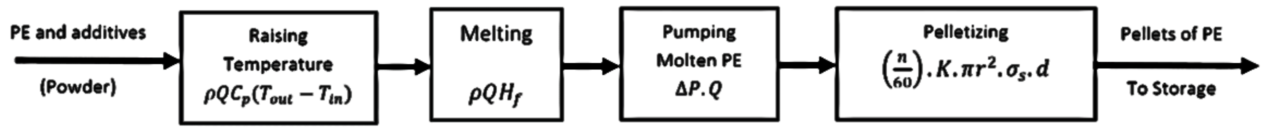

Figure 4. Main Processes in APU Plant with Equations for Required Power

In point 14, there are two processes where energy is required that include raising the temperature of PE powder, and fusion of the powder into PE melt. To get the intrinsic energy equations for each of these three processes, the power required for each can be expressed in equations (5) and (6) respectively referring to the work of Vlachopoulos 2001. First, the process of raising the temperature of polyethylene powder from its input temperature to the melting temperature which is dependent to the produced grade of polyethylene. The corresponding power required for raising the temperature is presented in equation (5) as follows:

$$P_1 = \rho Q C_p (T_{out} - T_{in}) \qquad (5)$$

Where; P_1: Power required for raising temperature (W).
ρ: Density of corresponding PE grade (Kg/m3).
Q: Volumetric flow rate (m3/s).
C_p : Specific Heat of PE (J/Kg °K).
T_{in} : Input Temperature (°C).
T_{out}: Output Temperature (°C).

Second process is the fusion to transform the polyethylene powder into molten polyethylene. In order to calculate the power required by this process, the mass flow rate is multiplied by the heat of fusion. For each produced grade of polyethylene the characteristic heat of fusion is measured in the laboratory, the equation (6) is used to evaluate the power of that process known that the mass flow rate is the multiplication product of the density and the volumetric flow rate.

$$P_2 = \rho Q H_f \qquad (6)$$

Where; P_2: Power required for melting (W).
ρ: Density of corresponding PE grade (Kg/m3).
Q: Volumetric flow rate (m3/s).
H_f: Heat of fusion for corresponding PE grade (J/Kg).

The next main process is pumping the molten polyethylene to get complete homogenization and to be ready for pelletizing indicated in Figure 3 by point (15). The power required for the pumping process is shown in equation (7).

$$P_3 = \Delta P\ Q \qquad (7)$$

Where; P_3: Power required for pumping of molten PE (W).
ΔP: Pressure difference between the output and input pressure of melt pump (Pa).
Q : Volumetric flow rate (m3/s).

The last process of the main manufacturing processes is the pelletizing process where the molten polyethylene is transformed into pellets which is the final form of the polyethylene product. The pellet in the case under study is a cylinder of 5 mm diameter and 5 mm height. The pelletizer consists of a die plate with a huge number of bores (1260 bores) and 16 knives rotating in perpendicular to the direction of the pumped molten polyethylene. In order to derive an equation for the power required by the pelletizer, some steps are described as follows; knowing that the area of a single bore of radius r in the die plate is $A = \pi r^2$, hence:

$$F = A.\sigma_s = \pi r^2.\sigma_s$$

Where;
F: Required force to cut a certain material (N).
σ_s: The shear strength of the material (Pa).
A: Area of a single bore where the force is applied (m2).
r: The radius of a single bore (m).

$$E_{single\ bore} = F.d$$

Where;
$E_{single\ bore}$: Energy consumed to cut one pellet of PE from a single bore (J).
F : Required force to cut PE (N).
d : Displacement or distance travelled in the direction of the force which is the bore diameter (m).

$$E_{all\ pellets} = K.E_{single\ bore}$$

Where;
$E_{all\ pellets}$: Energy consumed to cut all the PE pellets from the die plate bores in one revolution (J).
K : The total number of cut pellets per revolution.

$$P_{pelletizer} = \left(\frac{n}{60}\right).E_{all\ pellets}$$

Where;
$P_{pelletizer}$: Total power required by the pelletizer (W).
n : Rotational speed (rpm).

Substituting all the terms from the above equations, hence;

$$P_{pelletizer} = \left(\frac{n}{60}\right).K.\pi r^2.\sigma_s.d \qquad (8)$$

Now the aggregation of the four equations (5) to (8) yield the minimum total power required by the main processes of the additive and pelletizing unit from which the intrinsic energy can be calculated in a straightforward way. To get the main energy, which equals the summation of intrinsic energy per unit production in KWh/Ton, the summation of the above four terms will be divided by the feed flow rate of input PE powder in Ton/h and then divided by 1000 as shown in the following equation (9).

$$ME_i = \left(\frac{1}{1000\ \dot{m}}\right)\left(\rho Q\, C_p(T_{out} - T_{in}) + \rho Q H_f + \Delta P\ Q + \left(\frac{n}{60}\right).K.\pi r^2.\sigma_s.d\right) \qquad (9)$$

Where;
ME_i: Intrinsic Energy per unit product for a certain PE grade (KWh/Ton).
$\dot{m}$: Mass flow rate (Ton/h).
ρ : Density of corresponding PE grade (Kg/m3).
Q : Volumetric flow rate (m3/s).
C_p : Specific Heat of PE (J/Kg ^{o}K).
T_{in} : Input Temperature (^{o}C).
T_{out}: Output Temperature (^{o}C).
H_f : Heat of fusion for corresponding PE grade (J/Kg).
ΔP : Pressure difference across melt pump (Pa).
K : The number of cut pellets per revolution
σ_s : The shear strength of the material (Pa).
r : Single bore radius of the pelletizer die plate (m).
d : Single bore diameter of the pelletizer die plate (m).

4.2 Intrinsic Energy Results

Applying the above model to one of polyethylene grades will lead to the below results. Some considerations are included as follows:

- The data used are taken from real plant records with a little bit modifications for confidentiality issue.
- Pressure and volumetric flow rate values are averages of recorded operating values for the year under study.
- Density of PE grade is measured in laboratory and the values are averages for the year under study while specific heat is assumed to be constant as per high density polyethylene specification sheets of the plant under consideration.
- Melting temperature of the polyethylene powder differs dependently on the produced grade of polyethylene, in the current case, it is 128.1 ^{o}C as per laboratory measurements.

- Laboratory measurements of heat of fusion are done specially for the current research purpose as they are not commonly measured in the plant under consideration.
- Number of bores and bore diameter values are taken from the physical dimensions of the pelletizer die plate.
- The exact ultimate shear strength is commonly difficult to be measured and an approximate shear strength to be 0.75 of the ultimate tensile strength (Tres 2006) which is collected from specifications sheets included in the documentations of the plant under consideration and confirmed in laboratory for molten polyethylene at 120^{o}C.
- Unit conversion is considered to use SI unit in calculations.

For a selected polyethylene grade, the calculations of the power required for raising temperature, for polyethylene fusion, for pumping the molten polyethylene, and for pelletizing of the same PE grade is accomplished using equations (5), (6), (7), and (8) respectively where input data and results are shown in Tables 2, 3, 4, and 5 in the same sequence.

Table 2. Required Power for Raising Temperature to the selected PE Grade

PE Grade	Density (Kg/m^3)	Volume flow rate (m^3/h)	Specific Heat of HDPE (J/Kg ^{o}K)	T_{in} (^{o}C)	T_{out} (^{o}C)	Required Power P1 (W)
HDPE 1	938	15.25	1900	40	128.1	665120

Table 3. Required Power for Melting to the selected PE Grade

PE Grade	Density (Kg/m^3)	Volume flow rate (m^3/h)	Heat of Fusion (J/Kg)	Required Power P2 (W)
HDPE 1	938	15.25	171500	681450

Table 4. Required Power for Pumping of Molten PE grade

PE Grade	Volume flow rate (m^3/h)	ΔP for melt pump (Pa)	Required Power P3 (W)
HDPE 1	15.25	13410000	56806

Table 5. Required Power for Pelletizing the selected PE Grade

PE Grade	bore diameter d	Shear Strength σs (Pa)	Pelletizer Rotation Speed n (rpm)	Number of cut pellets per revolution K	Required Power Ppelletizer (W)
HDPE 1	0.005	1275000	560	21120	24674

The main energy can be calculated using equation (9) where the summation of intrinsic energy for the main manufacturing processes are presented in Table 6 which simply is the summation of the required power divided by 1000 $\dot{m}$, and the resulted values show the intrinsic energy of the main manufacturing processes in KWh/Ton.

Table 6. Intrinsic Main Energy calculated for the selected PE Grade

PE Grade	Mass flow rate (T/h)	Required Power P1 (W)	Required Power P2 (W)	Required Power P3 (W)	Required Power Ppelletizer (W)	Sum of Required Power (W)	ME_i (KWh/T)
HDPE 1	14.3	665120	681450	56806	24674	1423091	99.86

4.3 Finding Total Energy Consumption in APU Plant

The actual energy consumptions for the selected polyethylene grade are illustrated in Table 7 with the values recorded in the year of the study. The indirect energy consumed (IEC_i) is the energy consumed for lighting both inside the control building and outside in the plant added to energy consumed for air conditioning inside control rooms.

Table 7. Consumed Energy for the selected PE Grade in the year of study

PE Grade	Direct Energy Consumed				Indirect Energy Consumed	Total Energy Consumed
	Main	Auxiliary	Auxiliary	Auxiliary		
	Elec*	Elec*	Non-Elec	Total	Elec(*)	
	KWh	KWh	KWh	KWh	KWh	KWh
HDPE 1	5168049	327275	2384006	2711281	265501	8144830

(*) Electrical energy consumed corrected by multiplying by primary energy factor of 2.85 according to electrical energy generation efficiency in Egypt (Amin et al. 2013).

The total actual energy consumed (TEC_i) and other energy consumed components including MEC_i, AEC_i, and IEC_i will be presented in the form of specific energy consumption in KWh/T. In order to have these values, the consumed energy of each energy components for the selected PE grade in the year of the study shown in Table 7 will be divided by the corresponding produced quantity of 10782 Ton and the resulted values are shown in Table 8. Regarding the indirect energy calculation, the total indirect energy consumed in the year of study, which is in this case 1074327 KWh that can be multiplied by the electrical energy generation correction factor of 2.85 to be 3061831 KWh, divided by the corresponding total annual production of all grades in that year of 124342 Ton. The total energy consumed in the APU unit in the year of study is 102481MWh for all the production from different PE grades.

Table 8. Actual Energy Consumed in (KWh/Ton) for the selected PE Grade

PE Grade	DEC_i		IEC_i	TEC_i
	MEC_i	AEC_i		
HDPE 1	479.32	251.46	24.62	755.41

4.4 Energy Efficiency Evaluation for APU Plant

An analysis for the energy consumption within APU plant has been accomplished where it was observed that the average electrical energy consumed by main processes is about 90% of the total electrical energy consumed by APU plant and when compared to all energy consumed, given that auxiliary energy includes electrical and non-electrical energy, the energy consumed by main processes is about 63% of the total energy consumed as shown in Figure 5.

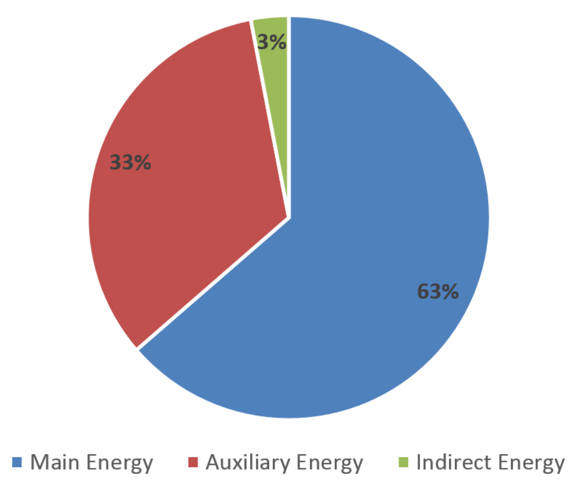

Figure 5. Comparison between Components of Total Energy Consumed

Hence, the intrinsic energy only will be considered and the energy efficiency indicator that will be used is main energy efficiency (MEE_i) which is the ratio between the intrinsic energy, the energy required by main processes, and the consumed energy by main processes as per equation (4) for energy efficiency of the main processes involved in producing one unit of product i and can be found as;

$$MEE_i = \frac{ME_i}{MEC_i} = \frac{99.86}{479.32} = 20.83\%$$

The values of the above energy efficiency indicator applied to different PE grades within the plant under consideration are ranging from 20.61% to 23.41% which indicate the low value of intrinsic energy when compared to the actual consumptions.

5. Conclusion and Recommendations for Future Work

The need for an indicator for energy efficiency is a crucial issue in these days where all industries had paid attention to energy conservation and energy management in order to achieve an effective reduction in energy consumption which leads to a contribution towards reduction of greenhouse gases and mitigation of climate change symptoms. The output of the proposed methodology when applied to APU plant as a significant energy user of a polyethylene plant introduced an indicator for energy efficiency of the APU plant that can be used for either benchmarking or as baseline in energy management system. The use of such indicator in benchmarking leads to design improvement in any new polyethylene plant as well as improvement in any operating plant when compared to a better one. On the other hand, when a company decides to implement an energy management system in compliance with certain international standards, ISO 50001:2011 as an example, there is always a requirement for developing a baseline against which further improvement can be compared. The indicator of energy efficiency introduced in the proposed model can be used in such case as a baseline when planning to implement an energy management system.

The APU plant case study is introduced to explain the idea of the proposed methodology of energy efficiency evaluation. The model is verified when expressive intrinsic energy equations are successfully developed for the main manufacturing processes while the calculated values by these equations have rational values when compared to the corresponding actual energy consumption.

Applying the proposed methodology for different products of the manufacturing unit, in this case different PE grades, is considered as an approach for verification and validation. Low values of energy efficiency indicator applied to different PE grades ensures the low value of intrinsic energy when compared to the actual consumptions. The results ensure that the model is valid for use in any industrial manufacturer for the purpose of having an energy efficiency indicator that can be used as either a benchmark figure or a baseline for monitoring further improvement within an industrial plant. There is an opportunity for future work to apply the methodology in other applications and to face the challenge of developing intrinsic energy equations for different manufacturing processes.

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