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Impact of the use of renewable materials on ecoefficiency of manufacturing processes

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IMPACT OF THE USE OF RENEWABLE MATERIALS ON THE ECO-EFFICIENCY OF MANUFACTURING PROCESSES

The use of renewable materials has attracted interest from a wide range of manufacturing industries looking to reduce their environmental and carbon footprints. As such, the development and use of bio-polymers has been largely driven by their perceived environmental benefits over conventional polymers. However, often these environmental claims, when challenged, are lacking in substance. One reason for this is the lack of quality data for all lifecycle stages. This applies to the manufacturing stages of packaging, otherwise known as 'packaging conversion', where for certain product/production types, a reduction in energy consumption of 25-30% from lower processing temperatures can be offset by an increase in pressure, cycle times and reject rates. The ambiguity of the overall environmental benefit achieved during this stage of the lifecycle, when this is the main driver for their use, highlights the need for a clearer understanding of impact such materials have on the manufacturing processes.

1 INTRODUCTION

The need for a sustainable supply of materials in manufacturing has never been greater. The relentless rise in global consumption, fuelled increasingly by the newly emerging economies, is putting unbearable pressure on the Earth's limited resources. The World Wide Fund for Nature (WWF), in their Living Planet Report 2010, estimate that by 2030 humanity will need the capacity of two Earths to sustain our current lifestyles [1]. This is particularly apparent in the extraction of non-renewable resources such as fossil fuels, many of which are already nearing a peak in supply, the most prominent example being crude oil [2]. Crude oil has many uses, the largest being liquid fuel in transport, however it is also the most widely used feedstock in polymer production, including those used in packaging applications. Finding alternatives to reduce our dependency on crude oil continues to be of the highest priority. One means to achieving this has been the replacement of oil-derived materials with renewable bio-derived ones. This approach has been advanced in the plastics packaging sector, with the introduction of bio-polymers; plastics made from naturally occurring polymers (mostly derived from plants) such as sugars, starches and cellulose. Bio-polymer packaging has been used commercially, mainly in niche and low performance applications, since the 1980's. More recently however, the development of higher performance materials, increased production capacity for bio-plastics (see Figure 1 [3]) and more competitive pricing has seen a significant growth in their adoption by leading brand owner multinationals, such as Coca Cola and Pepsico, in high performance applications [4]. One of the main attractions of bio-polymers is their perceived environmental benefits, however despite the environmental claims made by manufacturers, results of independent analysis, over the packs whole life-cycle, are less conclusive. Indeed, various government initiatives have promoted and supported the procurement of 'bio-based' and 'sustainable' products, despite the lack of scientific understanding of the real environmental benefits achievable [5]. A comprehensive review of 25

publicly available life cycle assessment (LCA) reports from the academic and commercial literature, spanning the time period between from 1997 to 2009 confirmed the lack of good quality LCA data for bio-polymer packaging, particularly for the production, use and end of life stages [4].

This paper highlights that, while bio-polymers provide a possible alternatives to conventional thermoplastics for plastics packaging, there are still a number of life cycle issues that need further investigation in particular their environmental impact during the packaging production stage. This paper outlines a method for calculating the ‘energy consumption versus waste generated’ for three types of packaging conversion processes, based on biopolymers and their main conventional plastic counterparts. These conversion processes represent the three most widely used plastic packaging formats namely; bag, bottles, and trays. A case study based on the production of a 500ml capacity plastic bottle for mineral water has been used to illustrate and assess the key areas of environmental gain and loss.

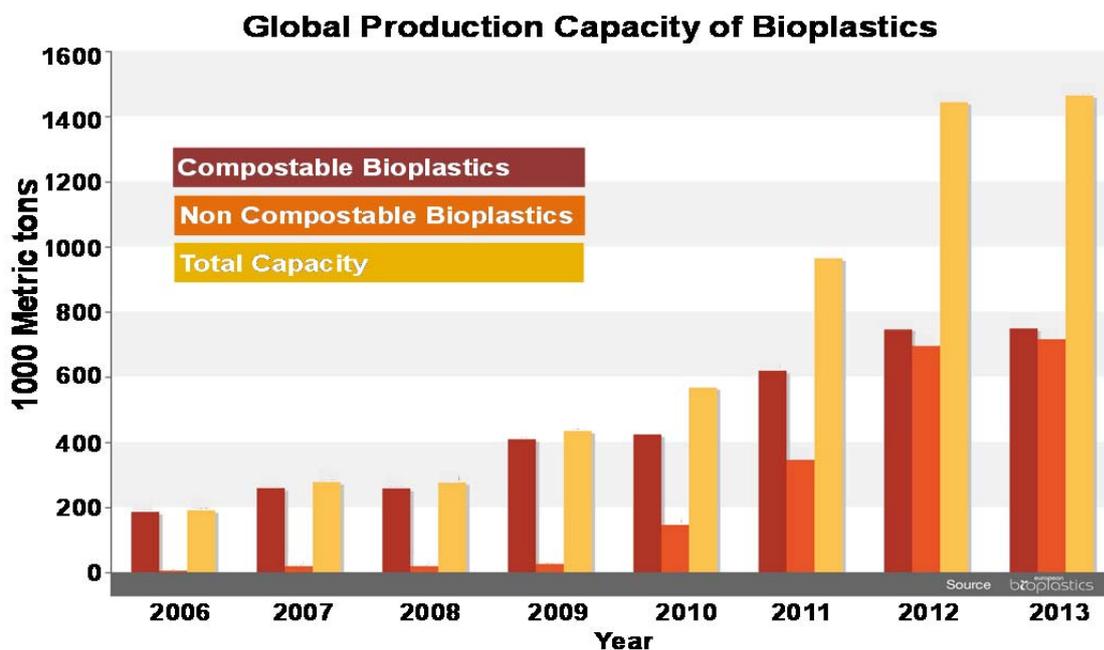


Figure 1: Global Production Capacity of Bioplastics (Sourced from European Bioplastics [3])

2 AN OVERVIEW OF BIO-POLYMER TYPES

The number of bio-polymers commercially available for plastics packaging continues to increase, however the first generation of bio-polymers most widely used are: Reconstituted Cellulose (RC), Polylactic Acid (PLA), Thermoplastic Starch (TPS), Polyhydroxylalkanoates (PHA). However, recently the range of conventional polymers produced (in full or in part) from a bio-derived precursor (i.e. bio-ethylene). These include; Polyethylene (PE), Polyethylene Terephthalate (PET) and Polypropylene (PP). This latter group, is often referred to under a number of classifications including: Class B Bio-Derived Polymers, Bio-Conventional Polymers or Non-Degradable Bio-polymers [4, 6]. However, as the processing of these polymers is identical to their oil derived counterparts, this research has focused primarily on the processing of the main first generation bio-polymer, PLA, which has

been used commercially for the production of the three aforementioned pack types (i.e. bags, bottles and trays).

3 PACKAGING CONVERSION PROCESSES

The final stage during the manufacturing process of most consumer products involves the filling and sealing of the goods into their designated package. In the food and drink sector, this process often involves the inline conversion of an intermediary material such as a reel of film or a pre-form into the individual pack. This conversion process requires key energy inputs, mainly in the form of heat, to shape, mold and/or seal the various packaging types. The three most commonly adopted plastic packaging conversion processes, as depicted in Figure 2, are:

- **Vertical form fill seal (VFFS)** used to manufacture flexible packages for loose products filled by weight, e.g. crisp packets.
- **Stretch blow molding** used to manufacture rigid containers such as bottles for packaging mainly liquid products, e.g. mineral water.
- **Plug assisted thermo/vacuum forming** used to manufacture mainly shallow one or two part semi rigid containers, e.g. trays for chocolates.

From comparison of the physical properties of Bio-polymers and Conventional polymers, it is asserted that thermal stages of these processes are where the most significant difference in theoretical energy consumption exists between the two material groups. However it should also be noted that in practice, other factors such as viscosity, cooling, cycle times and handling will also have an impact on overall energy consumption. The forming, molding and sealing processes are discussed in more details in the following sections.

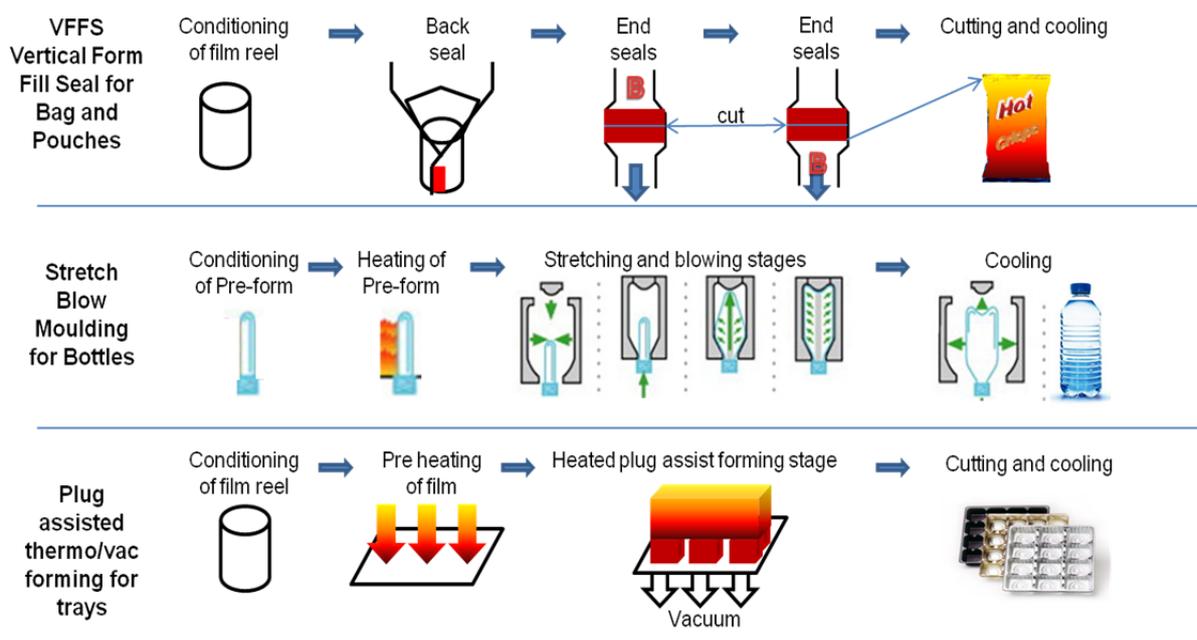


Figure 2: Key stages in three packaging conversion processes

3.1 Vertical Form Fill Seal (VFFS)

The key thermal input in this process, as shown in Figure 2, occur during the sealing of the film firstly down the length of the pack to create a tube, followed by the sealing of the ends to create a sealed bag. In practice these end seals are produced in pairs; the top of the lower bag and bottom of the upper bag are sealed at the same time and then separated by a horizontal cut at the midpoint. To measure the total heat energy used, the sum of the energy used to create all three seals should be calculated. Whilst there are a number of different sealing mechanisms in commercial use each having unique energy values associated with it, by calculating the theoretical energy used to fuse the two layers of film this will allow the comparison of the two material types regardless of the equipment used. Individual machine variations and efficiencies can then be attributed accordingly. The total theoretical heat energy used to seal one bag can be calculated using the equation 1 as derived from the standard equation for heat capacity of a solid with no transition phase:

$$E_{\text{Seal}} = m_{\text{Seal}}C(T_{\text{melt}} - T_{\text{ambient}}) [1]$$

Where:

E_{Seal} = the thermal energy used to seal a bag.

m_{Seal} = the mass of material to be fused.

C = the specific heat capacity of the polymer.

T_{melt} = the seal end temperature in degrees Celsius.

T_{ambient} = the seal starting temperature in degrees Celsius.

It should be noted that the m_{Seal} can be calculated from the surface area of the seal multiplied by the film gauge and the material density.

3.2 Stretch Blow Molding (SBM).

As illustrated in figure 2, the key thermal stage in this process occurs during the heating of the pre-form prior to blowing process. Whilst significant energy is used during the other stages of bottle making, this does not vary significantly in terms of the polymer used. The equation 2 can be used to calculate the thermal energy used during this stage of the bottle making process.

$$E_{\text{Mold}} = M_{\text{Mold}}C(T_{\text{melt}} - T_{\text{ambient}}) [2]$$

Where:

E_{Mold} = the thermal energy used to heat the pre-form.

M_{Mold} = the mass of material to be heated.

C = the specific heat capacity of the polymer.

T_{melt} = the end temperature required in degrees Celsius.

T_{ambient} = the starting temperature in degrees Celsius.

It should be noted that M_{Mold} can be calculated from multiplying the surface area of the seal, film gauge and the material density.

3.3 Plug-assisted Thermo/vacuum Forming (PaTF)

The key thermal stages in this process occur during the pre-heat and cooling stages, as shown in figure 2. Similarly, the equation 3 can be used to calculate thermal energy used during this process.

$$E_{\text{Form}} = M_{\text{Form}}C(T_{\text{melt}} - T_{\text{ambient}}) [3]$$

Where:

E_{Form} = the thermal energy used to form the tray.

M_{Form} = the mass of material to be formed.

C = the specific heat capacity of the polymer.

T_{melt} = Forming temperature in degrees Celsius.

T_{ambient} = Starting temperature in degrees Celsius.

It should be noted that M_{Form} is calculated by multiplying the surface area of the forming, the film gauge and the material density. Furthermore, in the cases where a heated plug assist is used then a smaller additional heat transfer occurs during the forming stage. However this is not included in the calculation in Equation 3.

4 PROCESSING TEMPERATURE VARIATIONS BETWEEN POLYMER TYPES.

The main energy saving in the processing of PLA compared to other conventional thermoplastics occurs during the heating stages. This is primarily due to the lower melting point of PLA, as shown in Figure 3, compared to other widely used packaging polymers. However other factors may also need to be considered in order to evaluate the overall environmental benefits achievable during this processing stage. One of the main considerations in this case is the potentially higher wastage levels associated with PLA as described in Section 5. Whilst the thermal processing calculations of the model are based on actual processing temperatures, wastage levels are theoretical and based on the observed processing limitations of each material.

4.3 Predicting the Impact of Tighter Thermal Processing Windows on Waste Generation.

Whilst PLA has a lower melt point than PET (see Figure 3), it has a much narrower optimal processing window due to its higher temperature sensitivity. The majority of the problems with material distribution and forming will occur at too low temperatures, whilst above the optimal processing temperature, problems with thermal degradation can occur resulting in higher rejection rates [7, 8]. Clearly, The number of rejects will vary case by case, however it is reasonable to assume that on a like for like basis, PLA bottle rejects will be higher than PET due to its greater temperature sensitivity, and this will rise exponentially as temperature fluctuations increase [8,9].

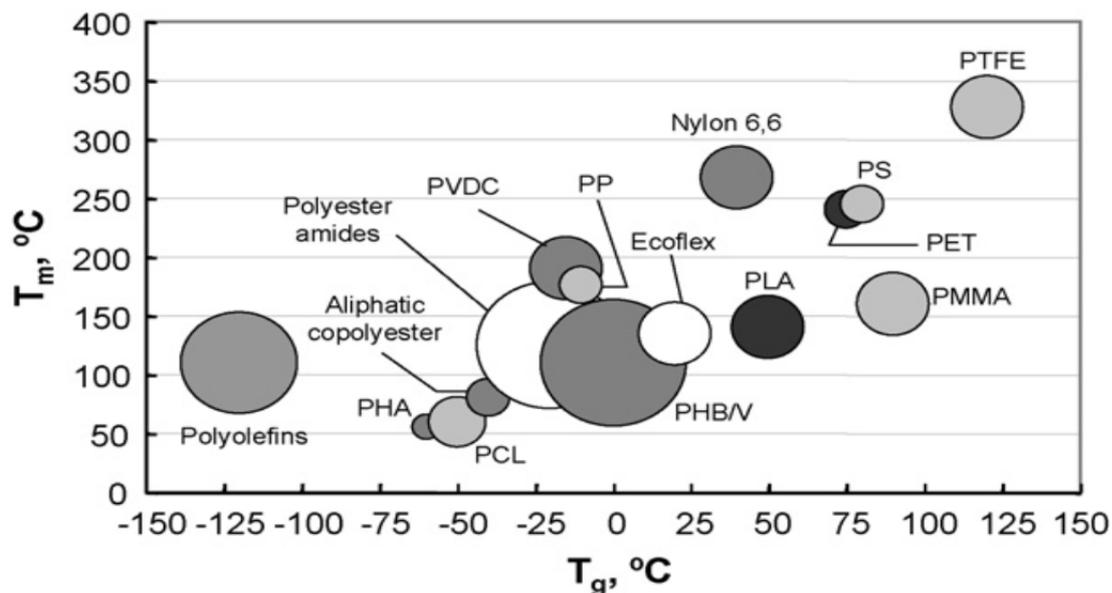


Figure 3: Comparison of glass transition and melting temperatures of PLA with other thermoplastics [7].

Using PLA and PET processing data obtained from both academic and industrial sources (6, 7, 8, 9), the different processing windows of PET and PLA have been estimated. A graph showing the likely increase in rejection rates between PLA and PET, as processing temperature deviates from the optimum, is illustrated in figure 4. It is proposed that this reject rate will vary, in part, according to how closely the optimum processing temperature can be maintained. Where the control is good, the difference in wastage levels between PLA and PET are unlikely to be significant, however as the level of control drops, the rate of rejects using PLA is likely to increase at a much greater rate compared to PET. The chart assumes a close to 0% reject rate at optimum processing temperature and a 100% rejection rate outside the processing window, as demonstrated in the experiments of Byrne *et al* as highlighted in their study on processing conditions for PLA and PET Polymers (9). An estimation of reject levels between these points was estimated using a standard parabolic distribution curve.

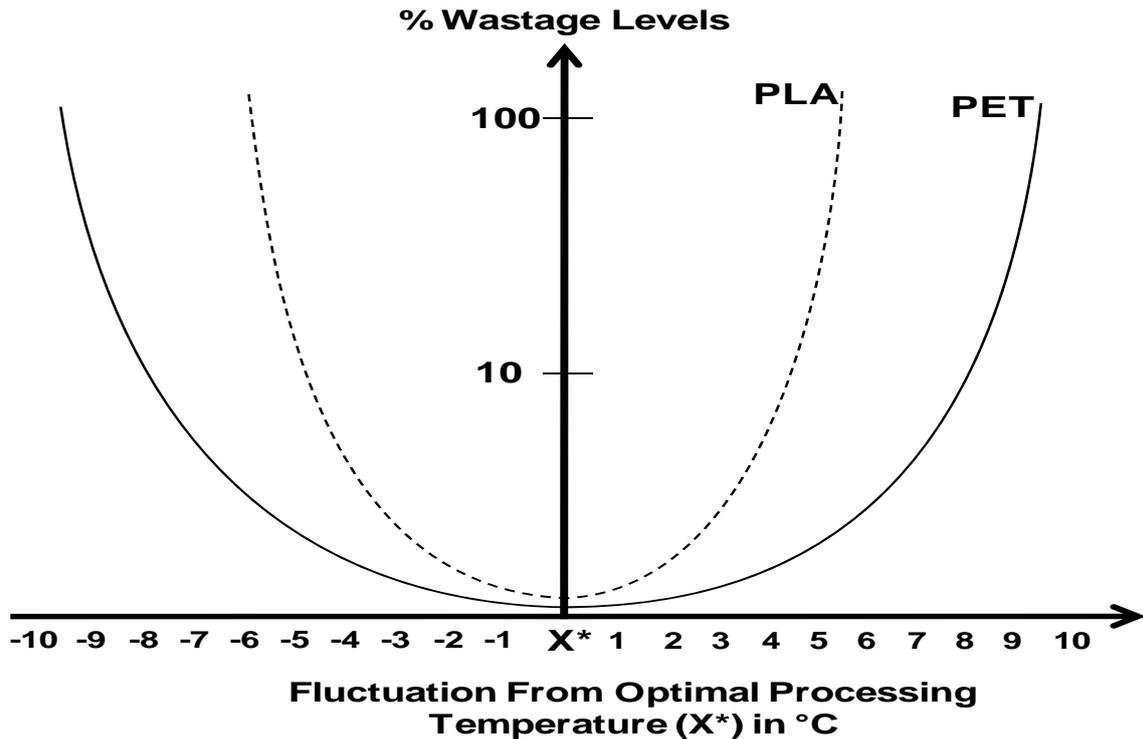


Figure 4: The higher wastage levels of PLA compared to PET due to effect of temperature control fluctuations on processing window size.

5 AN EXAMPLE CASE STUDY

The production of a plastic mineral water bottle is used as a case study to illustrate the issues related to energy used and rejection rates when using two PLA and PET polymers during the thermal processing stages. The data from a typical production system for a 500ml capacity mineral water bottle has been used in this case study, where the neck diameter for the bottle is 28mm and the weight is 24grams. It should be noted that for this case study the same weight was used for both PLA and PET, however opportunities for reducing weight (i.e. a lightweight bottle) using PLA may be possible but outside the scope of this initial study. The various thermal properties for the PLA and PET used are given in Table 1 [10]. It is assumed that one million bottles per year are produced on a twin tool machine operating one 8-hour shift at approx 4 cycles a minute.

The total heat energy used for the stretch blow moulding process has been calculated using the equation 2. All non thermal stages in the process, mechanical, handling and setup etc., were assumed to be equal between the two materials. In terms of calculating wastage, the thermal processing window for PET and PLA was assumed to be $\pm 2^{\circ}\text{C}$ of the optimum processing temperature X^* , as per Figure 4. For PET this gives a reject rate of circa 0.5%, whilst for PLA this would give a reject rate of circa 1.5%.

PROPERTY	aPLA	aPET
Thermal Conductivity (cal/cm-sec °C)	3.1 x 10 ⁻⁴	3.6 x 10 ⁻⁴
Specific Heat Capacity (cal/g-°C) above T _g	0.39	0.44
Glass Transition Temp T _g (°C)	55-60	70-79
Crystallization Temp T _c (°C)	100-120	120-155
Density (g/cm ³)	1.248	1.335
Thermal Expansion Coefficient x 10 ⁻⁶ (°C ⁻¹)	69	69
Melting temperature T _m (°C)	165	245

Table 1: Properties of Amorphous PLA and PET [10]

6 ANALYSIS OF RESULTS

The energy consumed, per bottle, during the thermal stages of the SMB process is summarised in Table 2. The thermal energy required for one PET bottle uses 2.65kJ whilst one PLA bottle requires 1.96kJ, and therefore the thermal energy saving of 0.69kJ per bottle. This indicates that the energy consumed, per bottle, during the thermal stages of the process when using PLA was 26% less than that used for PET. Thus, a total annual energy saving of 690,000kJ can be achieved in the production scenario of one million bottles per year.

Stretch Blow-Moulding for Bottle Manufacture	Heating of the Pre-form
Material Type	<i>Equation:</i> $E_{\text{mold}} = M_{\text{mold}}C(T_{\text{melt}} - T_{\text{ambient}})$ 1 Calorie = 4.187 Joules
PET	$E_{\text{mold}} = 24 \times 0.44 \times (85-25)$ $= 24 \times 0.44 \times (60)$ $= 634 \text{ calories or } 2.65\text{kJ}$
PLA	$E_{\text{mold}} = 24 \times 0.39 \times (75-25)$ $= 24 \times 0.39 \times (50)$ $= 468 \text{ calories or } 1.96\text{kJ}$

Table 2: Calculations of PET and PLA pre-form heating energy usage per bottle during the Stretch Blow-Moulding manufacturing process.

Using the example of 1 million bottles per year, the total number of rejects for PLA bottles based on the wastage levels of 1.5 % will be 15,000 compared to only 5,000 for PET based on its wastage levels of 0.5 %: To calculate the total energy lost through the production of reject bottles, it is assumed that the thermal process considered in this case study will only account for 25% of the total energy required to produce a PET bottle.

Therefore the total energy required to produce a PET bottle is:

$$(4 * 2.65\text{kJ}) = 10.6\text{kJ}$$

Similarly the total energy required to produce a PLA bottle is:

$$((10.6\text{kJ} - 2.65\text{kJ}) + 1.96\text{kJ}) = 9.91\text{kJ}$$

The total energy lost from the PET reject bottles is:

$$10.6\text{kJ} * 5000 = 53,000\text{kJ}$$

Similarly, the total energy lost from the PLA reject bottles is:

$$9.91\text{kJ} * 15000 = 148,650\text{kJ}$$

This gives an additional energy loss of 95,650kJ from PLA reject bottles. Therefore in this production scenario a net annual energy saving of 594,350 kJ will be achieved. Assuming the PET bottle reject rate remained at 0.5%, the reject rate for PLA bottles would have to exceed 7.5% to offset the energy savings made from lower processing temperature.

7 CONCLUDING DISCUSSIONS

The scarcity of resources and the rapid depletion of non-renewable provide some of the greatest challenges facing the manufacturing industry in the future. In this context, the substitution of non-renewable materials with renewable ones has been proposed as a possible solution in a number of applications. However, at present there are two major concerns with this solution:

- a) the additional demand for renewable materials may compete with other essential requirements, for example the impact of the rapid increase in bio-fuel and bio-materials demands on the food production capacity;
- b) the perceived environmental benefits of renewable materials may be offset by the concerns over their overall life cycle impact in particular during the manufacturing, use and end-of-life stages.

In this paper one such concern related to the wider green credentials of bio-polymers, in particular during the production stage, has been assessed. The results of the case study presented in the paper demonstrate that in a comparative study of a typical packing product using PLA and PET, the reduction in energy consumption during the production process using PLA could theoretically be offset by an increase in the number of rejects due its greater sensitivity to temperature variation. In practice however, normal reject rates would be well below the levels necessary for this to occur. Whilst the indications are that bio-polymers have the potential to reduce the environmental impact of plastics packaging at various stages of the life cycle, including the packaging conversion stage, a more detailed and complete life cycle assessment should be carried out for each to ensure that these benefits can be robustly defended.

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