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SUSTAINABILITY ENGINEERING APPLIED INTO THE PET PLASTIC SUPPLY CHAIN. A POLICY TOOL FOR INDUSTRY AND GOVERNMENT.

ABSTRACT.
This paper presents a practical application of sustainability engineering in industry and government. The work presented is part of a project sponsored by a consortium of industries who participate in the Polyethylene Tereftalate (PET) market as resin producers, bottle manufacturers, soft drinks producers, distributors and plastic recyclers in Mexico.

PET market in Mexico has increased substantially in the previous years to account for more than 300,000 tonnes. There is a public concern about the implications of PET use to the environment and also on the need for the Mexican government to be provided with analytical tools and results that describe the economic and environmental effects of PET due to environmental policy and market forces.

The research objectives were:
(i) to describe with a robust dynamic simulation model the behaviour of PET consumption as a function of: imports, exports, production capacity, demand, distribution costs/capacities, recycling technologies cost/capacities, landfill cost/capacities and environmental impact.
(ii) to perform a LCA of the PET from raw materials extraction to mechanical/chemical/thermic recycling.
(iii) to integrate the results of the dynamic simulation into the LCA and analyse the economic and environmental effect of various degrees of PET recycling.
(iv) to identify the optimal degree of PET recycling at which environmental impacts are minimum.
(v) to provide suggestions for analytical sound environmental policy.

Several interviews have been conducted to various industry makers and public servants, which combined with the economic data previously gathered has allowed to develop the first version of the simulation model. The simulation was conducted by using a computer software (Arena) which allows the inclusion of not only average values but also distribution function. The result is a model that predicts steady-state conditions for the market.

These market steady-state results were then incorporated into the LCA study in order to evaluate the emissions and environmental impacts related to different market and recycling conditions. The inventory of emissions contains considerable original data that has been gathered at various visits, inspections and interviews.

As such, this paper presents the effective use of various sustainability engineering tools that provide basis for decision making in industries and the Mexican federal government.

1. INTRODUCTION

Some decades ago soft drinks and water were bottled in glass. This has been a significant market for glass industries considering that more than 6,000 million gallons of drinks are sold every year (only in Mexico). In the last decade the Mexican market has experienced some transformations including the significant growth of bottled water and soft drink retailing. As a consequence of this growth, a new bottling material has been introduced: polyethylene terephtalate (PET). The main advantages of this material are its price, low weigh (thus, low transport costs), easiness to be blowed into almost any mold and neatness. This product has been successfully introduced in many markets around the world and in some cases it has experienced growth rates of two digits.

The environmental and market impacts of this rapid growth has brought attention to industries and government. Landfill space and materials consumption derived from bottle production and use are among the main drawbacks. However, PET is a recyclable material, which may represent a significant advantage in terms of environmental impact. Currently, there are no analytical tools to describe the effect of operations in the market structure and the environmental impact.

The aim of this project is to provide a joint analysis of the PET market's future situation and its environmental impact. The tools to be used are a simulation model for the market forecasting (including several possible future scenarios) and a Life Cycle Assessment (LCA) that allows us to understand the environmental effect of several operations related to this market. The framework presented in this work has been developed for the Mexican context but can easily be adapted into any other market.

2. PET MARKET MODEL

2.1 Model Description

PET goes through several stages during its life cycle as presented in Figure 1. PET resin can either be imported or produced in Mexico. There are three types of resin which is designed for there main segments: bottling, textile and films. Bottling PET is employed by carbonates, bottled water and oil producers mainly. Once the beverage is consumed, bottles are disposed into landfill while some may be collected by recyclers. Collected PET follows two mainstreams: recycling and exporting as raw material. There are three different recycling processes, these are chemical recycling, mechanical recycling and thermal recycling. The recycled material is then reintroduced to the production system.

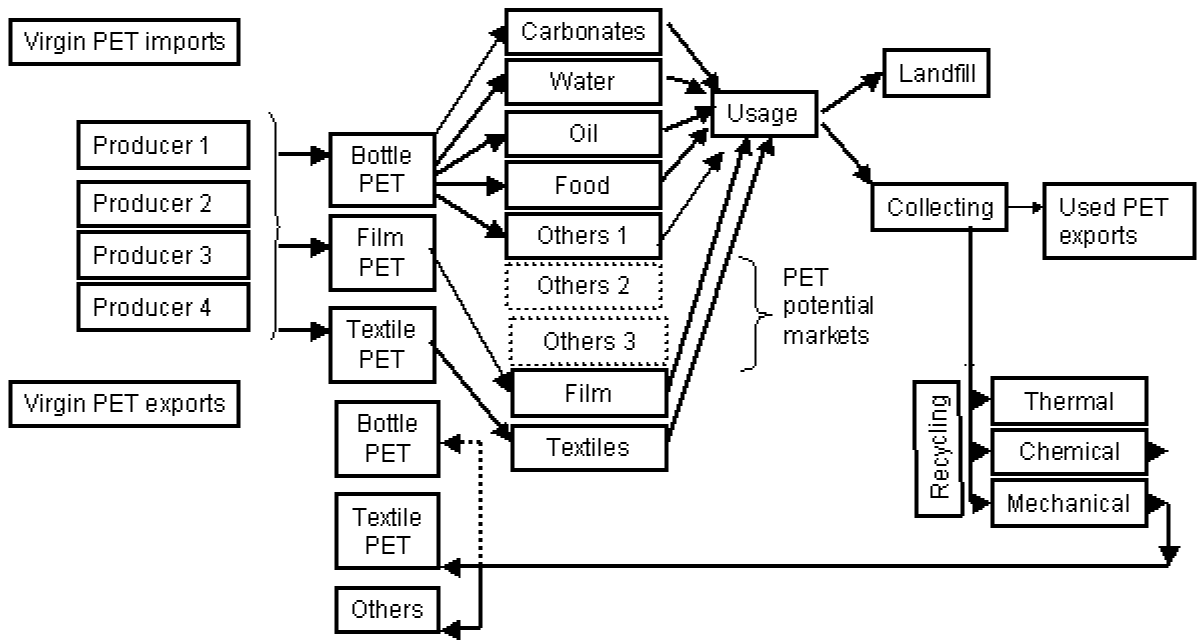


Figure 1. Schematic approach of PET market in Mexico

Market demand for PET is composed in great extension by soft drinks (mainly carbonates), water, and vegetal oil industries as shown in Figure 2.

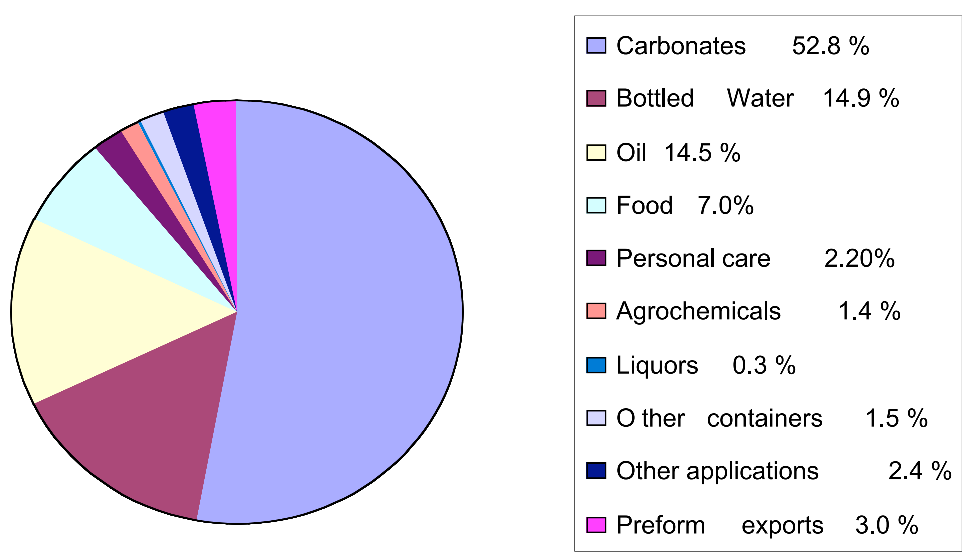


Figure 2. Market distribution of PET

Market distribution has not been constant in the previous years. Therefore, part of this work aimed to understand the behavior of each market segment in order to eventually develop a model demand forecasting. As such, historical and forecasted information on the growth of these sectors has been used for demand considerations. In addition the market model considers not only market growth but also the growth of PET usage inside each particular industry (some are still converting from aluminum or glass into PET).

2.2 Simulation Model

The objective of this PET simulation model is to provide users with a probabilistic approach to demand forecasts. This simulation model recreates PET market behavior. The main advantage of this simulation (as opposed to a regression analysis) is that companies can predict under a probabilistic risk assessment scheme, which scenarios are more probable to occur during the next years. In other words, knowing which scenario is more likely to occur, companies can develop strategies in order to compete with more information about their markets and operations.

This model parts from data gathered from several PET sub markets. Three types of data were collected regarding each market. First, the historical demand of PET for each of these markets; second, the growth rate of every market during the last years and the forecasted growth rates for future years; and finally the PET's share growth within each market. Probability distributions were estimated with this data for each market with respect to its PET demand growth rate. These growth rate probability distributions allow to establish which growth rate is more likely to happen for future years. The next step in this simulation is to forecast a probability distribution of PET demand for a certain year. With the probability distributions of every PET market growth rate and from the historical data of every PET market demand for a baseline year from which to start, a probability distribution can be generated in order to predict which demand scenarios are more likely to occur during a certain year. The probability distribution of each sector was adjusted into a statistical beta function. This function can be adapted into a wide range a data profiles and also can be adjusted into a specific range. Once the beta distributions were derived, it was incorporated into a scheme similar to the one showed in figure 3 in order to provide the outcome of PET demand for each year. In other words, demand for each market is first calculated by simulation, and finally these demands are added up in order to generate the probability distribution for the PET market in Mexico for the next year (Figure 3).

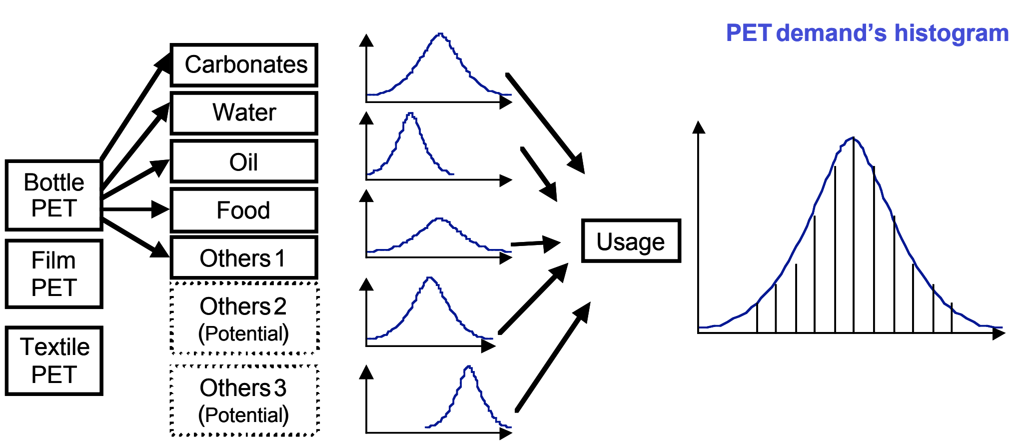


Fig 3. Schematic overview of the PET demand forecasting model.

The previous model was applied to generate various scenarios for PET demand in the following five years. Figures 4 and 5 show the results obtained from the simulation for the first year (2003) and the period 2003-2007, respectively. There are two graphs in Figure 4. The first one shows the number of simulations that were obtained in each demand interval, the second one shows the cumulative frequency, this is, the probability of the demand being less than or equal to the corresponding demand value.

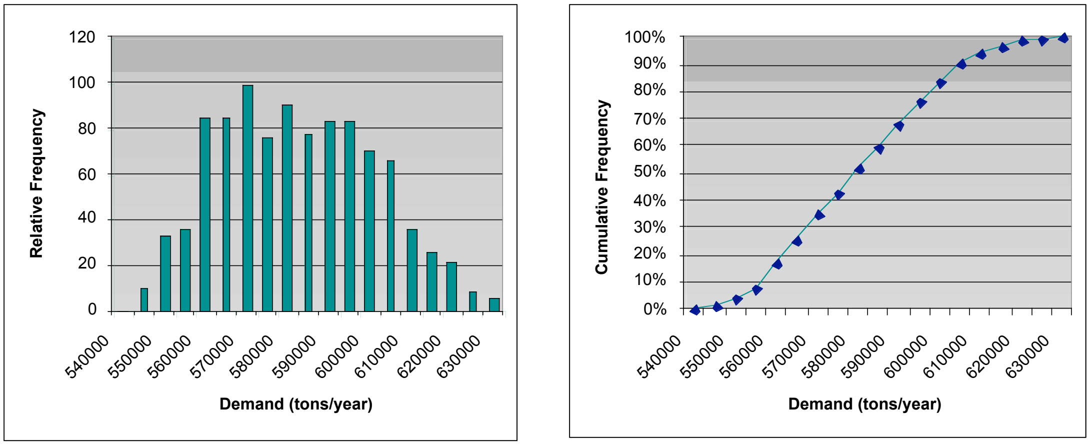


Fig 4. Forecasted PET demand for the first year (Distribution Curve)

From the graphs it was possible to observe that the most probable demand values for the first year are in were the range 555,000 to 605,000 tons. In addition, the probability for demand being less than or equal to 605,000 tons is 90%, and being less than 555,000 tons is around 8%. The average value was found to be 580,024 tons. The same analysis was carried out for the next four years. Results are presented in Figure 5. In order to preserve confidentiality of results, the "Y" axes presents values as a fraction of the total forecast demand for year 2007. However, trends presented represent the forecasted market behavior.

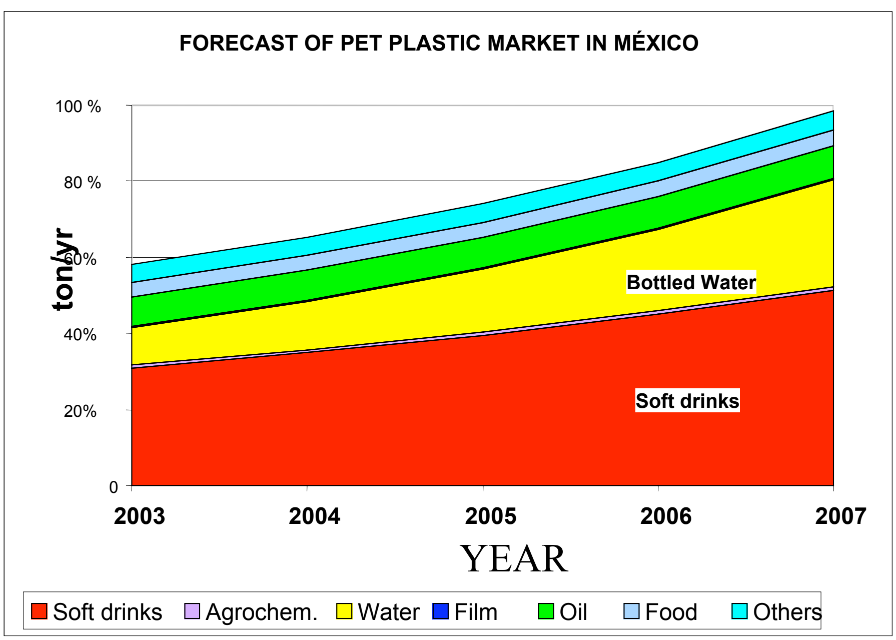


Fig 5. Forecast of PET plastic market in Mexico (2003-2007)

3. ENVIRONMENTAL PROCESS PERFORMANCE

The model presented in Figure 1 is also the basis to evaluate the environmental impact produced along the life cycle of PET (from Raw Materials Extraction to Recycling and final disposal). The methodology used to evaluate the environmental performance of the various processes related to PET is defined as Life Cycle Assessment.

3.1 Forecast for PET recycling quantity and rate

The simulation model was combined with visits to landfills and interviews with the managers of the main collecting and recycling companies. As a result it was possible to develop a forecast of the quantity of PET bottles that our sustainability model predicts. Furthermore, a new insight appeared: even though the total quantity of PET collected is increasing every year, the recycling rate (PET collected/ PET produced) of PET is decreasing (see Figures 6 and 7). This is due to the fact that market demand for PET grows faster than collecting infrastructure.

Fig 6. Forecast of PET collected in Mexico (2003-2007)

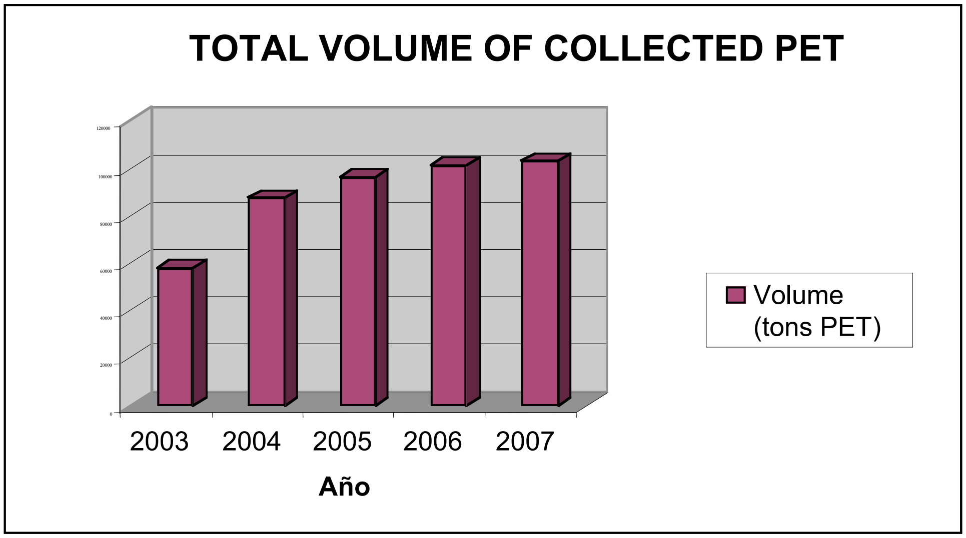
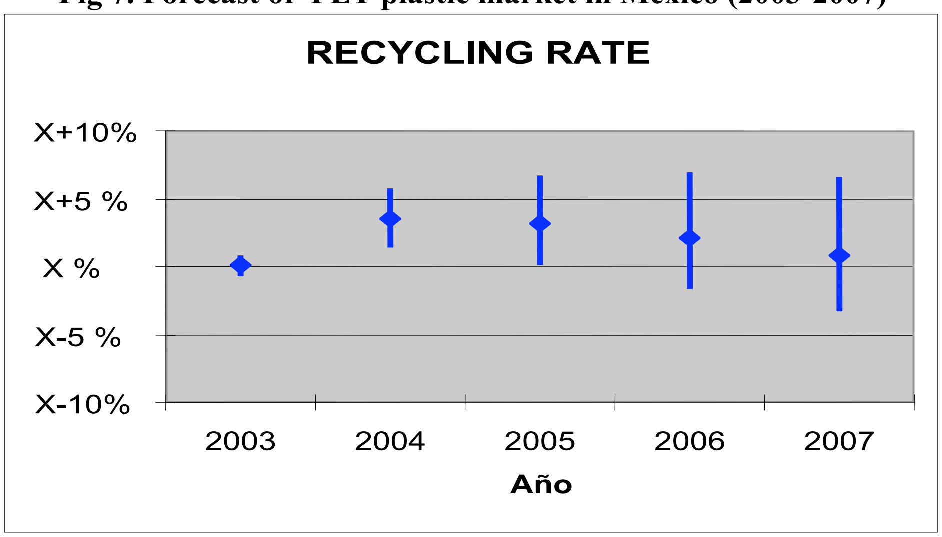


Fig 7. Forecast of PET plastic market in Mexico (2003-2007)



3.2 Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool used to determine environmental impacts of processes (Romero, 1998) or products. LCA allows to determine the amount of energy required for producing or operating and also to identify an inventory of pollutants emitted or generated.

This tools includes the emissions inventory phase where the amount pollutants discharges are quantified. The tools goes beyond production and use of a product to include further stages such as landfill, recycling, incineration, etc. It is a holistic examination of the damages it may cause to the environment ´from cradle to grave´.

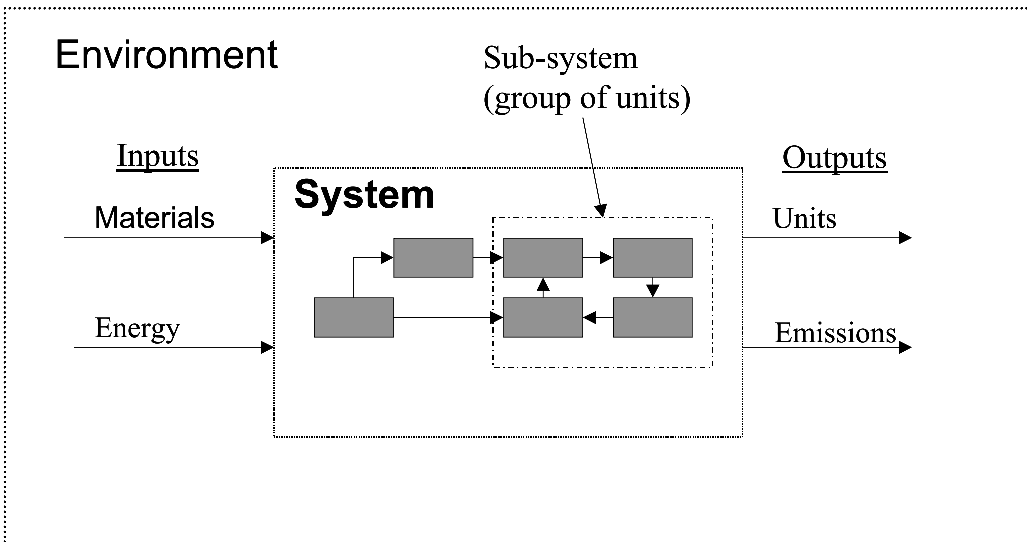


Fig 8. Production process inside the environment

3.3 Environmental impacts

The environmental impact, measured in terms of Global Warming Potential (GWP), of the PET life cycle is presented in Figure 9. The PET life cycle has two main parts: *beverage production* and post-use *waste scenario* process and the part where the two main negative sources of GW are included. In Figure 9, the line thickness is set to express the environmental load of each process flow. Red lines indicates adverse environmental impact while green lines represent a favorable environmental impact.

The main source of adverse GWP impact (measured in terms of CO2 equivalent emissions) of the Mexico's PET life cycle is the PET box, which represents the production of **PET** granulate. The second most significant source of adverse GWP effects is the **Blowing** process. This is due to the amount of electricity required to convert each perform into a bottle by means of blowing hot air.

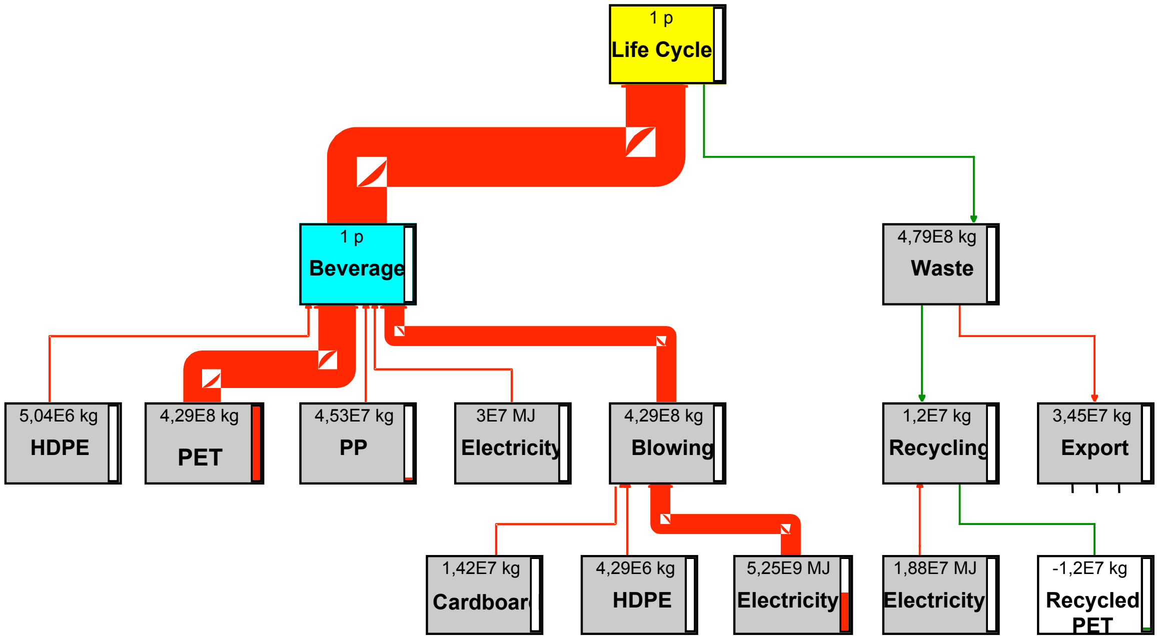


Figure 9. Environmental impact (Global Warming) of various stages in the supply chain

The waste scenario presented on the left side of the LCA presents different results. This issue is presented in more detail in Figure 10.

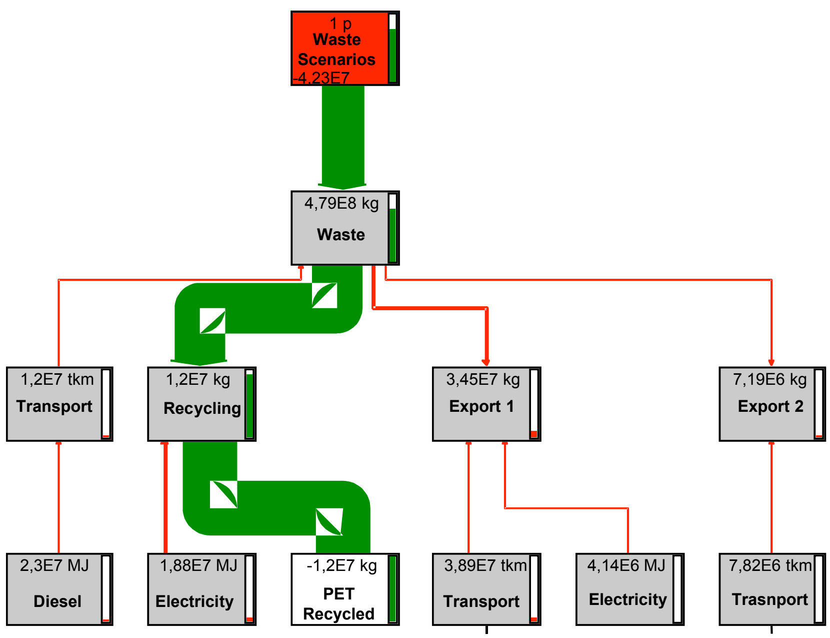


Figure 10. Environmental impact (Global Warming) of the waste scenario

The **Waste Scenario** process (described in figure 10) has an overall favorable GWP impact that reduces the total amount of equivalent CO_2 produced in Mexico. There is a favorable GWP impact related to PET **Recycling**. This thick green line indicates that recycling reduces the total amount of equivalent CO_2 emitted in Mexico as a consequence of PET production. However, the waste scenario also a adverse impact related to post-used PET transport (negative). The PET **Transport** includes **Exporting** and the general collecting of PET from the consumers to the collection centers.

4. SUSTAINABILITY ANALYSYS

The sustainability analysis aims to understand the effect of some processes into the whole environmental impact. Specifically, for this paper, two variables has been chosen: collecting distance and recycling rate.

4.1 Effect of collecting distance

The effects of collecting distance on the GWP impact are presented in the Figure 11. The kg of CO_2 equivalent presented were obtained using the results of the **Waste Scenario** GWP impacts presented in the figure 9. The reason behind this is that there are changes on the left side of the LCA since the amount of PET produced and blowed remains constant. Note that values of CO_2 equivalent emissions are negative, which indicates a favorable impact to the environment.

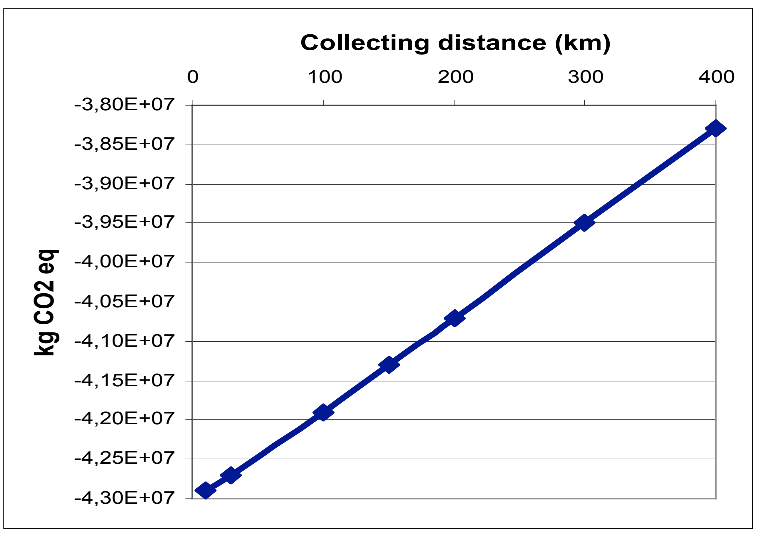


Figure 11. Effect of collecting distance on Global Warming Potential (GWP).

These negative values indicate that the overall environmental impact associated to the waste scenario (PET Recycling and Transport) is always favorable, despite the trade-off between (i) higher environmental impact at higher distances and (ii) lower environmental impact due to PET recycled. This means that CO2 emissions that results from transport are almost negligible compared to the CO2 emissions avoided due to PET recycling as opposed to PET production.

4.2 Effect of recycling rate

The simulation model and the LCA were integrated in order to explore the effect of reintroducing recycled PET into the market. Results are presented in Figure 12. The range for analysis is similar to the recycling rates that most of the developing countries have experienced. The total GWP decreases as a function of recycling rate. This quantifies the benefits derived from re-using PET. However, GWP values indicate that the adverse effect of GWP is so significant that it remains in the same order of magnitude even at higher recycling rates. Therefore, the most significant alternative to lower GWP impact is not to increase recycling rates at any cost but to use lower amounts of PET to deliver the same quantity of soft drinks. This insight suggests that companies will need to strive in order to find bottling alternatives that require lower amounts of PET.

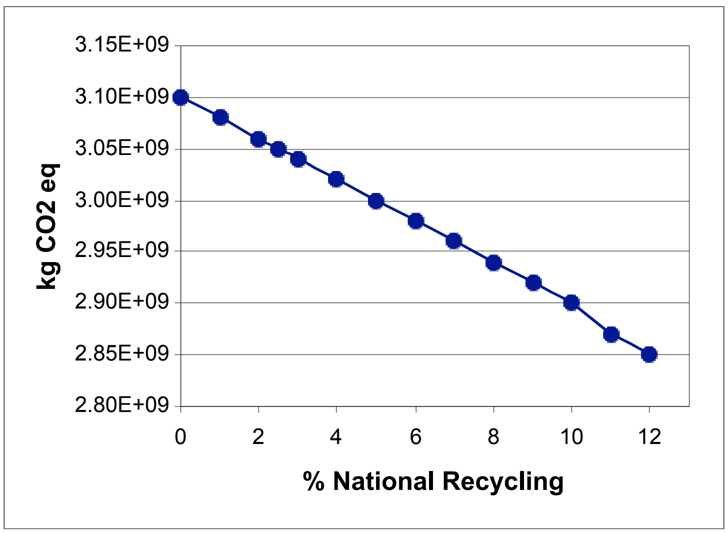


Figure 12. Effect of recycling on Global Warming Potential (GWP).

4.3 Optimal degree of solid waste (PET Bottles) collected/recycled

The previous results of both simulation and LCA were integrated in order to explore the effect of distance in both collecting and recycling. These calculations delivered the most important insight of this work: the existence (at relatively low values) of optimal degrees of solid waste collection/recycling at which total environmental impact is minimized.

Results presented in Figure 13 show that increasing recycling rates from 0 to ca. 35% generate lower environmental impacts (measured in terms of Global Warming Potential). However, after this point, the total GWP impact increases constantly. In terms of environmental policy, this means that after 35%, collecting PET represents higher cost and higher environmental impact.

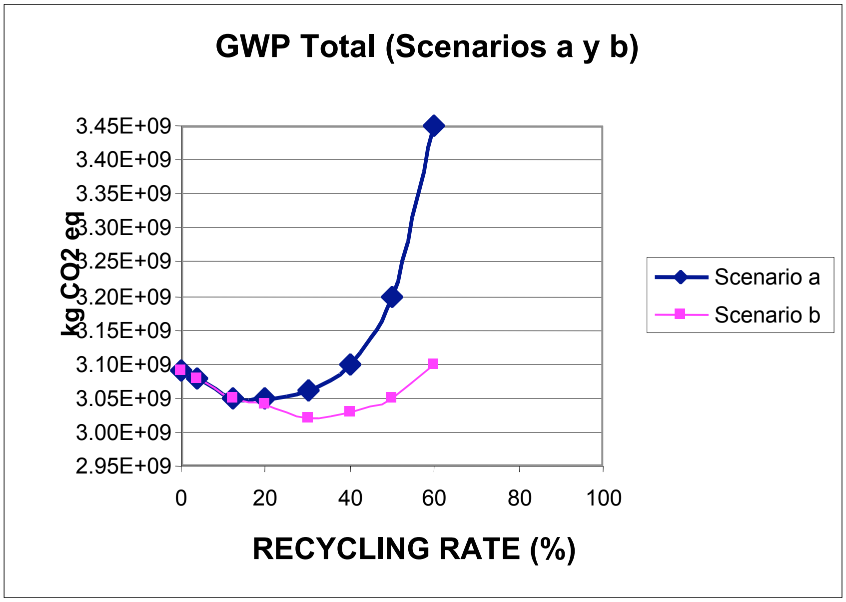


Figure 13. Effect of recycling rate on Global Warming Potential (GWP). Two distance scenarios (a and b)

5. CONCLUSIONS

This work has presented a general framework which aims to analyze the economic and environmental effects related to the introduction of a new product / process / material. In this paper, one of the most successfully introduced plastics material, PET, has been analyzed along its supply chain and life cycle.

Simulation models developed in this work for various processes and operations related to PET proved to be a significant source for understanding the main effects of market variations into the quantity of product demanded and consequently, production levels. Specifically, this model allowed to understand the impact of each sub-market (soft-drinks, bottled water, food, etc) into the overall demand. Results illustrate also the flow of materials along the supply chain.

Environmental performance was also an issue of concern. In this respect, the model was robust enough to describe the interactions and environmental effects related to each process in the supply chain: raw material extraction, raw material transformation, plastic production, perform bottles, beverage production, transport, use, disposal, collection, recycling and landfill. One of the main advantages of the analysis framework presented in this paper is that it supports the understanding of complex systems. Moreover, once characterized, the system can be continuously modified in order to understand the effect of various variables into the whole economic or environmental impact.

Results presented in this work show that increasing recycling rates from 0 to ca. 35% generate lower environmental impacts (measured in terms of Global Warming Potential).

However, after this point, the total GWP impact increases constantly. In terms of environmental policy, this means that after 35%, collecting PET represents higher cost and higher environmental impact.

The insight behind this research can easily be adapted into almost any process or material. As such, this work can be a basis for comparing different design alternatives and also to identify competitive advantages in the selection of products, process and materials.

6. ACKNOWLEDGMENTS

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