Cradle-to-Gate Life Cycle Assessment of Bottle-to-Bottle Recycling Plant: Case Study

Amira Ragab and Amna Ramzy

Abstract The main purpose of this study is to assess the environmental impacts of polyethylene terephthalate (PET) bottle-to-bottle recycling using life cycle assessment (LCA) methodology. Analysis was initially carried out using the material and energy flow analysis (MEFA), to assess material and energy efficiency of a PET recycling plant in Egypt using Umberto efficiency + software; followed by LCA using Umberto LCA software to assess cradle-to- factory gate of recycling post-consumer beverage bottles. The study has been conducted according to the ISO 14040/14044 standard. The functional unit is defined as 1 ton of recycled food-grade PET pellets. Depending on the cut-off approach it was discovered that the production of 1 Ton food-grade PET pellets results in 274 kg CO_2 equivalent which achieves greenhouse gas emission of nearly 84%. Based on the study it can be said that PET recycling offers significant environmental benefits in-relation to virgin PET pellets production.

Keywords Life cycle assessment · Commodity plastics · PET · Recycling · Energy efficiency

1 Introduction

Plastics have experienced a rapid advancement; it can be said that it is indispensable. Half of the plastics global production is intended for single-use applications that are just used once and then thrown out; resulting in the creation of 300 million tons of plastic waste yearly [1]. Tremendous efforts have been subjected towards reducing the amount of plastic waste found in the environment; the plastic stream has to be reduced from the origin; along with altering the plastic waste management [2].

Polyethylene terephthalate (PET) beverage bottle is considered one of the most essential packaging product [3]; as it contributes to 26% of the plastic raw material in Egypt. Shifting towards using recycled plastics has several advantages such as; preservation of fossil fuel, reducing energy consumption and municipal solid waste;

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in which, altogether contribute in reducing emissions [4, 5]. Sustainable consumption and production goal is one of the SDGs; with targets aiming to achieve sustainable management and efficient use of natural resources and considerably reduce waste generation through prevention, reduction, recycling and reuse [6]; this can be achieved through LCA to guarantee that all materials are effectively consumed throughout the life cycle stages [7].

Comprehensively the sustainability of a production system relies upon the material inputs, energy inputs, natural resources, and the product's life [8, 9]. Products were designed and developed without taking into consideration the impacts imposed on the environment, no recognition was taken regarding the product's lifecycle such as use, disposal, and raw material consumption; and, not taking into attention the environmental impacts derived by the product's overall lifecycle into the product design, the environmental dilemma cannot be resolved [10].

Life cycle assessment (LCA) is a systematic analytical tool designed for the environmental assessment of a product's life cycle stages; LCA has been adopted to assess PET applications, alternatives, in order to provide opportunities for environmental improvement [11]. Several studies have assessed disposal scenarios for PET consumer waste as landfill disposal, chemical recycling, energy recovery and mechanical recycling; and it had been manly agreed upon that mechanical recycling is environmentally favorable; consequently, it was demonstrated that the use of recycled PET in bottle production contributed to reduction of 27% in emissions compared to virgin PET [12]. The LCA approach had been formerly used in assessing the environmental sustainability of post-consumer PET; however, there is a limitation in assessing the mechanical recycling of PET in the developing countries. Egypt is considered a significant case due to the limitation of LCA studies regarding the mechanical recycling of post-consumer PET; additionally, Egypt's waste management is considered one of the great challenges for the PET recycling industry [13], limiting supply of post-consumer plastics to the recycling industries due to the reverse logistics link with the collectors and scrap dealers [14]. The purpose of this study is to inspect the environmental impacts of recycled PET bottles; and its contribution to the environment.

The common procedure in assessing PET recycling plants is the cut-off approach that differentiates the first life (virgin product) and second life (recycled product) as separate entities; in which, the after-use product from the first life doesn't bear any environmental burden when used as raw material in the second life as shown in (Fig. 1) [3]. Considering the cut-off approach, the post-consumer plastic bottles are regarded as the raw material for the recycling process "Cradle".

The cut-off approach is considered straight forward and easily conducted; unlike the system expansion method where data from the first life is required for analysis [3]. In this study the analysis was carried out using material and energy flow analysis (MEFA) to establish inventory for the LCA. The material and energy flow analysis (MEFA) were conducted for a PET recycling plant in Egypt; in the following order, determining the system boundaries, building a material flow network, data inventory, determining the functional unit and finally calculating material and energy flow. Life cycle assessment was the subsequent stage; using the cut-off approach. The LCA

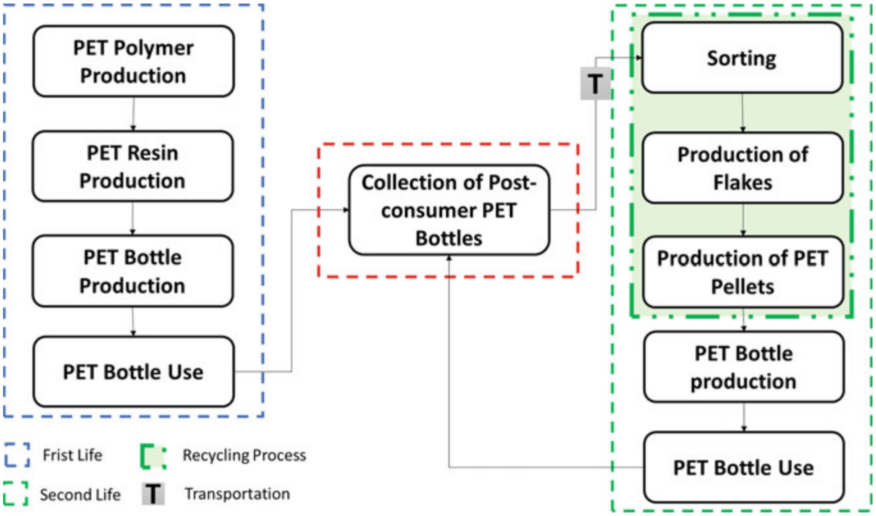


Fig. 1 Cradle-to-gate system boundary of recycling PET post-consumer bottles, based on the cut-off approach

approach is a method for analyzing energy and environmental burdens associated with a process or activity by identifying the energy and materials utilized, as well as solid waste discharged into the environment. From raw material extraction and processing to production, transportation, distribution, reuse, recycling, and final disposal, the evaluation covers the complete life cycle of the process or activity [11].

The recycling approach examined in this study practices mechanical recycling of post-consumed PET bottles to produce food grade PET pellets to be used in the remanufacturing process of PET bottles production. Recent study applied material and Energy flow analysis (MEFA) on the Starlinger stage; subsequently this study is to expand the analysis onto the whole production line using MEFA and LCA [15]. The main stages considered in the mechanical recycling process is TOMRA, AMUT and Starlinger. The TOMRA is the pre-sorting stage consisting of various processes to achieve solely clear colored, de-labeled and un-capped PET bottles; followed by the AMUT line which performs pre-washing, grinding and filling to reach quality-controlled PET flakes; the final stage to produce the final product is the Starlinger the main processes in this stage is the extruder to produced pelletized PET and the solid state polycondensation reactor (SSP) to achieve food-grade quality PET pellets.

2 Methodology

LCA methodology was carried out according to ISO 14040/14044.

2.1 Goal

The goal of this LCA is to identify sustainability impacts and optimization of recycled food-grade PET pellets intended for food and beverage applications. Food-grade PET pellets are used as a transitional product in the packaging industry. Recycled pellets contribute in reducing the environmental burden of landfilling or incineration of post-consumer beverage bottles. The main reason for this study is the investigation of the reduction potential of recycling to landfilling or incineration.

2.2 Scope

The scope of this LCA is post-consumer plastic bottles to be recycled as a food-grade PET pellets; the functional unit in this study is defined as one ton of food-grade PET pellets. The system boundary assigned in the scope of this LCA is cradle-to-gate; this includes the acquisition of post-consumer beverage bottles, transportation, raw materials, and energy, then followed by the transformation steps required to obtain the recycled product. The use and end of life is not taken into consideration; along with first life of the virgin product that had been disregarded by the cut-off principle, since the used beverage bottles are considered waste and waste doesn't endure any environmental impact from the first life.

The allocation assigned in this study is mass allocation; taking into consideration by-products and waste discharged during the recycling process; as, purge, fines, dust and mixed plastics consisting of polyolefins. The waste discharged are separated and each type of waste is managed differently; either, handled as waste or processed to be sold.

Life cycle impact assessment (LCIA) method is applied to the life cycle inventory data related to industrial processing, raw material, energy, resources, transportation and waste disposal; in which, all serve in the emissions released, are transformed into environmental impact categories. The environmental indicators selected are; non-renewable energy use (NREU), global warming potential (GWP), acidification, human toxicity and fresh water aquatic ecotoxicity.

The data for this study is provided by a recycling plant located in Cairo, Egypt. The data for production (Primary data) is measured based on the factory's data inventory for the time period of 2021–2022; secondary data where either obtained from a recent literature or the Ecoinvent database integrated in Umberto LCA+. Data collection was quantified based on the flow diagram of the production line to relate all the material exchanges and data categories for respective process. The inventory is listed in (Table 1); all data are functionalized in respect to the production of 1 Ton recycled food-grade PET.

Table 1 Inventory data for recycling process

		Value	Unit
Input			
	Post-consumer bottles	1.72	Ton
	Water	318.66	Kg
	Caustic soda	22.7	Kg
	Natural gas	20	m^3
	Electricity consumption	887.294	Kwh
Output			
	Dust	1.11	Kg
	Water loss	316	Kg
	Polyolefins	560	Kg
	Purge	29.12	Kg
	Metal flakes	8.31	Kg
	Non-food grade pellets	127.88	Kg
	Food grade pellets	1	Ton

2.3 *Limitation*

The limitation of this study for the data sources is the natural gas; no database was available for the natural gas production of Egypt; therefore, picking a country in the same region as Egypt was carried out and Natural Gas production, Algeria was used. Additionally, the raw materials import distance was averaged to a single location for simplicity (Table 2).

Table 2 Data sources

Data	Sources
PET bottle-to-pellets recycling	Collected from Bariq rPET pellets producers (Primary Data)
Electricity production Mix, Egypt	Ecoinvent v3.8
Transportation distances and raw materials used	Collected from Bariq rPET pellets producers (Secondary Data)
Land and water transportation	Ecoinvent v2.2
Market group for tap water	Ecoinvent v3.8
Natural gas production	Ecoinvent v3.8

3 Recycling PET Bottles into Pellets

3.1 Collection of Post-consumer Bottles

In Egypt, post-consumer bottles are collected with other household waste; it is collected on a local scale, sorted and compacted into bales. Regarding the energy requirements related to the baling of the bottles is neglected being insignificant in relation to the recycling process energy consumption; therefore, the environmental burden associated to the collection of the post-consumer bottles is the transportation. In the case of the recycling operation is in Egypt; however, fifty percent of their bottle consumption is imported.

3.2 Production of Recycled PET Pellets

The flow of the production of recycled PET flakes is shown in (Fig. 2) presorting is the first stage in the process, in order to separate the bottles based on color and material using an automated technology; as uncolored bottles are more favored and have higher material value [3]; the rejected bottles along with the undesired materials are either thrown out or sold as by-products; then, the bottles are disassembled as the caps and labels are removed, and are treated to be sold as a by-product. The bottles then go through multiple stages of cleaning, metal separating, de-dusting, optical color sorting, grinding and finally a drying unit to produce the PET flakes. The final stage is mainly consisted of an under-water pelletizing extruder to achieve the PET pellets followed by a post crystalizing unit and a reactor to achieve high quality, food-grade recycled PET pellets.

4 Life-Cycle Impact Assessment (LCIA) Results and Discussion

The LCA is conducted using Umberto LCA+, the flow of the mechanical recycling process is shown in (Fig. 3). The production process is categorized into presorting, prewashing, grinding and washing, mixing and filling and Starlinger (extrusion). As aforementioned the LCA is carried out based on the cradle-to factory gate methodology, using mass allocation. The figure shows the phases of the LCA from raw materials, production, to the final product and established by-products throughout the production process.

The assessment was conducted based on the inventory data supplied by the recycling plant in relation to 1 ton of recycled PET pellets shown in (Table 1), (Figs. 4, 5, 6, 7, 8 and 9) demonstrate Sankey diagram of the resulting assessment; which is

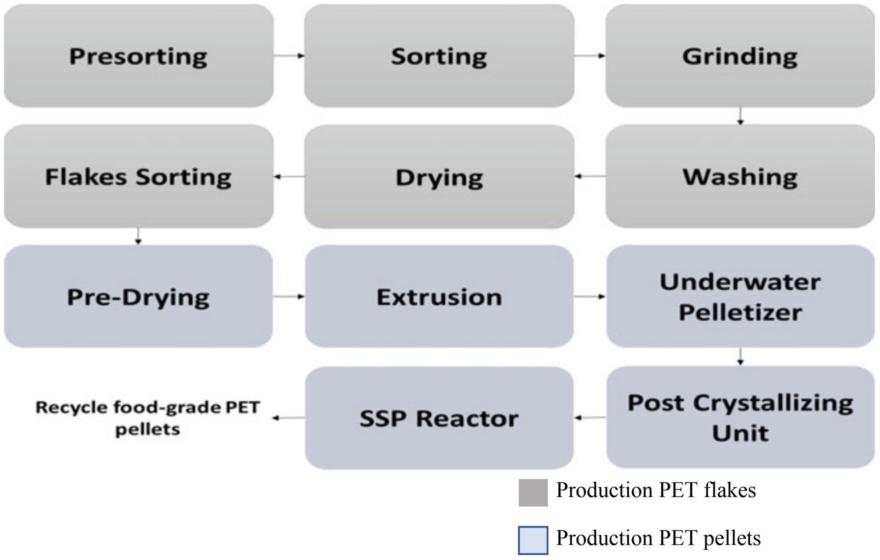


Fig. 2 Production of recycled PET pellets

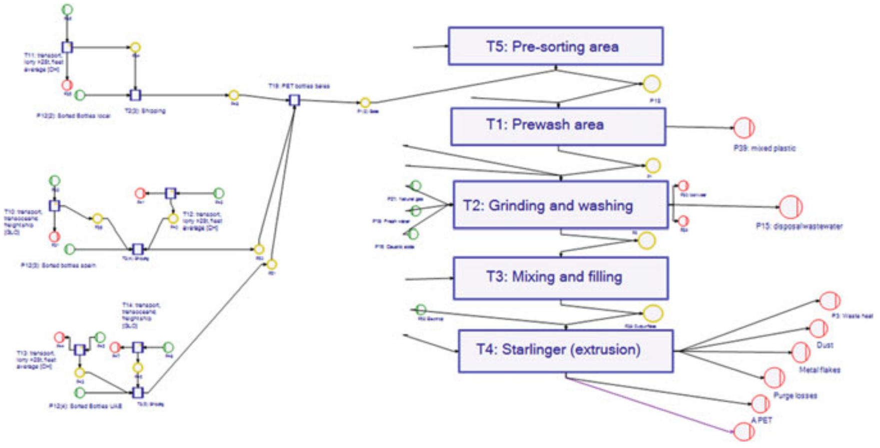


Fig. 3 Recycled PET pellets flow mapping

a flow diagram that improves the visual aspect and the performance of the diagram; as the width of the arrow represents the flow quantity for mass and energy flows.

As demonstrated in the previous figures Sankey diagram is a helpful tool in visualizing the mass and energy flows of the production line; based on the width of the line it is simple to establish the processes requiring the highest energy for future modifications [17].

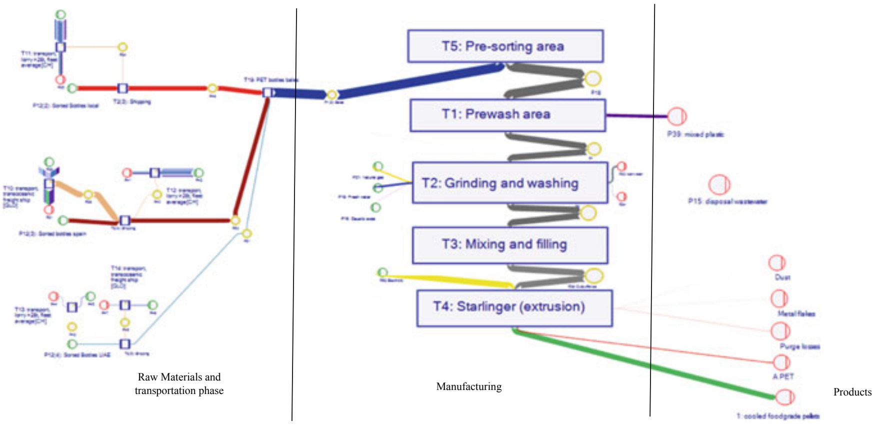


Fig. 4 Sankey diagram, total flows

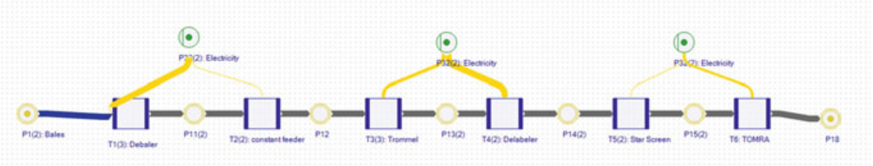


Fig. 5 T5: presorting area, Sankey

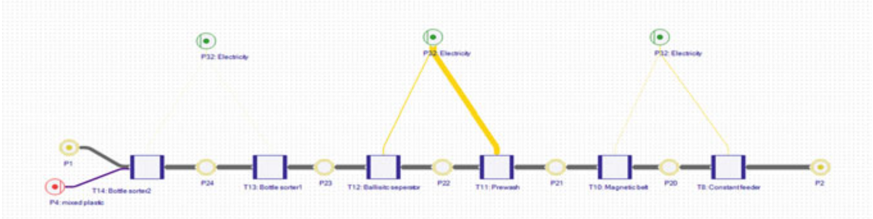


Fig. 6 T1: prewash area, Sankey

Fig. 7 T2 grinding and washing. Sankey

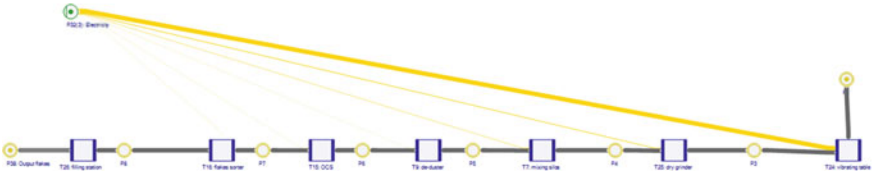


Fig. 8 T3 mixing and filling, Sankey

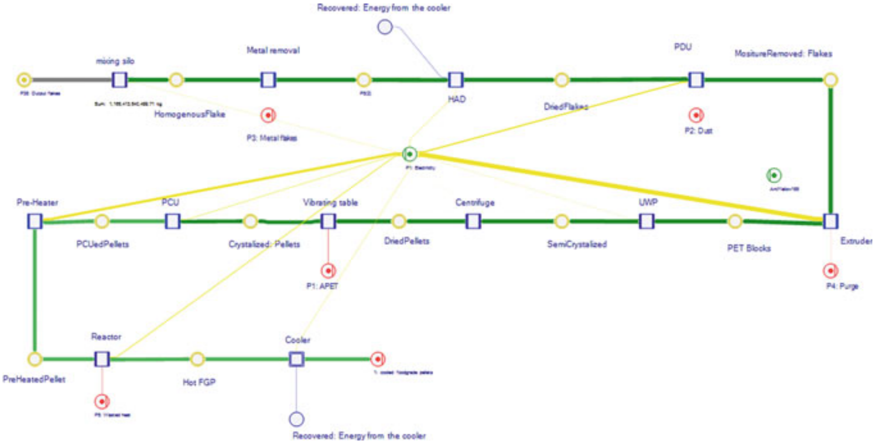


Fig. 9 T4 Starlinger (extrusion) area, Sankey

The by-products formed throughout the production cycle; doesn't contribute to the impact factors; as rather than being landfilled, they are sold to perform as a raw material in a different production process lowering the impact delivered by the recycling plant (Table 3).

The major impact is derived by the electricity consumption for the Manufacturing phase of the recycled PET pellets; resulting in high CO_2 equivalent; additionally, the manufacturing phase contribute in increasing other Impact categories as fossil depletion, water depletion and human toxicity as shown in (Fig. 10).

Analyzing the LCIA inventory results showed that most of the remaining impact factors is a result of the transportation in the raw material phase; Due to the issue of post-consumer bottle collection and the lack of waste management [18]; half of the recycled bottles are imported; therefore, resulting in an increase in the equivalent impact categories; nevertheless, the CO_2 equivalent of recycled PET production is 273.37 kg CO_2-Eq which is lower than the carbon footprint equivalent than that of virgin PET pellets production by 84% [12].

Taking into consideration the impact of the geographical area onto the energy consumption [16], due to the difference of electricity mix in different areas [14]. The same production could be carried out in a different are with high renewable energy resources could lead to a lower carbon-footprint equivalent; additionally, the

Table 3 LCIA results for 1 ton of food grade recycled PET pellets, based on the "Cut-off" approach, cradle-to-factory gate of the recycling stage

LCIA factors	Equivalent Impact		
	Raw materials phase	Manufacturing phase	Gate Phase
Climate change w/o LT, GWP100 w/o LT (kg CO_2-Eq)	78.29	259.05	0.24
Fossil depletion w/o LT, FDP w/o LT (kg oil-Eq)	28.25	119.43	0.07
water depletion w/o LT, WDP w/o LT (m^3)	0.26	1.38	0.57
human toxicity w/o LT, HTPinf w/o LT (kg 1,4-DCB-Eq)	2.99	5.99	0.06 kg
freshwater eutrophication w/o LT, FEP w/o LT (kg P-Eq)	1.41E-03	3.78E-04	1.46E-05
terrestrial acidification w/o LT, TAP100 w/o LT (kg SO_2-Eq)	1.06	0.5	9.71E-04
urban land occupation w/o LT, ULOP w/o LT (m^2a)	0.55	0.32	2.97E-03

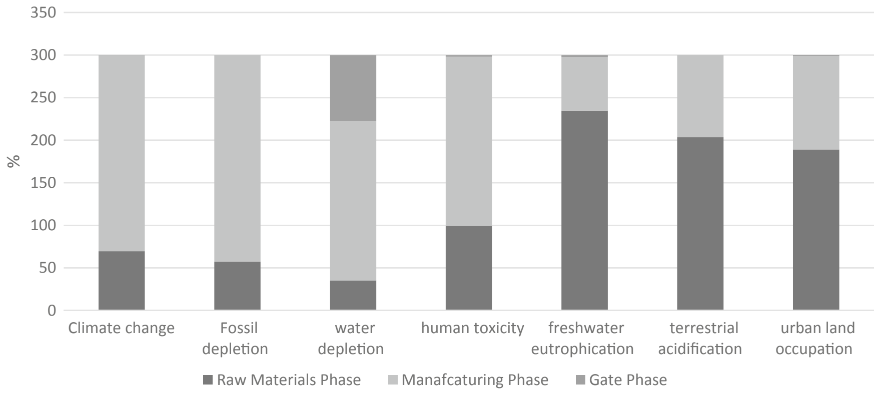
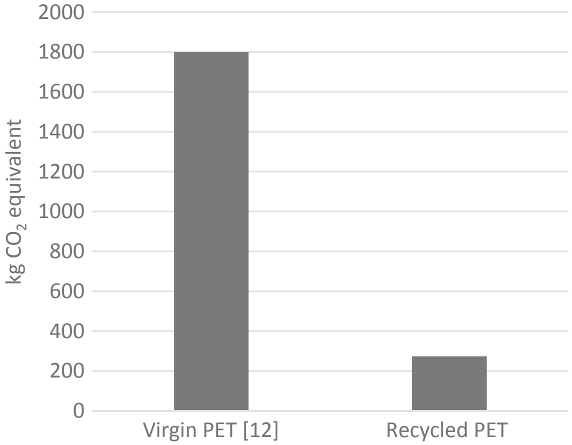


Fig. 10 Normalized LCIA results for 1 ton of food grade recycled PET pellets, based on the "Cut-off" approach, cradle-to-factory gate of the recycling stage

geographical location contributes to the availability of post-consumer bottles through effective waste management systems that will contribute in lowering alternative impact categories (Fig. 11).

Fig. 11 Carbon footprint equivalent of 1 ton recycled and virgin PET pellets



5 Conclusion

In this case study, the environmental impacts of bottle-to-bottle recycling were investigated with main contribution in the reduction potential of recycling to landfilling or incineration of post-consumer bottles. The LCA results demonstrated for the geographical location Egypt. The method applied to this study is cut-off using mass allocation approach. LCA results show that the total climate change impact of high-quality food-grade PET pellets results in 84% GWP savings in relation to that of virgin PET. Electricity usage contributes the most in the impact categories assessed for the Raw material, Manufacturing and gate phases. The cut-off applied to the system resulted in two cuts resulting in a Gate-to-Gate assessment; which in this case study of recycling called Cradle-to-gate assigning the post-consumer bottles as the raw material “cradle” for the recycling process. This case study provides a fragmented assessment of the complete LCA of beverage bottles; which can be integrated in an extensive study; System expansion method is not simple to apply as it requires detailed dataset. Overall environmental benefits from recycling post-consumer beverage bottles is significant in-relation to single-use virgin materials improving ecoefficiency, evading manufacturing of virgin materials and reducing landfilling or incineration (Figs. 12 and 13).

Fig. 12 Egypt's percentage of total electrical power generating capacity

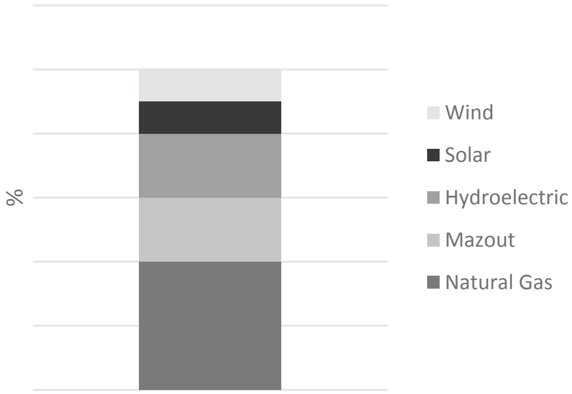
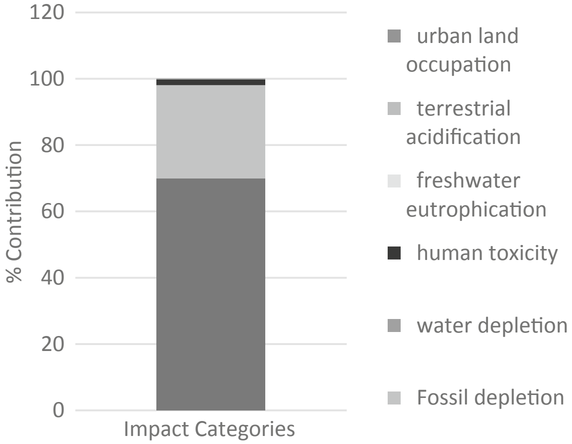


Fig. 13 Egypt's electricity production mix, Impact categories contribution/Kwh



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