The integrated plastic waste management: a technical-economical assessment of an integrated sorting – feedstock recycling system

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Abstract

The production of wide typology of polymeric-based materials, such as engineered polymers and multi-layered compounds, and the increased amount of thermoplastic materials in general, resulted in a gap between the real market demand for secondary polymer-based materials and the amount and quality offered by the existing waste management systems. The plastic waste disposal is a question of increasing importance that can be correctly managed only by integrating different routes for recycling/recovery of these high-value materials. The feasibility of integration between existing system and feedstock recycling process has been assessed by using the method of scenarios' comparison. The plastic waste taken as reference is that coming from the urban and commercial sources, mainly composed by packaging materials. Three scenarios have been assessed on the basis of performances' indexes that compare the capability to obtain new goods or substitutes of virgin materials and energy other than the needs of landfilling. The reference scenario (A) is the most applied in Europe nowadays: it consists in a centralised mechanical sorting at the material recovery facility (MRF) followed by the mechanical recycling for the obtained pure streams of PET (sorted by colour) and HDPE to obtain secondary goods and landfilling, or energy recovery (B), for the remaining residue. The alternative scenario C considers how the feasibility of the whole network should be affected by the introduction of the polyolefins-to-oil (PtO) conversion. Results indicate that the integrated scenario C is the best one since maximize the recycling and recovery indexes with a very low landfilling index.

Introduction

Last data from Plastics Europe show that 322 millions of tons of plastic materials were produced worldwide in 2015 and 335 millions in 2016 [1]. The extensive production of plastics created also a question related to plastic waste disposal. The large variety of plastics and their various utilisation involves the necessity to find different processes able to obtain an environmental correct disposal and an optimised material and energy recovery. Depending on their physical and chemical characteristics, the collected plastic waste can be sent to a mechanical recycling treatment, to a feedstock and chemical recycling process or to an energy recovery unit [2]. The processes to be included in the management system for plastic waste exploitation have to be able to use the "equivalent petroleum amount" of plastic waste several times: as material, feedstock and fuel.

The mechanical recycling of plastics should be preferred when a mono-material collection of plastics must be treated, since the cost of the separation processes is very high: more than 70kWh/t is required by sorting the plastic waste into monomaterial streams suitable to be recycled into materials or feedstock. Otherwise, if a mixture of different polymers has to be treated, it could be convenient to take into account the feedstock recycling and, as last option, the energy recovery processes. The utilisation of feedstock recycling requires a sorting to remove contaminants such as chlorine-plastics and specific plastics not suitable for the chosen process: for example, the feedstock recycling carried out by recurring to thermochemical process requires the absence of plastics containing heteroatoms i.e. PET, PVC [3]

The energy recovery should be limited to mixture of plastics that cannot be conveniently addressed to the above cited routes since once the it is realised no other ways to recover matter is possible. Unfortunately, this “last option” is largely applied today for all the plastics that are not separately collected at household and for plastics that have no market for mechanical recycling without applying other more preservative processes as overriding options. The worst route, unfortunately largely applied in the last years, is the landfilling of this waste.

The global market of plastic waste and that of secondary materials obtained by plastics, including polyolefins, changed starting from 2013 when China, the most important importing Country of this waste and low-quality

polyolefins, set up the “Green Fence” to temporarily restrict the import flows and type and, in 2017, set up the permanent ban of the import of nonindustrial plastic waste [4].
The two consequences of this policy are: the increase of landfilling and incineration and the increasing of disposal tipping fee for plastic waste that is approaching the stable value of 150€/t [5].

The plastic conversion into oil (or to feedstock, more in general) is not applied in wide scale but it can become an interesting integration, not a competitor, of the above described standard management system. The PtO process can be obtained by using commercially available technologies listed in the table 1. These Companies have, or had, demonstration plants in operation. The proposed technologies differ each to other for the plastic feeding type (e.g. pure polyolefins or mixed plastic), reactor feeding type (batch or continuous), presence or catalyst or not. The common point of all technologies proposed for PtO is the limited scale; a typical capacity of 20.000t/year is proposed. This limitation suggests considering these technologies as integration at local/regional level of MRF. In other words, these plants can be conveniently located in the MRF boundary since they have capacities in line with the plastic waste produced by these sorting&recovery plants.

Tab. 1 List of technological suppliers for feedstock recycling plants

	Short Name	**Website**
1	Agilyx	www.agilyx.com
2	Alphakat	www.alphakat.de
3	Anhui Oursun	www.plastic-oil.com www.oursunchina.com
4	APC	http://pyrolysisplant.com
5	BlueAlp	www.bluealp.nl http://www.petrogas.nl/
6	Climax	www.climaxglobalenergy.com
7	Envion	www.envion.com
8	GEEP	www.geepglobal.com
9	JBI	http://www.plastic2oil.com
10	Klean Industries	www.kleanindustries.com
11	MK Aromatics	www.mkaromatics.com
12	Nexus Fuels	www.nexusfuels.com
13	Plastic Advanced	www.plastic2x.com
14	Plastic Energy Ltd. (former: Cynar)	http://www.plasticenergy.net
15	Polymer	http://www.polymerenergy.com
16	PRYME	www.pryme-cleantech.com
17	Pyrocrat Systems - see AgileProcessChemicals	www.pyrocratsystems.com
18	Renewlogy	www.renewlogy.com
19	Res Polyflow	http://www.respolyflow.com/
20	Vadxx	https://vadxx.com/

Materials
The plastic waste collected by separate collection has a composition affected by several factors such as the wellness level, the GDP per capita and the educational level of inhabitants and the quality of the waste management and collection service provided by the municipality.
The reported composition (Table 2) is related to waste collected by a door-by-door collection system, in an Italian region characterised by a medium value of GDP (around 29.000€ p.c.), a well-structured and organised system to carry out the separate collection but a lack of post-collection infrastructure [6].

Tab. 2 Composition of mixed plastic waste - MPW

Plastic packaging (27% PET, 11% PE)	52%
Aluminium packaging	1%
Ferrous packaging	8%

Paper & cardboard	3%
Glass	4%
Other recyclables	2%
Foreign matter	9%

RESULTS

Description of base case and alternative scenarios

The base case scenario is labelled “scenario A” and refers to the actual plastic waste management network. Alternative scenarios B and C are set up in order to measure the improving of the overall sustainability of the network in term of recovered materials and energy. Scenario B is normally applied for which Countries having a sufficient residual capacity of incineration plants or other energy recovery options such as foundries and cement kilns licensed to use the plastic derived fuels.
Scenarios A, B and C, described in the following, have a common item: a Material Recovery Facility (MRF). The detailed analysis of the material flows for the MRF is reported under form of block diagram in the Figure 1 [6].
In the scenario A, the Material Recovery Facility receives the plastic waste collected in the urban area following a set of aggregation rules:

- Allowable: liquid containers, flexible packagings, cans, rigid metal packagings, …
- Not allowable: biowaste, toys, glass and inerts, electronic and electric waste, …

In particular, the mixed plastic waste (MPW) entering the MRF is formed by thermoplastic packaging materials, ferrous and non-ferrous packaging waste, with a limited fraction of paper that can be recycled with a higher efficacy when is collected as mono-material stream. The composition of MPW is given in table 2.
This waste is managed in a typical MRF in order to sort the original MPW into mono-material streams of PET, HDPE, polyolefins, ferrous metals, aluminium and a residual waste identified as MPR. The MRF is composed by mechanical equipment using physical-chemical properties such as density, size and wavelength reflected off by the materials and a series of conveyor belts designed to guarantee an optimal distribution and a speed, angle and direction suitable to be addressed in the best way to the following equipment. The automatic debailing system is designed to “de-densify” and meter baled materials with a limited size reduction. The apparatus is formed by shafts in low speed rotation so avoiding intense size reduction. The mean size of materials exiting from this apparatus is 50-300mm. The flow coming from the debailing system is addressed to balistic sorter that sort out the incoming flow into 2D and 3D flows. The 2D flow is conveyed to a belt conveyor; this belt addresses the material with suitable speed and good distribution to optical sorter using the Near-InfraRed (NIR) technology that separates the polyolefin material by recognizing them as “positive flow”. This means that the detector is set-up to individuate materials made by polymers such as PE, PP, PS and the ejection system of the sorter push them into a conveyor belt connected with the following sorter. The rest of material is indicated as “negative flow” and it is addressed to the “MPR”. The 3D flow is addressed to magnetic separator where the ferromagnetic materials are detected and removed and to a series of NIR. NIRs sort the PET streams by colour and the HDPE. A final NIR is dedicated to recycle the undetected materials to the MRF inlet. The last check is dedicated to aluminium detection by means of an eddy current device; all the remaining material constitutes the residue of MRF.

This latter residue is mainly composed by non-recyclable plastics but it also contains polymers such as PET and polyolefins because of the non-unitary sorting efficacy of the MRF. In fact, the interception efficiencies during the household separation are not unitary [6] as well as the sorting efficacy cannot be unitary too. These losses of efficacy resulted in the following typical composition of MPR (table 3).

Tab. 3 Composition of plastic waste residue - MPR

Polyolefins	**47%**
Ferrous metals	**1,0%**
Aluminium	**1,0%**
PET + PVC + other polymers	**42%**
Foreign materials (biowaste, glass, …)	**9%**

This residue is addressed to landfill or, when suitable plants are available, to incineration together with municipal solid waste.
The landfilling is considered in the base case scenario A, reported in the Figure 2. Data have been evaluated by using the STAN software [] and the material flow assessment method [].

The alternatives have been considered in the scenarios B and C, reported in the figures 3 and 4. These scenarios differ for the integration of processes suitable to increase the material and energy recovery and the minimization of landfilling. In particular the aim is to avoid the landfilling of material with a potentially high-added value.

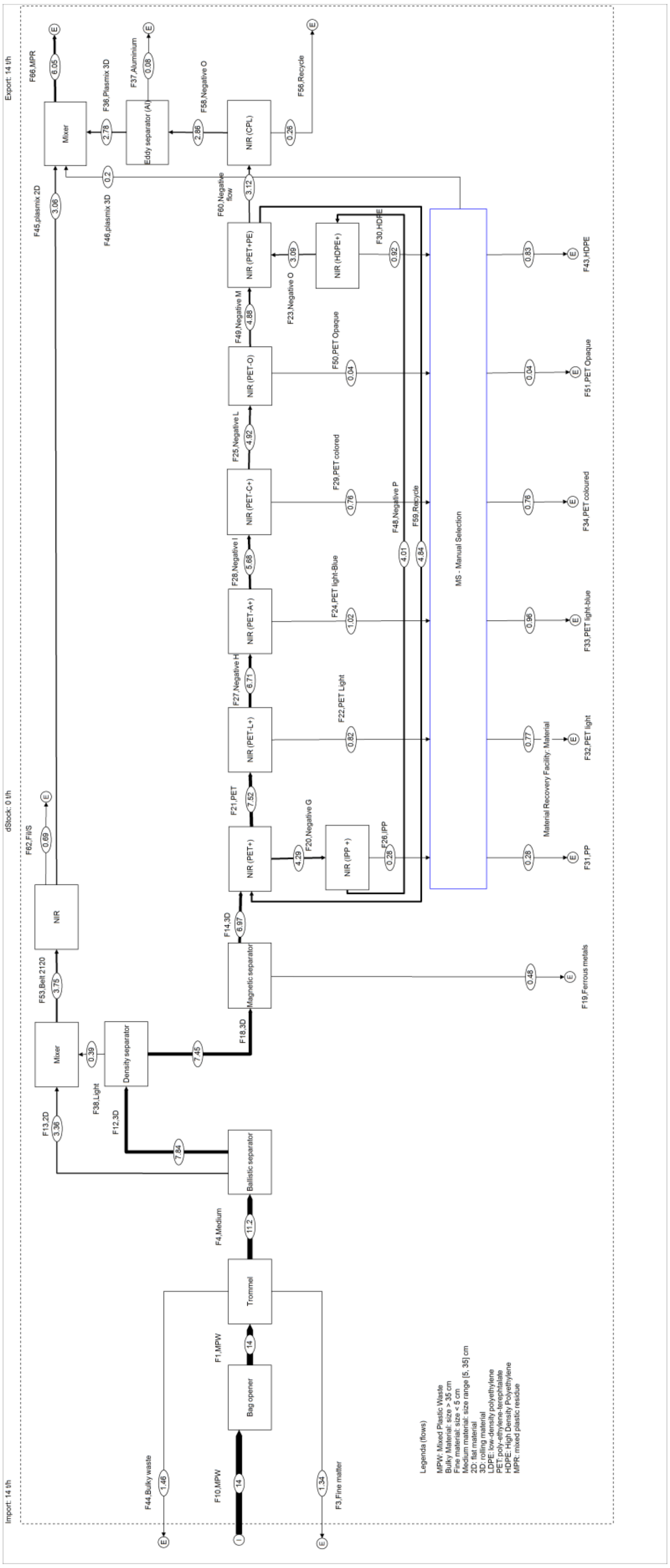

Fig. 1 Material flows assessment of material recovery facility taken as reference [6]

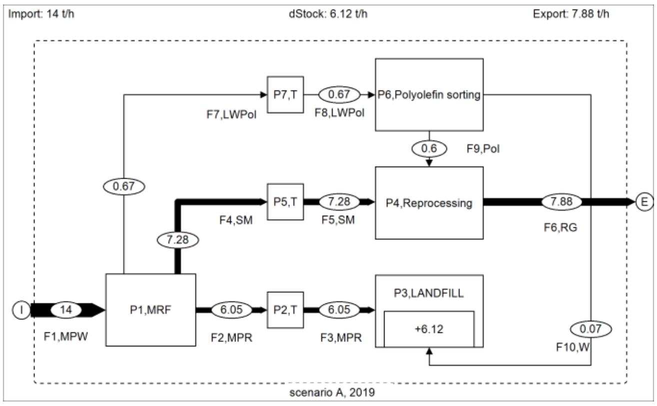

Fig. 2 Scenario A: base case with MPR landfilling

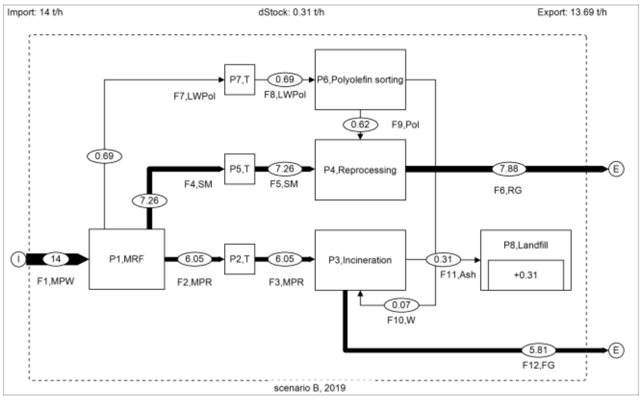

Fig 3 Scenario B: alternative case with MPR incineration

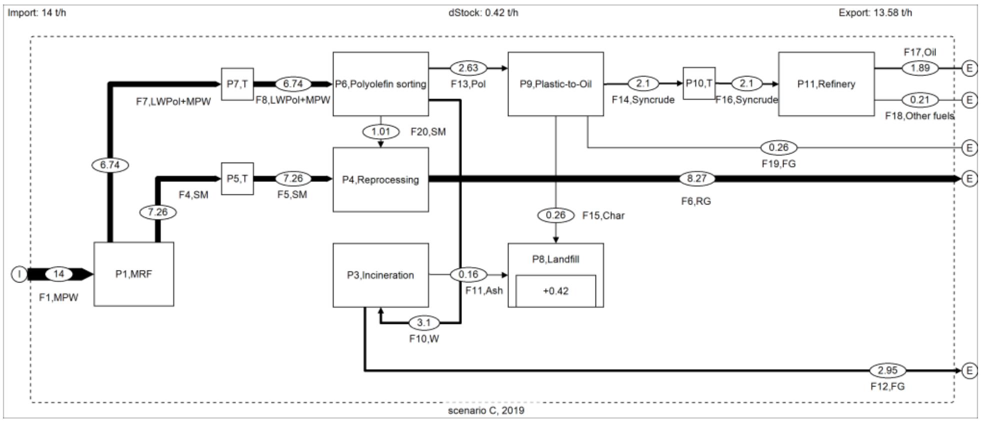

Fig 4 Scenario C: alternative case with MPR incineration and plastic-to-oil integration

The plastic-to-oil process (P9 in Figure 4) is carried out by means of thermolysis process of polyolefins. The low-temperature pyrolysis of these polymers produces a spectrum of hydrocarbons ranging from high-boiling molecules (boiling temperature > 340°C) to hydrogen and methane [9, 10]. The largest part of the produced stream can be defined a synthetic crude oil (syncrude). This feedstock can be added to crude oil in a refinery to produces gasoline, diesel, jet fuel. By assuming to separate the permanent gas by the rest by using a total condenser, the flows F17 and F18 represent the diesel fraction and the light hydrocarbons (boiling temperature < 212°C) fraction.

Results and discussion

The comparison between the scenarios A, B and C has been made by defining some performance's indexes. The first set of indexes are related to the mass flows of: material recycled as new goods ($Y_{M,MR}$), materials used as fuel in processes for energy production ($Y_{M,ER}$) and the materials landfilled ($Y_{M,L}$). The exact definition is the following:

$$Y_{M,MR} = \frac{mass\ flow\ of\ recycled\ goods\ (\sum_i F_i)}{mass\ flow\ of\ F1}$$

$$Y_{M,ER} = \frac{mass\ flow\ of\ materials\ utilised\ as\ fuels\ (\sum_j F_j)}{mass\ flow\ of\ F1}$$

$$Y_{M,L} = \frac{mass\ flow\ of\ materials\ addressed\ to\ landfill\ (\sum_k F_k)}{mass\ flow\ of\ F1}$$

These indexes are reported in table 4 and demonstrate that the highest material recycling yield is obtained for scenario C while the minimum landfill demand is obtained for scenario B. Actually, an improvement of scenario C can be obtained by choosing a technology to perform the PtO process that can recover the char in the framework of the process itself; in this way the demand for landfill space reduces at 0.011t/t that is the half of the corresponding index for scenario B. This technology is not available on the market yet, but it has been recently patented [11].

Tab. 4 Performance mass-based indexes for scenarios A, B and C

Scenario	Material recycling yield ($Y_{M,MR}$, t/t)	Energy recovery yield ($_{M,ER}$, t/t)	Landfill yield ($Y_{M,L}$, t/t)
A	0.563	0	0.437
B	0.563	0.415	0.022
C	0.741	0.229	0.030

The assessment of feedstock energy flows is also interesting to evaluate the performance and the sustainability of the proposed scenarios. Both mass and energy flow rates have been then reported in the table 5. It is possible to note that the reported data clearly show that the scenarios B and C do not landfill any material with a residual feedstock energy. This feature is crucial in order to maximise the exploitation of materials and avoid fire risks in the landfill itself. It is also a requisite of European regulations and of all criteria related the sustainability of waste management.

Tab. 5 Mass and feedstock energy flows for scenarios A, B and C

SCENARIO A	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	
From	Ext	P1	P2	P1	P5	P4	P1	P7	P6	P6	P2 + P6
To	P1	P2	P8	P5	P4	Ext	P7	P6	P4	P8	P8
Mass flow rate, t/h	14	6,05	6,05	7,26	7,28	7,88	0,67	0,67	0,6	0,07	6,12
High Heating Value, MJ/t	28,76	37,20	37,20	20,71	20,71	22,19	40,05	40,05	40,05	40,05	37,24
Feedstock energy, MJ/h	402,6	225,1	225,1	150,4	150,8	174,8	26,8	26,8	24,0	2,8	227,9

SCENARIO B	F1	F2	F3	F4	F7	F8	F9	F10	F5	F6	F11	F12
From	Ext	P1	P2	P1	P1	P7	P6	P6	P5	P4	P3	P3
To	P1	P2	P3	P5	P6	P6	P4	P3	P4	Ext	P8	Ext
Mass flow rate, t/h	14	6,05	6,05	7,26	0,67	0,67	0,62	0,07	7,28	7,88	0,31	5,81

High Heating Value, MJ/t	28,76	37,20	37,20	20,71	40,05	40,05	40,05	40,05	20,71	22,19	0	0
Feedstock energy, MJ/h	402,6	225,1	225,1	150,4	26,8	26,8	24,8	2,8	150,8	174,9	0,0	0,0

SCENARIO C	F1	F4	F7	F8	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19
From	Ext	P1	P1	P7	P6	P3	P3	P6	P9	P9	P10	P11	P11	FG
To	P1	P5	P7	P6	P8	P8	Ext	P9	P10	P8	P11	Ext	Ext	Flue gas
Mass flow rate, t/h	14	7,26	6,74	6,74	3,1	0,16	2,95	2,63	2,1	0,26	2,1	1,89	0,21	P9
High Heating Value, MJ/t	28,76	22,97	35,00	35,00	34,64	0	0	35	42,06	20	45,4	45,4	12,03	Ext
Feedstock energy, MJ/h	402,6	166,8	235,9	235,9	107,4	0,0	0,0	92,1	88,3	5,2	95,3	85,8	2,5	0,26

The same indexes measuring the scenario performance reported with reference to the mass flows have been defined and evaluated regarding the energy flows. These “energy yields” are defined as:

$$Y_{E,MR} = \frac{energy\ flow\ of\ recycled\ goods\ (\sum_i F_i)}{energy\ flow\ of\ F1}$$

$$Y_{E,ER} = \frac{energy\ flow\ of\ materials\ utilised\ as\ fuels\ (\sum_j F_j)}{energy\ flow\ of\ F1}$$

$$Y_{E,L} = \frac{energy\ flow\ of\ materials\ addressed\ to\ landfill\ (\sum_k F_k)}{energy\ flow\ of\ F1}$$

The values of these indexes (Tab. 6) confirm that the Scenario C strongly improve the performance of the waste management system by maximizing the recovery of high-value materials, both secondary materials and secondary feedstocks, minimize the energy recovery and allows to send to landfill only mineralised waste.

Tab. 6 Performance energy-based indexes for scenarios A, B and C

Scenario	Material recycling yield ($Y_{E,MR}$, t/t)	Energy recovery yield ($Y_{E,ER}$, t/t)	Landfill yield ($Y_{E,L}$, t/t)
A	0.434	0.000	0.566
B	0.434	0.566	0.000
C	0.691	0.296	0.013

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