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Appendix A

The contribution of plastic recovery to resource efficiency and greenhouse gases (GHG) savings

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1. Dynamic Material Flow Analysis (MFA) of plastics: data and assumptions

1.1. Accounting method of flows

The system under study concerns only material flows, and the calculation of both stocks and flows, which is then based only on the principle of mass conservation; thus, the total input consisting of flows from previous process should be equal to products production, stock and loss according to equation [Eq. A1]. In addition, the products production can be calculated based on the production yield (γ) as expressed in equation [Eq. A2]; thus, loss can be calculated as fixed in equation [Eq. A3]. Consumption can be calculated by equations [Eq. A4] or [Eq. A5].

$$P_{i,j}^{INPUT} = P_{i,j}^{production} + P_{i,j}^{stock} + P_{i,j}^{loss} \quad \text{[Eq. A1]}$$

$$P_{i,j}^{production} = P_{i,j}^{INPUT} \cdot \gamma \quad \text{[Eq. A2]}$$

$$P_{i,j}^{loss} = P_{i,j}^{INPUT} \cdot (1-\gamma) \quad \text{[Eq. A3]}$$

$$P_{i,j}^{consumption} = P_{i,j}^{production} + P_{i,j}^{import} - P_{i,j}^{export} \quad \text{[Eq. A4]}$$

$$P_{i,j}^{consumption} = P_{i+1,j}^{INPUT} \quad \text{[Eq. A5]}$$

where P= Processes; i= indicator for processes; j=indicator for the studied years; INPUT= products entering process i in year j; production=products produced in process i in year j; stock=products stocked from process i in year j; Loss=products discarded from process i in year j; Import= products imported to process i in year j; Export= products exported from process i in year j; consumption=products consumed from process i in year j.

Each flow is calculated in three ways; it is calculated directly based on statistics, calculated by combining statistics with coefficients and deduced using the mass balance.

1.1. Raw Materials for plastics [A]

A plastic material is an organic solid, essentially a polymer or combination of polymers of high molecular mass. The production of polymers begins with a distillation process in an oil refinery. The distillation process involves the separation of heavy crude oil into lighter groups called fractions (Plastic Europe, 2013). One of these fractions, naphtha, is the crucial element for the production of plastics which is passed to the next stage of monomer production. The monomer is then converted to the desired grade of polymer as determined by the application needs of the converted product (BREF, 2007). Almost all plastics are currently derived from fossil sources, mainly oil and gas. Only 0.1-0.2% is derived from renewable organic sources such as starch, corn or sugar (JRC, 2012). Approximately, 4% of the world oil production goes to make plastics, the 6% goes to other industries and the remaining 90% is devoted to heating oil and locomotion

(ANAIP, 2013). In this study we consider that all plastic is produced from imported oil, since there is no oil in Spain, and we assumed that 4% of the imported oil goes to make plastics. Data of imported oil was obtained from the Ministry of Economy and Competitiveness (Datacomex, 2013).

1.2. Virgin plastics production [B]

There are many different types of synthetic polymers; with these being used in wide variety of applications. They can be classified as thermoplastics, polyurethanes, thermosets, adhesives, coatings and sealants (Salmons and Mocca, 2010). In addition, a classification is made between thermoplastics: standard thermoplastics and engineering thermoplastics. The former have limited stress and low temperature resistance, and are used mainly for inexpensive or disposable products and packaging; while the latter have higher strength and thermal resistance, and are used in applications requiring wear resistance, long life expectancy, flame resistance and / or the ability to endure cyclic stress loading (Salmons and Mocca, 2010). In this study we focus into the main standard thermoplastics which are low density polyethylene (LDPE), high density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), expanded polystyrene (EPS), polyvinyl chloride (PVC), polyethylene terephthalate (PET) and ethyl vinyl acetate (EVA). Remaining plastics (i.e., engineering, polyurethanes, etc) are categorized as others in this study. Data of virgin plastics production was obtained from the Spanish National Statistics Institute (INE, 2013) and data of the trade from the Ministry of Economy and Competitiveness (Datacomex, 2013).

1.2.1. **Additives**

In addition, more often than not, plastics contain a main polymer and a bespoke load of additives to improve specific properties (e.g. hardness, softness, UV resistance, flame formation resistance, etc). The content of additives in plastics varies widely, from less than 1% in PET bottles and up to 50-60% in hard PVC (JRC, 2012). In this study we assume an average content of additives of 20%.

1.3. Plastics products manufacture [C]

Plastic articles are produced from the synthetic polymer, usually in powder, granulate, pellet or flake form, by a range of different processes (JRC, 2012) or and/by recycled polymers. However, the opportunity of using recycled polymers as substitutes of virgin polymers is very much influenced, and limited, by the end-use application (JRC, 2012). In section 1.6 more detail and explanations are given for the recycling life stage and recycled polymers. The following classification for plastics products was followed in this study: Monofilament rods, sticks and profiles products; rigid tubes, pipes and hoses products; plates, sheets, films, foils and strips products; packaging products; construction products; and other products. Data of plastic products production was obtained from the Spanish National Statistics Institute (INE, 2013) and data of the trade from the Ministry of Economy and Competitiveness (Datacomex, 2013).

1.4. Use [D]

Plastic materials are used in a variety of end-use applications and in this study we consider the following classification: agriculture, electric and electronic, construction, packaging, automotive and others. Data of plastics products consumed were obtained through [Eq. A5] with data from Cicloplast (Cicloplast, 2009). According to Eurostat,

this data represents total plastic packaging put in the market, considering the import of plastic packaging within other consumption products.

Besides, the use life cycle stage is different from other processes because most of the final products may serve in the use stage for a long time and will not be consumed, an in-use stock of plastics will gradually form and enlarge in a defined geographical area such as a city or a country. To calculate the in-use stock we have used the following equation [Eq. A6]:

$$P_j^{stock} = P_{D,j}^{consumption} + P_{j-1}^{stock} - P_{E,j}^{production} \qquad \text{[Eq. A6]}$$

1.5. Collection and sorting [E]

Plastic waste generated after consumption is collected after a consumer cycle, either separately (i.e., selective collection plastic waste) or mixed with the refuse fraction of municipal solid waste (i.e., refuse plastic waste), and in this stage we considered both collections. Data of plastic waste generated was obtained the National Association of Plastic Recyclers (ANARPLA, 2013) and Eurostat (Eurostat, 2013) and data of the trade from the Ministry of Economy and Competitiveness (Datacomex, 2013). We considerer that the plastic selective collected is sent to sorting plants to eliminate the impurities but also to separate the plastic waste itself into the different plastic polymer categories and/or colors (JRC, 2012). We calculated the material loss based on mass balance. After sorting, recovered plastic can be sent to recycling or energy recovery and losses are sent to landfill. The refuse plastic waste is collected within the refuse fraction.

1.6. Recycling [F]

Two main types of recycling can be distinguished, mechanical and chemical (also called feedstock recycling). Mechanical recycling involves the melting of the polymer, but not

its chemical transformation. To a much smaller extent, recycling also takes place via chemical recycling, also called feedstock recycling, where a certain degree of polymeric breakdown takes place (JRC, 2012). Recycling plastic as chemical feedstock in industrial processes is negligible in Spain and is not considered in this paper. Data on quantity of plastic waste recycled were obtained from the Spanish Centre of Plastic (CEP, 2012) and data by type of plastic recycled were obtained from the National Association of Plastic Recyclers (ANARPLA, 2013). Beside, plastic waste can be recycled into a secondary raw material to form new products directly, or in combination with virgin plastic material. The material efficiency of recycling plants was assumed of 85% (JRC, 2012) and the options for use of recycled plastic depend on the quality and polymer homogeneity of the material (JRC, 2012). The following classification reflects the markets for the recycled polymer in Spain in 2009 (Cicloplast, 2009): pipes (26%), rubbish bags (11%), other films and bags (23%), bottles and drums (4%), industrial pieces (15%), household (2%) and others(19%). We use these percentages for all years studied.

1.7. Energy recovery [G] and landfill [K]

Data of plastic waste sent to energy recovery was obtained from Eurostat (Eurostat, 2013). Total plastic waste sent to landfill is the sum of the losses from sorting and recycling and the refuse plastic waste containing in the refuse fraction.

2. Results of MFA of plastics from 1999 to 2011 in Spain

Table A1: Virgin plastics production from 1999 to 2011 in Spain by type

	Virgin plastic (t)								
	HDPE	**LDPE**	**PP**	**PVC**	**PS**	**EPS**	**PET**	**EVA**	**Others**
1999	370,706	425,479	913,258	405,990	133,702	34,900	*430,464*[e]	54,028	1,154,265
2000	416,691	476,684	911,185	379,035	124,616	34,309	*475,206*[e]	52,386	1,192,350
2001	388,607	593,506	602,132	407,332	131,778	36,437	*475,928*[e]	65,489	1,152,240
2002	375,368	535,872	626,048	392,002	137,542	35,376	*507,680*[e]	71,559	1,313,234
2003	478,505	551,720	591,127	376,636	181,098	46,032	*527,887*[e]	70,068	1,407,427
2004	498,748	555,824	665,854	403,068	180,284	50,808	*564,691*[e]	77,367	1,478,941
2005	400,587	731,765	990,488	589,157	189,262	45,591	515,700	67,637	1,471,943
2006	443,978	609,172	888,156	631,174	212,607	55,362	515,700	78,007	1,474,554
2007	497,016	750,891	936,846	653,838	194,661	65,165	534,094	90,889	1,877,483
2008	440,926	600,092	909,439	577,951	176,174	59,961	554,812	79,215	1,682,836
2009	382,975	535,896	865,003	524,505	178,752	41,520	452,270	80,217	1,370,564
2010	383,330	608,002	934,514	613,420	140,006	27,179	711,350	85,018	1,541,921
2011	424,363	698,023	932,941	550,762	153,231	38,363	742,771	85,517	1,584,635

[e]=estimated data

Table A2: Virgin plastics consumption from 1999 to 2011 in Spain by type

	Virgin plastic (t)								
	HDPE	**LDPE**	**PP**	**PVC**	**PS**	**EPS**	**PET**	**EVA**	**Others**
1999	569,233	539,424	743,250	557,238	164,701	54,133	407,976	27,876	1,023,110
2000	563,181	561,206	742,971	508,735	183,074	72,608	429,964	52,386	1,292,847
2001	636,435	756,112	443,949	549,910	156,116	61,121	430,173	65,489	1,145,834
2002	762,651	767,936	553,733	531,548	153,231	55,098	477,704	71,559	1,200,822
2003	856,711	804,972	500,267	471,983	183,039	75,626	499,561	70,068	1,348,221
2004	904,929	822,043	516,848	515,531	182,219	69,363	527,342	77,367	1,399,216
2005	833,290	952,471	890,175	690,537	197,622	93,369	422,086	67,637	1,458,706
2006	926,432	852,628	756,878	717,579	227,569	102,321	385,507	77,902	1,446,075
2007	966,087	923,801	818,290	708,731	236,026	82,349	516,595	67,066	1,794,826
2008	865,488	773,002	722,148	576,712	190,131	88,465	525,490	55,392	1,572,000
2009	734,462	641,400	812,654	490,786	192,709	71,897	495,496	80,202	1,194,490
2010	622,836	616,997	723,833	526,346	157,983	42,429	722,342	85,018	1,312,111
2011	736,494	733,632	735,238	382,675	135,692	42,091	632,731	85,517	1,301,499

Table A3: Plastic waste collection in Spain from 1999 to 2011

	Collection (t)				
	Agriculture	**Electronics**	**Construction**	**Automotive**	**Others**
1999	*138,875*[e]	*69,438*[e]	*34,719*[e]	*86,797*[e]	*295,109*[e]
2000	*149,163*[e]	*74,581*[e]	*37,291*[e]	*93,227*[e]	*316,970*[e]
2001	*164,625*[e]	*82,313*[e]	*41,156*[e]	*102,891*[e]	*349,828*[e]
2002	*164,875*[e]	*82,438*[e]	*41,219*[e]	*103,047*[e]	*350,359*[e]
2003	*175,913*[e]	*87,956*[e]	*43,978*[e]	*109,945*[e]	*373,814*[e]
2004	*182,897*[e]	*91,448*[e]	*45,724*[e]	*114,311*[e]	*388,656*[e]
2005	*195,663*[e]	*97,831*[e]	*48,916*[e]	*122,289*[e]	*415,783*[e]
2006	*201,875*[e]	*100,938*[e]	*50,469*[e]	*126,172*[e]	*428,984*[e]
2007	*209,875*[e]	*104,938*[e]	*52,469*[e]	*131,172*[e]	*445,984*[e]
2008	*198,125*[e]	*99,063*[e]	*49,531*[e]	*123,828*[e]	*421,016*[e]
2009	*180,365*[e]	*90,182*[e]	*45,091*[e]	*112,728*[e]	*383,275*[e]
2010	171,830	94,591	45,279	114,608	382,453
2011	171,346	104,256	41,302	93,215	359,963

[e]=estimated data

Table A4: Plastic waste recycling in Spain from 1999 to 2011

	Recycling (t)				
	Agriculture	**Electronics**	**Construction**	**Automotive**	**Others**
1999	26,136	2,284	993	70	10,288
2000	47,076	4,758	1,055	988	10,491
2001	29,369	5,252	1,124	988	-
2002	29,430	6,282	680	783	8,528
2003	32,579	6,966	800	1,121	19,865
2004	47,133	8,450	1,189	1,566	68,667
2005	64,060	7,905	1,409	1,150	64,145
2006	69,405	11,184	1,978	3,482	50,407
2007	66,677	18,553	2,513	5,273	41,372
2008	56,069	10,104	2,813	10,203	34,077
2009	46,011	11,309	3,598	5,760	33,120
2010	48,336	10,946	1,245	9,512	38,069
2011	51,575	17,492	21,386	9,946	26,267

Table A5: Export trade by type of polymer (PE, PS, PVC, PP and others) from 1999 to 2011

	Export (t)				
	PE	**PS**	**PVC**	**PP**	**Others**
1999	2,482	812	2,717	7	-
2000	1,913	718	766	73	-
2001	2,097	186	945	343	-
2002	2,668	520	452	452	-
2003	9,995	1,285	1,246	1,154	-
2004	17,329	845	2,923	1,421	-
2005	20,307	763	2,642	1,931	-
2006	22,132	1,937	2,693	2,830	-
2007	31,552	2,451	3,555	3,096	-
2008	31,116	3,143	2,119	3,785	-
2009	35,897	3,508	1,702	4,658	-
2010	63,521	3,821	4,584	13,435	132,743
2011	34,684	2,340	6,518	9,563	139,911

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