Supplement of Adv. Geosci., 45, 105–113, 2018
https://doi.org/10.5194/adgeo-45-105-2018-supplement

Advances in Geosciences

Supplement of

Carbon in global waste and wastewater flows – its potential as energy source under alternative future waste management regimes

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Table of Contents

S1 Introduction

The information presented here is intended to extend and provide more detailed information on the projections of waste and wastewater (COD and BOD content) generation, underlying assumptions, and data sources used.

S2 Methods

Key assumptions for calculations of waste carbon content and potentials for biogas and energy-recovery are presented in Table S1.

Table S1. Key assumptions to determine carbon content and energy generation

Activity	**Variable**	**Description/assumption**	**Reference**
Solid waste	Maximum carbon conversion	77 % of total organic carbon available is decomposed	IPCC, 2006
Organic waste	Waste conversion rate to biogas	150 m3 biogas kg^{-1} waste	Kigozi et al., 2014
Manure	Water content of manure	85% water content	Höglund-Isaksson, 2015
Manure	Manure conversion rate to biogas	33.53 m3 ton^{-1} manure when manure is co-digested	Based on IEA, 2014
Co-digestion (80% manure + 20% organic waste)	Wet substrate conversion rate to energy	380 KWh/ton wet substrate	Höglund-Isaksson, 2015
Co-digestion (80% manure + 20% organic waste)	Waste conversion rate to biogas co-digestion	65.295 m3 ton-1	Höglund-Isaksson, 2015
Biogas	Biogas from anaerobic digestion composition	60% CH4 + 40% CO2	IPCC, 2006
Landfill gas	Landfill gas composition	50% CH4 + 50% CO2	Spokas et al., 2006
Landfill gas	Gas efficiency collection rate	60%	Spokas et al., 2006
Biogas	Energy from biogas (before conversion)	6.1 kWh m^{-3} biogas	de Mes et al., 2003
Biogas	Biogas thermal value	22 MJ m^{-3} biogas	Spokas et al., 2006
Biogas	Biogas density	1.132 kg m-3	Karellas et al., 2010
Incineration solid waste (Low Heating value- LHV)	Food waste	5.5 MJ Kg^{-1}	Noukeu et al., 2016
	Plastic waste	27.8 MJ Kg^{-1}	Consonni and Viganò, 2011
	Paper waste	16.20 MJ Kg^{-1}	
	Wood waste	18.84 MJ Kg^{-1}	
	Textile waste	19.88 MJ Kg^{-1}	
	Rubber waste	22.5 MJ Kg^{-1}	
	Other waste	5.69 MJ Kg^{-1}	
Industrial wastewater	COD conversion rate to biogas	0.35 m3 biogas kg^{-1} COD	de Mes et al., 2003
Industrial wastewater	Maximum methane production capacity	0..25 kg CH_4 Kg COD	IPCC, 2006
Industrial wastewater	Effluent untreated temperature	30°C	Noukeu et al., 2016
Domestic wastewater	COD conversion rate to biogas	0.84 m3 biogas kg^{-1} COD	de Mes et al., 2003
Domestic wastewater	Country specific per capita BOD taken from IPCC Guidelines 2006	BOD_5	IPCC, 2006. Volume 5. Waste, Table 6.4
Domestic wastewater	BOD conversion rate to biogas	0.84 m3 biogas kg^{-1} BOD	IPCC, 2006Volume 5. Waste, Table 6.2
Methane solubility in wastewater	Methane solubility	45% of CH_4 produced at 30°C	Liu et al., 2014
Primary treatment	COD/BOD removal efficiency	35%-40%	Cakir and Stenstrom, 2005
Anaerobic treatment	COD/BOD removal efficiency	80%	Cakir and Stenstrom, 2005

S2.1 Wastewater and solid waste projections up to 2050

Industrial solid waste: Table S2 presents industrial waste generation by income group classification (see Table S5) and type of manufacturing industry type.

Table S2. Total industrial waste generation in 2010 in Mt

Income group	Food industry	Pulp and paper industry	Rubber industry	Textile industry	Wood industry	Other manufacturing industry	Total	Reference
Low	161	16	3	9	19	958	1167	
Middle low	154	19	12	6	36	1171	1398	Höglund-Isaksson, 2012, Eurostat, 2017, OECD, 2017
Middle	14	3	1	3	3	79	103	
Middle high	23	13	13	2	4	78	133	
High	103	98	47	7	59	338	651	
World	455	149	76	26	121	2624	3452	

Municipal solid waste - Description of data and variables used to estimate waste generation elasticities: The dataset for EU28 countries and some OECD countries covers between 17 and 19 years. For the rest of the countries, the dataset covers between 4 and 10 years. In total, the unbalanced panel data set comprises 684 observations. Data on municipal solid waste generation in kilogram per capita are obtained from different sources (see Table S3). In order to control for the influence of population growth, waste generation per capita is chosen instead of total waste generation as dependent variable in elasticity estimations (Lebersorger and Beigl, 2011). All variables are specified in logarithmic form in order to provide parameter estimates that can be directly interpreted as elasticity values.

Table S3.Dataset description

Country	Years	Waste generation data - Source
EU 28 countries	1995-2012	Eurostat (retrieved 2016)
Japan	1995-2013	OECD (retrieved 2016)
Norway	1995-2014	OECD (retrieved 2016)
Colombia	2003-2011	SSPD 2011
Israel	2001-2013	OECD (retrieved 2016)
Mexico	1995-2012	OECD (retrieved 2016)
Turkey	1995-2013	OECD (retrieved 2016)
Serbia	2006-2013	Eurostat (retrieved 2016)
Macedonia	2008-2014	Eurostat (retrieved 2016)
Malaysia	1996-2000	Department of statistics Malaysia (accessed 2016)
Kenya	1998-2009	
Montenegro	2008-2013	Eurostat (retrieved 2016)
Bosnia and Herzegovina	2008-2013	Eurostat (retrieved 2016)
Australia	2006-2011	OECD (retrieved 2016)
Switzerland	1995-2013	OECD (retrieved 2016)
Peru	2012-2015	Municipalidad Metropolitana de Lima (MML) 2015

In terms of explanatory variables (see Table S4), generation of waste has primarily been linked to economic growth and increases in population and urbanization (Johnstone and Labonne, 2004; Mazzanti and Nicolli, 2011; Mazzanti and Zoboli, 2008, 2009). Income is a major driver of municipal waste generation (Mazzanti and Zoboli, 2008). Gross domestic product has been widely used as the economic parameter to project waste generation (Daskalopoulos et al., 1998).

Table S4. List of variables

Variable	Definition	Source	Mean	Standard Deviation	Minimum	Maximum
Dependent Variable						
MSW	Municipal solid waste generated Kg per person per year	See Table S2	383.71	113.82	101.1	667
Explanatory Variables						
GDP	Gross domestic product USdollar2010 per person per year	World Bank (accessed 2016)	28517.61	20440.94	4945.95	110001.1
UR	Average Annual Rate of Change of the Percentage Urban by Major Area, Region and Country	United Nations -world populations prospects (2014)	71.01	13.17	19	97.73

Elasticity estimation models: Historical data on municipal solid waste generation per capita (dependent variable) are plotted against GDP per capita (independent variable) in order to visualize the relationship between the two variables and to identify possible clusters of municipal waste generation (Fig. S1).

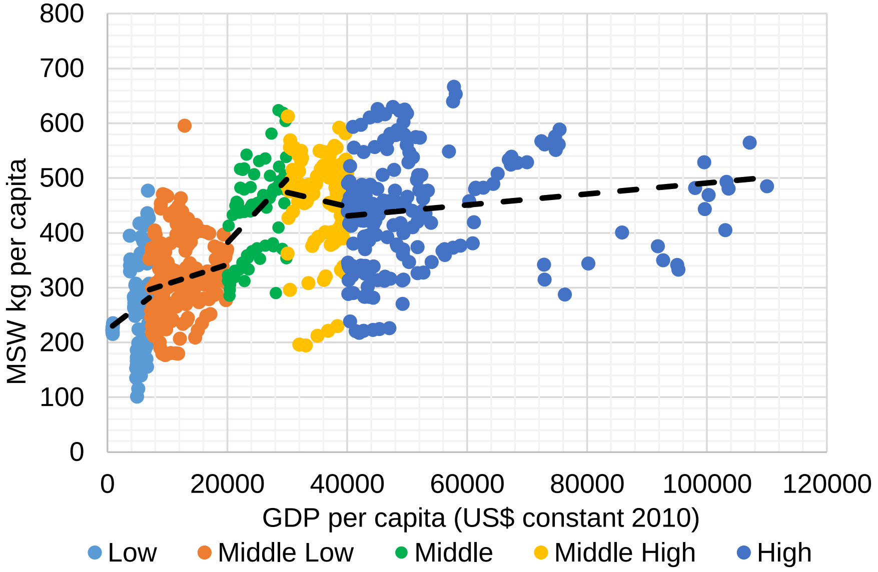


Fig. S1. Municipal solid waste vs GDP per cap.

The definition of the different income groups was carried out based on the distribution of the scatterplot. Table S5 shows the countries belonging to each of the five income groups in 2010 (which is the base year for the projections). Note that in the subsequent projections, countries may over time move out of their initial income group and into a higher income group following an increase in the GDP per capita consistent with the macroeconomic scenario of the IEA World Energy Outlook 2017 (IEA, 2017). Hence, the group distribution of the municipal solid waste generation is dynamic over time.

Table S5. Country by income group in base year 2010

Income group	**Country/region**
High	Austria, Australia, Belgium, Canada, China (Hong Kong and Macau), Denmark, Finland, France, Germany, Iceland, Ireland, Japan (Chugoku Shikoku, Chubu, Hokkaido-Tohoku, Kanto, Kinki), Luxembourg, Netherlands, Norway, Sweden, Switzerland and United States of America.
Middle - High	Brunei, Israel, Italy, Japan (Kyushu Okinawa), South Korea (Busan), New Zealand, Singapore, Spain and United Kingdom.
Middle	Cyprus, Greece, South Korea (Seoul – Inchon, South region), Malta, Portugal, Slovenia and Taiwan.
Middle – Low	Argentina, Caribbean (includes countries in the Caribbean region), Chile, China (Shanghai), Croatia, Czech Republic, Estonia, Hungary, Iran, South Korea (North region) , Latvia, Lithuania, Malaysia (Peninsular Malaysia), Mexico, North Africa (includes Algeria, Morocco, Libya, Tunisia, Sudan), Poland, Romania, Russia (Europe and Asia), Saudi Arabia, Slovak Republic, Turkey and Uruguay.
Low	Afghanistan, Albania, Armenia, Azerbaijan, Bangladesh (Dhaka and rest of Bangladesh), Belarus, Bhutan, Bosnia and Herzegovina, Bolivia, Brazil, Bulgaria, Cambodia, Central America, China (Anhui, Beijing, Chongqing, Fujian, Gansu, Guangdong, Guangxi, Guizhou, Hainan, Hebei, Heilongjiang, Henan, Hubei, Hunan, Jilin, Jiangsu, Jiangxi, Liaoning, Inner Mongolia, Ningxia, Qinghai, Shaanxi, Sichuan, Tianjin, Tibet, Xinjiang, Yunnan and Zhejiang) , Colombia, Ecuador, Egypt, Former Soviet Union States (includes Tajikistan, Turkmenistan and Uzbekistan), Georgia, India (Andhra Pradesh, Assam, West Bengal, Bihar, Chhattisgarh, Delhi, North East (excl Assam), Goa, Gujarat, Haryana, Himachal Pradesh, Jharkhand, Karnataka, Kerala, Maharashtra, Manipur, Orissa, Punjab, Rajasthan, Tamil Nadu, Uttarakhand, Uttar Pradesh, Jammu Kashmir), Indonesia (Jakarta, Java Sumatra and rest of Indonesia), Kazakhstan, North Korea, Kosovo, Kyrgyzstan, Laos, Macedonia, Malaysia (Sarawak Sabah and Kuala Lumpur), Iran, Moldova, Mongolia, Montenegro, Myanmar, Nepal, Other African countries (includes all other African countries), Pakistan (Karachi, NW frontier provinces Baluchistan, Punjab and Sindh), Paraguay, Peru, Philippines (Bicol, Luzol and Manila), South Africa, Serbia, Sri Lanka, Thailand (Bangkok, Central Valley, North Eastern Plateau, Northern Highlands and Southern Peninsula) , Ukraine, Venezuela and Vietnam (North and South).

The panel data analysis is performed to determine the elasticity of the different variables on the generation of municipal solid waste per capita. Pooled OLS, fixed effects and random effects estimator models are run to test the effects of the explanatory variables on municipal waste generation per capita. In the pooled models a single slope is calculated for all countries and the between (cross-sectional) and within (time) variances are bluntly added up. When the cross-sectional variance is eliminated and the slopes are based on time variance only, the model is denoted a within estimator whereas in between models the time variance is eliminated and only cross-sectional variance is considered in the elasticity parameter. In fixed effect models, the within estimator is describing the slope while the country-specific effects are captured as country-specific constants. Finally, random effect model treats the individual effects as random variables and the variance is a weighted average of within and between variance (Hsiao, 1986). Three different tests are applied to select the appropriate model. A Lagrange Multiplier (LM) test is applied to test for the cross-sectional dependence in heterogeneous panels (test random effects vs pooling). An F test is used to test for individual effects based on the comparison between the within and the pooling model and a Hausman test is used to evaluate the difference in vector coefficients between the fixed and random effects models. Here, we explore the possible effects of the explanatory variables on municipal solid waste generation and we test the hypothesis that there are no individual effects, against that there are individual effects. In order to test for a potential presence of homogeneity a Bartlett test is conducted. The Bartlett test is used to test if groups or samples have equal variances, however, the test is sensitive to normality. Therefore, two tests that are less sensitive to normality such as the Chi-square test and Fligner-Killen test are conducted as well (Table S6).

Table S6. Test homogeneity of variances

Test	Hypothesis	Results	Ho
Barlest test	Ho: $\sigma_0^2 = \sigma_1^2 = \cdots \sigma_k^2$ Ho: $\sigma_0^2 \neq \sigma_1^2$	29.407***	Rejected
Chi square test	Ho: $\sigma^2 = \sigma_0^2$ Ha: $\sigma^2 \neq \sigma_0^2$	9.48***	Rejected
Fligner-Killeen	Ho: $\sigma^2 = \sigma_0^2$ Ha: $\sigma^2 \neq \sigma_0^2$	27.44***	Rejected

The results of the elasticity estimations of municipal solid waste generation to GDP per capita and urbanization rate and the functions for waste generation projections are presented in Table S7. The LM test favoured in all cases the random effect over the OLS model, meaning that there is evidence of significant differences across countries. F test for individual effects favoured always the fixed effect model over the OLS, which means that the fixed effect are non-zero and finally, the Hausman test rejected the random effect model, which assume that the slope coefficients of the two models do not differ and it favoured the fixed effect model. Furthermore, due to the fact that waste composition influences energy generation, projections of waste compositions are relevant. In particular, low income countries tend to have a considerably higher fraction of food waste in the total municipal waste generated than high income countries. Therefore, changes in the future composition of waste are projected based on an estimated elasticity of food waste generation to GDP per capita. Due to limited access to historical data on food waste generation, the elasticity is estimated from a sample of 156 observations of in an unbalanced panel. A fixed effects model was favoured on the basis of Hausman test as the better explanatory model with a resulting elasticity of food waste generation to GDP per capita of 0.42 (Table S7).

Table S7. MSW generation elasticities to GDP and Urbanization rate

Dependent Variable	Unit	Income group (U$ dollars per capita year)	Number of observations	Explanatory variable	OLS	Fixed Effect	Random Effect	LM - test	Hausman -test
Municipal solid waste	Kt per capita	< 7000	98	Constant	4.96 (10.50)***	n.a	2.44 (3.97)***	84.92	3.66
				GDP per capita	0.06 (1.21)	*0.41 (5.38)****	0.36 (5.04)***		
				Urbanization rate					
				R-square	0.01	0.25	n.a		
		>=7000 - <20000	193	Constant	4.15 (8.42)***	n.a	3.68 (6.96)***	38.22	0.002
				GDP per capita	0.16 (3.19)**	*0.22 (3.73)****	0.21 (3.92)***		
				Urbanization rate					
				R-square	0.05	0.07	n.a		
		>=20000 - <30000	75	Constant	-0.92 (-0.56)	n.a	-0.35 (-0.23)	21.99	0.001
				GDP per capita	0.69 (4.30)***	*0.62 (4.23)****	0.62 (4.30)***		
				Urbanization rate					
				R-square	0.20	0.21	n.a		
		>30000 - <40000	108	Constant	5.98 (2.23)*	n.a	2.82 (1.53)	140.56	20.93
				GDP per capita	-0.16 (-0.68)	*0.80 (7.31)****	0.55 (5.40)		
				Urbanization rate	0.43 (2.01)*	*-3.27(-4.43)****	-0.60 (-1.33)***		
				R-square	0.04	0.37	n.a		
		>=40000	210	Constant	3.33 (3.72)***	n.a	-0.10 (-0.07)	52.22	17.43
				GDP per capita	0.17 (2.55)*	*1.07 (8.20)****	0.84 (7.10) ***		
				Urbanization rate	0.18(1.38)	*-1.28 (-3.66)****	-0.67 (-2.28)*		
				R-square	0.043	0.26	n.a		
		All income groups	684	Constant	3.85 (21.10)***	n.a	4.03 (8.61)***	95.64	10.45
				GDP per capita	0.24 (17.51)***	0.43 (13.13)***	0.37 (13.72)***		
				Urbanization rate	-0.08 (-1.52)	-0.45 (-2.27)*	-0.43 (-3.42)***		
				R-square	0.4	0.21	n.a		
Food waste	Kt per capita	All income groups	156	Constant	4.05 (9.32)***	n.a	2.78 (4.29)***	40.54	9.78
				GDP per capita	0.05 (1.33)	*0.42 (4.22)****	0.18 (2.85)**		
				R-square	0.01	0.12	n.a		

Where:, $\varepsilon_{it}=u_i+v_{it}$ *is an error term which is separated into an individual effects term and a residual omitted variables term, and* $\varepsilon_{it} \sim IID\left(0, \sigma_{\varepsilon}^{2}\right)$ *is an error term which are assumed to be normally distributed with mean zero and constant variance.*

Although, there are more availability of data for developed countries, it was possible to find a limited set of about ten developing countries for which enough information was available to include in the estimation of elasticities of municipal solid waste generation to GPD per capita and urbanization rates. However, due to a general lack of data from developing countries on food waste generation, the elasticity estimates for food waste generation are based on data from Eurostat (2016) and cover mainly developed countries. In addition, only GDP per capita and changes in the urbanization rate are used as explanatory variables. In reality, many more factors are likely to influence the generation of municipal waste, in particular household-specific factors e.g., household size, type of dwellings, rural or urban, income distribution, etc. It would have been desirable to conduct the elasticity estimations at a more disaggregated level, representing the diverse circumstances within a country, however, this was not possible due to limitations in data availability.

Table S8 presents municipal waste generation rates and composition for the year 2010 (base year for projections). Since yearly information on waste composition is limited (especially for developing countries), the most recent available data is used. References apply to the waste management data as well.

Table S8. Municipal solid waste generation and composition in 2010.

Income group	**No. of countries/regions**	**Municipal solid waste generation**			**Composition (weighted average across countries)**							
		Mt year $^{-1}$	**Kg cap^{-1} day^{-1}**	**Range Kg cap^{-1} day^{-1}**	**Food**	**Paper**	**Plastic**	**Glass**	**Metal**	**Wood**	**Textile**	**Other**
Low	112	1249	0.67	0.06 - 1.94	0.51	0.09	0.09	0.03	0.02	0.06	0.04	0.17
Middle low	23	246	0.87	0.16-1.51	0.44	0.16	0.09	0.07	0.02	0.06	0.03	0.12
Middle	8	31	1.03	0.85-1.54	0.31	0.24	0.12	0.05	0.05	0.07	0.03	0.14
Middle high	9	107	1.40	0.78-1.90	0.29	0.25	0.13	0.06	0.03	0.02	0.03	0.19
High	22	456	1.77	0.80-2.19	0.25	0.30	0.13	0.06	0.07	0.05	0.05	0.10
World	174	2088	0.83	0.06-2.19	0.43	0.15	0.10	0.04	0.03	0.06	0.04	0.15

Source: Low: Forouhar and Hristovski, 2012, Wiedinmyer et al., 2014, Hoornweg and Bhada-Tata, 2012, Arzumanyan, 2014, Anon, 2009; Bhuiyan, 2010; Zakir Hossain et al., 2014, Penjor, 2007, Viceministerio de agua potable, 2012, Castagnari, 2005, Eurostat 2016, Ministry of Environment PNH, 2010; Mongtoeun, 2015, Bo-Feng et al., 2014; China Statistical Yearbook, 2007; Wang and Nie, 2001, Larochelle et al., 2012; Martínez, 2015, M. Sim et al., 2013, Kumar et al., 2009; Sharholy et al., 2008, Damanhuri et al., 2009; Meidiana and Gamse, 2010; Pasang et al., 2007, Vermenchiva et al., 1999, Sang-Arun and Pasomsouk, 2012, Cvetkovska and Rushiti, 2013, Budhiarta et al., 2012; Manaf et al., 2009, agath P and Hengesbaugh, 2016, Viraraghavan, 2005, Bello et al., 2016; Parrot et al., 2009, Mahar et al., 2007, Organización Panamericana de la Salud, 2001, Department of Environmental Affairs, 2012, ISWA, 2011; Vukmirovic, 2012, Hikkaduwa et al., 2015; Karunarathne, 2015, Tanakwang and Tangtinthai, 2010, International Finance Corporation, 2010, Instituto Nacional de Estadística, 2012, Nguyen, 2005, Thang, 2011.

Middle low: Gonzalez, 2010; Savino, 1999, Hoornweg and Bhada-Tata, 2012, Bräutigam and Gonzalez, n.d.), Bo-Feng et al., 2014; China Statistical Yearbook, 2007; Wang and Nie, 2001, Eurostat 2016, Alavi Moghadam et al., 2009; Damghani et al., 2008, Ryu, 2010, Budhiarta et al., 2012; Manaf et al., 2009, Gomez et al., 2008, Bello et al., 2016; Okot-Okumu, 2012; Parrot et al., 2009; SWEEPNET, 2012,

Middle: Eurostat 2016, Chieueh and Yu, 2006; Tsai and Chou, 2006

Middle High: Wiedinmyer et al., 2014, Ministry of environmental protection, 2012, Eurostat 2016, OECD, 2016 ;Ministry of the Environment, 2012, ISWA, 2011, Bai and Sutanto, 2002, Burnley, 2007; Daskalopoulos et al., 1998

High: Eurostat 2016, Asase et al., 2009, Bo-Feng et al., 2014; China Statistical Yearbook, 2007; Wang and Nie, 2001, OECD, 2016 ;Ministry of the Environment, 2012, EPA, 2012

S2.2 Carbon content determination and energy calculations

S2.2.1 Solid waste

In order to quantify the carbon content of industrial and municipal solid waste and the respective flows, the following approach is used (calculations are always carried out by region for the 174 countries/regions and with annual results presented for every five years):

1. Quantification of DOC and FC in municipal and industrial solid waste using IPCC default values for DOC and FC (IPCC, 2006, Volume 5, Chapter 2).
2. Identification by country/region of the application rate of current (and future) waste management technologies/systems (EUROSTAT 2016, OECD 2016, UNFCCC CRF Tables 2016 and documents referenced in Table S8 supplement material). This study distinguishes various management options for each of the solid waste fractions. Description of each of the options can be found in Table S8. The assessment of the carbon flows is then carried out applying Eq. (S1). and Eq. (S2):

$$\mathrm{DOC}_{m,s;j} = \mathrm{W}_{s,j} * \mathrm{DMC}_{s,j} * \mathrm{DOCd}_{s,j} * \mathrm{Appl}_{m,s,j} * 0.01 \quad \text{Eq. (S1)} \quad ; \quad \mathrm{FC}_{m,s;j} = \mathrm{W}_{s,j} * \mathrm{FCC}_{s,j} * \mathrm{Appl}_{m,s,j} * 0.01 \quad \text{Eq. (S2)}$$

Where: $\mathrm{DOC}_{m,s,j} / \mathrm{FC}_{m,s;j}$ is the amount of Degradable Organic Carbon (DOC)/ Fossil Carbon (FC) in dry waste type j in sector s (municipal/industrial) going to a specific treatment m ; $\mathrm{W}_{s,j}$ is the amount of waste type j generated in sector s (municipal/industrial); $\mathrm{DMC}_{s,j}$ is the Dry Matter Content (DMC) in % of wet waste j generated in sector s (municipal/industrial); $\mathrm{DOCd}_{s,j}$ is the DOC in % of dry waste j generated in sector s (municipal/industrial); $\mathrm{FCC}_{s,j}$ is the fraction of Fossil Carbon in % of Total Carbon in waste j generated in sector s (municipal/industrial) and $\mathrm{Appl}_{m,s,j}$ is the application of the waste treatment option m to waste type j generated in sector s (municipal/industrial).

3. Estimation of energy recovery from municipal and industrial solid waste: This study identifies anaerobic digestion, landfill with gas recovery and use and waste incineration as the three main treatment technologies to convert waste into a source of energy.

Anaerobic digestion: Biogas generation is calculated using Eq. (S3) from Höglund-Isaksson, 2015 and Eq. (S4) :

$$\mathrm{BCD} = (\mathrm{TS} * \mathrm{Y}_{cd}) \quad \text{where} \quad \mathrm{TS} = \mathrm{MaxM} + \left(\frac{\mathrm{MaxM}*100}{80}\right) * 0.2 \quad \text{Eq. (S3)} \quad ; \quad \mathrm{BSS} = \left(\mathrm{S} * \mathrm{Y}_{o,m}\right) \quad \text{Eq. (S4)}$$

Where: BCD is biogas from co-digestion; TS is total substrate; Y_{cd} is the biogas yield of co-digestion when 80% manure - 20% organic waste ; MaxM is the maximum manure available for co-digestion; BSS is the biogas single substrate; S is the substrate and ; $\mathrm{Y}_{o,m}$ is the biogas yield when digestion only organic waste or only manure.

Landfill: Landfill gas generation is accounted for with a lag of 10 years for fast degrading organic waste and 20 years for slow degrading waste. Landfill gas generation is calculated using Eq. (S5) based on (IPCC, 2006, Volume 5, Chapter 2 and Chapter 3):

$$\mathrm{LG} = \left(\left(\mathrm{DOC}_{s;j} * 0.77 * \mathrm{F} * {}^{16}\!/_{12}\right) + \left(\mathrm{DOC}_{m,s;j} * 0.77 * \mathrm{F} * {}^{44}\!/_{12}\right)\right) * 0.60 * {}^{1}\!/_{1.132} \quad \text{Eq. (S5)}$$

Where: LG is landfill gas; $DOC_{s;j}$ is the amount of Degradable Organic Carbon (DOC) in dry waste type j in sector s (municipal/industrial) going to landfills with gas recovery; 0.77 is the maximum carbon conversion; F is the fraction of CH4 - CO_2 in generated landfill gas (0.50); $^{16}/_{12}$ is the molecular weight ratio CH_4/C; $^{44}/_{12}$ is the molecular weight ratio CO_2/C; 0.60 is the gas collection efficiency rate and 1.132 kg m^{-3} is the biogas density.

Incineration: Energy from incineration is calculated using the Low Heating Value (LHV) of each of the waste fractions. LHV represents the usable heat released from waste and varies according to waste type (Demirbas, 2004). Energy from incineration is calculated using Eq. (S6).

$$\mathrm{EI} = \mathrm{W}_{s,j} * \mathrm{LHV}_j \qquad \text{Eq. (S6)}$$

Where: EI is energy gained from incineration; $W_{s,j}$ is the amount of waste type j generated in sector s (municipal/industrial) going to incineration with energy recovery (municipal/industrial) and LHV_j is the low heating value of waste typej.

Table S9 presents the different management options implemented for each waste type.

Table S9. Solid waste management technologies

Solid waste management technology	Municipal solid waste								Industrial solid waste				
	Food	Glass	Metal	Other	Paper	Plastic	Textile	Wood	Food	Pulp and paper	Rubber	Textile	Wood
Open burned	X			X	X	X	X	X	X	X	X	X	X
Scattered and/or disposed to water-courses	X	X	X	X	X	X	X	X	X	X	X	X	X
Unmanaged solid waste disposal site - low humidity - < 5m deep	X			X	X		X	X	X	X		X	X
Unmanaged solid waste disposal site - high humidity - > 5m deep	X			X	X		X	X	X	X		X	X
Compacted landfill	X	X	X	X	X	X	X	X	X	X	X	X	X
Covered landfill	X			X	X		X	X	X	X		X	X
Landfill gas recovery and flaring	X			X	X		X	X	X	X		X	X
Landfill gas recovery and used	X			X	X		X	X	X	X		X	X
Low quality burning of waste	X			X	X	X	X	X	X	X	X	X	X
Incineration (poor air quality controls)	X			X	X	X	X	X	X	X	X	X	X
Incineration (high quality air pollution controls - energy recovery)	X			X	X	X	X	X	X	X	X	X	X
Anaerobic digestion	X								X				
Composting	X								X				
Recycling		X	X		X	X	X	X					X

S2.2.2 Wastewater

In order to quantify the organic content in industrial and municipal wastewater and its respective flows, the following approach is used (calculations are carried out by country/region and year):

1. Quantification of BOD in untreated domestic wastewater and COD in untreated industrial wastewater using the IPCC method (based on IPCC, 2006, Volume 5, Chapter 6, Equation 6.4 and Equation 6.6).
2. Identification by country/region of the application rate of current (and future) use of wastewater management technologies/systems (EUROSTAT 2016, OECD 2016, UNFCCC CRF Tables 2016 and some official national documents). This study distinguishes various wastewater management options for each of the two wastewater types. A description of each option can be found in Table S10. The assessment of the organic material flows is then carried out applying Eq. (S7) and Eq. (S8) based on Höglund-Isaksson et al., 2015

$$\mathrm{COD} = \mathrm{WW_i} * \mathrm{P_i} * \mathrm{COD_i} * \mathrm{Appl_{m,i}} * 0.01 \quad \text{Eq. (S7)} \quad ; \quad \mathrm{BOD} = \mathrm{POP_i} * \mathrm{BOD_i} * \mathrm{Appl_{m,i}} * 0.01 \quad \text{Eq. (S8)}$$

Where: COD is Chemical Oxygen Demand (organic degradable material) in industrial wastewater; $\mathrm{WW_i}$ is the amount of wastewater generated per tonne of product in industrial sector i; $\mathrm{P_i}$ is amount of production product in sector i; $\mathrm{COD_i}$ is total organic degradable material content in the wastewater measured as COD in industrial sectors i, BOD is Biochemical Oxygen

Demand (organic degradable material) in domestic wastewater; POP_i is population; BOD_i is per capita BOD (default values used from IPCC, 2006, Volume 5, Chapter 6, Table 6.4) and $Appl_{m,s,j}$ is the application of the wastewater treatment option m to treat domestic/industrial wastewater.

3. Estimation of the energy potential from domestic and industrial anaerobic wastewater with gas recovery. Volumes of biogas from industrial and domestic wastewater treatment are calculated by applying Eq. (S9)

$$\mathrm{BWWI\ (BWWD)} = \mathrm{COD(BOD)} * \mathrm{Appl_{at}} * 0.01 * (1 - \mathrm{Reff_{pt}}) * \mathrm{Reff_{at}} * \mathrm{F_{COD}}\ (\mathrm{F_{BOD}}) * \mathrm{TCF} * (1 - \mathrm{f}) * \mathrm{Y} \quad \text{Eq. (S9)}$$

Where: BWWI is biogas generation from industrial/*BWWD* domestic wastewater treatment; COD is Chemical Oxygen Demand , *BOD* is Biochemical Oxygen Demand in domestic wastewater; $\mathrm{Appl_{at}}$ is the application in % of the anaerobic wastewater treatment to industrial/domestic sector i; $\mathrm{Reff_{pt}}$ is the COD/BOD removal efficiency primary treatment (before anaerobic treatment a primary removal of floating and settleable material is needed (Cakir and Stenstrom, 2005)); $\mathrm{Reff_{at}}$ is the COD/BOD removal efficiency anaerobic treatment; $\mathrm{F_{COD}}$ is the maximum CH_4 production capacity per Kg COD; $\mathrm{F_{BOD}}$ is the maximum CH_4 production capacity per Kg BOD, TCF is temperature correction factor (just for domestic wastewater) (see Höglund-Isaksson et al., 2015. Section 3.4.2) f is the rate of CH_4 solubility (depends on wastewater temperature (Liu et al., 2014) and $Y = 0.35\ m^3$ is the biogas yield per Kg COD removed, 0.84 m^3 is the biogas yield per Kg BOD removed.

One of the challenges of wastewater treatment is the removal of nitrogen and phosphorus to avoid eutrophication of the water bodies. For that purpose, around 35% of the COD in wastewater is needed for biological nitrogen removal (Hu et al., 2011) and hence unavailable for biogas generation. Therefore, an additional estimation of biogas generation representing the balance between COD and nitrogen removal is also carried out. To compensate for the 35% of COD needed for the removal of nitrogen, estimations of biogas generation assuming that the primary sludge is anaerobically digested and partially converted into biogas is also performed for the MFR scenarios. This process is represented in Eq (S10) where $(1 - \mathrm{Reff_{pt}})$ representing the removal efficiency (35%) of primary treatment is removed and a factor representing the 35% COD demanded for nitrogen removal is added $(1 - \mathrm{COD_N})$. However, this process does not add benefits in terms of biogas generation since the effect of adding the COD of primary sludge is cancelled by the COD demanded for nitrogen removal.

$$\mathrm{BWWI\ (BWWD)} = \mathrm{COD(BOD)} * \mathrm{Appl_{at}} * 0.01 * \mathrm{Reff_{at}} * (1 - \mathrm{COD_N}) * \mathrm{F_{COD}}\ (\mathrm{F_{BOD}}) * \mathrm{TCF} * (1 - \mathrm{f}) * \mathrm{Y} \quad \text{Eq. (S10)}$$

Table S10. Wastewater treatment technologies

Wastewater treatment technology	Domestic wastewater			Industrial wastewater		
	Uncollected	Centralized collection	Decentralized collection	Food	Pulp and paper	Other manufacturing industry
Uncollected	X	X	X	X	X	X
Collected but untreated		X	X	X	X	X
Primary treatment		X		X	X	X
Aerobic treatment		X		X	X	X
Anaerobic secondary and/or tertiary treatment without gas recovery		X		X	X	X
Anaerobic secondary and/or tertiary treatment with gas recovery		x		X	X	X
Latrine/ Septic tank			X			

S2.3 Waste and wastewater management scenarios

Description of the measures adopted in the different scenarios are presented below. Each scenario builds on the one before:

- <u>CLE ‘current legislation’</u>: The scenario assumes efficient implementation of the existing waste/wastewater legislation. In countries/regions where no waste legislation exists -CLE- represents the current waste management situation.
- <u>MFR ‘maximum technically feasible phase-in of waste and wastewater management’</u>: A scenario that assumes the implementation of the ‘best available technology’ to improve waste and wastewater management systems without regarding costs but considering constrains that could limit the applicability of certain technologies and assumes a phase-out of waste going to landfills, being dumped or openly burnt. Waste flows are redirected to recycling, treatment with energy recovery, or controlled incineration with energy recovery. The maximum recycling potential of waste streams are applied as follow: 90% of municipal paper and textile waste recycled by 2030 – 80% of municipal plastic and wood waste recycled by 2030. 100% incineration of industrial solid waste by 2030, 100% of food waste treated in anaerobic digesters with biogas recovery by 2050 and 100% of collected industrial and domestic wastewater treated in anaerobic processes by 2050.
- <u>MFR + PCY + PLA ‘maximum technically feasible phase-in of waste and wastewater management’ + ‘policy implementation + ‘plastic incineration’</u>: The scenario adopts the MFR + policies for reducing the generation of food and plastic municipal solid waste + maintains current municipal plastic waste recycling rates and sends excess plastics to incineration for energy recovery to represent the current recycling market plastic situation. The policies are assumed to

reach a maximum municipal food waste rate reduction of 50% by the year 2030 based on Lipinski et al., 2013 and based on the target adopted by the United Nations Assembly in 2015 of halving per capita food waste at the retail and consumer level as a part of the 2030 Sustainable Development Goals and a maximum municipal plastic waste rate reduction of 50% by the year 2030 as a part of the 2030 Sustainable Development Goals.

- <u>MFR + PCY + REC 'maximum technically feasible phase-in of waste and wastewater management' + 'policy implementation' + 'maximum recycling capacity'</u>: This scenario adopts the MFR + PCY + reaches the maximum possible recycling capacity for all waste streams (including plastic). For wastewater, the scenario includes a capacity to increase the collection (reaching 100%) and treatment of wastewater in urban areas.
- <u>MFR + PCY + REC + IMP 'maximum technically feasible phase-in of waste/wastewater management' + 'policy implementation' + 'maximum recycling capacity' + 'technology efficiency improvement'</u>: This scenario adopts the MFR + PCY+ REC + technological development to increase biogas yield formation and to reduce losses during the treatment processes for both solid waste and wastewater. Improvements include e.g. adding accelerants (biological or chemical) to improve the metabolic conditions for microorganism growth and therefore biogas formation (Mao et al., 2015), recovery of the dissolved methane in wastewater, improvement of the biogas recovery rates. For incineration, improvements include an increase of the Low Heating Value (LHV), increase in the efficiency of input/air flow and reduction of energy losses during the process.

S2.4 Limitations and uncertainty of the waste and wastewater management scenarios

In this study, anaerobic digestion of waste and anaerobic wastewater treatment are analysed independent of the type of anaerobic reactor e.g. Anaerobic Sludge Blanket (UASB), CSTR and Anaerobic filter (AF-Fixed film) (Barber and Stuckey, 1999). Different reactors involve different flow modes, retention times and organic load rates, which are all factors that affect the efficiency of biogas formation (Mao et al., 2015). Furthermore, default IPCC values for biogas rate formation under average normal operating conditions are used to estimate biogas generation. However, it is well known that the microbial community is extremely sensitive and if not properly managed the process would be affected resulting in reduced biogas production (Munk Bernhard et al., 2010).

Regarding incineration and waste heating values a similar situation to the anaerobic treatment is present; incineration is treated as a general technology independent of the type of incinerator. In addition, although a specific Low Heating Value (LHV) is used for each waste fraction, the variability between regions/countries was not taken into account due to a lack of regional data. In general, the scenarios presented do not take into account the losses of substrates during transport and handling, which may result in a lower substrate input actually going into the treatment facilities.

Given the global scope and the wide range of different types of input data going into estimations, it is unavoidable that a certain degree of uncertainty is present in the results. E.g., for developing countries, a lack of country-specific data on quantities of waste and wastewater, implemented treatment modes, and current energy/biogas recovery rates, has been bridged by using default assumptions adapted from neighbouring countries or regions.

3 Results by major world regions

3.1 Carbon content and flows in solid waste

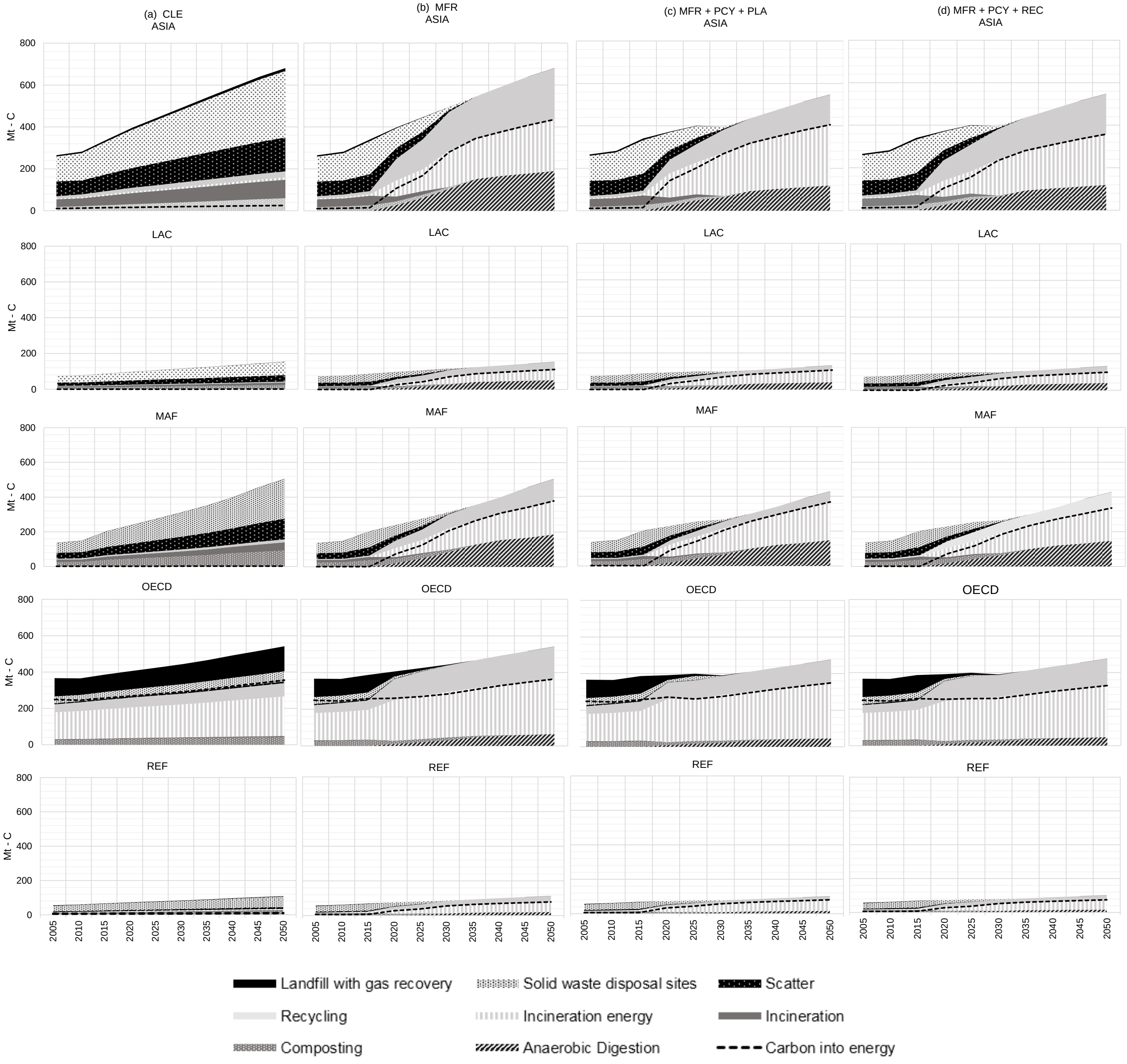
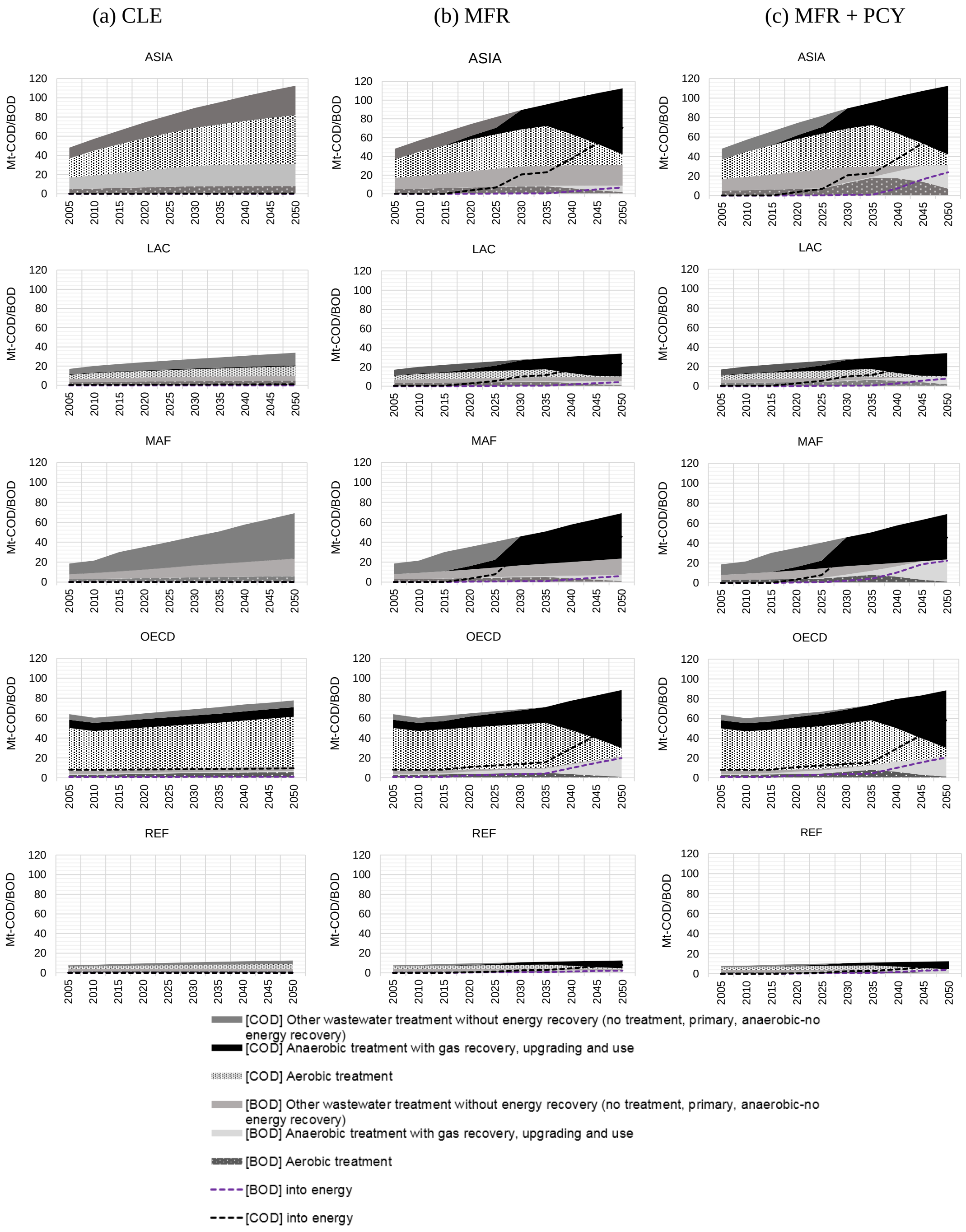


Fig. S2. Carbon flows – solid waste by region

3.2 BOD and COD flows in wastewater


(a) CLE

(b) MFR

(c) MFR + PCY

Fig. S3. BOD and COD flows by region

3.3 Maximum energy potential from waste and wastewater

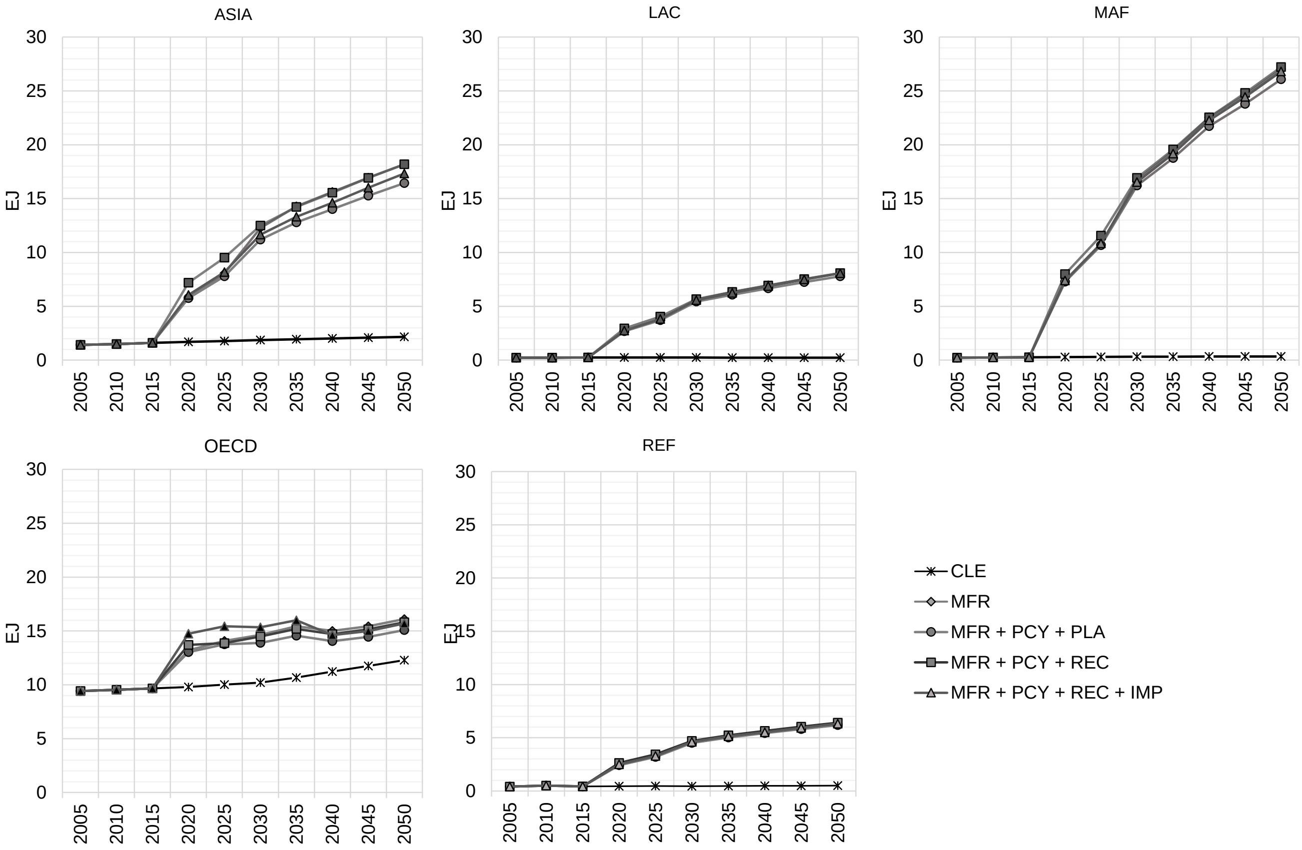


Fig. S4. Maximum energy potential from waste and wastewater by region

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