Appendix for Chapter 6 of Plastic & Climate: The Hidden Costs of the Plastic Planet

Chapter 6 of the report aims to examine direct and indirect GHG emissions and emission offsets from the disposal stage of the plastic lifecycle. Sound Resource Management Group, Inc. built a calculation model to quantify GHG emissions from plastic waste management through incineration, disposal at landfills, and recycling. The calculations are based on existing estimates of annual worldwide plastic generation (**1. Worldwide Plastics Production**) and disposal (**5. Worldwide Distribution of Plastic Wastes Among Management Options**). The scope of the analysis is adjusted to plastic packaging (**2. Plastic Packaging Portion of Plastics Production**) due to the lack of worldwide data on the polymeric composition of all plastic. Depending on the ratio of combustible carbon content in plastic packaging (**3. Plastics Packaging Polymeric Composition, Combustible Carbon Content, & Power Generation**), power generation potential of energy recovery at incinerators (**4. Life Cycle Carbon Emissions from Power Generation (kg CO2e per kWh)**) is estimated. As the potential emission offsets from energy recovery are affected by the energy grid, a conservative prediction from the U.S. Energy Information Administration (EIA) on natural gas and renewable energy ratio in the energy mix (**Distribution of Energy Recovery Offsets in 2015)** is taken into account. In our analysis, only solar, wind, and geothermal power are counted as renewable energy sources. Combining these parameters and estimates, the analysis presents GHG emissions per ton of plastic packaging by different types of waste disposal methods (**7. Climate Impacts of Plastics Waste Management Options (kg CO_2e/metric ton)**).

The base year of the data set is 2015 (**I. Parameters, Estimates and Assumptions (2015)**) and two more data sets were reproduced, taking into account future prospects for 2030 and 2050 (**II. Parameters, Estimates and Assumptions (2030), III. Parameters, Estimates and Assumptions (2030)**). While the data on the portion of plastic packaging, polymeric composition, and proportion of each waste management method remains the same, the increase in the amount of plastic produced and the changes in the energy grid results in a significant difference compared to the current status. The growth rate of plastic production is based on the outlook that the industry projects, and the same EIA source is used to estimate natural gas and renewable ratio in the year 2030 and 2050.

Lastly, data sets used for Figure 14 are included at the end of this appendix (**IV. GHG Emissions from waste incineration with energy recovery (plastic packing only)**).

I. Parameters, Estimates and Assumptions (2015)

1. Worldwide Plastics Production (million metric tons - Mt) in 2015	320

Source: Material Economics, The Circular Economy; PlasticsEurope & EPRO, Plastics the Facts 2016

2. Plastic Packaging Portion of Plastics Production	39.9%

Source: PlasticsEurope & EPRO, Plastics the Facts 2016

3. Plastics Packaging Polymeric Composition, Combustible Carbon Content, & Power Generation	**Comp.**	**C %**	**M Btu/t**	**kWh/t**
Polyethylene (PE) Film (e.g., LDPE - low density PE)-bone dry, no moisture	30%	84%	43.9	2236
Polyethylene (PE) Containers (e.g., HDPE - high density PE)-bone dry, no moisture	13%	84%	44.1	2247
Polypropylene (PP)-bone dry, no moisture	23%	84%	44.0	2241
Polyethylene Terephthalate (PET)-bone dry, no moisture	20%	61%	23.4	1180
Polystyrene (PS)-bone dry, no moisture	13%	90%	39.7	2025
Polyvinyl Chloride (PVC)-bone dry, no moisture	3%	36%	17.4	861
Total/Average	100.0%	79%	38.6	1,966

Source: Material Economics, The Circular Economy; PlasticsEurope & EPRO, Plastics the Facts 2016; U.S. EPA, Advancing Sustainable Materials Management: 2015 Tables and Figures; U.S. EPA, Documentation for GHG Emission and Energy Factors Used in WARM - Containers, Packaging and Non-Durable Goods Chapters, Feb. 2016
Notes: (1) 2 percentage points deducted from EPA estimates for carbon percentage content to account for ash and/or incomplete combustion in MSW incinerators. (2) Estimates for kWh/metric ton based on EPA estimated MSW incinerator power generation efficiency of 17.8%

4. Life Cycle Carbon Emissions from Power Generation (kg CO_2e per kWh)			Memo: Stack Emissions Only
Solar	0.09	includes fuel extraction, processing and transport	0
Natural Gas	1.25	includes fuel extraction, processing and transport	1.01
Coal	2.40	includes fuel extraction, processing and transport	2.33
PE & PP (bone dry basis, no moisture content)	1.37	stack emissions only	1.37
PET (bone dry basis, no moisture content)	1.89	stack emissions only	1.89
PS (bone dry basis, no moisture content)	1.63	stack emissions only	1.63
PVC (bone dry basis, no moisture content)	1.53	stack emissions only	1.53
Weighted average for plastic packaging	1.51	stack emissions only	1.51

Source: Kim, H. C.; Fthenakis, V.; Choi J-K.; Turney, D. E., 2012. Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation – Systematic Review and Harmonization. *Journal of Industrial Ecology* 16 (S1): S110-S121; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* 44 (20): 7944-7949; Morris, J., 2017. Recycle, Bury, or Burn Wood Waste Biomass? LCA answer depends on carbon accounting, displaced fuels, emissions controls, and impact costs. *Journal of Industrial Ecology*, 21 (4): 844-856; Whitaker, M. B.; Heath, G. A.; Burkhardt, III, J. J.; Turchi, C. S., 2013. Life Cycle Assessment of a Power Tower Concentrating Solar Plant and the Impacts of Key Design Alternatives. *Environmental Science & Technology* 47: 5896-5903; Farquharson, D., *et al*, 2016. Beyond Global Warming Potential: A Comparative Application of Climate Impact Metrics for the Life Cycle Assessment of Coal and Natural Gas Based Electricity. *Journal of Industrial Ecology,* 21 (4): 857-873; ICF International, 2016. *Finding the Facts on Methane Emissions: A Guide to the Literature*, prepared for The Natural Gas Council by ICF International, Fairfax, VA; National Academy of Sciences, 2018. *Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape*, Transportation Research Board Special Report 325, Washington, DC: The National Academies Press; Raimi, D., 2017. *The Fracking Debate: The Risks, Benefits, and Uncertainties of the Shale Revolution*. Columbia University Press, New York, NY; Raimi, D., 2018. The Shale Revolution and Climate Change, Resources for the Future Issue Brief 18-01, RRF, Washington, DC; and Venkatesh, A., *et al*, 2011. Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Natural Gas End-Uses and its Effects on Policy. *Environmental Science & Technology, 45* (19): 8182-8189.

List of Sources for Solar and Natural Gas Carbon Footprints: Alvarez, R. A., et al, 2018. Assessment of methane emissions from the U.S. oil and gas supply chain. Science 361: 186-188; Farquharson, D., et al, 2016. Beyond Global Warming Potential: A Comparative Application of Climate Impact Metrics for the Life Cycle Assessment of Coal and Natural Gas Based Electricity. Journal of Industrial Ecology, 21 (4): 857-873; ICF International, 2016. Finding the Facts on Methane Emissions: A Guide to the Literature, prepared for the Natural Gas Council; Kim, H. C.; Fthenakis, V.; Choi J-K.; Turney, D. E., 2012. Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation – Systematic Review and Harmonization. Journal of Industrial Ecology 16 (S1): S110-S121; Morris, J., 2017. Recycle, Bury, or Burn Wood Waste Biomass? LCA answer depends on carbon accounting, displaced fuels, emissions controls, and impact costs. Journal of Industrial Ecology, 21 (4): 844-856; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. Environmental Science & Technology 44 (20): 7944-7949; National Academy of

Sciences, 2018. Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape, Transportation Research Board Special Report 325, Washington, DC: The National Academies Press; Raimi, D., 2018. The Shale Revolution and Climate Change, Resources for the Future Issue Brief 18-01, Washington, DC: RRF; Raimi, D., 2017. The Fracking Debate: The Risks, Benefits, and Uncertainties of the Shale Revolution. Columbia University Press, Hew York, NY; Venkatesh, A., et al, 2011. Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Natural Gas End-Uses and Its Effects on Policy. Environmental Science & Technology, 45 (19): 8182-8189; Whitaker, M. B.; Heath, G. A.; Burkhardt, III, J. J.; Turchi, C. S., 2013. Life Cycle Assessment of a Power Tower Concentrating Solar Plant and the Impacts of Key Design Alternatives. Environmental Science & Technology 47 ( ): 5896-5903.

5. Worldwide Distribution of Plastic Wastes Among Management Options			
Collected			Unmanaged
Incineration	Landfilling	Collected for Recycling	Open dumping and burning, uncontrolled release to land & water
14%	40%	14%	32%

Source: Ellen MacArthur Foundation (2016). The New Plastics Economy: Rethinking the Future of Plastics

6. Distribution of Energy Recovery Offsets in 2015	
Natural Gas	83%
Renewables	17%

Source: U.S. EIA, International Energy Outlook, 2017 (data for 2015)

7. Climate Impacts of Plastics Waste Management Options (kg CO_2e/metric ton)									
	Recycling	**Landfill**	**Open Dump**	**Incinerate with Energy Recovery**	**Incinerate without Energy Recovery**	**Open Burn**	**Litter to Oceans**	**Litter to Other Water Bodies**	**Litter to Land**
<u>Activities/Processes</u>									
Collection/Self-Haul	45	35	35	35	35				
Material Handling	650	25		38	38				

Virgin Material Offset	-2,090								
Biodegradation		0	0				0	0	0
Incineration									
With Energy Recovery				2,894					
Natural Gas Offsets				-2,040					
Renewable Energy Offsets				-30					
Without Energy Recovery					2,894				
Open Burning						2,894			
Totals	-1,395	60	35	898	2,967	2,894	0	0	0

Source: SRMG & FCE, GHG Footprints for Three Packaging Materials Used in CA, June 2018; Morris, 2010, op. cit.; RTI, Decision Support Tool for MSW Management; SRMG, Measuring Environmental Benefits Calculator (MEBCalc^{TM}), version 6, 2017; U.S. EPA, Documentation for GHG Emissions and Energy Use Factors Used in WARM - Landfilling, Feb. 2016; U.S. EPA, Solid Waste Management and Greenhouse Gases - A Life-Cycle Assessment of Emissions and Sinks (3rd edition), 2016; Morris, Recycle, Bury, or Burn Wood Waste Biomass? LCA Answer Depends on Carbon Accounting, Emissions Controls, Displaced Fuels, and Impact Costs, Journal of Industrial Ecology, 2017.

Notes: Calculations of impacts for each management option based on parameters, estimates and assumptions detailed in spreadsheet sections 1 through 5 above, and in the additional references cited here in this section 6. Material Handling includes handling at transfer and disposal facilities. No estimate is provided for hauling to recycling or disposal facilities due to lack of data on worldwide distances that collected recyclables and wastes are hauled. GHG emissions for truck, rail, and ship/barge transport would be on the order of .036, .011, and .006 kg CO_2e per metric ton, per kilometer, respectively -- e.g., 3.6, 1.1 and 0.6 kg CO_2e, respectively, for 100 kilometers.

II. Parameters, Estimates and Assumptions (2030)

1. Worldwide Plastics Production (million metric tons - Mt) in 2030	548

Source: Material Economics, The Circular Economy; PlasticsEurope & EPRO, Plastics the Facts 2016

Note: Global plastic production is estimated to grow at the rate of 3.5- 3.8 percent annually 2015-2030 (ICIS) and 3.5 percent annually 2030-2050 (International Energy Agency World Energy Outlook 2015). A growth rate of 3.65 percent was applied in this analysis as the Ellen MacArthur Foundation report, 'The New Plastics Economy' projected that plastic production will be 1124 million metric tons by 2050. World Economic Forum (2016), The New Plastics Economy: Rethinking the future of plastics, January 2016; Ellen MacArthur Foundation (2016), op. cit.

2. Plastic Packaging Portion of Plastics Production	39.9%

Source: PlasticsEurope & EPRO, Plastics the Facts 2016

3. Plastics Packaging Polymeric Composition, Combustible Carbon Content, & Power Generation	**Comp.**	**C %**	**M Btu/t**	**kWh/t**
Polyethylene (PE) Film (e.g., LDPE - low density PE)-bone dry, no moisture	30%	84%	43.9	2236
Polyethylene (PE) Containers (e.g., HDPE - high density PE)-bone dry, no moisture	13%	84%	44.1	2247
Polypropylene (PP)-bone dry, no moisture	23%	84%	44.0	2241
Polyethylene Terephthalate (PET)-bone dry, no moisture	20%	61%	23.4	1180
Polystyrene (PS)-bone dry, no moisture	13%	90%	39.7	2025
Polyvinyl Chloride (PVC)-bone dry, no moisture	3%	36%	17.4	861
Total/Average	100.0%	79%	38.6	1,966

Source: Material Economics, The Circular Economy; PlasticsEurope & EPRO, Plastics the Facts 2016; U.S. EPA, Advancing Sustainable Materials Management: 2015 Tables and Figures; U.S. EPA, Documentation for GHG Emission and Energy Factors Used in WARM - Containers, Packaging and Non-Durable Goods Chapters, Feb. 2016

Notes: (1) 2 percentage points deducted from EPA estimates for carbon percentage content to account for ash and/or incomplete combustion in MSW incinerators. (2) Estimates for kWh/metric ton based on EPA estimated MSW incinerator power generation efficiency of 17.8%

4. Life Cycle Carbon Emissions from Power Generation (kg CO_2e per kWh)			Memo: Stack Emissions Only
Solar	0.09	includes fuel extraction, processing and transport	0
Natural Gas	1.25	includes fuel extraction, processing and transport	1.01
Coal	2.40	includes fuel extraction, processing and transport	2.33
PE & PP (bone dry basis, no moisture content)	1.37	stack emissions only	1.37
PET (bone dry basis, no moisture content)	1.89	stack emissions only	1.89
PS (bone dry basis, no moisture content)	1.63	stack emissions only	1.63
PVC (bone dry basis, no moisture content)	1.53	stack emissions only	1.53
Weighted average for plastic packaging	1.51	stack emissions only	1.51

Source: Kim, H. C.; Fthenakis, V.; Choi J-K.; Turney, D. E., 2012. Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation – Systematic Review and Harmonization. *Journal of Industrial Ecology* 16 (S1): S110-S121; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* 44 (20): 7944-7949; Morris, J., 2017. Recycle, Bury, or Burn Wood Waste Biomass? LCA answer depends on carbon accounting, displaced fuels, emissions controls, and impact costs. *Journal of Industrial Ecology*, 21 (4): 844-856; Whitaker, M. B.; Heath, G. A.; Burkhardt, III, J. J.; Turchi, C. S., 2013. Life Cycle Assessment of a Power Tower Concentrating Solar Plant and the Impacts of Key Design Alternatives. *Environmental Science & Technology* 47: 5896-5903; Farquharson, D., *et al*, 2016. Beyond Global Warming Potential: A Comparative Application of Climate Impact Metrics for the Life Cycle Assessment of Coal and Natural Gas Based Electricity. *Journal of Industrial Ecology,* 21 (4): 857-873; ICF International, 2016. *Finding the Facts on Methane Emissions: A Guide to the Literature*, prepared for The Natural Gas Council by ICF International, Fairfax, VA; National Academy of Sciences, 2018. *Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape*, Transportation Research Board Special Report 325, Washington, DC: The National Academies Press; Raimi, D., 2017. *The Fracking Debate: The Risks, Benefits, and Uncertainties of the Shale Revolution*. Columbia University Press, New York, NY; Raimi, D., 2018. The Shale Revolution and Climate Change, Resources for the Future Issue Brief 18-01, RRF, Washington, DC; and Venkatesh, A., *et al*, 2011. Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Natural Gas End-Uses and its Effects on Policy. *Environmental Science & Technology, 45* (19): 8182-8189.

List of Sources for Solar and Natural Gas Carbon Footprints: Alvarez, R. A., et al, 2018. Assessment of methane emissions from the U.S. oil and gas supply chain. Science 361: 186-188; Farquharson, D., et al, 2016. Beyond Global Warming Potential: A Comparative Application of Climate Impact Metrics for the Life Cycle Assessment of Coal and Natural Gas Based Electricity. Journal of Industrial Ecology, 21 (4): 857-873; ICF International, 2016. Finding the Facts on Methane Emissions: A Guide to the Literature, prepared for the Natural Gas Council; Kim, H. C.; Fthenakis, V.; Choi J-K.; Turney, D. E., 2012. Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation – Systematic Review and Harmonization. Journal of Industrial Ecology 16 (S1): S110-S121; Morris, J., 2017. Recycle, Bury, or Burn Wood Waste Biomass? LCA answer depends on carbon accounting, displaced fuels, emissions controls, and impact costs. Journal of Industrial Ecology, 21 (4): 844-856; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. Environmental Science & Technology 44 (20): 7944-7949; National Academy of

Sciences, 2018. Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape, Transportation Research Board Special Report 325, Washington, DC: The National Academies Press; Raimi, D., 2018. The Shale Revolution and Climate Change, Resources for the Future Issue Brief 18-01, Washington, DC: RRF; Raimi, D., 2017. The Fracking Debate: The Risks, Benefits, and Uncertainties of the Shale Revolution. Columbia University Press, Hew York, NY; Venkatesh, A., et al, 2011. Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Natural Gas End-Uses and Its Effects on Policy. Environmental Science & Technology, 45 (19): 8182-8189; Whitaker, M. B.; Heath, G. A.; Burkhardt, III, J. J.; Turchi, C. S., 2013. Life Cycle Assessment of a Power Tower Concentrating Solar Plant and the Impacts of Key Design Alternatives. Environmental Science & Technology 47 ( ): 5896-5903.

5. Worldwide Distribution of Plastic Wastes Among Management Options			
Collected			Unmanaged
Incineration	Landfilling	Collected for Recycling	Open dumping and burning, uncontrolled release to land & water
14%	40%	14%	32%

Source: Ellen MacArthur Foundation (2016). The New Plastics Economy: Rethinking the Future of Plastics

6. Distribution of Energy Recovery Offsets in 2030	
Natural Gas	68%
Renewables	32%

Source: U.S. EIA, International Energy Outlook, 2017 (data for 2030)

7. Climate Impacts of Plastics Waste Management Options (kg CO_2e/metric ton)									
	Recycling	**Landfill**	**Open Dump**	**Incinerate with Energy Recovery**	**Incinerate without Energy Recovery**	**Open Burn**	**Litter to Oceans**	**Litter to Other Water Bodies**	**Litter to Land**
Activities/Processes									
Collection/Self-Haul	45	35	35	35	35				
Material Handling	650	25		38	38				

Virgin Material Offset	-2,090								
Biodegradation		0	0				0	0	0
Incineration									
With Energy Recovery									
Natural Gas Offsets				-1,671					
Renewable Energy Offsets				-57					
Without Energy Recovery					2,894				
Open Burning						2,894			
Totals	-1,395	60	35	1,240	2,967	2,894	0	0	0

Source: SRMG & FCE, GHG Footprints for Three Packaging Materials Used in CA, June 2018; Morris, 2010, op. cit.; RTI, Decision Support Tool for MSW Management; SRMG, Measuring Environmental Benefits Calculator (MEBCalc^{TM}), version 6, 2017; U.S. EPA, Documentation for GHG Emissions and Energy Use Factors Used in WARM - Landfilling, Feb. 2016; U.S. EPA, Solid Waste Management and Greenhouse Gases - A Life-Cycle Assessment of Emissions and Sinks (3rd edition), 2016; Morris, Recycle, Bury, or Burn Wood Waste Biomass? LCA Answer Depends on Carbon Accounting, Emissions Controls, Displaced Fuels, and Impact Costs, Journal of Industrial Ecology, 2017.

Notes: Calculations of impacts for each management option based on parameters, estimates and assumptions detailed in spreadsheet sections 1 through 5 above, and in the additional references cited here in this section 6. Material Handling includes handling at transfer and disposal facilities. No estimate is provided for hauling to recycling or disposal facilities due to lack of data on worldwide distances that collected recyclables and wastes are hauled. GHG emissions for truck, rail, and ship/barge transport would be on the order of .036, .011, and .006 kg CO_2e per metric ton, per kilometer, respectively -- e.g., 3.6, 1.1 and 0.6 kg CO_2e, respectively, for 100 kilometers.

III. Parameters, Estimates and Assumptions (2050)

1. Worldwide Plastics Production (million metric tons - Mt) in 2050	1090

Source: Material Economics, The Circular Economy; PlasticsEurope & EPRO, Plastics the Facts 2016
Note: Global plastic production is estimated to grow at the rate of 3.5- 3.8 percent annually 2015-2030 (ICIS) and 3.5 percent annually 2030-2050 (International Energy Agency World Energy Outlook 2015). A growth rate of 3.65 percent was applied in this analysis as the Ellen MacArthur Foundation report, 'The New Plastics Economy' projected that plastic production will be 1124 million metric tons by 2050. World Economic Forum (2016), The New Plastics Economy: Rethinking the future of plastics, January 2016; Ellen MacArthur Foundation (2016), op. cit.

2. Plastic Packaging Portion of Plastics Production	39.9%

Source: PlasticsEurope & EPRO, Plastics the Facts 2016

3. Plastics Packaging Polymeric Composition, Combustible Carbon Content, & Power Generation	**Comp.**	**C %**	**M Btu/t**	**kWh/t**
Polyethylene (PE) Film (e.g., LDPE - low density PE)-bone dry, no moisture	30%	84%	43.9	2236
Polyethylene (PE) Containers (e.g., HDPE - high density PE)-bone dry, no moisture	13%	84%	44.1	2247
Polypropylene (PP)-bone dry, no moisture	23%	84%	44.0	2241
Polyethylene Terephthalate (PET)-bone dry, no moisture	20%	61%	23.4	1180
Polystyrene (PS)-bone dry, no moisture	13%	90%	39.7	2025
Polyvinyl Chloride (PVC)-bone dry, no moisture	3%	36%	17.4	861
Total/Average	100.0%	79%	38.6	1,966

Source: Material Economics, The Circular Economy; PlasticsEurope & EPRO, Plastics the Facts 2016; U.S. EPA, Advancing Sustainable Materials Management: 2015 Tables and Figures; U.S. EPA, Documentation for GHG Emission and Energy Factors Used in WARM - Containers, Packaging and Non-Durable Goods Chapters, Feb. 2016
Notes: (1) 2 percentage points deducted from EPA estimates for carbon percentage content to account for ash and/or incomplete combustion in MSW incinerators. (2) Estimates for kWh/metric ton based on EPA estimated MSW incinerator power generation efficiency of 17.8%

4. Life Cycle Carbon Emissions from Power Generation (kg CO_2e per kWh)			Memo: Stack Emissions Only
Solar	0.09	includes fuel extraction, processing and transport	0
Natural Gas	1.25	includes fuel extraction, processing and transport	1.01
Coal	2.40	includes fuel extraction, processing and transport	2.33
PE & PP (bone dry basis, no moisture content)	1.37	stack emissions only	1.37
PET (bone dry basis, no moisture content)	1.89	stack emissions only	1.89
PS (bone dry basis, no moisture content)	1.63	stack emissions only	1.63
PVC (bone dry basis, no moisture content)	1.53	stack emissions only	1.53
Weighted average for plastic packaging	1.51	stack emissions only	1.51

Source: Kim, H. C.; Fthenakis, V.; Choi J-K.; Turney, D. E., 2012. Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation – Systematic Review and Harmonization. *Journal of Industrial Ecology* 16 (S1): S110-S121; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. *Environmental Science & Technology* 44 (20): 7944-7949; Morris, J., 2017. Recycle, Bury, or Burn Wood Waste Biomass? LCA answer depends on carbon accounting, displaced fuels, emissions controls, and impact costs. *Journal of Industrial Ecology*, 21 (4): 844-856; Whitaker, M. B.; Heath, G. A.; Burkhardt, III, J. J.; Turchi, C. S., 2013. Life Cycle Assessment of a Power Tower Concentrating Solar Plant and the Impacts of Key Design Alternatives. *Environmental Science & Technology* 47: 5896-5903; Farquharson, D., *et al*, 2016. Beyond Global Warming Potential: A Comparative Application of Climate Impact Metrics for the Life Cycle Assessment of Coal and Natural Gas Based Electricity. *Journal of Industrial Ecology,* 21 (4): 857-873; ICF International, 2016. *Finding the Facts on Methane Emissions: A Guide to the Literature*, prepared for The Natural Gas Council by ICF International, Fairfax, VA; National Academy of Sciences, 2018. *Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape*, Transportation Research Board Special Report 325, Washington, DC: The National Academies Press; Raimi, D., 2017. *The Fracking Debate: The Risks, Benefits, and Uncertainties of the Shale Revolution*. Columbia University Press, New York, NY; Raimi, D., 2018. The Shale Revolution and Climate Change, Resources for the Future Issue Brief 18-01, RRF, Washington, DC; and Venkatesh, A., *et al*, 2011. Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Natural Gas End-Uses and its Effects on Policy. *Environmental Science & Technology, 45* (19): 8182-8189.

List of Sources for Solar and Natural Gas Carbon Footprints: Alvarez, R. A., et al, 2018. Assessment of methane emissions from the U.S. oil and gas supply chain. Science 361: 186-188; Farquharson, D., et al, 2016. Beyond Global Warming Potential: A Comparative Application of Climate Impact Metrics for the Life Cycle Assessment of Coal and Natural Gas Based Electricity. Journal of Industrial Ecology, 21 (4): 857-873; ICF International, 2016. Finding the Facts on Methane Emissions: A Guide to the Literature, prepared for the Natural Gas Council; Kim, H. C.; Fthenakis, V.; Choi J-K.; Turney, D. E., 2012. Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation – Systematic Review and Harmonization. Journal of Industrial Ecology 16 (S1): S110-S121; Morris, J., 2017. Recycle, Bury, or Burn Wood Waste Biomass? LCA answer depends on carbon accounting, displaced fuels, emissions controls, and impact costs. Journal of Industrial Ecology, 21 (4): 844-856; Morris, J., 2010. Bury or burn North American MSW? LCAs provide answers for climate impacts & carbon neutral power potential. Environmental Science & Technology 44 (20): 7944-7949; National Academy of

Sciences, 2018. Safely Transporting Hazardous Liquids and Gases in a Changing U.S. Energy Landscape, Transportation Research Board Special Report 325, Washington, DC: The National Academies Press; Raimi, D., 2018. The Shale Revolution and Climate Change, Resources for the Future Issue Brief 18-01, Washington, DC: RRF; Raimi, D., 2017. The Fracking Debate: The Risks, Benefits, and Uncertainties of the Shale Revolution. Columbia University Press, Hew York, NY; Venkatesh, A., et al, 2011. Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Natural Gas End-Uses and Its Effects on Policy. Environmental Science & Technology, 45 (19): 8182-8189; Whitaker, M. B.; Heath, G. A.; Burkhardt, III, J. J.; Turchi, C. S., 2013. Life Cycle Assessment of a Power Tower Concentrating Solar Plant and the Impacts of Key Design Alternatives. Environmental Science & Technology 47 ( ): 5896-5903.

5. Worldwide Distribution of Plastic Wastes Among Management Options			
Collected			Unmanaged
Incineration	Landfilling	Collected for Recycling	Open dumping and burning, uncontrolled release to land & water
14%	40%	14%	32%

Source: Ellen MacArthur Foundation (2016). The New Plastics Economy: Rethinking the Future of Plastics

6. Distribution of Energy Recovery Offsets in 2050	
Natural Gas	60%
Renewables	40%

Source: U.S. EIA, International Energy Outlook, 2017 (data for 2050)

7. Climate Impacts of Plastics Waste Management Options (kg CO_2e/metric ton)									
	Recycling	**Landfill**	**Open Dump**	**Incinerate with Energy Recovery**	**Incinerate without Energy Recovery**	**Open Burn**	**Litter to Oceans**	**Litter to Other Water Bodies**	**Litter to Land**
Activities/Processes									
Collection/Self-Haul	45	35	35	35	35				
Material Handling	650	25		38	38				

Virgin Material Offset	-2,090								
Biodegradation		0	0				0	0	0
Incineration									
With Energy Recovery									
Natural Gas Offsets				-1,474					
Renewable Energy Offsets				-71					
Without Energy Recovery					2,894				
Open Burning						2,894			
Totals	-1,395	60	35	1,422	2,967	2,894	0	0	0

Source: SRMG & FCE, GHG Footprints for Three Packaging Materials Used in CA, June 2018; Morris, 2010, op. cit.; RTI, Decision Support Tool for MSW Management; SRMG, Measuring Environmental Benefits Calculator (MEBCalc^{TM}), version 6, 2017; U.S. EPA, Documentation for GHG Emissions and Energy Use Factors Used in WARM - Landfilling, Feb. 2016; U.S. EPA, Solid Waste Management and Greenhouse Gases - A Life-Cycle Assessment of Emissions and Sinks (3rd edition), 2016; Morris, Recycle, Bury, or Burn Wood Waste Biomass? LCA Answer Depends on Carbon Accounting, Emissions Controls, Displaced Fuels, and Impact Costs, Journal of Industrial Ecology, 2017.

Notes: Calculations of impacts for each management option based on parameters, estimates and assumptions detailed in spreadsheet sections 1 through 5 above, and in the additional references cited here in this section 6. Material Handling includes handling at transfer and disposal facilities. No estimate is provided for hauling to recycling or disposal facilities due to lack of data on worldwide distances that collected recyclables and wastes are hauled. GHG emissions for truck, rail, and ship/barge transport would be on the order of .036, .011, and .006 kg CO_2e per metric ton, per kilometer, respectively -- e.g., 3.6, 1.1 and 0.6 kg CO_2e, respectively, for 100 kilometers.

IV. GHG Emissions from waste incineration with energy recovery (plastic packing only)

year		Plastic production (million metric ton)	Amount of plastic packaging (39.9%, metric ton)	GHG emissions from incineration with energy recovery (kg CO2e/metric ton)	Ratio of incineration with energy recovery in waste management methods	Annual GHG emissions from waste incineration with energy recovery (metric ton)
2015	current state	320	127,680,000	898	14%	16,051,930
2030	Industrial outlook (increased plastic production and incineration)	548	218,652,000	1,240	31%	84,049,829
	Increased plastic incineration with no growth in plastic production	320	127,680,000	1,240	31%	49,080,192
	Increased plastic production with no growth in the ratio of waste incineration	548	218,652,000	1,240	14%	37,957,987
	BEST Case Scenario (plastic packaging halved by 2030, reaching zero by 2050)	160	63,840,000	1,240	7%	5,541,312
2050	Industrial outlook (increased plastic production and incineration)	1,090	434,910,000	1,422	50%	309,221,010
	Increased plastic incineration with no growth in plastic production	320	127,680,000	1,422	50%	90,780,480
	Increased plastic production with no growth in the ratio of waste incineration	1,090	434,910,000	1,422	14%	86,581,883
	BEST Case Scenario (plastic packaging halved by 2030, reaching zero by 2050)	0	0	0	0	-

Source: Material Economics, The Circular Economy; PlasticsEurope & EPRO, Plastics the Facts 2016. Calculations are based on the data present in I, II, III of this Appendix.