January 2023

Assessing Options For Reducing Greenhouse Gas Emissions And Increasing Energy Production From Municipal Solid Waste Utilizing EPA Models

Marcus Richburg

Assessing Options for Reducing Greenhouse Gas Emissions and Increasing Energy Production from Municipal Solid Waste Utilizing EPA Models

by

Marcus Richburg

Bachelor of Science, The University of Alabama, 1996
Master of Science, The University of Alabama, 1998
Master of Business Administration, Troy University, 2000

A Dissertation
Submitted to the Graduate Faculty

of the

University of North Dakota

In partial fulfillment of the requirements

For the degree of

Doctor of Philosophy

Grand Forks, North Dakota

August 2023

This dissertation submitted by Marcus Richburg in partial fulfillment of the requirements for the Degree of Doctor of Philosophy Energy Engineering from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

DocuSigned by:
Michael Mann
48F0545EE5FF405...
Michael Mann

DocuSigned by:
Soizik Laguette
2ACCC464604A4F5...
Soizik Laguette

DocuSigned by:
Dr. Stanley Olusegun Tomomewo
894BC27CC43F4AB...
Dr. Stanley Olusegun Tomomewo

DocuSigned by:
Taufique Mahmood
3F7DA8280EB4408...
Taufique Mahmood

This dissertation is being submitted by the appointment advisory committee as having met all of the requirements of the School of Graduate Studies at the University of North Dakota and is hereby approved.

DocuSigned by:
Chris Nelson
2E0AF088C733403...

Chris Nelson
Dean of the School of Graduate Studies

7/31/2023

Date

PERMISSION

Title	Assessing Options for Reducing Greenhouse Gas Emissions and Increasing Energy Production from Municipal Waste Utilizing EPA Models
Department	Energy Engineering
Degree	Doctor of Philosophy

In presenting this dissertation in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the library of this University shall make it freely available for inspection. I further agree that permission for extensive copying for scholarly purposes may be granted by the professor who supervised my dissertation work or in his absence, by the Chairperson of the department or the Dean of the School of Graduate Studies. It is understood that any copying or publication of other use of this dissertation or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my dissertation.

Marcus Richburg
August, 2023

TABLE OF CONTENTS

TABLE OF CONTENTS v

LIST OF FIGURES xi

LIST OF EQUATIONS xxii

ACKNOWLEDGEMENTS xxiii

ABSTRACT xxv

CHAPTER ONE: INTRODUCTION 1

1.1 Background 1

1.2 What is Climate Change and Global Warming 4

1.3 The Connectivity of Greenhouse Gases and Anthropogenic Global Warming 5

1.4 Greenhouse Gas Reduction Efforts 7

1.5 Movement to Net-Zero Emissions 14

1.6 Current Emissions Issues 15

1.7 Research Objectives 29

1.8 Research Questions 30

CHAPTER TWO: LITERATURE REVIEW 32

2.1 Municipal Solid Waste Introduction 32

2.2 Municipal Solid Waste and GHG Emissions 32

2.2.1 Landfill Gas Capture and GHG Emissions 39
2.2.2 Combustion to Energy Pathway 42
2.2.3 Other MSW to Energy Pathways 44
2.3 Modeling of Emissions and Methane Generation 48
2.4 Waste-to-Energy Policy in the United States 55
2.5 Waste Management in the United States 56
CHAPTER THREE: METHODOLOGY 62
3.1 Introduction 62
3.2 Research Design 62
3.2.1 Data Source 63
3.2.2 Data Timeline 63
3.2.3 Research Sequence 63
3.3 Model Structures 65
3.3.1 WARM Model 65
3.3.2 WARM Model Analysis 71
3.3.3 LandGEM Model 71
3.3.4 Energy Potential 75
3.4 Assumptions and Limitations 77
CHAPTER FOUR: MODELING RESULTS 79
4.1 Introduction 79

4.2 WARM Model Data 80
4.2.1 WARM Model - Theoretical Calculation 82
4.2.2 Theoretical Paper Data 82
4.2.3 Theoretical Food Waste Data 87
4.2.4 Theoretical Yard Trimmings Data 92
4.2.5 Theoretical Mixed Plastics Data 96
4.2.6 Theoretical Electronics Data 101
4.2.7 Theoretical Metals Data 106
4.2.8 Glass Data 110
4.2.9 Carpet Data 115
4.2.10 Tires Data 119
4.2.11 Mixed MSW Data 123
4.2.12 Summary of Theoretical Calculations 126
4.3 WARM Model – "Business as Usual" Calculations 128
4.3.1 "Business as Usual" Paper Data 129
4.3.2 "Business as Usual" Food Waste Data 133
4.3.3 "Business as Usual" Yard Trimmings Data 136
4.3.4 "Business as Usual" Mixed Plastics Data 139
4.3.5 "Business as Usual" Electronics Data 143
4.3.11 Summary of "Business as Usual" Calculations 162

4.4 WARM Model – "Business as Usual" Full Generation Calculations 163

4.4.1 "Business as Usual" Full Generation Emissions Avoided 164

4.4.2 "Business as Usual" Full Generation Energy Savings 165

4.4.3 Full Generation Wages Impact 166

4.4.4 Summary of "Business as Usual" Full Generation Calculations 168

4.5 WARM Model - Practical Modeling 168

4.5.1 Practical Modeling – Emissions Avoided 170

4.5.2 Practical Modeling – Energy Savings 172

4.5.3 Practical Modeling – Wages Impact 173

4.5.4 Practical Modeling – Summary 175

4.6 LandGEM Model Data 176

4.7 Landfill Gas Energy Potential Data 180

CHAPTER FIVE: MODELING ANALYSIS & DISCUSSION 183

5.1 Introduction 183

5.2 Theoretical Modeling Analysis & Discussion 183

5.2.1 Theoretical Emissions Avoided 183

5.2.2 Theoretical Paper Emissions Avoidance 184

5.2.3 Theoretical Food Waste Emissions Avoidance 184

5.2.4 Theoretical Yard Trimmings Emissions Avoidance 185

5.2.5 Theoretical Mixed Plastics Emissions Avoidance 185

5.2.6 Theoretical Electronics Emissions Avoidance 186
5.2.7 Theoretical Metals Emissions Avoidance 186
5.2.8 Theoretical Glass Emissions Avoidance 186
5.2.9 Theoretical Carpet Emissions Avoidance.. 187
5.2.10 Theoretical Tire Emissions Avoidance.. 187
5.2.11 Theoretical Mixed MSW Emissions Avoidance 187
5.2.11 Theoretical Emissions Avoidance Summary... 188
5.3 Theoretical Energy Savings 189
5.3.1 Theoretical Paper Energy Savings... 189
5.3.2 Theoretical Food Waste Energy Savings... 190
5.3.3 Theoretical Yard Trimmings Energy Savings 191
5.3.4 Theoretical Mixed Plastics Energy Savings 191
5.3.5 Theoretical Electronics Energy Savings.. 192
5.3.6 Theoretical Metals Energy Savings... 193
5.3.7 Theoretical Glass Energy Savings... 193
5.3.8 Theoretical Carpet Energy Savings 194
5.3.9 Theoretical Tires Energy Savings.. 195
5.3.10 Theoretical Mixed MSW Energy Savings... 195
5.3.11 Theoretical Energy Savings Summary 196
5.4 "Business as Usual" Modeling Analysis & Discussion 197

5.4.1 Emissions Avoided, Energy Savings, and Wages Impact 198

5.5 Practical Modeling 199

5.6 LandGEM and Landfill Gas Energy Potential 200

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS 202

6.1 Introduction 202

REFERENCES 205

LIST OF FIGURES

Figure 1.1: World population 1950 through 2050 (Researchgate.net, 2023) 1

Figure 1.2: The Greenhouse Effect (Ranveer et al., 2015). 3

Figure 1.3: Halogenated source gases and their impact on stratospheric ozone (Chipperfield et al., 2020) 8

Figure 1.4: Global greenhouse gas emissions since 1990. (US EPA, 2016d) 9

Figure 1.5: GHG emissions for Canada, 1990 – 2020 (Canada, 2007) 12

Figure 1.6: Global energy-related CO_2 emissions through 2050 (EIA Projects Global Energy-Related CO2 Emissions Will Increase through 2050, n.d.)... 15

Figure 1.7: Total global GHG emissions trends (Lamb et al., 2021).. 18

Figure 1.8: Total regional GHG emissions trends (Lamb et al., 2021) 18

Figure 1.9: Global greenhouse gas emissions by sector, 2016 (Ritchie et al., 2020) 19

Figure 1.10: Inter-linkages between agriculture and climate change (Pant, 2009) 21

Figure 1.11: Energy inputs, greenhouse gas emissions, and products during crop cultivation (Mohammadi et al., 2014) 22

Figure 1.12: Drivers of deforestation for agriculture (Goers et al., 2009)................................... 23

Figure 1.13: Process of anaerobic decomposition (Mitchell & Gu, 2009) 25

Figure 1.14: Landfill gas (LFG) emissions generated from landfilled organic waste (Dincă et al., 2018)... 26

Figure 1.15: Trend of CH_4 emissions from landfills pre and post closure (Lou & Nair, 2009) ... 26

Figure 1.16: Land-use change and contribution to global warming (Kim & Kirschbaum, 2015) 28

Figure 2.1: Municipal solid waste treatment options (A. Kumar & Samadder, 2017)................ 33

Figure 2.2: MSW-to-energy landscape of the ten US EPA regions in 2015 (Mukherjee et al., 2020) 35
Figure 2.3: Energy recovery potential of different WTE technologies for different MSW stream (A. Kumar & Samadder, 2017) 36
Figure 2.4: Eight outcomes of energy from municipal solid waste (Kaur et al., 2021) 38
Figure 2.11: Landfill life cycle, LFG generation vs LFG collection (Scarlat et al., 2015) 41
Figure 2.12: Comparison of GasSim, LandGEM, and HELGA simulations (Dincă et al., 2018) 52
Figure 2.13: Methane emissions from a municipal landfill with a 50-year operating life. Lower green curve shows emissions assuming 75% capture of methane on site (Jobson & Khosravi, 2019) 54
Figure 2.14: Total MSW generated in the United States in 2018 (US EPA, 2017) 56
Figure 2.15: Municipal solid waste management: 2016-2011 by methodology (US EPA, 2017). 57
Figure 2.16: Percent of total municipal solid waste that is burned with energy recovery in selected countries (Waste-to-Energy (MSW) - U.S. Energy Information Administration (EIA), 2022) 58
Figure 2.17: Total MSW recycling by material (US EPA, 2017) 58
Figure 2.18: Recycling tonnages by material, 1960-2018 (US EPA, 2017) 59
Figure 2.19: Diagram of Materials Recovery Facility (MRF) (www.dakotavalleyrecyclingmn.govcom) 61
Figure 3.4: Steps one and two of WARM analysis inputs (US EPA, 2016a) 66
Figure 3.5: Step three of WARM analysis inputs (US EPA, 2016a) 67
Figure 3.6: Step four of WARM analysis inputs (US EPA, 2016a) 67

Figure 3.7: Step five of WARM analysis inputs (US EPA, 2016a).. 68

Figure 3.8: Step five of WARM analysis inputs (US EPA, 2016a).. 68

Figure 3.9: Step six of WARM analysis inputs (US EPA, 2016a) 69

Figure 3.10: Step seven of WARM analysis inputs (US EPA, 2016a).. 70

Figure 3.11: Step eight of WARM analysis inputs (US EPA, 2016a).. 70

Figure 3.12: Step one of LandGEM model inputs (US EPA, 2005).. 71

Figure 3.13: Step two of LandGEM model inputs (US EPA, 2005) 72

Figure 3.14: Step three of LandGEM model inputs (US EPA, 2005) 73

Figure 3.15: Step four of LandGEM model inputs (US EPA, 2005)... 74

Figure 3.16: Step five of LandGEM model inputs (US EPA, 2005) 75

Figure 4.1: MSW annual tonnage - Montgomery County, AL landfill (M. Richburg 2023) 79

Figure 4.2: Theoretical GHG emissions avoided – paper (M. Richburg, 2023)........................... 84

Figure 4.3: Theoretical energy savings – paper (M. Richburg, 2023)... 85

Figure 4.4: Theoretical wages impact – paper (M. Richburg, 2023)... 87

Figure 4.5: Theoretical GHG emissions avoided – food waste (M. Richburg, 2023) 88

Figure 4.6: Theoretical energy savings - food waste (M. Richburg, 2023)................................. 90

Figure 4.7: Theoretical wages impact – food waste (M. Richburg, 2023) 91

Figure 4.8: Theoretical GHG emissions avoided – yard trimmings (M. Richburg, 2023) 93

Figure 4.9: Theoretical energy savings – yard trimmings (M. Richburg, 2023) 94

Figure 4.10: Theoretical wages impact – yard trimmings (M. Richburg, 2023) 96

Figure 4.11: Theoretical GHG emissions avoided – mixed plastics (M. Richburg, 2023)........... 98

Figure 4.12: Theoretical energy analysis – mixed plastics (M. Richburg, 2023)......................... 99

Figure 4.13: Theoretical wages impact – mixed plastics (M. Richburg, 2023).......................... 101

Figure 4.14: Theoretical GHG emissions avoided – electronics (M. Richburg, 2023) 102

Figure 4.15: Theoretical energy savings – electronics (M. Richburg, 2023) 104

Figure 4.16: Theoretical wages impact – electronics (M. Richburg, 2023) 105

Figure 4.17: Theoretical GHG emissions avoided – metals (M. Richburg, 2023) 107

Figure 4.18: Theoretical energy savings – metals (M. Richburg, 2023) 108

Figure 4.19: Theoretical wages impact – metals (M. Richburg, 2023) 110

Figure 4.20: Theoretical GHG emissions avoided – glass (M. Richburg, 2023)....................... 111

Figure 4.21: Theoretical energy savings – glass (M. Richburg, 2023)...................................... 113

Figure 4.22: Theoretical wages impact – glass (M. Richburg, 2023).. 114

Figure 4.23: Theoretical GHG emissions avoided – carpet (M. Richburg, 2023)...................... 116

Figure 4.24: Theoretical energy savings – carpet (M. Richburg, 2023).................................... 117

Figure 4.25: Theoretical wages impact – carpet (M. Richburg, 2023)...................................... 118

Figure 4.26: Theoretical GHG emissions avoided – tires (M. Richburg, 2023)........................ 120

Figure 4.27: Theoretical energy savings – tires (M. Richburg, 2023)....................................... 121

Figure 4.28: Theoretical wages impact – tires (M. Richburg, 2023)... 123

Figure 4.29: Theoretical GHG emissions avoided – mixed MSW (M. Richburg, 2023)........... 124

Figure 4.30: Theoretical energy savings – mixed MSW (M. Richburg, 2023) 125

Figure 4.31: "Business as Usual" GHG emissions avoided – paper (M. Richburg, 2023) 130

Figure 4.32: "Business as Usual" energy savings – paper (M. Richburg, 2023)....................... 131

Figure 4.33: "Business as Usual" wages impact – paper (M. Richburg, 2023)......................... 132

Figure 4.34: "Business as Usual" GHG emissions avoided – food waste (M. Richburg, 2023) 134

Figure 4.35: "Business as Usual" energy savings – food waste (M. Richburg, 2023).............. 135

Figure 4.36: “Business as Usual” GHG emissions avoided – yard trimmings (M. Richburg, 2023) 137
Figure 4.37: “Business as Usual” energy savings – yard trimmings (M. Richburg, 2023) 138
Figure 4.38: “Business as Usual” GHG emissions avoided – mixed plastics (M. Richburg, 2023) 140
Figure 4.39: “Business as Usual” energy savings – mixed plastics (M. Richburg, 2023) 141
Figure 4.40: “Business as Usual” wages impact – mixed plastics (M. Richburg, 2023) 142
Figure 4.41: “Business as Usual” GHG emissions avoided – electronics (M. Richburg, 2023) 144
Figure 4.42: “Business as Usual” energy savings – electronics (M. Richburg, 2023) 145
Figure 4.43: “Business as Usual” wages impact – electronics (M. Richburg, 2023) 146
Figure 4.44: “Business as Usual” emissions avoided – metals (M. Richburg, 2023) 147
Figure 4.45: “Business as Usual” energy savings – metals (M. Richburg, 2023) 148
Figure 4.46: “Business as Usual” wages impact – metals (M. Richburg, 2023) 149
Figure 4.47: “Business as Usual” GHG emissions avoided – glass (M. Richburg, 2023) 150
Figure 4.49: “Business as Usual” wages impact – glass (M. Richburg, 2023) 152
Figure 4.50: “Business as Usual” GHG emissions avoided – carpet (M. Richburg, 2023) 153
Figure 4.51: “Business as Usual” energy savings – carpet (M. Richburg, 2023) 154
Figure 4.52: “Business as Usual” wages impact – carpet (M. Richburg, 2023) 155
Figure 4.53: “Business as Usual” GHG emissions avoided – tires (M. Richburg, 2023) 156
Figure 4.54: “Business as Usual” energy savings – tires (M. Richburg, 2023) 157
Figure 4.55: “Business as Usual” wages impact – tires (M. Richburg, 2023) 158
Figure 4.56: “Business as Usual” GHG emissions avoided – mixed MSW (M. Richburg, 2023) 160

Figure 4.57: "Business as Usual" energy savings – mixed MSW (M. Richburg, 2023) 161

Figure 4.58: "Business as Usual" GHG emissions avoided – full generation (M. Richburg, 2023) 165

Figure 4.59: "Business as Usual" full generation energy savings (M. Richburg, 2023) 166

Figure 4.60: "Business as Usual" full generation wages impact (M. Richburg, 2023) 167

Figure 4.61: Practical model – emissions avoided (M. Richburg, 2023) 171

Figure 4.62: Practical model – energy savings (M. Richburg, 2023) 173

Figure 4.63: Practical model – wages impact (M. Richburg, 2023) 174

Figure 4.64: LandGEM model data sheet – landfill gas & methane (M. Richburg, 2023) 178

Figure 4.65: LandGEM model data sheet – carbon dioxide and NMOC (M. Richburg, 2023) . 179

Figure 4.66: LandGEM model – gas emissions (M. Richburg, 2023)....................................... 180

Figure 4.67: Energy potential - LandGEM (M. Richburg, 2023) 182

Figure 4.68: Energy potential decline curve -. LandGEM (M. Richburg, 2023) 182

Figure 5.1: Energy savings equivalency – paper (M. Richburg, 2023) 190

Figure 5.2: Energy savings equivalency – food waste (M. Richburg, 2023)............................. 191

Figure 5.3: Energy savings equivalency – yard trimmings (M. Richburg, 2023) 191

Figure 5.4: Energy savings equivalency – mixed plastics (M. Richburg, 2023) 192

Figure 5.5: Energy savings equivalency – electronics (M. Richburg, 2023)............................. 193

Figure 5.6: Energy savings equivalency – metals (M. Richburg, 2023).................................... 193

Figure 5.7: Energy savings equivalency – glass (M. Richburg, 2023) 194

Figure 5.8: Energy savings equivalency – carpet (M. Richburg, 2023) 194

Figure 5.9: Energy savings equivalency – tires (M. Richburg, 2023) 195

Figure 5.10: Energy savings equivalency – mixed MSW (M. Richburg, 2023) 196

LIST OF TABLES

Table 1.1: Summary of trends in observed climatic variables (Wuebbles & Jain, 2001)............... 3

Table 1.2: Gas content of the earth's atmosphere (Al-Ghussain, 2019).. 5

Table 1.3: Annex I countries from Kyoto Protocol (Huang et al., 2008) 11

Table 1.4: COP Meetings since the Paris Agreement.. 13

Table 1.5: Carbon dioxide emission in the World by region (1990-2035) (Ahiduzzaman & Islam, 2011) the numbers are in billion tonne 16

Table 1.6: Carbon dioxide emission per capita in the World by region (1990 – 2035) (Ahiduzzaman & Islam, 2011) the numbers are in tonne per person 17

Table 2.1: A comparison of air emission – waste-to-energy and fossil fuel plants (Psomopoulos et al., 2009) 34

Table 2.2: Economic benefits of captured CH_4 in Oman (Abushammala et al., 2016) 40

Table 2.3: Methane potential from landfill (Scarlat et al., 2015) 41

Table 2.4: Comparison of energy characteristics of gasification and combustion processes (Vaish et al., 2019) 44

Table 2.5: The parameters and product yields for three pyrolysis processes (Hasan et al., 2021)47

Table 2.6: Landfills in Washington State with no LFG collection system (Jobson & Khosravi, 2019).. 50

Table 2.7: Landfills in Washington State with LFG collection system (Jobson & Khosravi, 2019) 50

Table 2.8: Organic waste weight by material type used in WARM model for two landfilling types: landfilling with and without LFG collection system (Jobson & Khosravi, 2019) 51

Table 2.9: Net CO_2 equivalent emission in mega tonnes (MT CO_2e) from diversion of organic waste from landfilling to composting (Jobson & Khosravi, 2019) 51
Table 4.1: Montgomery County, AL landfill 2022 monthly average 80
Table 4.2: Current landfill conditions based upon WARM model calculations........................... 81
Table 4.3: Theoretical GHG emissions avoided - paper.. 83
Table 4.4: Theoretical energy savings - paper 85
Table 4.5: Theoretical wages impact - paper 86
Table 4.6: Theoretical GHG emissions avoided - food waste 88
Table 4.7: Theoretical energy savings - food waste 89
Table 4.8: Theoretical wages impact - food waste 91
Table 4.9: Theoretical GHG emissions avoided – yard trimmings 92
Table 4.10: Theoretical energy savings – yard trimmings... 94
Table 4.11: Theoretical wages impact – yard trimmings... 95
Table 4.12: Theoretical GHG emissions avoided – mixed plastics... 97
Table 4.13: Theoretical energy savings – mixed plastics 99
Table 4.14: Theoretical wages impact – mixed plastics 100
Table 4.15: Theoretical GHG emissions avoided – electronics... 102
Table 4.16: Theoretical energy savings – electronics.. 103
Table 4.17: Theoretical wages impact – electronics.. 105
Table 4.18: Theoretical GHG emissions avoided – metals.. 106
Table 4.19: Theoretical energy savings – metals... 108
Table 4.20: Theoretical wages impact – metals... 109
Table 4.21: Theoretical GHG emissions avoided – glass 111

Table 4.22: Theoretical energy savings – glass ... 112

Table 4.23: Theoretical wages impact – glass ... 114

Table 4.24: Theoretical GHG emissions avoided – carpet ... 115

Table 4.25: Theoretical energy savings – carpet ... 117

Table 4.26: Theoretical wages impact – carpet ... 118

Table 4.27: Theoretical GHG emissions avoided – tires ... 119

Table 4.28: Theoretical energy savings – tires ... 121

Table 4.29: Theoretical wages impact – tires ... 122

Table 4.30: Theoretical GHG emissions avoided – mixed MSW ... 124

Table 4.31: Theoretical energy savings – mixed MSW ... 125

Table 4.32: Theoretical wages impact – mixed MSW ... 126

Table 4.33: Summary of GHG emissions for the theoretical case ... 127

Table 4.34: Summary of energy savings for the theoretical case ... 127

Table 4.35: Summary of the wage impact for the theoretical case ... 128

Table 4.36: "Business as Usual" research methodology assumptions ... 129

Table 4.37: "Business as Usual" GHG emissions avoided - paper ... 130

Table 4.38: "Business as Usual" energy savings – paper ... 131

Table 4.39: "Business as Usual" wages impact – paper ... 132

Table 4.40: "Business as Usual" GHG emissions avoided - food waste ... 133

Table 4.41: "Business as Usual" energy savings – food waste ... 134

Table 4.42: "Business as Usual" wages impact – food waste ... 135

Table 4.43: "Business as Usual" GHG emissions avoided – yard trimmings ... 136

Table 4.44: "Business as Usual" energy savings – yard trimmings ... 137

Table 4.45: “Business as Usual” wages impact – yard trimmings 138

Table 4.46: “Business as Usual” GHG emissions avoided – mixed plastics............................. 139

Table 4.47: “Business as Usual” energy savings – mixed plastics.. 141

Table 4.48: “Business as Usual” wages impact – mixed plastics... 142

Table 4.49: “Business as Usual” GHG emissions avoided – mixed electronics 143

Table 4.51: “Business as Usual” wages impact – electronics... 145

Table 4.52: “Business as Usual” GHG emissions avoided – metals 146

Table 4.53: “Business as Usual” energy savings – metals.. 148

Table 4.54: “Business as Usual” wages impact – metals.. 149

Table 4.55: “Business as Usual” GHG emissions avoided – glass.. 150

Table 4.56: “Business as Usual” energy savings – glass 151

Table 4.57: “Business as Usual” wages impact – glass 152

Table 4.58: “Business as Usual” GHG emissions avoided – carpet 153

Table 4.59: “Business as Usual” energy savings – carpet 154

Table 4.60: “Business as Usual” wages impact – carpet 155

Table 4.61: “Business as Usual” GHG emissions avoided – tires... 156

Table 4.62: “Business as Usual” energy savings – tires... 157

Table 4.63: “Business as Usual” wages impact – tires 158

Table 4.64: “Business as Usual” GHG emissions avoided – mixed MSW 159

Table 4.65: “Business as Usual” energy savings – mixed MSW 160

Table 4.66: “Business as Usual” wages impact – mixed MSW 161

Table 4.67: Summary of GHG emissions for the “Business as Usual” case 162

Table 4.68: Summary of energy savings for the “Business as Usual” case............................... 163

Table 4.69: Summary of the wage impact for the “Business as Usual” case 163

Table 4.70: “Business as Usual” full generation GHG emissions avoided 164

Table 4.71: “Business as Usual” full generation energy savings.. 166

Table 4.72: “Business as Usual” full generation - wages impact 167

Table 4.73: Summary of “Business as Usual” full generation case... 168

Table 4.74: Practical research methodology assumptions 169

Table 4.75: Practical model – emissions avoided.. 171

Table 4.76: Practical research – energy savings 172

Table 4.77: Practical model - wages impact 174

Table 4.78: Practical model - summary 175

Table 4.79: Montgomery County Landfill waste acceptance per year 176

Table 5.1: Theoretical MSW treatment by material for maximum emissions avoided 188

Table 5.2: Theoretical MSW treatment by material for maximum energy savings................... 196

Table 5.3: Comparison of modeling results.. 200

LIST OF EQUATIONS

Equation 1.1 6

Equation 1.2 7

Equation 1.3 27

Equation 1.4 27

Equation 2.1 51

Equation 2.2 53

Equation 3.1 76

Equation 3.2 76

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my professor and chair of my committee, Dr. Michael Mann, for his immeasurable and invaluable guidance, patience, and support throughout my journey in the Ph.D. program. I would also like to express my sincere appreciation to Dr. Soizik Laguette, Dr. Olusegun Tomomewo, and Dr. Taufique Mahmood for your valuable advice and knowledge that you have shared during this dissertation and coursework. A heartfelt thanks to my family, especially you Nicole, and friends for hanging with me throughout this endeavor. Finally, to my wife, Erika, and my daughters, Teagan and Brinley: your love, patience, and understanding, helped me from the beginning to the completion of the program. Having the three of you on this journey made it that much better of an experience.

To my mother, Mable Richburg, in loving memory.

ABSTRACT

The population of the planet surpassed the 8-billion-person mark in 2022, and the increase in population has brought about an increase in waste, both household and commercial. The municipal solid waste that is created is primarily stored in landfills, particularly in the United States. These landfills release methane and carbon dioxide into the atmosphere, creating what is known as anthropogenic emissions, due to their being caused by man-made issues. These two primary gases, along with others, make up greenhouse gases, and their reduction is key to potentially reducing or even reversing the greenhouse effect.

Total municipal solid waste generation in the United States reached 292.4 million tons in 2018, which was an increase from the 268.7 million tons in 2017. Of the 292.4 million tons in 2018, over 146 million tons were sent to landfills, over 69 million tons were recycled, and 34 million tons were combusted for energy. The large amount of waste sent to landfills creates a significant opportunity to avoid emissions, increase energy savings, produce energy through renewable energy, and create wage impacts, or employment, by way of recycling.

The opportunity to study the avoidance of emissions, energy savings, and wage or employment impact, comes from a life-cycle analysis of the municipal solid waste. The studying of potential energy production will come from the emissions generated by the landfill over its lifespan. This dissertation will address both life-cycle analysis and landfill gas generation in the form of modeling. The life-cycle analysis will utilize an EPA model called the Waste Reduction Model (WARM), which takes a cradle-to-grave approach and analyzes alternatives to the current

waste management methodology. The Landfill Gas Emissions Model (LandGEM) provides an estimation of the gases from the municipal solid waste landfill, which will then be utilized to provide an energy potential estimate. The dissertation will evaluate the models with the primary goal of producing a practical option or strategy to simulate the largest quantity of emissions avoided, the largest possible energy savings, and greatest renewable energy potential.

CHAPTER ONE: INTRODUCTION

1.1 Background

The population of the planet in 2022 reached just over 8 billion people (Figure 1.1), and with this comes the need to have in place the massive infrastructure to feed, house employ, and energize economies.

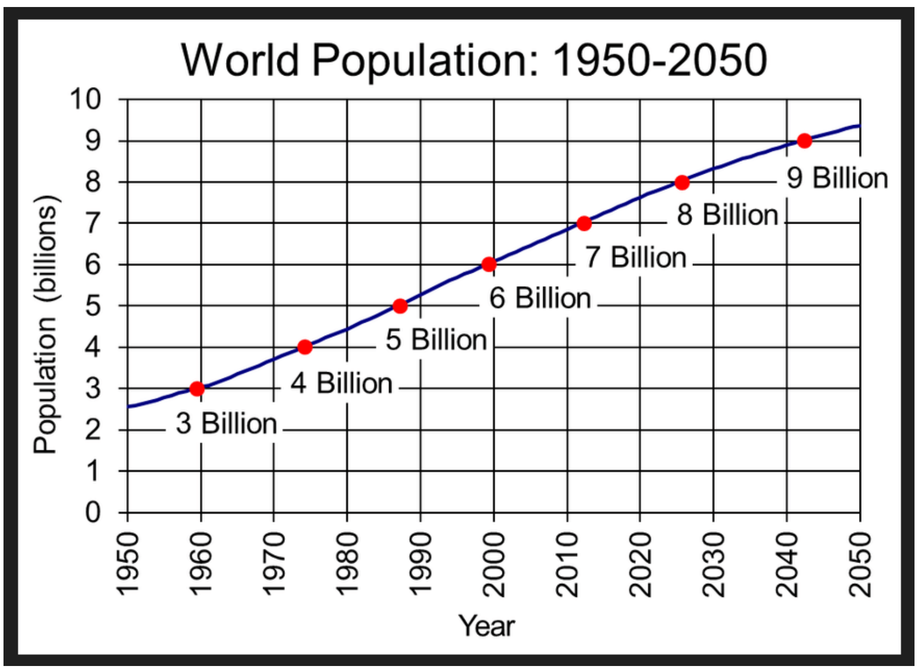


Figure 1.1: World population 1950 through 2050 (Researchgate.net, 2023)

The current trajectory is not positive. One such issue of note is the invasion of Ukraine by Russian forces, which prompted Russian gas supply to Europe to be restricted, causing mounting worries of low supply and rising prices. Alternative energy sources are being pursued but are currently insufficient to meet needs. With the lack of alternative sources to meet current supply, European countries are building coal fired plants to replace low natural gas supplies and pursuing new fossil-fuel sources. Worldwide gasoline costs are rising, producing wide-spread dismay about the economic cost. These current challenges are overshadowing worldwide efforts to cut fossil-fuel use and reduce greenhouse gas (GHG) emissions, which are the steps that are urgently needed to limit warming to 1.5 °C (Alavosius et al., 2022).

There is an extensive amount of evidence indicating that the earth's climate has warmed during the past century as shown in Table 1.1. Foremost among this evidence are compilations of the variation in global mean sea surface temperature and in surface air temperature over land and sea (Wuebbles & Jain, 2001). Climatologists believe that increasing atmospheric concentration of carbon dioxide and other "greenhouse gases" released by human activities, such as burning of fossil fuels and deforestation, are warming the Earth. The mechanism, commonly known as the "greenhouse effect", is what makes the Earth habitable. Figure 1.2 shows how gases in the atmosphere act like the glass of a greenhouse, letting the sunlight in and preventing heat from escaping. But human activities have altered the chemical composition of the atmosphere through the buildup of greenhouse gases-primarily carbon dioxide, methane, and nitrous oxide (Ranveer et al., 2015).

Table 1.1: Summary of trends in observed climatic variables (Wuebbles & Jain, 2001)

Variable	Analysis period	Trend or change
Surface air temperature and SST	1851–1995	0.65±0.15°C
Alpine glaciers	Last century	Implies warming of 0.6–1.0°C in alpine regions
Extent of snowcover in the NH	1972–1992	10% decrease in annual mean
Extent of sea ice in the NH	1973–1994	Downward since 1977
Extent of sea ice in the SH	1973–1994	No change, possible decrease between mid 1950s and early 1970s
Length of the NH growing season	1981–1991	12±4 days longer
Precipitation	1900–1994	Generally increasing outside tropics, decreasing in Sahel
Heavy precipitation	1910–1990	Growing in importance
Antarctic snowfall	Recent decades	5–20% increase
Global mean sea level	Last century	1.8±0.7 mm/year

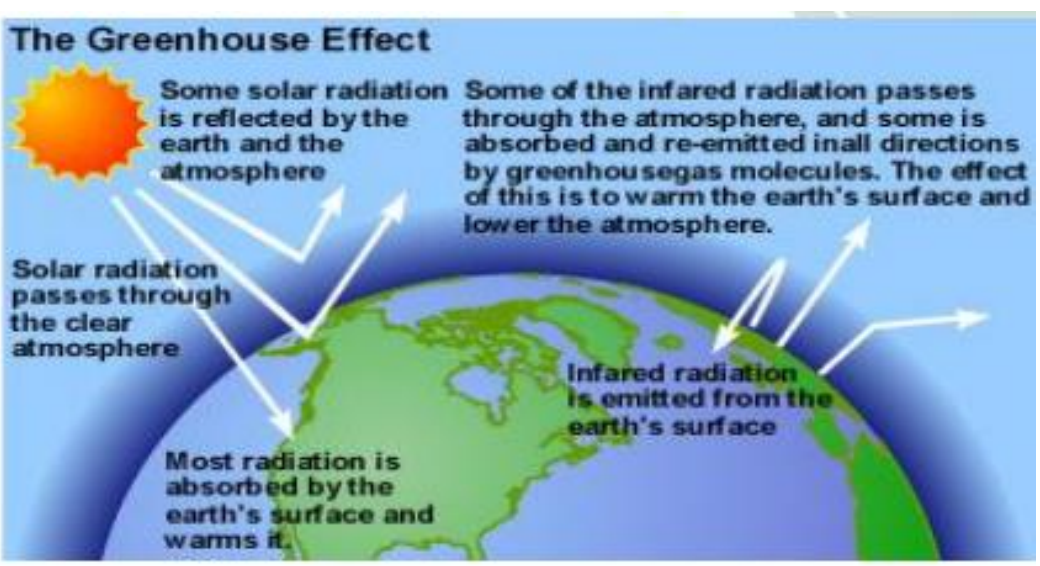


Figure 1.2: The Greenhouse Effect (Ranveer et al., 2015).

1.2 What is Climate Change and Global Warming

The terms "climate change" and "global warming" have often been used interchangeably, referring to what is taking place with conditions around the world. However, these terms have two distinct meanings. NASA defines climate change as "long-term change in the average weather patterns that have come to define Earth's local, regional, and global climates" (NASA, n.d.). The observed changes that have been tracked since the mid-20th century are primarily influenced by human activities, which primarily arise from the burning of fossil fuels. NASA then defines global warming as the "long-term heating of Earth's surface observed since the pre-industrial period (between 1850 and 1900) due to human activities, primarily fossil fuel burning, which increases heat-trapping greenhouse gas levels in Earth's atmosphere (NASA, n.d.).

The atmosphere of the earth is made up of three main gases, nitrogen, oxygen, and argon. There are other gases in smaller quantities, including both greenhouse gases (GHGs) and pollutants as shown in Table 1.2. The permanent gases (nitrogen, oxygen, argon) percentage does not change, but the trace gas percentage (carbon dioxide, methane, nitrous oxides, and ozone) will change daily, seasonally, and annually. GHGs can absorb and reradiate infrared radiation (Al-Ghussain, 2019).

Over the last fifty years, computer models have simulated the Earth's climate. These simulations have predicted that the concentration of greenhouse gases has been increasing, thereby this increase would cause a warming of the Earth's surface. This data revealed that in the 1980s, the cooling trend that was taking place reversed. Because the warming trend might have naturally occurred, the term or theory distinguishing naturally occurring warming from that caused by man-made is termed "Anthropogenic Global Warming" or AGW (Connolly et al., 2020).

Table 1.2: Gas content of the earth's atmosphere (Al-Ghussain, 2019).

Gas name	Percentage (%)
Nitrogen	78
Oxygen	21
Argon	0.9
Carbon dioxide	0.0935
Neon	0.004675
Helium	0.001299
Methane	0.000442
Nitrous oxide	0.000078
Ozone	0.00001

In 2007, the Intergovernmental Panel on Climate Change (IPCC) released a report, their Fourth Assessment, stating that the global surface temperature has increased 0.74 ± 0.18 °C between 1901 and 2000. With this increase, many non-normal activities have taken place to include climate change, rising sea levels, glacier retreat, and disappearing islands (S. Kumar et al., 2012).

1.3 The Connectivity of Greenhouse Gases and Anthropogenic Global Warming

The first connection of the greenhouse theory seems to have come from the French physicist Jean Fourier, who in the early 1800s, believed that the atmosphere of the earth acts like a greenhouse by letting sunlight in, while blocking radiant heat from escaping back into space (Mintzer, 1990). However, it was the Swedish scientist Svante Arrhenius that began to quantify how carbon dioxide (CO_2) played a significant part in the heating and cooling of the earth.

Arrhenius believed that industrialization, or the burning of fossil fuels over a lengthy time period would cause a doubling of CO_2 (Anderson et al., 2016). There were many other scientists that contributed to the study of how CO_2 and other gases were possibly contributing to the increases in global warming, but by the early 1980s, a cohesive principle thought regarding AGW was in place. The idea that the trace gases, methane (CH_4), nitrates, ozone, and other gases emitted from industry and other sources, contributed significantly to AGW. It was also revealed that methane (CH_4) had a 20 times higher greenhouse effect than CO_2, which means that one ton of methane will absorb 20 times the amount of energy than CO_2 over a given time period (Weart, 2010).

Even though the trace gases are significant contributors to AGW, many scientists and engineers consider anthropogenic CO_2 emissions as the driving force behind AGW. But they also believe that natural processes contribute to global warming as well (Florides & Christodoulides, 2009). The scientific community can believe that this is a two-step process. First, the greenhouse effect takes place by trapping radiant heat in, thereby creating the climate change effect. Secondly, with the release of gases into the atmosphere, then the trapping of those gases, we then see the long-term effects of these systems to cause a warming of the planet. One researcher believes that there are three contributors or causes to the climate change/global warming problem. The first problem is the production of methane and CO_2 contributing to greenhouse gases, seen in equations 1.1 and 1.2, the second problem is the contribution from nature, and the third problem comes from human contributions (Rajak, 2021).

Combustion of fossil fuels:

$$6\ O_2 + C_6H_{12}O_6 \text{ ----------> } 6\ H_2O + 6\ CO_2 + \text{energy} \qquad \textit{Equation 1.1}$$

Production of methane during microbial metabolic process:

CH_3COOH -----------> $CO_2 + CH_4$ *Equation 1.2*

1.4 Greenhouse Gas Reduction Efforts

With global warming being a hotbed issue around the world, there have been many attempts to reduce global warming through global initiatives. The calls for action began with the Toronto Conference on the Changing Atmosphere in June 1988, which concluded that atmosphere change is a result of human negligence (Morrisette, 1991). Although some of the first calls to action began in the 1970s, the 1987 Montreal Protocol on Substances the Deplete the Ozone Layer, organized by the United Nations, was the first multilateral environmental agreement to achieve universal ratification. This purpose of this agreement was to prevent uncontrolled global depletion of the stratospheric ozone layer and associated large increases in surface UV-B radiation (Barnes et al., 2019).

With the signing of the Montreal Protocol and its ratification in 1989, which was accepted worldwide by most countries, substances such as chlorofluorocarbons (CFCs) and bromine containing halons have been mostly phased out of use. The result from the agreement has been a detected increase in the concentration of stratospheric ozone in the upper stratosphere and above Antarctica. Figure 1.3 shows how halogenated source gases affect the stratospheric ozone (Chipperfield et al., 2020).

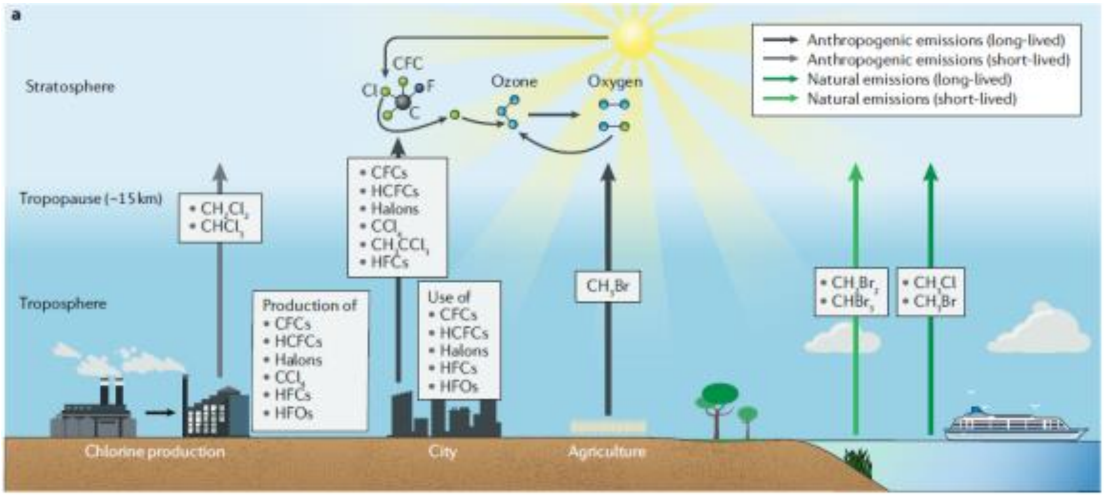


Figure 1.3: Halogenated source gases and their impact on stratospheric ozone (Chipperfield et al., 2020)

While the Montreal Protocol (1987) was a significant step in the fight to combat climate change, a new institution was formed in 1992 called the United Nations Framework Convention on Climate Change (UNFCCC) (Oh, 2022). This convention includes 196 countries and the European Union (EU) and it attempts to come to decisions by a consensus of its members. The convention entered into force in 1994 and one year later, in 1995, the authoritative body, called the Conference of the Parties (COP), first met (Kuyper et al., 2018). So not to jeopardize the global climate, the goal of the UNFCCC is to stabilize GHG concentrations to a certain level. The Montreal Protocol does not control all greenhouse gases, so members of UNFCCC must develop, update periodically, and publish national inventories of anthropogenic emissions. They must then make these available to the COP (Khalida, 2018).

Between the creation of the UNFCCC in 1992 and 1995, greenhouse gas emissions levels continued to increase worldwide, which made it clear that a solid commitment must be made by the governments of developed countries that action on climate change must be taken. This action must also be able to convince industries and the public to also act (Gupta, 2016). On December

11, 1997, the Kyoto Protocol (KP) was introduced by the UNFCCC in Kyoto, Japan, and it was the first protocol to be added to the UNFCCC of 1992. This protocol introduced legally binding targets and it also added targets to reduce greenhouse gas emissions (Leggett, 1998). The goal of the Kyoto Protocol was to install an international system that would reduce emission levels for six greenhouse gases; CO_2, CH_4, N_2O, hydrofluorocarbons (HFC), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) (Mirasgedis et al., 2002). The primary requirement of the KP was to require the industrialized nations that signed the agreement, to show that they would have made progress towards a 5-percent decrease in GHG emissions from the 1990 levels. Figure 1.4 shows the global GHG emissions level in 1990 for the six greenhouse gases to be reduced. This progress would have to be displayed by 2005, and the final target by 2012 (Prins & Rayner, 2008).

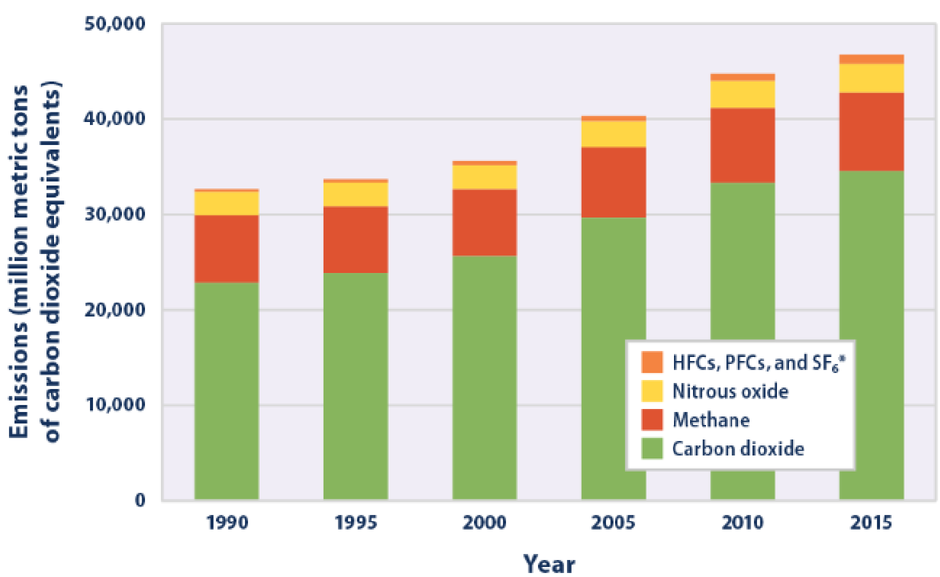


Figure 1.4: Global greenhouse gas emissions since 1990. (US EPA, 2016d)

When the KP was signed by 37 countries and the EU, this group was called the Annex I countries as shown in Table 1.3. These countries were a representation of the industrialized world in the 1990s (Almer & Winkler, 2017). When the KP was signed, countries such as China and India, were not required to reduce emission levels as they were developing nations. Also, the George W. Bush administration refused to meet the KP requirement due to three reasons which were: 1) the science behind climate change was not a certain science; 2) US competitiveness might be weakened by mandatory reduction targets; and 3) China and India should be involved in the negotiations. The KP was fully placed into force on February 16, 2005, after Russia's signing of it in October of 2004 (X. Li & Lin, 2013).

Table 1.3: Annex I countries from Kyoto Protocol (Huang et al., 2008)

Annex II Parties		Economies in Transition, EIT		Others
Australia	AUS	Belarus	BLR	Liechtenstein
Austria	AUT	Bulgaria	BGR	Monaco
Belgium	BEL	Croatia	HRV	Turkey
Canada	CAN	Czech Republic	CSK	
Denmark	DNK	Estonia	EST	
Finland	FIN	Hungary	HUN	
France	FRA	Latvia	LVA	
Germany	DEU	Lithuania	LTU	
Greece	GRC	Poland	POL	
Iceland	ISL	Romania	ROM	
Ireland	IRL	Russia	RUS	
Italy	ITA	Slovak Republic	SVK	
Japan	JPN	Slovenia	SVN	
Luxembourg	LUX	Ukraine	UKR	
Netherlands	NLD			
New Zealand	NZL			
Norway	NOR			
Portugal	PRT			
Spain	ESP			
Sweden	SWE			
Switzerland	CHE			
United Kingdom	UK			
United States	USA			

One major question that can be asked is “what have the results been from the initiation of these agreements, particularly the Kyoto Protocol?” In 2011, approximately six years after the KP was put into force, Canada, Japan, and Russia withdrew from their commitments to the protocol. One major issue that stands out is that while Canada was committed to keeping its GHG emissions to 6% below 1990 levels (see figure 1.5), the country emitted 17% higher levels in 2012 which causes penalties and a withdrawal of Canada from the KP (Nanda et al., 2016).

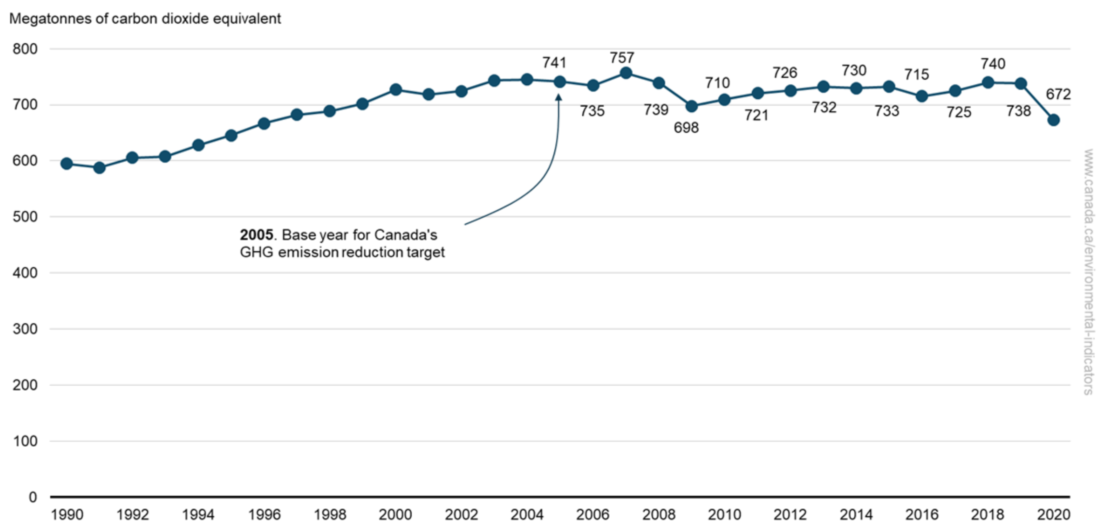


Figure 1.5: GHG emissions for Canada, 1990 – 2020 (Canada, 2007)

As there is a collective belief that the Kyoto Protocol is deemed as failing or failed, a new effort was created to reduce global emission levels, to keep the global temperature from increasing, and thereby contributing to the growing climate change issue. On December 12, 2015, a new agreement called the "Paris Agreement", was approved by 196 Parties at the COP 21 in Paris, France. The agreement was initiated on November 4, 2016. The main goal of the agreement is to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels" and engage in efforts "to limit the temperature increase to 1.5 °C above pre-industrial levels" (*The Paris Agreement | UNFCCC*, n.d.). These GHG levels are to reach a net zero level during the second half of the 21st Century. If the temperature is limited to the 1.5 °C level, there has been a recommendation that the net zero goal must be reached by earlier period of 2030-2050 (Rhodes, 2016). To secure an adoption of the Paris Agreement, items called Nationally Determined Contributions (NDCs) were utilized. These NDCs apply to each signatory and feature three key parts: 1) basically each country that is a part of the UNFCCC has submitted an NDC; 2) the NDC gives a country flexibility to adapt their goals to their particular circumstances and priorities; 3) the Paris Agreement "creates five-year cycles of review and updating that are designed to ensure that NDCs become more ambitious over time" (Pauw et al., 2020).

Since the inception of the Paris Agreement at COP 21, the Conference of Parties have held yearly meetings except for 2020 due to COVID-19, and at these meetings new policies have emerged to attempt to strengthen the emission reducing measures from COP 21. Table 1.4 summarizes the global initiatives undertaken since COP21 (Paris Agreement).

Table 1.4: COP Meetings since the Paris Agreement

Location	Session	Focal Issue
Sharm el-Sheikh, Egypt	COP 27	Effort to boost low emissions energy; increased funding to low income nations for GHG emission reduction
Glasgow, United Kingdom of Great Britain and Northern Ireland	COP 26	Glasgow Climate Pact to reaffirm the Paris Agreement; plan to reduce coal power; focus on the 1.5 °C limit
Madrid, Spain	COP25	Rules for a carbon market and other international agreements
Katowice, Poland	COP 24	Rules to implement the Paris Agreement, to come into effect in 2020
Bonn, Germany	COP 23	First meeting after US withdrawal; outline steps for Paris Agreement
Marrakech, Morocco	COP 22	First meeting of parties to Paris Agreement; Water scarcity, water

		cleanliness, water-related sustainability

COP 28 will take place November 30 through December 12, 2023, in Expo City, Dubai.

1.5 Movement to Net-Zero Emissions

After the signing of the Paris Agreement, countries needed to begin implementing strategies to reduce emissions to achieve a net-zero goal. Over the last few decades, there have been frequent weather events that have reached extreme levels. The Intergovernmental Panel on Climate Change (IPCC) has argued that with the temperature rise having reached 1 °C by 2017 and the prediction is that the 1.5 °C level will be reached between 2030 and 2052. If the 1.5 °C level is surpassed, then we will possibly incur damage to our natural and human systems (Wimbadi & Djalante, 2020).

The movement to a net-zero emissions comes in many forms, however the main driver in reducing emissions is through the reduction of fossil fuel burning. The powering of a country's economy would come by using clean energy. However, there are still many factors to consider if the goal of net-zero will be reached. One factor in reaching net-zero emissions is the opposite path that takes place between developed countries and those that are still developing. Developed countries will see a decrease in CO_2 emissions between 2020 and 2050, while due to an energy increase demand, developing countries will see an increase in CO_2 emissions (Khalifa et al., 2022).

Outside of the fossil fuel burning issue, landfills pose a significant issue regarding GHG emissions issues and the move to curb global emissions. Municipal solid waste (MSW) has been disposed of in primarily two ways - burning or placing it in a dumpsite. As the global population increased significantly in the 20th century in addition to waste generation per capita, MSW generation increased proportionally. With this increase, landfills began to contribute greatly to anthropogenic climate change and now account for approximately 5% of GHG emissions (Zhang et al., 2019). As the global population was increasing, the main issues with landfills were public health and safety issues. In addition to this, landfill gas capture and utilization was also important (Lou & Nair, 2009).

1.6 Current Emissions Issues

It is projected that through the year 2050, global emissions of CO_2 from energy related sources will continue to increase (see Figure 1.6), thereby contributing to the issue of global warming and climate change.

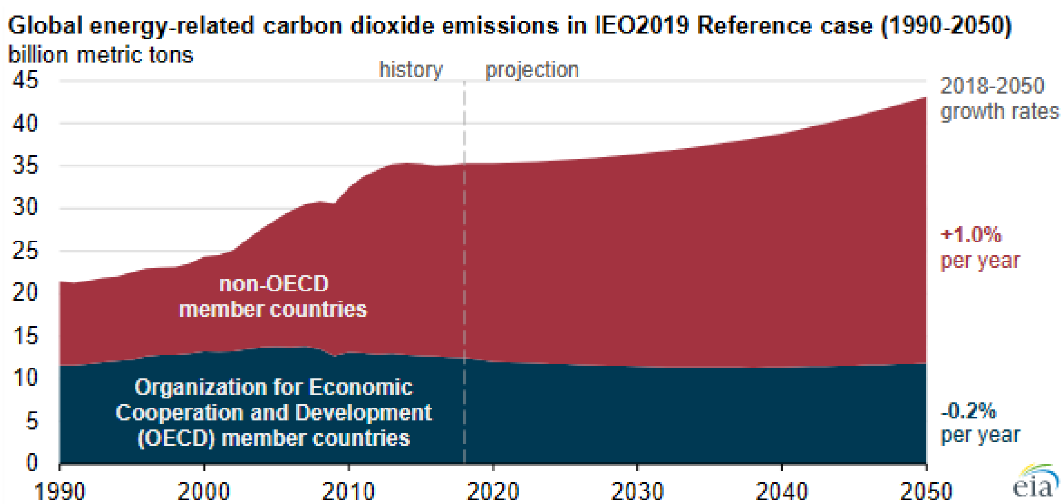


Figure 1.6: Global energy-related CO_2 emissions through 2050 (EIA Projects Global Energy-Related CO2 Emissions Will Increase through 2050, n.d.)

Data has shown that industrially developed countries have produced the majority of GHGs, but over the last ten to fifteen years, developing countries have exceeded the GHG emissions output of developed countries. Much of the energy-related emissions increase has been seen in countries such as China and India, and in regions such as Asia, Africa, and the Middle East (Shahsavari & Akbari, 2018). Historical data and current projections in Table 1.5, show that energy-related CO_2 emissions worldwide increase by 1.3% a year from 2007 through 2035. This increase is primarily from developing countries, however on a per capita basis, the emissions are lower in these developing countries compared to developed countries as shown in Table 1.6 (Ahiduzzaman & Islam, 2011).

Table 1.5: Carbon dioxide emission in the World by region (1990-2035) (Ahiduzzaman & Islam, 2011) the numbers are in billion tonne

Region	History		Projections					Average annual percentage change	
	1990	2007	2015	2020	2025	2030	2035	1990–2007	2007–2035
OECD countries	11.5	13.7	13.0	13.1	13.5	13.8	14.2	1.0	0.1
North America	5.8	7.0	6.7	6.9	7.2	7.4	7.7	1.1	0.3
Western Europe	4.2	4.4	4.1	4.0	4.0	4.1	4.1	0.3	−0.2
Asia	1.6	2.3	2.1	2.2	2.3	2.3	2.4	2.1	0.2
Non-OECD countries	10.0	16.0	18.5	20.7	23.0	25.5	28.2	2.8	2.0
Europe and Eurasia	4.2	2.9	2.9	2.9	3.0	3.0	3.2	−2.2	0.3
Asia	3.7	9.4	11.2	13.0	14.9	16.9	19.0	5.7	2.5
Middle East	0.7	1.5	1.9	2.1	2.3	2.5	2.7	4.6	2.1
Africa	0.7	1.0	1.2	1.2	1.3	1.5	1.6	2.6	1.7
Central and South America	0.7	1.2	1.3	1.4	1.5	1.6	1.7	3.1	1.4
Total World	21.5	29.7	31.5	33.8	36.5	39.3	42.4	1.9	1.3

Table 1.6: Carbon dioxide emission per capita in the World by region (1990 – 2035) (Ahiduzzaman & Islam, 2011) the numbers are in tonne per person

Region	History		Projections					Average annual percentage change	
	1990	2007	2015	2020	2025	2030	2035	1990–2007	2007–2035
OECD countries	11.0	11.6	10.5	10.4	10.4	10.5	10.6	0.3	−0.3
North America	16.0	15.8	14.1	13.8	13.7	13.6	13.5	−0.1	−0.6
United States	20.0	19.8	17.5	17.1	16.8	16.5	16.2	−0.1	−0.7
Canada	17.0	17.8	15.4	14.7	14.6	14.7	14.8	0.3	−0.7
Mexico	3.6	4.1	3.9	4.2	4.5	4.9	5.5	0.8	1.0
Western Europe	8.4	8.1	7.4	7.2	7.1	7.1	7.1	−0.2	−0.5
Asia	8.5	11.4	10.6	10.9	11.3	11.7	12.2	1.7	0.2
Non-OECD countries	2.4	2.9	3.1	3.3	3.5	3.7	4.0	1.3	1.1
Europe and Eurasia	12.3	8.5	8.5	8.7	8.9	9.3	9.8	−2.1	0.5
Asia	1.3	2.7	2.9	3.2	3.6	3.9	4.3	4.2	1.7
Middle East	5.2	7.5	8.4	8.5	8.5	8.5	8.8	2.2	0.6
Africa	1.0	1.0	1.1	1.0	1.0	1.0	1.1	0.1	0.1
Central and South America	1.9	2.5	2.6	2.6	2.7	2.8	2.9	1.6	0.4
Total World	4.1	4.5	4.3	4.4	4.6	4.8	5.0	0.5	0.4

The IPCC has divided global GHG sources into five categories: 1) energy systems; 2) industry; 3) buildings; 4) transport; and 5) AFOLU (agriculture, forestry, and other land uses). (Lamb et al., 2021). The emissions trends of the five categories at the global level are displayed in Figure 1.7 and Figure 1.8 displays the emissions levels at the regional level.

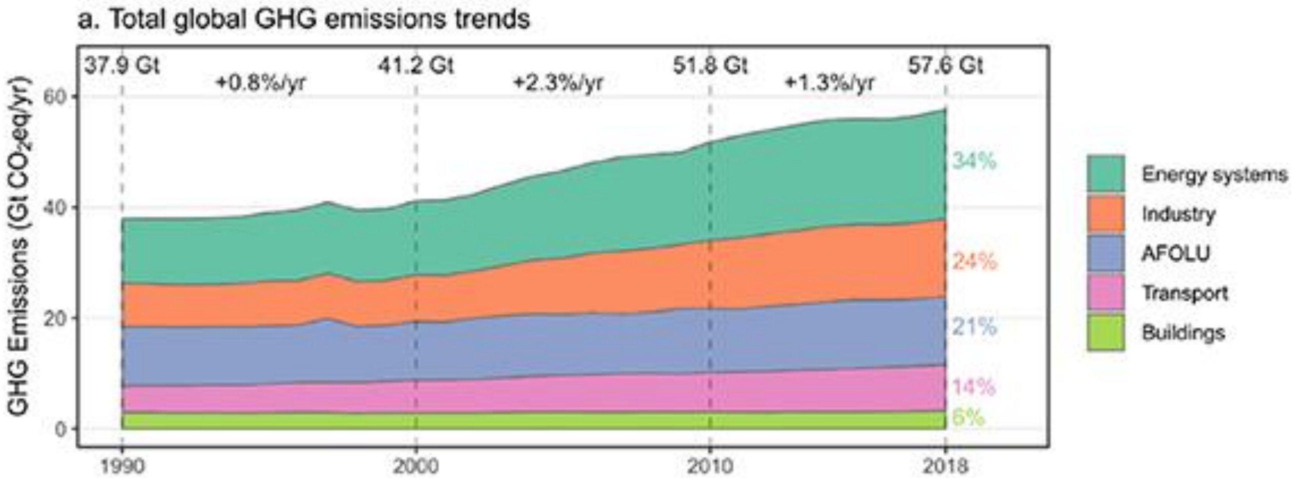


Figure 1.7: Total global GHG emissions trends (Lamb et al., 2021)

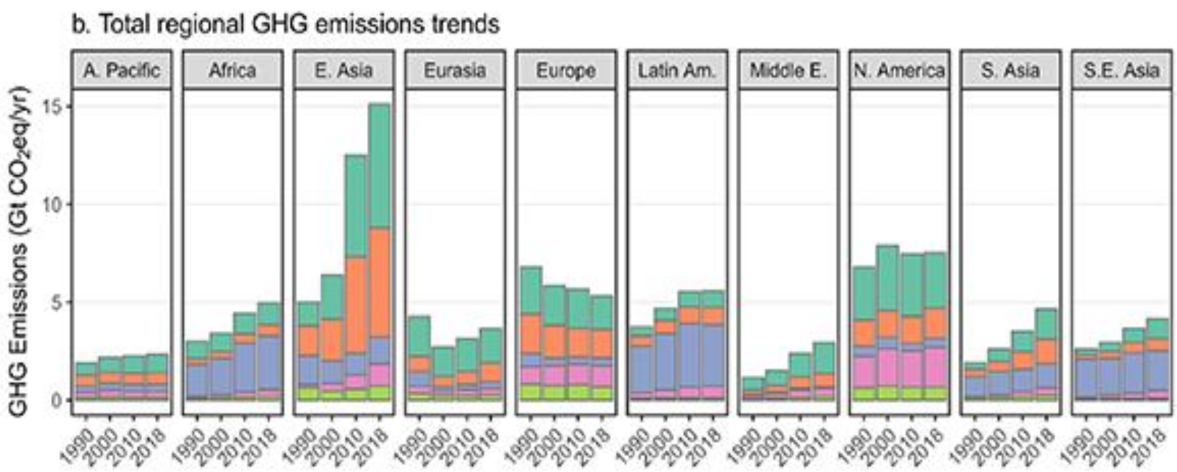


Figure 1.8: Total regional GHG emissions trends (Lamb et al., 2021)

In 2016, approximately 49.4 billion tonnes of GHGs were emitted into the atmosphere compared to 49.8 billion tonnes in 2019 (Ritchie et al., 2020) (Ge et al., 2020). Of the 49.4 and 49.8 billion tonnes respectively, the emissions are divided up amongst energy systems, areas that utilize energy, and AFOLU. Also included in those areas is waste, which is the focus of this research and dissertation. Figure 1.9 displays the areas that GHG emissions were emitted from.

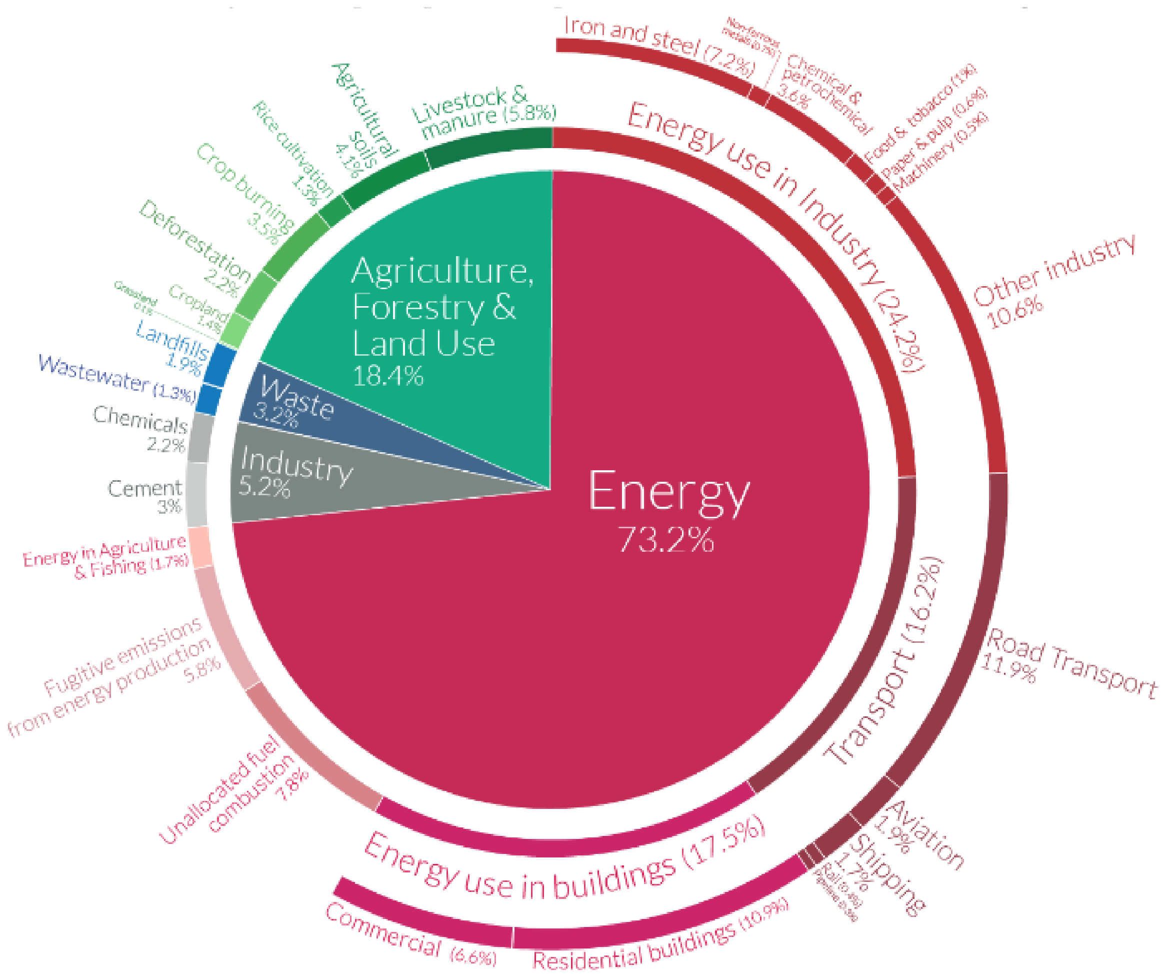


Figure 1.9: Global greenhouse gas emissions by sector, 2016 (Ritchie et al., 2020)

The energy sector is the major contributor to GHG emissions. In 2016 the energy sector contributed 73% of GHG emissions. This area is then sub-divided into segments to include energy use in industry, transport, energy use in buildings, and others. The subsection of energy use in buildings encompassed 17.5% of the emissions in the energy sector. Increasing the usage of information and communication technology (ICT) could possibly reduce GHG emissions. Use of ICT reduced electrical consumption by 49% and 13% between the companies and increased use of ICT could possibly reduce GHGs by 9.1 $GtCO_2e$ (Minter, 2013).

Energy use in industry accounted for 24.2% of the energy sector. The use of electricity in the production of materials and goods is the largest source of GHG emissions. One such activity within energy use is emissions related to chemicals and petrochemicals. Fertilizer production, or the phosphate industry, has experienced a significant rate of expansion, which in turn has had a negative impact on the global ecosystem. Like other industries, decarbonation and the move to renewable energy within facilities will assist with reducing emissions. Also, the implementation of programs to increase energy efficiency, optimization of energy consumption, and technology improvements, will move the industry towards low or net-zero emissions (Ouikhalfan et al., 2022). Recycling also provides a method of reducing energy demands and the production of GHG emissions.

Transportation is another section within energy use that contributes significantly to global GHG emissions. The transportation sector accounts for 16.2% of GHG emissions worldwide. To reduce emissions within the transportation sector, three ideas have been proposed: 1) improve engine efficiency; 2) introduction of low carbon fuels; and 3) reduce vehicular miles traveled. Also, policy and regulations are believed to be options that can help reduce GHG emissions. Examples of policy and regulatory alternatives are cap and trade, a carbon tax, low carbon fuel standards, renewable fuel standards, and CAFE (Corporate Average Fuel Economy) standards (Andress et al., 2011). Although road transportation is the largest contributor to GHG emissions in the transportation sector, other transportation modes such as aviation, marine, and rail contribute to emissions, but in smaller quantities. Railway transportation is recognized as green transportation and is considered one of the healthiest form of transportation for the environment

(Aminzadegan et al., 2022). Marine shipping has advantages over other shipping methods, however high GHG emissions come from this transportation form, primarily in ports and coastal areas. The use of heavy fuel oil (HFO), which is the lowest grade oil produced, produces high emissions. The alternative of renewable fuels is becoming increasingly available at a commercial level to assist in reducing emissions (Ni et al., 2020).

The AFOLU sector contributed 18.4% of GHG emissions in 2016 which include livestock, agricultural soils, deforestation, and crop burning. The agriculture sector produces a large quantity of emissions worldwide. These emissions are at every step of production, beginning with soil preparation, seed planting, harvesting, storage, and distribution (Gołasa et al., 2021). Figure 1.10 shows the connection between agriculture, emissions, and climate change while Figure 1.11 shows the output of GHG emissions from energy inputs and its products during the full crop cycle. Energy efficiency is crucial at every step of agriculture production to reduce GHG emissions even though the requirement of energy is lower for agriculture compared to manufacturing and other production sectors (Alluvione et al., 2011).

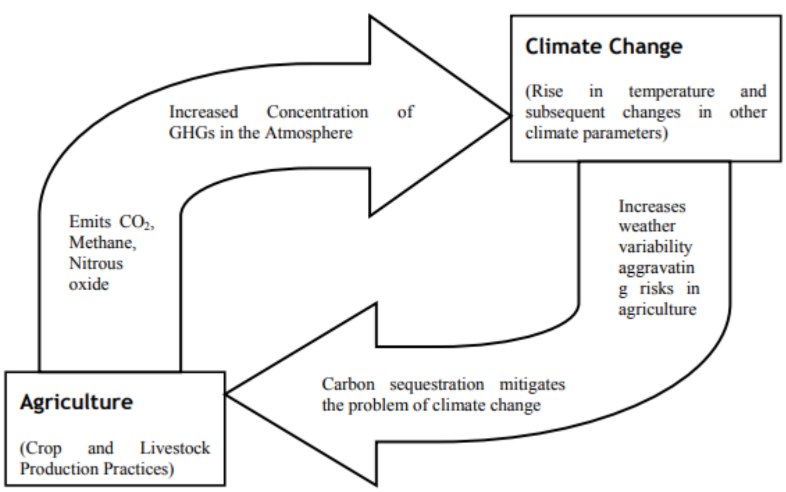


Figure 1.10: Inter-linkages between agriculture and climate change (Pant, 2009)

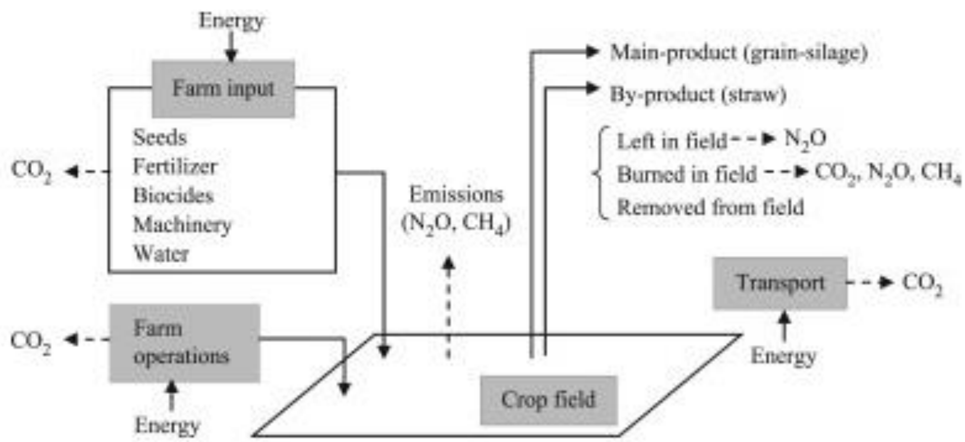


Figure 1.11: Energy inputs, greenhouse gas emissions, and products during crop cultivation (Mohammadi et al., 2014)

The main sources of emissions from agriculture come from enteric fermentation, soil and manure management, and consumption of fossil fuels. Nitrogenous fertilizer use has increased the emissions of N_2O in the agricultural sector (Pant, 2009). The U.S. EPA reported that CO_2, CH_4, and N_2O are the primary gases of concern as it relates to agriculture. Research shows that enteric fermentation at 21% and manure management at 8% are the greatest contributors to CH_4 emissions. Rice paddies and agricultural burning provides small contributions to CH_4 emissions (Johnson et al., 2007). As it relates to other sectors of greenhouse gas emissions, agriculture is different because it is both an emitter of GHGs and it serves as a sink. In the fight against GHG emissions, agriculture can operate from the supply side and demand side. In its operation from the supply side to mitigate emissions, this can occur with items such as crop rotation, improving nutrients, improving manure management, and water management. From the demand side, opportunities such as carbon sequestering, bio-energy crops, and reducing food waste can mitigate emissions (Pathak, 2015).

Deforestation, particularly across the tropics, is a large source of GHG emissions accounting for approximately 2.6 gigatonnes of CO_2 emissions per year (Pendrill et al., 2019). Although deforestation and forest degradation make up 2.2% of AFOLU emissions, the 4-5 million hectares (ha) of forest that is lost per year causes the percentage to be viewed much higher. The largest deforestation rate, approximately 50%, takes place in two countries, Indonesia and Brazil, approximately 700,000 ha and 2 million ha respectively (Meijer, 2015). There are many underlying drivers as it relates to deforestation and the emissions that are produced. Those drivers have been documented ranging from single postulate to complex models as shown in Figure 1.12 (Goers et al., 2009).

Socioeconomic Factors	Institutional Factors	Economic Factors
• Population Growth • Urbanization • Poverty and Economic Inequalities • Transportation Infrastructure • Agricultural Technology	• Property Rights and Land Tenure • Governance Regulatory Enforcement, Corruption, and Political Stability	• International Trade and Economic Integration • National Economic Policy • Household and Local Economies • Household-Level Decision Making

Figure 1.12: Drivers of deforestation for agriculture (Goers et al., 2009)

As the demand for food continues to increase, particularly in developing countries, food production has increased which has also led to increased GHGs and other pollutants. In countries such as India, which accounts for 17% of the world's population, to continue to quickly turnover fields for crop production, crop burning or paddy burning has become frequent, which has also led to copious environmental problems to include GHG emissions and raised levels of particulate matter (PM) (Bhuvaneshwari et al., 2019). Rice is an important agricultural product in countries such as Egypt, China, India, and Thailand. It is estimated by the IPCC in its 2007 report that paddy fields had an annual global emission rate of 60 Tg/yr of CH_4. This burning also emits CO_2, N_2O, CO, and PM (Radwan, 2013).

In the 2016 data report of worldwide GHG emissions, waste made up 3.2% of global GHG emissions. This was primarily between two sources, wastewater, and landfills. Wastewater was 1.3% of the total emissions and these are direct emissions from biological processes during treatment consisting of CO_2, CH_4, and N_2O. Due to the production of CO_2, CH_4, and N_2O, wastewater treatment plants (WWTPs) are considered one of the largest of the minor GHG emissions generators (Kyung et al., 2015). During the operation of WWTPs, there are indirect emissions, primarily CO_2 that result from energy generation within the plant. Improved energy efficiency is the proposition to reduce emitted CO_2 during production (Campos et al., 2016).

Landfill GHG emissions, which is the research topic of this dissertation, accounted for 1.9% of waste GHG emissions in 2016 data. More importantly, landfills are the third largest emitter of anthropogenic methane emissions in the U.S., accounting for approximately 14.5 percent of these emissions in 2020 (US EPA, 2016c). Landfills, which were labeled "sanitary landfill" during the 1930s, were necessary creations to ease both environmental and health problems. However, landfills have also become significant contributors to climate change through the release of GHGs. CH_4, N_2O, and CO_2 are GHGs that are generated from anaerobic (Figure 1.13) and aerobic biodegradation of municipal solid waste (MSW) (Zhang et al., 2019). It is estimated that the approximately 3 billion people living in urban areas generate nearly 1.3 billion tonnes of solid waste each year. The MSW is estimated to increase to 4 billion tonnes by 2100. From this comes both possible detriment and opportunity if managed correctly (Pour et al., 2018).

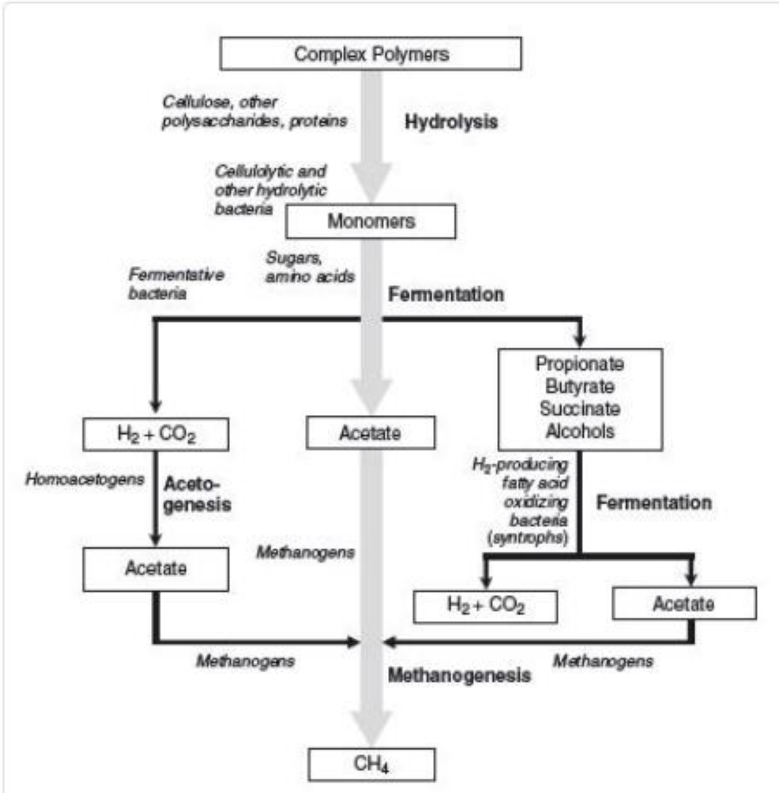


Figure 1.13: Process of anaerobic decomposition (Mitchell & Gu, 2009)

In the determination of GHGs from landfills, CH_4 is the only gas accounted for although CO_2 and N_2O are also released (see Figure 1.14). There is an agreement that due to the CO_2 that emits from waste is biogenic, then it does not add to GHG emissions. Even when landfills are closed between years 21 and 25, GHGs will continue to be emitted for possibly 200 plus years as seen in Figure 1.15 (Lou & Nair, 2009).

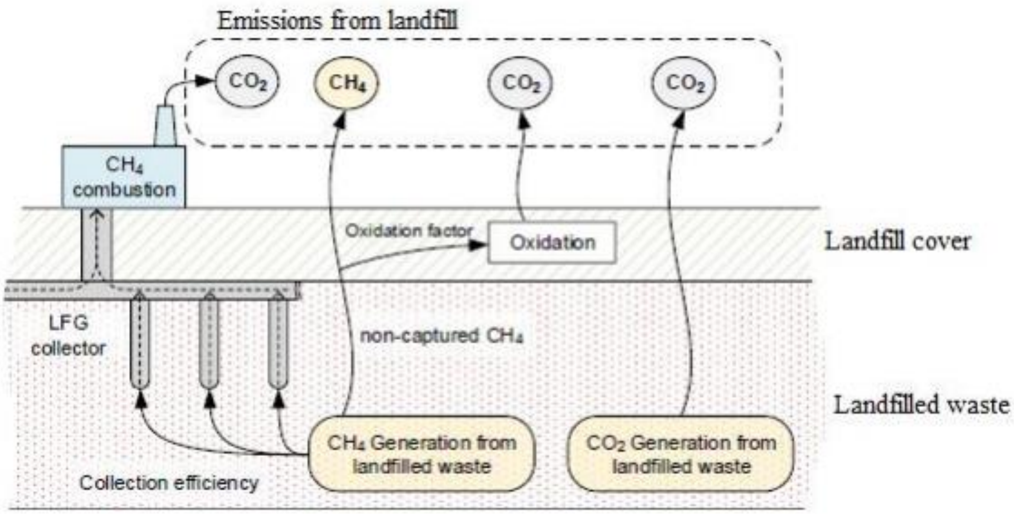


Figure 1.14: Landfill gas (LFG) emissions generated from landfilled organic waste (Dincă et al., 2018)

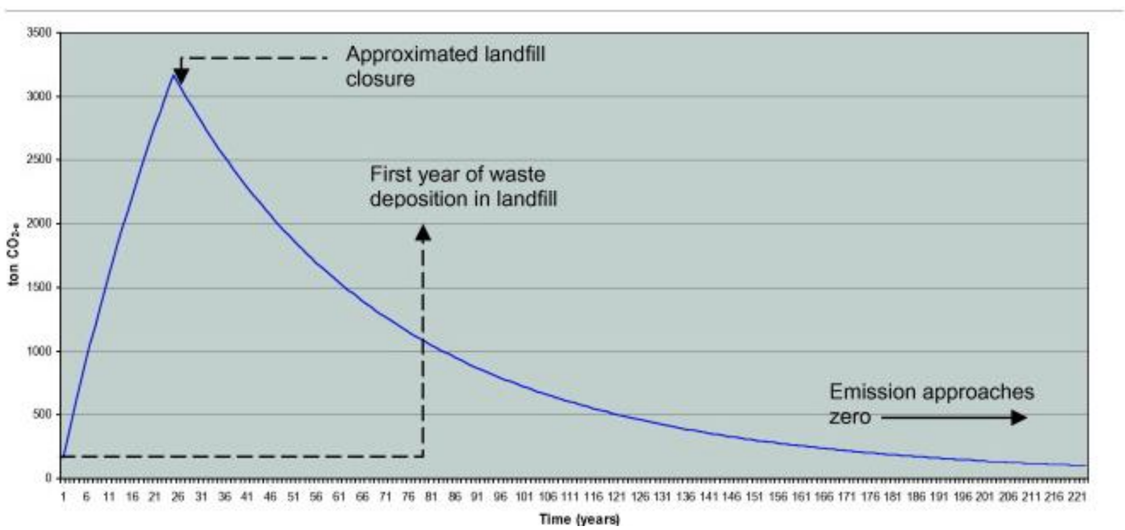


Figure 1.15: Trend of CH_4 emissions from landfills pre and post closure (Lou & Nair, 2009)

Industry has two primary contributors to GHG emissions - chemicals and cement. Regarding cement, this is a direct manufacturing process in which during the cement production phase, limestone decomposition emits CO_2. Limestone primarily consists of calcium carbonate, the main ingredient, and magnesium carbonate. The breakdown and emitting of CO_2 is shown in equations 1.3 and 1.4 (Ma et al., 2016).

$$CaCO_3 = CaO + CO_2 \uparrow \qquad \textit{Equation 1.3}$$

$$MgCO_3 = MgO + CO_2 \uparrow \qquad \textit{Equation 1.4}$$

There are two factors in the research regarding climate change and driving forces of such research. One direction in the research of climate change is how human use and behavior towards land-use has created a changing ecosystem, which in turn has caused a rise in emission levels. The second research on climate change is how at a national level, households and their behavior have contributed significantly to the growing emissions rate (Rosa & Dietz, 2012).

In the research as it relates to land-use, the changing eco-system, and GHG emissions, a study by Kim and Kirschbaum in 2015 reviewed the impact of land-use changes and the environmental impacts from GHGs. Even though fossil fuels are the primary factor for the greenhouse gas effect, land-use change, i.e., deforestation, is a factor that contributes to the increase in GHG emissions (Kim & Kirschbaum, 2015). Figure 1.16 displays the change in emissions between conversions of various land usage. In the figure, as land-use is converted, the green arrows indicate a reduction in GHG emissions, while red arrows indicate an increase in emissions. With the increase in global population, continued deforestation for additional cropland, will continue to increase GHG emissions (Niu et al., 2020) (Verburg et al., 2009). With an increase in emissions, comes the probability of climate change. Due to climate change, there is a chance for lower agricultural yields, and when this occurrence takes place, the further clearing of lands for agricultural purposes will probably occur (Schmidhuber & Tubiello, 2007).

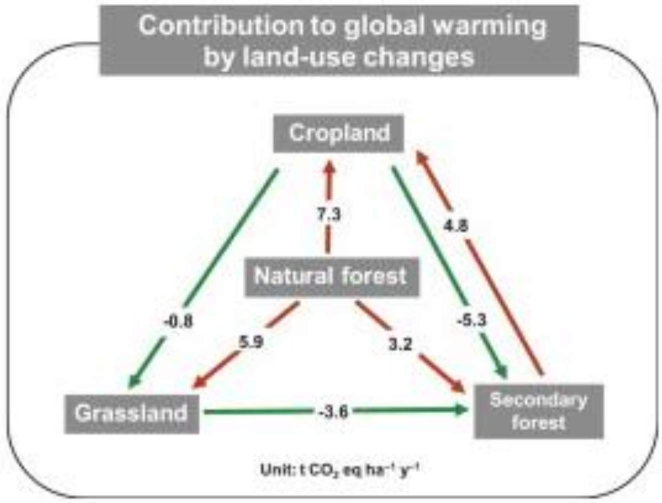


Figure 1.16: Land-use change and contribution to global warming (Kim & Kirschbaum, 2015)

The second research on climate change, which has studied at a national level on how household behaviors contribute to the growing emissions rate, has focused on several areas to include consumption, population, number of households, age structure, and rate of growth (Rosa & Dietz, 2012). Most research that primarily focused on GHG emissions was directed towards the production level, which resulted in fewer studies on how consumers played a part in GHG emissions. One study believed that imports driven by developed countries, and the high GHG emissions that come from the consumption of these goods, does not assist with an environmentally friendly goal of responsible consumption. By placing much of the blame on the producers, there is a shift as to who should be responsible for GHG emissions (Feng et al., 2017) (Bastianoni et al., 2004) (Wackernagel & Rees, 1998). There are two principles regarding GHG emissions: 1) the production-based principle states that producers take on the responsibility of GHG emissions; 2) the consumer-based principle states that consumers are responsible for GHG emissions that are calculated by an input-output model. The main thought from these two principles is that consumers are the drivers of emissions, but with the access to technology that involves cleaner production, producers are more than capable to share in the responsibility of GHG emissions (Feng et al., 2017) (Bastianoni et al., 2004) (Lenzen et al., 2007).

1.7 Research Objectives

Due to the crisis of AGW and climate change, there are problems that must be solved in the most economically efficient way and in an expedient fashion. If MSW rates are going to continue to increase and there are no efforts to reduce the rates sustainably, then alternatives must continue to be put forth to solve these problems. Even though some of these methods are currently in existence, changes, both by addition and subtraction, can be made. The concept of this dissertation came about in several steps:

1) Recycling and composting are waste diversion options designed to keep waste out of landfills, but what if there are no diversion options?
2) If most refuse items, including recyclable items, are going to landfills, and there is a drive to reduce methane emissions, what options can be used to solve this problem?
3) How can emissions be calculated based on different waste management scenarios?
4) With the move to reduce fossil fuel usage, how can landfill methane emissions be utilized in energy production?
5) What program(s) can be utilized to determine the emissions from the type of MSW scenario utilized?
6) What program(s) can be utilized to determine methane production from MSW generated?

In many communities, there are little to no recycling opportunities, and this reduces or eliminates the opportunity to contribute to the reduction of GHG emissions. With this lack of an option, MSW landfills continue to fill with potential recyclable, source reduced, and compostable materials, therefore increasing GHG emissions. The availability of this extra waste material creates an opportunity to generate energy through various renewable options and possible new technologies, while contributing to a reduction in GHG emissions. This dissertation will analyze different scenarios based on factors that consider the amount of MSW generation and its material percentages, then calculate GHG emissions based on how the MSW will be disposed of. After the emissions calculations, MSW tonnage will be utilized to calculate landfill methane gas, which will then analyze the potential energy production. The emissions calculator will come from the EPAs Waste Reduction Model (WARM) and the landfill methane calculator will come from the EPAs Landfill Gas Model (LandGEM). The emissions from both models will be used to estimate the potential energy from the landfill and analyze the differences between the two projections.

1.8 Research Questions

This dissertation will review the following research questions:

1) What combination of MSW treatment strategies will result in the theoretical maximum GHG emissions avoidance and energy savings?
2) What combination of MSW treatment strategies can provide maximum GHG emissions avoidance and energy savings utilizing actual data if minimal to zero alternatives are available and are they comparable to the theoretical strategies?

3) What is the theoretical energy production that can be achieved from the landfill using the emissions produced?

With landfills both contributing to methane emissions and sourcing potential energy, the opportunity to harness and utilize a potential hazard will be analyzed. Having a source that has a negative and a potential positive has created two hypotheses. The first hypothesis is: an optimal mix of MSW treatment strategies (source reduction, recycling, combustion, landfilling, and composting) to create a maximum GHG emissions avoidance, while maximizing energy savings, can be modeled to match individual landfills. The second hypothesis is: waste-to-energy and landfilling can be used as the primary method in the absence of recycling, source reduction, and composting as a realistic option to achieve maximum GHG emissions and expand renewable energy production.

CHAPTER TWO: LITERATURE REVIEW

2.1 Municipal Solid Waste Introduction

The purpose of this section is to review the various strategies that have been proposed to reduce GHG emissions from landfills while also generating energy. Landfilling is the most common way to handle MSW, however there are methods associated with landfills to reduce GHG emissions. As waste continues to increase worldwide, additional landfills will be developed, thereby increasing the amount of GHGs emitted to the atmosphere. With the need to reduce GHGs from landfills, there also comes an opportunity to produce waste-to-energy pathways that can reduce GHGs from landfills, utilize available renewable energy sources, and decrease the need for fossil fuels.

2.2 Municipal Solid Waste and GHG Emissions

Due to the continued increase in MSW disposal, countries have explored various ways to utilize their waste. As waste continues to increase, GHGs will also continue to increase. Kumar and Samadder (2017) outlined MSW to energy using thermal conversion, biological conversion, and landfilling as the pathways (Figure 2.1). Their work stated that energy demands at the end of the century are expected to be six times greater than the current demand, and that alternatives are needed to replace fossil fuels and reduce climate change, thereby WTE is a favorable option (A. Kumar & Samadder, 2017).

Figure 2.1: Municipal solid waste treatment options (A. Kumar & Samadder, 2017)

A study by Psomopoulos and others in 2009 stated that WTE provides substantial benefits compared to fossil fuel utilization, while reducing environmental hazards. It was estimated that WTE reduced GHG emissions by 1 tonne of CO_2 per tonne of waste that was combusted rather than landfilled without gas recovery. Also, combustion of MSW in WTE to facilities potentially reduced emissions by 26 million tonnes of CO_2 (Table 2.1) (Psomopoulos et al., 2009).

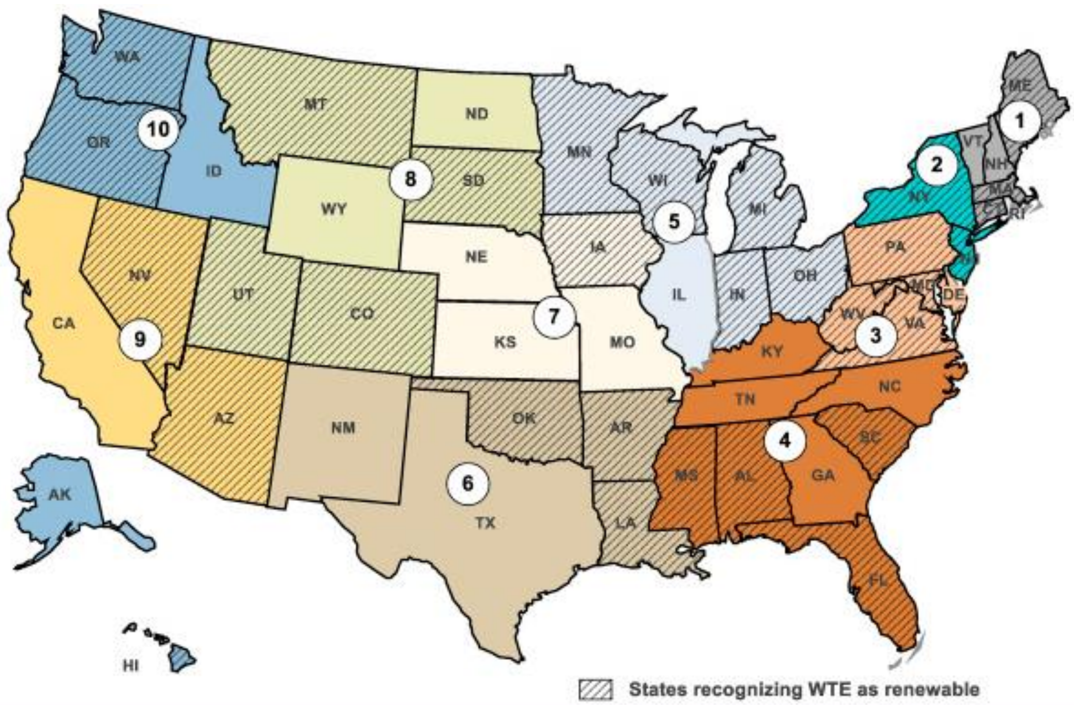
Table 2.1: A comparison of air emission – waste-to-energy and fossil fuel plants (Psomopoulos et al., 2009)

Fuel	**Air emissions (kg/MW h)**		
	Carbon dioxide (CO_2)	**Sulphur dioxide (SO_2)**	**Nitrogen oxides**
MSW	379.66	0.36	2.45
Coal	1020.13	5.90	2.72
Oil	758.41	5.44	1.81
Natural gas	514.83	0.04	0.77

Mukherjeee and others (2020) wrote that in 2015, the EPA reported that 238.5 million tonnes of MSW was generated in the U.S., in which there has been a significant increase over the last ten to twenty years. The U.S. is the largest generator of MSW in the world, however only approximately 12.8% of the waste is used for energy recovery. Of the 765 MSW based WTE plants worldwide, the U.S. operated only 86 of these facilities across 25 states. These facilities are rare in the U.S. due to the large capital costs and the lack of support from local governments (Mukherjee et al., 2020).

As shown in Figure 2.1, there are thermal, non-thermal, and biological options regarding MSW to energy options. An important factor regarding WTE is the composition of the waste. In the Mukherjee and others, 2020, report, the authors stated that elemental analysis of MSW from the ten U.S. EPA regions shown in Figure 2.2 needs to be conducted to determine WTE potential and identify gaps that might exist. A study by Bradfield, 2014, focused on "thermochemical conversion, specifically pyrolysis of solid wastes as a means of energy product recovery. Before a specific waste stream can be used in WTE or RDF (refuse derived fuels) contexts, its composition and degradation behavior needs to be investigated" (Bradfield, 2014). Kumar and

Samaddar (2017) stated that the most effective WTE pathway was dependent on the type of MSW. Figure 2.3 displays three different WTE pathways and the streams to make those pathways most effective. The best components for anaerobic digestion, which produces LFG, would be food and yard waste. Gasification is the best option to treat plastics, and incineration is the best method for any waste streams (A. Kumar & Samadder, 2017).



US Regions	1	2	3	4	5	6	7	8	9	10	Total
WTE (in %)	41	21	17	6	4	0	0	2	2	3	96
Landfill (in %)	24	52	54	73	76	78	76	79	51	53	616
Recycling (in %)	27	23	24	19	15	11	22	9	37	32	219
Composting (in %)	8	4	5	2	5	11	2	10	10	10	67
Population (in millions)	14.8	28.4	30.1	66.4	52.5	42.4	14.1	49.7	49.7	13.5	361.6

Figure 2.2: MSW-to-energy landscape of the ten US EPA regions in 2015 (Mukherjee et al., 2020)

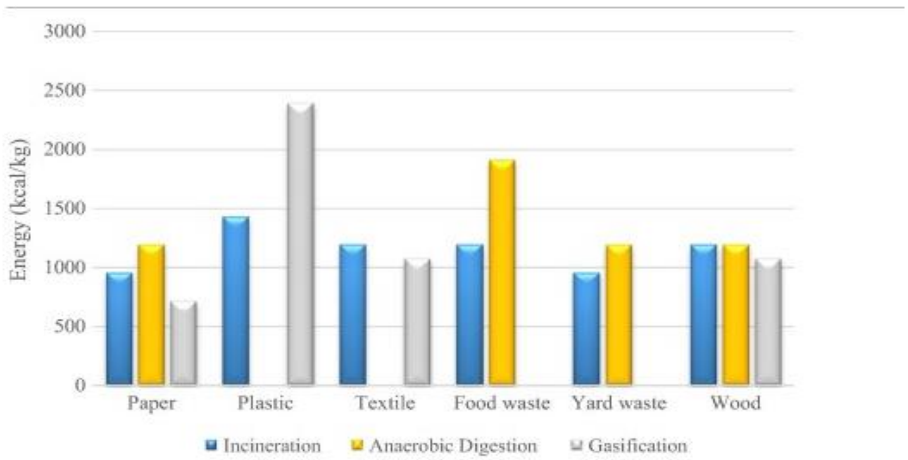


Figure 2.3: Energy recovery potential of different WTE technologies for different MSW stream (A. Kumar & Samadder, 2017)

Kaur and others (2021) documented that WTE created eight positive outcomes from producing energy from MSW (Figure 2.4). The first outcome of less dependence on fossil fuel is a universally held belief. Weitz and others in 2002 concluded that producing electricity from MSW in a WTE facility would avoid 5 MMTCE that would have been produced by fossil fuel energy generation. It also avoided 6 MMTCE of GHG emissions from landfill emissions (Weitz et al., 2002).

The second outcome that was stated by Kaur and others (2021) is that sustainable cities and communities will be achieved with WTE. Ismail and Dincer (2022) studied the use of a multigeneration integrated system to produce hydrogen from waste to meet the needs of a community regarding electricity, heat, and fresh water to address clean energy and sustainability. The multigeneration integrated system used solar power as the energy source to power a pyrolysis reactor converting plastic waste to syngas. The system generated 21,610 kW of electricity, which is comparable to powering 6 average homes for a year. The produced methane was processed to produce hydrogen at a total rate of 0.6 kg/s (Ismail & Dincer, 2022).

Outcome number three by Kaur and others relates to responsible consumption and production (Kaur et al., 2021). Sustainable Development Goals are 12 targets created by the United Nations to sustain the livelihoods of current and future generations. The responsible consumption and production goal is to rationalize, restructure, and phase out harmful fossil fuel subsidies. Fossil fuel subsidies boost wasteful energy production and consumption, which intensifies climate change. Enhancing production of clean energy would end the subsidies and sustain consumption (Arora & Mishra, 2023).

The fourth outcome by Kaur and others is related to climate action (Kaur et al., 2021). Fernandez-Gonzalez and others (2017) stated that pyrolysis and gasification would not only produce necessary energy, but it would also reduce greenhouse gas emissions. The paper also stated that with population growth and the continued use of landfills, alternatives such as pyrolysis will become the best option in the future (Fernández-González et al., 2017) (Psomopoulos et al., 2009).

The fifth outcome by Kaur and others is the employment opportunities that arise from energy production from MSW (Kaur et al., 2021). Demirbas (2009), stated that power generation from renewables instead of fossil fuels creates lasting, important socioeconomic impacts for local economies. These impacts include increases in employment, and other factors that affect local and regional economies (Demirbas, 2009).

The sixth outcome of energy from MSW is the economic growth that is created by this form of renewables (Kaur et al., 2021). To enhance growth of WTE from MSW, states can provide incentives and tax credits to those who hold Renewable Obligation Certificates (ROCs) who practice renewable energy (Mukherjee et al., 2020).

The seventh outcome of energy from MSW is clean water and segregation. Properly controlled landfills that control the collection, segregation, LFG, and leachate can reduce infiltration into groundwater. With the proper treatment of landfill leachate, energy can be generated and groundwater protected (Roy et al., 2022).

The eighth outcome of energy from MSW is good health and well-being (Kaur et al., 2021). Controlled and engineered landfills can provide protection against hazards that would take place in open-dumping or uncontrolled landfills. These landfills protect against infiltration of leachates into groundwater and against environmental pollution and health risks. Controlled landfills also provide systems to capture LFG that would otherwise emit into the air and produce energy from this captured gas (Siddiqua et al., 2022).

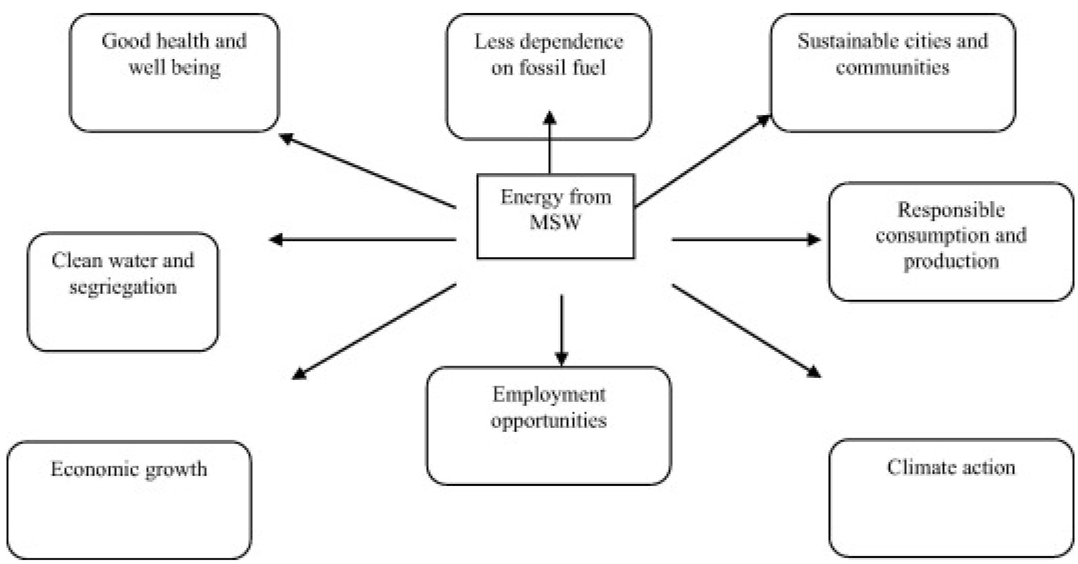


Figure 2.4: Eight outcomes of energy from municipal solid waste (Kaur et al., 2021)

2.2.1 Landfill Gas Capture and GHG Emissions

Landfill gas capture (LFG) is one method that is utilized to capture emissions escaping into the air. This gas capture can be converted and utilized as renewable energy. This also assists in reducing odors and additional hazards that contribute to global climate change. A study by Johari and others in 2012 found that in Malaysia, with landfilling as the primary MSW disposal method with open dumping, most of the GHGs escape to the atmosphere. The MSW generation in Malaysia in 2010 was approximately 8.2 million tonnes, which had an estimated 310,000 tonnes per year of CH_4 released with a CO_2 equivalent of 6.5 million tonnes. Utilizing the captured methane in a Clean Development Mechanism (CDM) or other renewable energy project, a carbon credit of 257 million Malaysian Ringgit ($85 million US dollar equivalent) would have been realized. Along with the carbon credit, electrical generation of 1.9×10^9 kWh would have been achieved, thereby generating RM570,000,000 or $190,000,000 in US dollars (Johari et al., 2012). A study by Larson and others, 2021, of U.S. landfills, highlighted that LFG capture not only served to conserve resources, but it has also been designated as a renewable resource, which qualifies it for electricity production tax credits (Larson et al., 2021). The study by Johari et.al (2012) did not utilize the WARM or LandGEM models to calculate methane emissions, it utilized methodology from the IPCC (Johari et al., 2012)

As of 2015 in Oman, there were 300 dumpsites and seven engineered landfills, which would account for high amounts of GHGs being released into the atmosphere. A study by Abushammala and others in 2015 researched the amounts of MSW generated and disposed in the dumpsites and landfills and calculated the predicted CH_4 emissions in addition to equivalent CO_2 emissions between the years 2016 and 2030 using the IPCC model. The research agreed with that performed by others to include Rosa and Dietz 2012, that as population increased, consumption would also increase, thereby causing an increase in GHG emissions in landfills in developing countries. Between 2016 and 2030, it is estimated that although CH_4 and CO_2 emissions will increase due to population growth, an estimated that carbon reduction could bring in revenue of 128 million Omani Riyal (OMR) or US$333 million. The sale of electricity would bring in OMR112 million or US$291 million during the aforementioned period and as shown in Table 2.2 (Abushammala et al., 2016).

Table 2.2: Economic benefits of captured CH_4 in Oman (Abushammala et al., 2016)

Years	Estimated methane emissions (tonnes)	[a]Equivalent CO_2 emissions (tonnes)	[b]Revenue from carbon credits [c](OMR)	Equivalent electricity generation (kWh)	Revenue from electricity sale (OMR)
2016	49,605	1,240,114	6,294,076	3.06×10^8	5,509,088
2017	51,742	1,293,553	6,565,299	3.2×10^8	5,746,484
2018	53,956	1,348,898	6,846,198	3.3×10^8	5,992,350
2019	56,249	1,406,212	7,137,088	3.5×10^8	6,246,961
2020	58,622	1,465,558	7,438,294	3.6×10^8	6,510,601
2021	61,080	1,527,003	7,750,152	3.8×10^8	6,783,565
2022	63,625	1,590,615	8,073,009	3.9×10^8	7,066,155
2023	66,259	1,656,464	8,407,216	4.1×10^8	7,358,680
2024	68,985	1,724,622	8,753,147	4.3×10^8	7,661,467
2025	71,807	1,795,164	9,111,174	4.4×10^8	7,974,842
2026	74,728	1,868,166	9,481,692	4.6×10^8	8,299,149
2027	77,748	1,943,709	9,865,102	4.8×10^8	8,634,741
2028	80,875	2,021,874	10,261,818	5×10^8	8,981,979
2029	84,109.8	2,102,744	10,672,267	5.2×10^8	9,341,237
2030	87,456	2,186,407	11,096,890	5.4×10^8	9,712,902

A report by Scarlat (2015) and others performed research on LFG from MSW in African nations. They first stated that “energy is a critical issue for Africa, where a large number of people do not have access to energy.” This is where MSW to energy by LFG can be utilized. The researchers were in line with what Lou and Nair (2009) proposed as it relates to LFG collection after a landfill opens and can continue well after the landfill closes as shown in Figure 2.11. As it relates to methane potential from the landfills, Scarlat (2015) and others utilized several models, as shown in Table 2.3, however in conducting the potential methane generated to estimate potential energy recovered, the IPCC method was utilized. The study estimated that if waste increased as projected, then the amount of energy recovered in 2012 would be 155 PJ and 366 PJ in 2025. From this energy recovery, electricity generation in 2012 could reach 62.5 TWh and 122.2 TWh in 2025 (Scarlat et al., 2015).

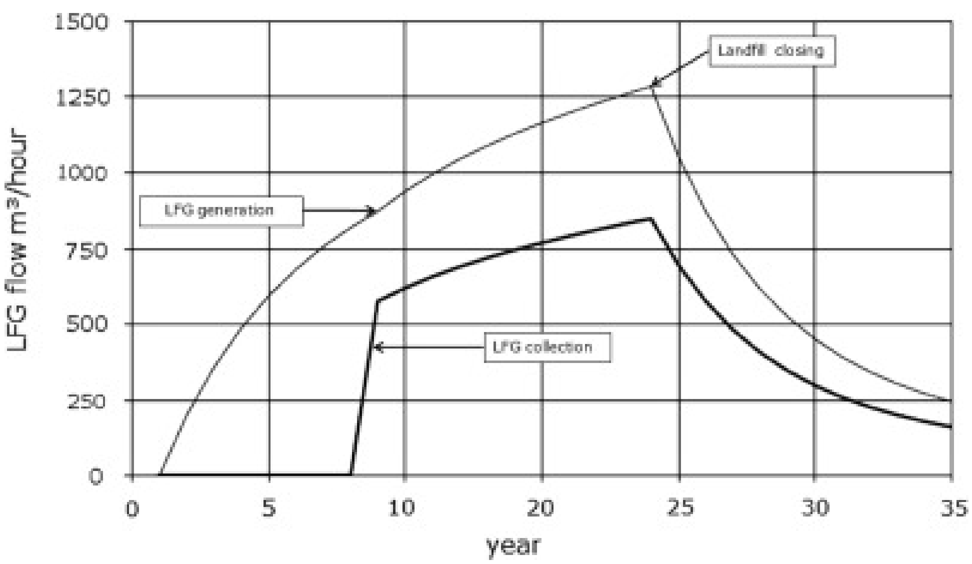


Figure 2.11: Landfill life cycle, LFG generation vs LFG collection (Scarlat et al., 2015)

Table 2.3: Methane potential from landfill (Scarlat et al., 2015)

	L_0 (Nm^3/tonne waste)	Half-time (years)
IPCC model	88	4–23
TNO-model	84	7
GasSim	71	6–15
Landgem (conventional)	171	14
Landgem (arid)	101	35

Even though landfilling is the more economical way of waste disposal, landfills in the United States can recover landfill gas as a generator for both electricity and heat (Mukherjee et al., 2020). LFG projects can be used to generate electricity, it can be used both on-site for power generation or sold directly to other users, and as a power source for alternative fuel vehicles. LFG also has environmental benefits that include direct emissions reduction by turning methane into CO_2 by either burning or flaring, or avoided emissions by utilizing the methane to supply power that would have been used by fossil fuels (S. Li et al., 2015).

2.2.2 Combustion to Energy Pathway

The United States Environmental Protection Agency (USEPA) stated that in 2018, 34.6 million tons of MSW was combusted or incinerated in the United States. This is approximately 12 percent of the total 292.4 million tons of MSW generated in the U.S. (US EPA, 2017). There has been both support and opposition to the combustion of MSW. The supporters of combustion believe that the modern process of combustion is a more environmentally friendly method of waste disposal than landfilling, while the opponents of combustion state that the process requires a substantial investment in the infrastructure development. Opponents also argue that combustion will dissuade opportunities such as recycling to reduce MSW (Karim & Corazzini, 2019).

In 2014 there were 80 waste-to-energy (WTE) incinerators operating in the United States (Makarichi et al., 2018). However, by 2018, there were only 75 of these WtE facilities operating in the United States, having a daily MSW throughput of 94,243 tons and a gross electric capacity of 2,534 MW (Michaels & Krishnan, 2018). Even though there has been a decline in WtE facilities in the United States, worldwide there has been an increase of WtE facilities. This is due to the process having overcome most its limitations, in addition to declining space for landfills, and new technology for environmental protection (Makarichi et al., 2018).

Incineration systems operational in the United States utilize either mass burn, refuse derived fuel (RDF), or modular systems. These systems have both their advantages and disadvantages. The advantages are they can utilize unprocessed or unsorted MSW and they reduce solid waste volume and divert waste from landfills. The disadvantages of incineration systems are they require air pollution control systems that are expensive, rigorous environmental permitting, and there can be some pre-drying that is required of the feedstock, which then leaves pollutants that require landfilling (Mukherjee et al., 2020).

A study by Ram and others state that incineration is a technology that is an effective and sound technology, however they believe that the challenges that still lie with incineration are characterization, valorization, heavy metal removal from ash, and air emissions. Their study, which primarily focused on incineration in China, stated that there are problems with the MSW composition, mainly that it has high moisture content and low calorific value (LCV), which is opposite of fossil fuels. However, new methods have been proposed to assist with raising the LCV and lowering the moisture content, which in turn has reduced the use of fossil fuels and has allowed incineration technology to surpass landfilling (Ram et al., 2021).

Kaur and others concluded in their study that incineration had both its advantages and disadvantages. Advantages of incineration is that it can be incinerated on site, it needs less space than a landfill, and even though incineration can be more costly than landfilling, the cost can be recovered through power generation. Disadvantages of incineration are the high setup cost, skilled labor is needed, and not all materials are combustible due to high moisture content. There are also factors to be considered during the consideration of electrical generation which are the loss of energy due to fuel moisture, non-combusted carbon, and the loss of energy through the walls of the container (Kaur et al., 2021).

2.2.3 Other MSW to Energy Pathways

<u>Gasification</u>

Gasification is another process in the pathway of producing energy from MSW. The thermochemical process is achieved through heating in an oxygen-lean or free environment, to convert the large molecules in solid form into gaseous, smaller molecules (Lee, 2022). The gasification process, due to the elevated temperature at which it takes place, releases a mixture of carbon monoxide and hydrogen which is known as syngas, as well as other gases (Vaish et al., 2019). A comparison of the gasification and incineration processes is shown in Table 2.4.

Table 2.4: Comparison of energy characteristics of gasification and combustion processes (Vaish et al., 2019)

Metrics of comparison	Termiska gasification process	Battelle gasification process	Essex County mass burn incineration plant	SEMASS suspension-fired incineration plant
MSW capacity (tons/year)	642,400	341,275	831,105	910,000
RDF capacity (tons/year)	506,255	239,075	N/A	N/A
HHV of product gas (MJ/m^3)	7.5	18.6	N/A	N/A
HHV of product gas (GJ per ton MSW)	6.8	7.1	N/A	N/A
Volume of product gas (m^3/ton MSW)	906	396.5	6700+	6700
Gross power rating (MW)	74.5	47	76	78
Gross power generation (kWh/ton MSW)	781	703	501	660
Facility power needs (kwh/ton MSW)	130	70	23	110
Energy consumption for RDF (kWh/ton MSW)	15	21	N/A	
Net power for sale (kWh/ton MSW)	636	612	476	550

The Termiska process is a technology that combines bubbling and a circulating fluidized bed that is operating at 850°C, while the Battelle gasification process is a technology that utilizes a circulating fluidized bed of sand, reacting with steam at near atmospheric pressure (Vaish et al., 2019).

The study by Lee concluded that gasification is a technique that can be utilized in a larger commercialized setting by reducing operational costs. Also, the removal of CO_2 is crucial in the increase of the H/CO content of the syngas for high-value products (Lee, 2022). Vaish and others concluded that gasification is attractive because it can solve two problems, management of MSW and energy recovery from MSW due to its sustainable and environmentally friendly process (Vaish et al., 2019).

Kaur and others stated that with using the Fischer Tropsch process, syngas can be used in the production of items such as hydrogen, methanol, and other synthetic fuels. In treating mixed MSW with a higher quality of inorganic waste, syngas is the most sustainable technology compared to incineration due to the production of large amounts of heat, energy, and multiple secondary fuels. Another positive reason for using gasification, particularly at a small scale, is that if gasification systems have internal combustion engines, the engine can be operated for prolonged periods, giving off minimal emissions and having higher electricity efficiency (Kaur et al., 2021).

Plasma Gasification

The use of plasma in gasification of MSW is gaining interest in the United States due to the ability to use an assortment of waste, including standard MSW, tires, and others, to include hazardous and non-hazardous. The advantages of using plasma in gasification include it being a cleaner and more efficient WTE technology, more syngas production, and due to the high operating temperatures, inorganic waste is removed as slag, and there are lower toxic materials in syngas compared to incineration. The main disadvantage of plasma use is that there is no commercial technology currently in operation in the United States, however, the military is studying how feasible plasma gasification would be for waste management at military installations (Mukherjee et al., 2020).

The researchers believe that there are greater benefits to utilizing plasma gasification in the WTE process. Their conclusions regarding plasma gasification are that due to the high temperatures used, bonds of the waste will dissociate, which will then allow any type of waste to be used. Also, dust and gases, both toxic and non-toxic, are not released to the environment due to the plasma gasification taking place inside a completely closed system (Kaur et al., 2021).

Pyrolysis

Pyrolysis is a process where materials are heated in the absence of oxygen, usually above 500 °C. Due to the lack of oxygen, there is no combustion but rather decomposition into gases and bio-char (USDA, 2021). Due to global energy demands and an unstable fuel market, pyrolysis is a sustainable and efficient way to treat MSW and provide a solution to energy demands (Al-Salem et al., 2017).

One study evaluated three pyrolysis processes and detailed the recovery products of each, as shown in Table 2.5. All three methods, slow, fast, and flash, produce syngas, however, flash pyrolysis will produce the highest percentage of syngas, but it also generates high quantities of oxygen, heavy metals, and nitrogen (Hasan et al., 2021).

Table 2.5: The parameters and product yields for three pyrolysis processes (Hasan et al., 2021)

Pyrolysis process	Reaction temp. (°C)	Heating rate (°C/s)	Residence time	Feedstock size	Product yield (wt%)		
					Bio-oil	Biochar	Syngas
Slow	~300	0.1–0.8	25 min – 35 h	Briquette, whole	10–30	25–65	10–50
Fast	400–700	10–100	0.5–2 s	Finely ground	40–70	15–25	10–20
Flash	700–900 or above	1000	<0.5 s	As small as possible	10–20	10–15	60–80

Ram and others stated that pyrolysis generates various chemicals and fuels through its treatment of MSW. Their analysis is that pyrolysis provides a cleaner process over incineration by generating lower amounts of air pollutants which can easily be washed from the syngas, which avoids the release of the pollutants into the atmosphere (Ram et al., 2021).

Hasan et al. conducted a study on energy recovery from MSW using pyrolysis technology which determined that pyrolysis can be a promising option for reducing environmental impacts from MSW. They also stated that pyrolysis offers ready-to-use fuel, easily and securely. However, they indicated that pyrolysis is complicated and has several factors influencing the process, including temperature, heating rate, and the composition of the MSW. Pyrolysis also emits toxic gases such as HCl, H_2S, SO_2, and NH_3 during its process (Hasan et al., 2021).

A study by Bhatt and others in 2021 reviewed using the plasma pyrolysis process to minimize MSW and produce energy. Their study stated that the plasma process generated a considerable amount of hydrogen without harming the environment. The process has high development, operational, and maintenance cost, but maintaining these costs are offset by the length of generation of syngas and hydrogen from the process (Bhatt et al., 2022).

2.3 Modeling of Emissions and Methane Generation

EPA Waste Reduction Model (WARM)

The Waste Reduction Model (WARM) was created by the Environmental Protection Agency (EPA) to "provide high-level estimates of potential greenhouse gas (GHG) emissions reductions, energy savings, and economic impacts from several different waste management practices" (US EPA, 2016a).

A study by Mohareb and others analyzed the WARM model along with the Federation of Canadian Municipalities-Partners for Climate Protection (FCM-PCP) quantification tool, the Intergovernmental Panel on Climate Change (IPCC) 1996 guidelines, and the IPCC 2006 guidelines. The authors stated that the WARM model views items such as carbon emissions and sinks in a unique fashion. The model uses a simple method in understanding the carbon balance of waste operations (Mohareb et al., 2011).

A 2021 study by Castigliego and others studied the emissions of commercial and residential solid waste streams in Boston, MA. The work estimated environmental impacts in the city and included a quantification of lifecycle GHG emissions. The WARM model was used to assess the impact of the waste; however, it was stated that the model was limited in its capability to determine how waste management decisions would affect overall systems over a long period. The study utilized waste audits and non-mappable WARM materials were excluded from the study, which was approximately 13% of the MSW stream (Castigliego et al., 2021).

Dengler and others (2022) undertook a study to understand how results are affected when different emissions factors are involved. Emissions factors from the EPA's Factors Hub and the UK's Department for Environment, Food & Rural Affairs (DE-FRA) were employed, then placed into WARM for Factors Hub and MELMod for DEFRA. WARM provided results across a complete life cycle and calculated both positive and negative CO_2E results when recycling and landfilling or recycling and incineration were combined. However, WARM provided GHG emission results that were incompatible with GHG data reporting per GHG Protocol. The authors also pointed out that WARM is superior to US EPA Factors Hub when comparative waste management strategies with potential alternatives are needed (Dengler et al., 2022).

A 2019 study by Muth and others, analyzed the environmental and economic effects of food loss and waste interventions in the United States. Their study did not utilize the full scope of WARM, but they observed that WARM could generate estimates of the environmental impact of food loss and waste (FLW). They noted that multiple third parties utilize WARM estimates of environmental impact to educate organizations about how food waste can impact the environment and also use it to change people's behavior towards food waste (Muth et al., 2019).

Jobson and Khosravi performed a review in 2019 of volatile organic compound data and an estimation of GHG emissions in compost facilities in Washington state. The authors utilized the WARM model in an exercise of GHG emission accounting for Washington State landfill data. This exercise would perform a comparative analysis of how GHGs would be affected if organic waste had been composted instead of landfilled. The study calculated that if food waste is landfilled instead of composted, then there is a net gain of 0.71 CO_2e per ton of GHGs to the atmosphere. Landfills with LFG recovery were analyzed separately from those without LFG recovery. The landfills with no LFG recovery are shown in Table 2.6, while those with LFG recovery are in Table 2.7. The total waste in each landfill is needed to help calculate GHG emissions (net MT CO_2e). A breakdown of organic material by type and its total weight is shown in Table 2.8, while Table 2.9 shows the net CO_2 of diverting organic material from landfills to composting. The work concluded that with food waste being the largest source of landfilled material and composting being a significant decreasing factor of GHGs, WARM calculates that composting organic material is a better option than landfilling to reduce GHGs.

Table 2.6: Landfills in Washington State with no LFG collection system (Jobson & Khosravi, 2019)

Landfill Name	Waste in place (tons)
Rainbow Valley LF	300,000
Ryegrass LF	464,000
Sudbury Road LF	1,102,317
Terrace Heights LF	6,198,335
Vashon LF	477,037

Table 2.7: Landfills in Washington State with LFG collection system (Jobson & Khosravi, 2019)

Landfill Name	Waste in place (tons)
Port Angeles LF	1,026,000
Purdy LF	473,243
Roosevelt Regional Municipal Solid Waste Landfill	53,506,278
Tacoma City Solid Waste Facility	5,588,721
Thurston County Waste and Recovery Center	2,135,753

Table 2.8: Organic waste weight by material type used in WARM model for two landfilling types: landfilling with and without LFG collection system (Jobson & Khosravi, 2019)

Material	**weight in tons in landfills *without* LFG collection system**	**weight in tons in landfills *with* LFG collection system**
Yard Trimmings	666,252	4,892,940
Branches	683,335	5,018,400
Food Waste	1,879,172	13,800,599

Table 2.9: Net CO_2 equivalent emission in mega tonnes (MT CO_2e) from diversion of organic waste from landfilling to composting (Jobson & Khosravi, 2019)

	Net MT CO_2e	
Material	landfills *without* LFG collection system	landfills *with* LFG collection system
Yard Trimmings	20,020	147,028
Branches	148,745	1,169,390
Food Waste	-1,338,469	-9,829,690

EPA Landfill Gas Emissions (LandGEM)

The EPA Landfill Gas Emissions (LandGEM) model "is an automated estimation tool with a Microsoft Excel interface that can be used to estimate emissions rates for total landfill gas, methane, carbon dioxide, nonmethane organic compounds, and individual air pollutants from municipal solid waste landfills" (US EPA, 2005).

LandGEM is based on a first-order decomposition rate as follows:

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k\, L_0 \left(\frac{M_i}{10}\right) * \; e^{-kt_{ij}} \qquad \text{Equation 2.1}$$

Where: Q_{CH4} = annual methane generation in the calculation year (m^3/year);

i = 1 year time increment;

n = (calculation year) – (initial year of waste acceptance);

j = 0.1 year time increment;

k = methane generation rate ($year^{-1}$);

L_0 = potential methane generation capacity (m^3/Mg);

M_i = mass of waste accepted in the i^{th} year (Mg);

t_{ij} = age of the j^{th} section of waste mass M_i accepted in the i^{th} year (decimal years, eg. 3.2 years)

Dinca and others conducted a study analyzing LandGEM against three other simulation models: Afvalzorg, GasSim, and EPER model France. Each model predicts methane generation and uses first-order kinetics in the predictions. The study also concluded that LandGEM is the most used of the automated estimation tools, and through simulation, predicts a higher volume of gas production over time, as shown in Figure 2.12. It also states that the components of the waste are a very important part of methane generation (Dincă et al., 2018).

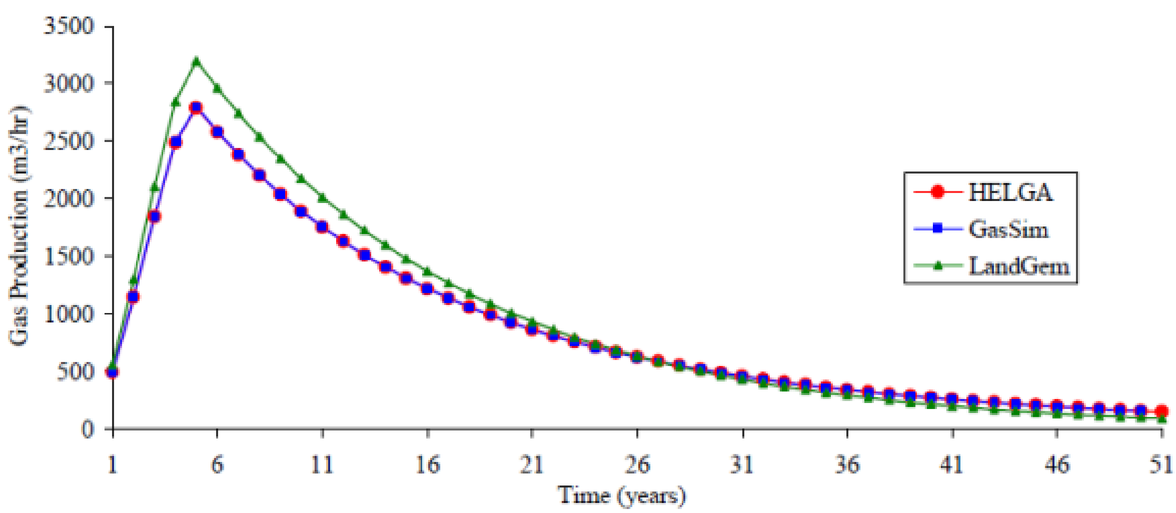


Figure 2.12: Comparison of GasSim, LandGEM, and HELGA simulations (Dincă et al., 2018)

A 2019 study by Sun et al. evaluated the optimal model parameters for predicting methane generation in a group of landfills in the United States. The study collected data from 21 U.S. landfills to estimate the best-fit k, the first-order decay rate. However, instead of utilizing the previous LandGEM formula, where Q_{CH4} is the amount of methane generated for a specific year, the study used a redeveloped formula. The formula was changed to account for a time-varying collection efficiency (Sun et al., 2019). The new equation is:

$$Q_m = \frac{kL_0}{12} \sum_{i=1}^{n} \sum_{j=0.1}^{1} \alpha_{ij} M_i \cdot e^{-k\left(\frac{m-i}{12}\right)} \quad \textit{Equation 2.2}$$

Where: Q_m = Calculated CH_4 collection for a specific month m (m^3 CH_4 $month^{-1}$);

M_i = the mass of waste accepted in the i^{th} month (Mg), i ranges from one to m;

(m-i)/12 = age of waste buried in the i^{th} month (yr);

α_{ij} = is the collection efficiency for the i^{th} month's waste placement, in the j^{th} month since the first month when CH_4 collection data were available;

n = number of months during which the CH_4 collection were available (Wang et al., 2013) (Sun et al., 2019).

In the Sun et al. study, the primary focus was to determine the best-fit values for L_0 and k, where L_0 is an assumed value, and k is a function of it. Methane generation and collection are estimated by these values. The characteristics of the landfills in the study were that they had at least ten years of MSW disposal data and five years of volume and composition data on the collected gas, except for two wells only had four years of data. Sun et al. concluded that L_0 in its definition as CH_4 potential, factors in other parameters which include the moisture content of the waste, operations, and the climate (Sun et al., 2019).

The study by Jobson and Khosravi (2019) also evaluated CO_2e emissions from CH_4 emissions from landfilling activities and the CO_2e emissions using CH_4 and N_2O emissions from composting activities. The study used assumptions of constant annual tonnage and the default LandGEM values for k and L_0. Although materials differ between landfills and compost facilities, the organic degradable carbon value between the two was similar. Using a period of fifty years and a 75% capture efficiency, the total amount of methane generated during that time period was 1.2 x 10^9 kg CO_2E shown in Figure 2.13 (Jobson & Khosravi, 2019).

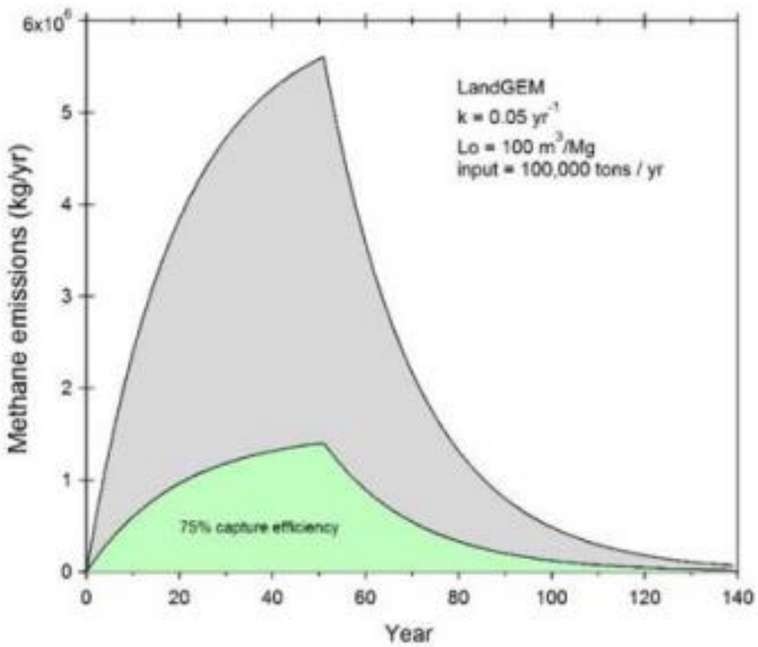


Figure 2.13: Methane emissions from a municipal landfill with a 50-year operating life. Lower green curve shows emissions assuming 75% capture of methane on site (Jobson & Khosravi, 2019)

Amornsamankul (2019) and others evaluated the LandGEM model against three other models including the TNO model, based on waste characteristics in the Netherlands; the Afvalzorg model, which is similar to the TNO model, except for the conversion factor; and the EPER Germany model, which factors the degradable carbon and waste amount. Their study concluded that the LandGEM model was advantageous because of its user-friendly spreadsheet environment, but its disadvantage is that the model used confusing and complicated mathematics (Amornsamankul et al., 2019).

Faour and others (2007) set out to determine first-order model parameters using data from 29 wet landfills that had short-term waste placement and long-term gas collection data. The study concluded that the LandGEM model fit the data well, and the model parameters are highly dependent on environmental conditions such as moisture and temperature, along with capture efficiency (Faour et al., 2007).

2.4 Waste-to-Energy Policy in the United States

The United States presently does not have a written policy to address WTE. There are many policies and legislation in place to address emissions and the move to net zero emissions from LFG while promoting clean energy at the same time. The 2011 study by Amini and Reinhart stated that the creation of a long-term policy for renewable energy, particularly from LFG, would require a reliable estimation of the energy potential. Economic benefits from LFG production could be increased by drafting legislation or creating policy (Amini & Reinhart, 2011).

A study by Chai et al. (2016) reported on the US Renewable Fuel Standard, which was authorized in 2005 and expanded in 2007, which required over 100 billion L of renewable fuels by 2022. In 2008, the Energy Improvement Act allowed local governments developing LFG projects to qualify for tax credits instead of paying interest. (Chai et al., 2016).

Li and others in 2015 concluded that to get owners of landfills to commit to LFG projects, four policies must be implemented. The first policy is investment tax credits (ITC) that cover a portion of the fixed costs. The second policy is production tax credits (PTC) which are energy output based. The third policy is state-level grants for renewable energy, and the fourth policy is Renewable Portfolio Standards (RPS), which would require a utility to generate or acquire a minimum percentage of electricity from renewable sources (S. Li et al., 2015).

2.5 Waste Management in the United States

Municipal Solid Waste in the United States

In 2018, 292.4 million tonnes of solid waste were generated, which was an increase from the 268.7 million tonnes that was generated in 2017. Figure 2.14 displays the breakdown by percentage of the different types of materials placed in landfills (US EPA, 2017).

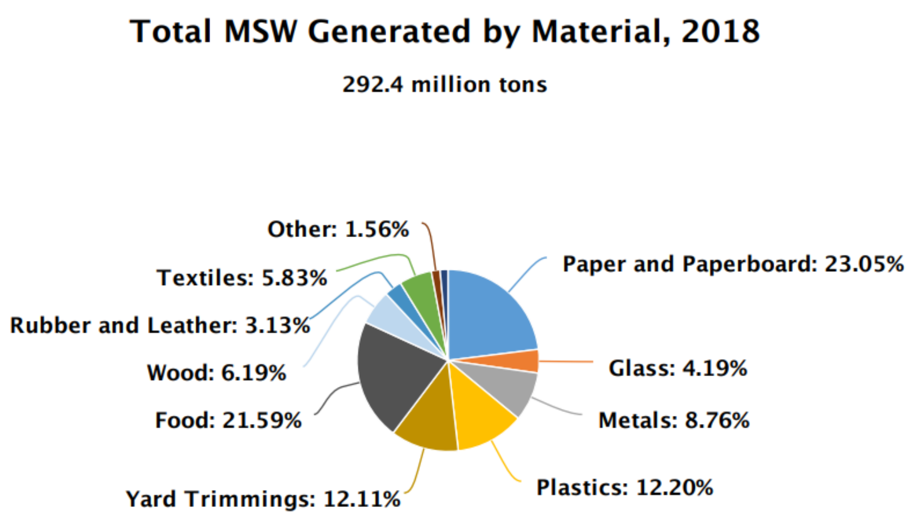


Figure 2.14: Total MSW generated in the United States in 2018 (US EPA, 2017)

Figure 2.15 shows the breakdown of how solid waste has been managed in the United States between the years 1960 and 2018. Of the 292.4 million tonnes of solid waste generated in 2018, landfilling is still the most popular option for management of waste. Over one hundred forty-six

(146) million tonnes of generated waste were landfilled. Recycling was the second most popular way of handling waste. Over sixty-nine (69) million tonnes of MSW in the United States was recycled, while thirty-four (34) million tonnes was combustion for energy recovery, and composting made up close to twenty-five (25) million tonnes (US EPA, 2017).

The United States is the world's largest economy at approximately 25.5 trillion dollars (*United States GDP 1990-2022*, 2023), it generates the largest amount of MSW at approximately 292.4 million tonnes per 2018, but only develops about 11.8% of MSW for energy recovery compared to countries such as Japan at 75%, Scandinavia at 76%, and France at 38% (Figure 2.16) (Mukherjee et al., 2020) (US EPA, 2017) (*Waste-to-Energy (MSW) - U.S. Energy Information Administration (EIA)*, 2022)

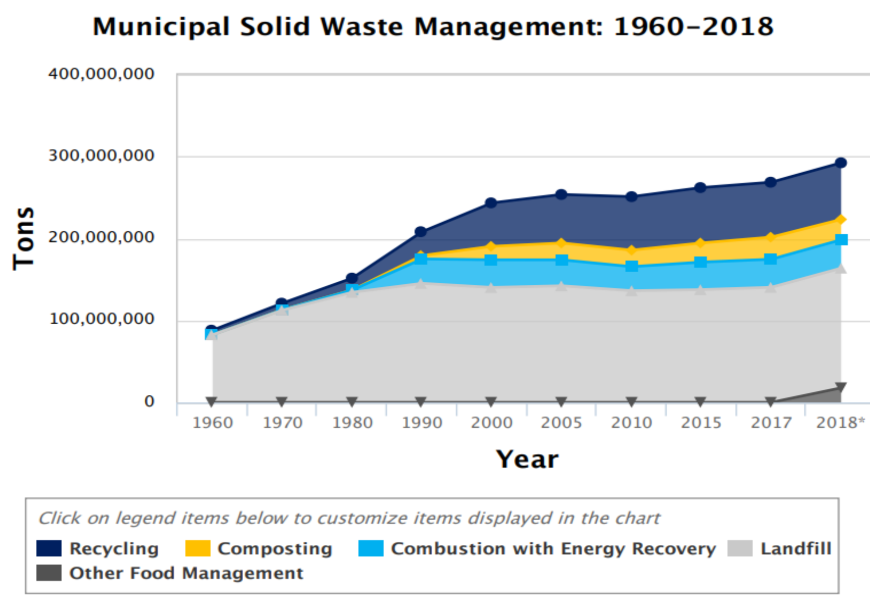


Figure 2.15: Municipal solid waste management: 2016-2011 by methodology (US EPA, 2017).

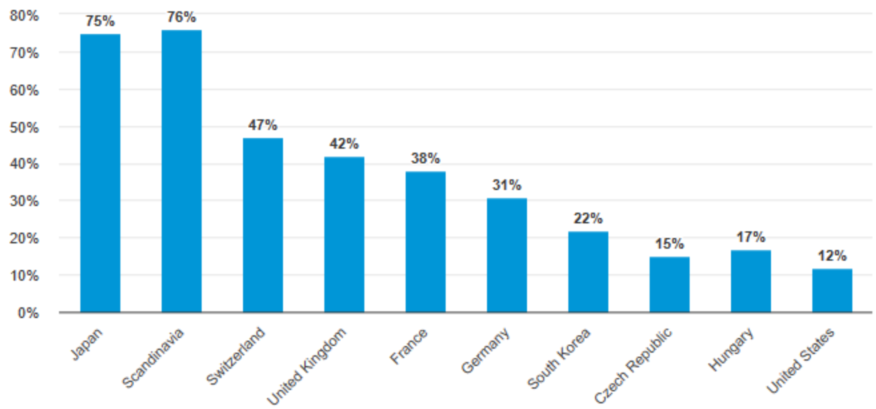


Figure 2.16: Percent of total municipal solid waste that is burned with energy recovery in selected countries (Waste-to-Energy (MSW) - U.S. Energy Information Administration (EIA), 2022)

<u>Recycling</u>

In 2018, more than 69 million tons of MSW was recycled in the United States. Figure 2.17 displays the breakdown by material of goods recycled. Figure 2.18 shows how recycling has increased over the years with tonnage and by products and materials (US EPA, 2017).

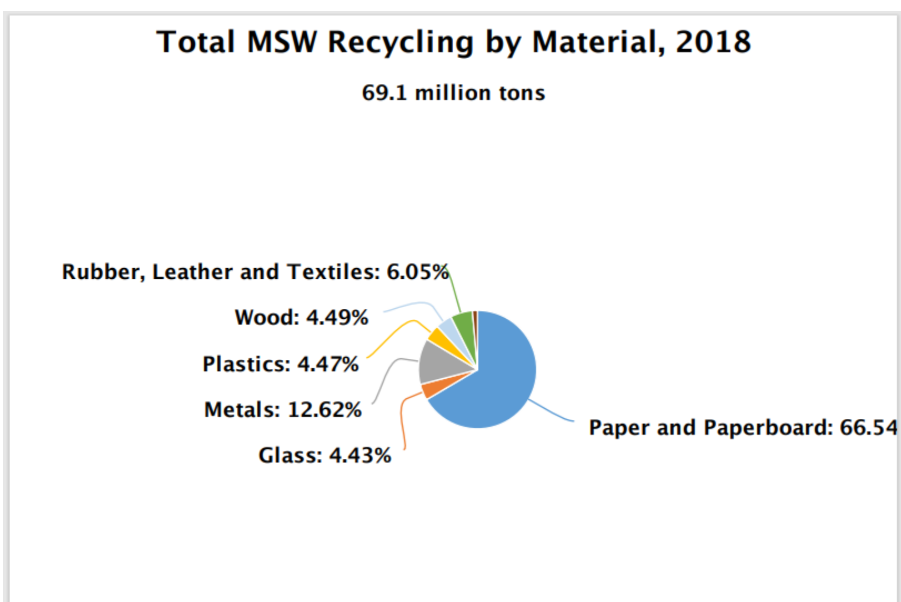


Figure 2.17: Total MSW recycling by material (US EPA, 2017)

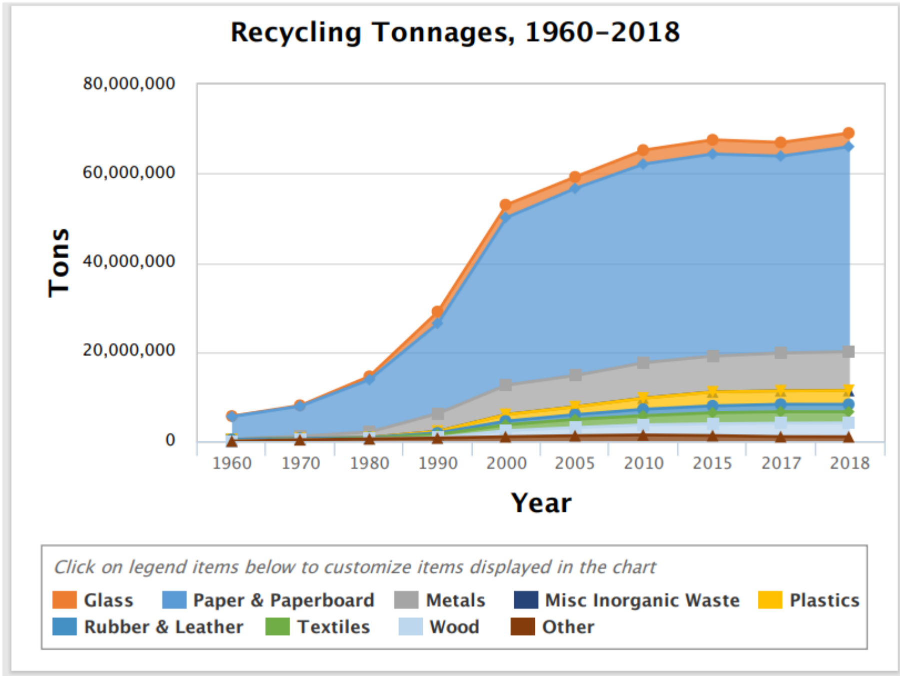


Figure 2.18: Recycling tonnages by material, 1960-2018 (US EPA, 2017)

Attention to the growing issue of recycling in the United States has been pointed out by those who work in the solid waste industry and those that cover it in the main-stream media. The prevalent issue is that prices have fallen for recycled goods and that it is no longer economical for processing to occur and ship to predominantly Asian markets (Rogoff & Ross, 2016). Renee Cho stated in a 2020 article that the recycling system in the United States is broken due to several factors. One, is that many items are not recyclable, such as plastic straws, bags, and eating utensils, which are either landfilled or incinerated. A second factor is the ban by China in handling over half of the world's waste. Contamination caused much of this material to be either strewn across the landscape or disposed of in the ocean (Cho, 2020).

McMahon stated in a 2021 article that recycling is failing for three reasons. The first reason is that there is underinvestment. The second reason is under-participation from producers, and the third reason is the unchanging laws that were enacted thirty to forty years ago (McMahon, 2021).

The EPA has recently studied removing circular arrows due to possible misleading labels about items that can and cannot be recycled. Also, there is a surplus of plastics with low value that end up in processing plants. With an abundance of plastics and no place to send them due to China banning these items, these plastics end up in either a landfill or an incinerator (Ajasa, 2023).

When China stopped receiving “recyclables” from the United States, there was a pile-up of so-called plastics in many communities. Due to this ban, many recycling programs closed, which sent more refuse to landfills and incinerators. There is a belief that additional steps need to be taken in collecting recyclables, primarily cardboard and plastics, which has led to the designing of a recycling roadmap by the EPA for a national recycling strategy (Calma, 2021).

One option to improve recycling rates would be the building of a materials recovery facility. Materials recovery facility, or “MRF” (murf), is a facility that collects and separates materials for recycling, which are then purchased by buyers for secondary manufacturing or usage. To attempt to achieve a circular economy, MRFs are vital because they separate waste into multiple streams that have different economic value, which in turn reduces waste deposited into landfills (Olafasakin et al., 2023). The MRFs can receive waste as either single stream recycling (SSR) or dual stream recycling (DSR). Single stream recycling is where the materials come from a single source and is normally considered as “dirty”, whereas dual stream recycling is where the materials have been sorted by the consumer or commercial source and comes to the facility as “clean”. Over the last ten plus years, SSR has increased in popularity due to its ease in using just one recycling bin, as opposed to 2 or more recycling bins. This has attracted more participation and it has also reduced the cost for recycling companies. In the U.S., SSR has increased from 22% in 2005 to 73% in 2014, and of the MRFs built since 2007, 77% are SSR facilities (Damgacioglu et al., 2020).

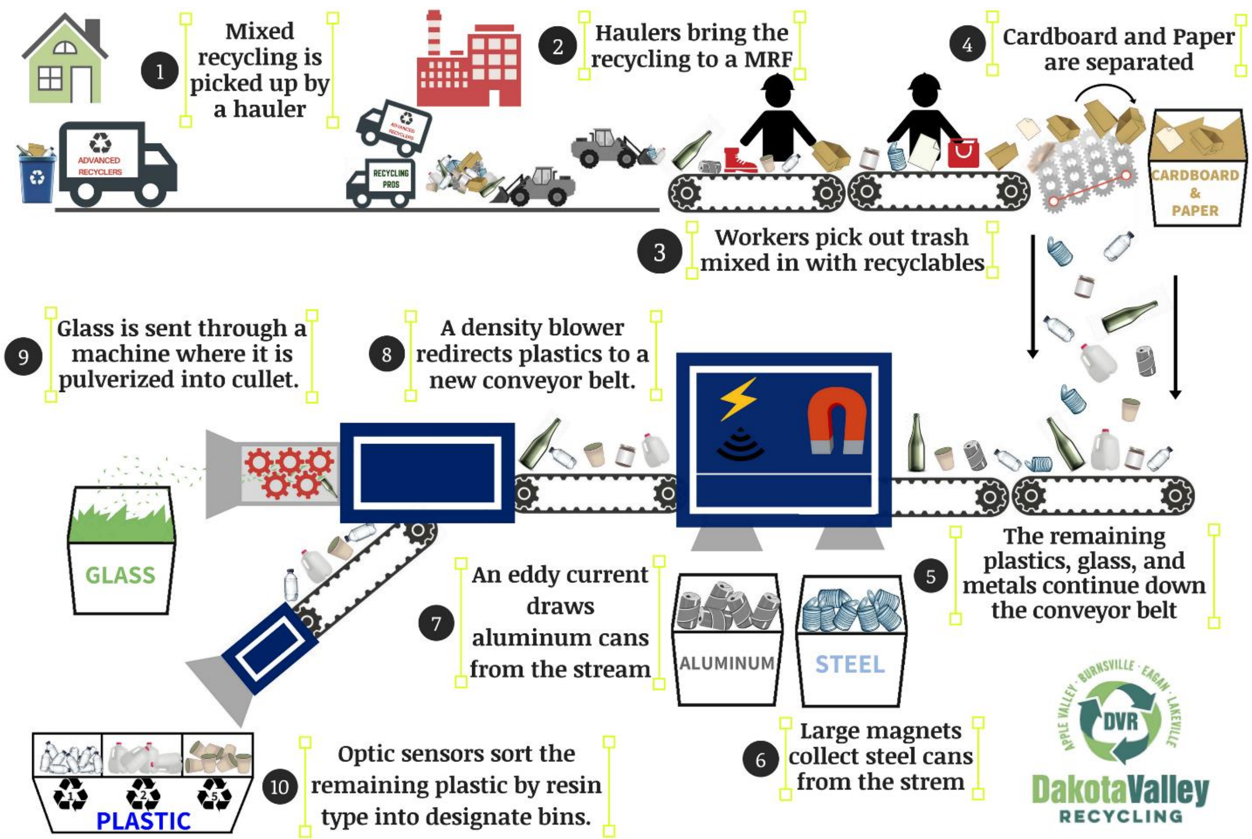


Figure 2.19: Diagram of Materials Recovery Facility (MRF) (www.dakotavalleyrecyclingmn.govcom)

CHAPTER THREE: METHODOLOGY

3.1 Introduction

The purpose of this research is to use a two-part strategy to calculate avoided GHG emissions emitted from landfills while calculating potential energy production from the landfill, then performing a comparison of the WARM and LandGEM models for both emissions and energy potential. The data source for this study will be historical data from an existing landfill in Alabama. Two models will use the data to calculate the GHG emissions and the amount of methane that the landfill will generate. The WARM model will calculate the emissions rate and the rate change when alternatives are utilized instead of one hundred percent landfilling of materials. The WARM model uses a life cycle approach in its evaluation. The LandGEM model calculates the actual direct methane from the landfill, along with other emitted gases, which can then calculate potential energy by way of an energy potential equation. The energy potential will provide an answer in kilowatts per hour, which will then convert to BTUs. The landfill will provide data testing the hypothesis and the three research questions.

3.2 Research Design

The focus of this study is to evaluate two models that provide emissions data but present the findings in different perspectives. The objective is to create a standardized method for cases when alternative methods of waste management are limited and landfilling is the conventional option, which in turn will simulate the largest quantity of emissions possibly avoided, the largest possible energy savings, and greatest renewable energy potential. That method will also review which new technologies can also be incorporated into the discussion to assist with both maximum GHG avoidance and energy savings. With the calculation of methane generated from the LandGEM model, options for utilizing the energy potential will be analyzed, along with an evaluation of emissions from the WARM model, to determine energy potential, and provide a comparison.

3.2.1 Data Source

The entity for the focus of this study is the sanitary landfill for Montgomery County, AL and the landfill data for this research was extracted from the Alabama Department of Environmental Management (ADEM) website.

3.2.2 Data Timeline

The timeline for the data that was collected for this research is January 1993 through December of 2022. The MSW data that was utilized for calculating percentages of material was from EPA data from the last year produced, which was 2018.

3.2.3 Research Sequence

The research was performed in multiple steps, culminating with answering the research questions that were presented in Chapter 1. The first phase in the research was to accumulate the data from the Alabama Department of Environmental Management's (ADEM) website for the County of Montgomery, AL sanitary landfill.

The second phase of the research was utilizing the EPA's website containing data pertaining to waste generation in the United States. This website, which has data through the year 2018, presented a breakdown of the total waste generated by material. The total waste generated data was calculated into a percentage by material and then transferred to an Excel spreadsheet.

The third phase of the research was to take the landfill data from Montgomery County, AL, and place it into the Excel spreadsheet to determine the percentage of each material by weight. The Excel spreadsheet was formulated the same as the WARM model, to make for easy transferring of data. This phase was necessary due to the WARM model having individual materials segmented out and calculating the avoided GHG emissions by the weight of those individual materials.

The fourth phase of the research was to create various scenarios for the theoretical and actual models. From there the tonnage would be placed into each waste management category by material to generate results.

The fifth phase of the research was to transpose the data from the Excel spreadsheet and place it in the WARM model. The WARM model has two options that can be utilized. The first option is to place the data in the web application, while the second option is the Excel spreadsheet option, The Excel spreadsheet option was chosen to it being a simpler option to transpose the data from the Excel spreadsheet that was created to the WARM model.

The sixth phase of the research was to take the calculations from the WARM model and place the data into the spreadsheet to perform a GHG emissions analysis, an energy analysis, and a wage analysis, for the multiple scenarios that corresponded to the theoretical and actual research components. This data was then entered into a second spreadsheet, selecting the most appropriate numbers, and then graphing the data.

The seventh phase of the research after the analyzation of the WARM model results, was to place the raw landfill data acquired in the first phase into the LandGEM model to begin calculations of the methane generation over an established period. The LandGEM model accepts inputs to include the opening and closing of the landfill, or the model can perform the closing year calculation for the landfill. The model also allows for the changing of variables, i.e., methane generation rate, potential methane generation capacity, non-methane organic carbon (NMOC) concentration, and methane content. The standard variables are aligned with the Clean Air Act (CAA) regulations; however, the variables can be changed to include wet conditions, which will result in the generation of more gas at a faster rate. Once the data and variables are input, the model will perform calculations to include total landfill gas, methane, carbon dioxide, and NMOC.

The seventh phase of research after performing the calculations with the LandGEM model, was to introduce the emissions results from the WARM and LandGEM models into the energy potential equation to generate results.

3.3 Model Structures

This section will describe the models that were utilized in the research and its application for each research question.

3.3.1 WARM Model

The WARM Model will be used to answer research question number one in combination with the template shown in Figure 3.2. As stated in section 3.2, once the landfill data has been collected, the parameters or boundaries for the calculations can begin. The user, in this case, the researcher, begins to review a series of steps after inputting the data accordingly. WARM gives the user the opportunity to create multiple scenarios to determine be best option for avoidance or reduction of GHG emissions.

Step one, which is the left side of the analysis inputs (Figure 3.4), allows the user to describe the baseline waste generation and management for their selected MSW program. The user has the option to omit materials that are not generated in their community or materials they do not want to analyze. The options for the waste management scenario weights must equal the tonnage generated.

Step two, which is the right side of the analysis inputs section (Figure 3.4), allows for the user to create alternative scenarios for waste management that was created in the baseline. The only addition that was not in the baseline scenario is the tons source reduced. Also, the model states that when generation is increased, then that additional waste should be entered into the source reduced column as a negative value. When generation is decreased, that decreased value should be entered under the source reduced column as a positive number.

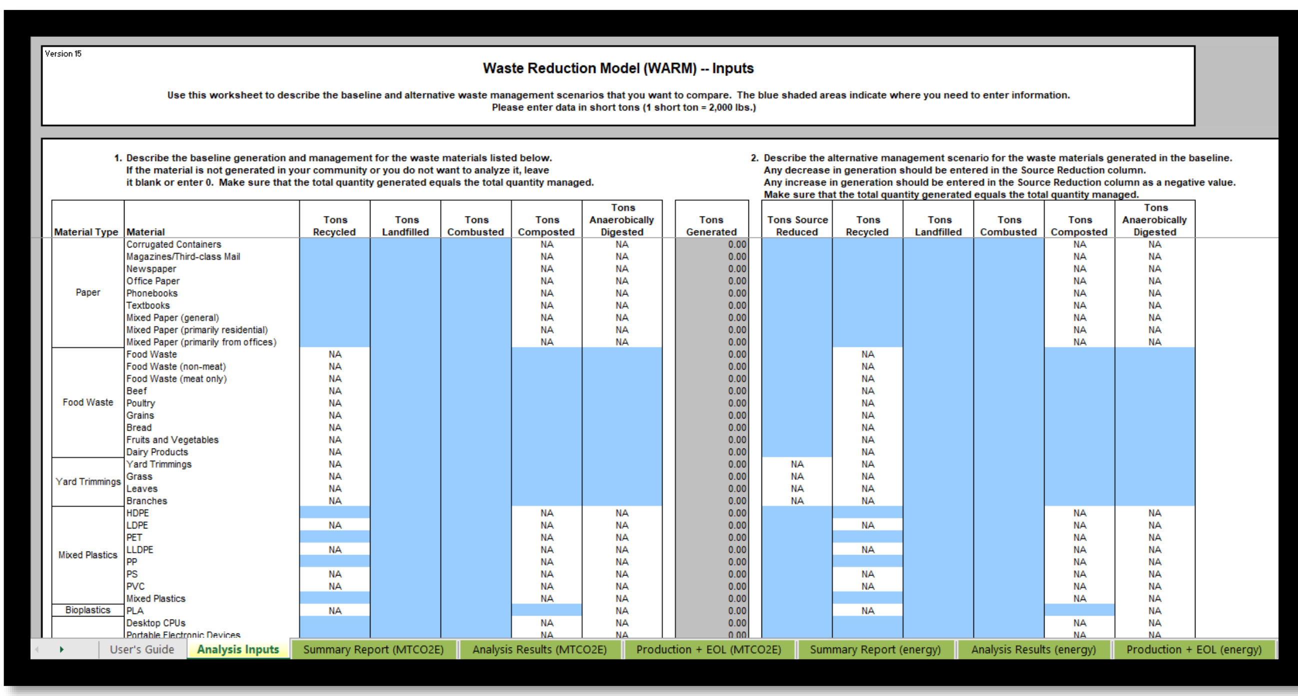


Figure 3.4: Steps one and two of WARM analysis inputs (US EPA, 2016a)

Step three in the inputs segment is the selection of either the individual state that the waste management is taking place in, or a national average can be utilized (Figure 3.5). This selection is for the avoidance of electricity-related emissions in the landfilling and combustion pathways. The EPA will assign the appropriate regional marginal electricity grid mix emission factor that is based on the location of the solid waste management system.

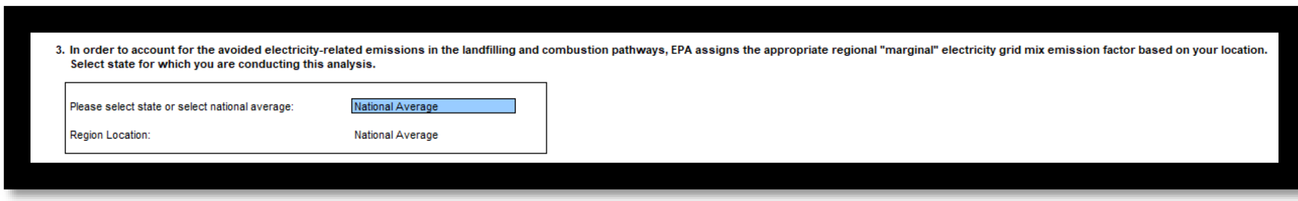


Figure 3.5: Step three of WARM analysis inputs (US EPA, 2016a)

The fourth step in the inputs segment allows for the choosing of whether material related to source reduction would come from a mix of virgin and recycled materials, or one hundred percent (100%) virgin materials (Figure 3.6). The model notes that "the source reduction benefits of both the "current mix" and "100% virgin" inputs are the same (US EPA, 2016).

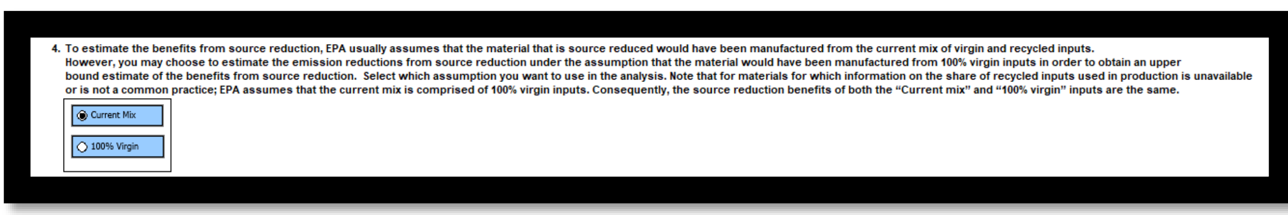


Figure 3.6: Step four of WARM analysis inputs (US EPA, 2016a)

The fifth step is determining whether the landfill has a landfill gas (LFG) control system in place (Figure 3.7). This selection will allow for the calculation of emissions from the landfill. If the user does not know if an LFG control mechanism is currently in place, then they can select the “National Average” option. The user can then also choose if for LFG recovery or no LFG recovery. If there is LFG recovery, then the user moves to step 6a, if not, then they move to step eight (8). When the user answers question 6a, they move to question 6b, which will allow the user to select the landfill gas collection efficiency, ranging from typical operation to California regulatory collection requirements (Figure 3.8).

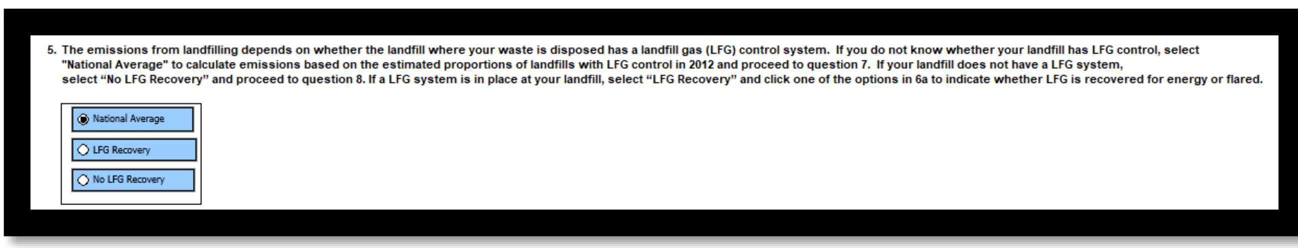


Figure 3.7: Step five of WARM analysis inputs (US EPA, 2016a)

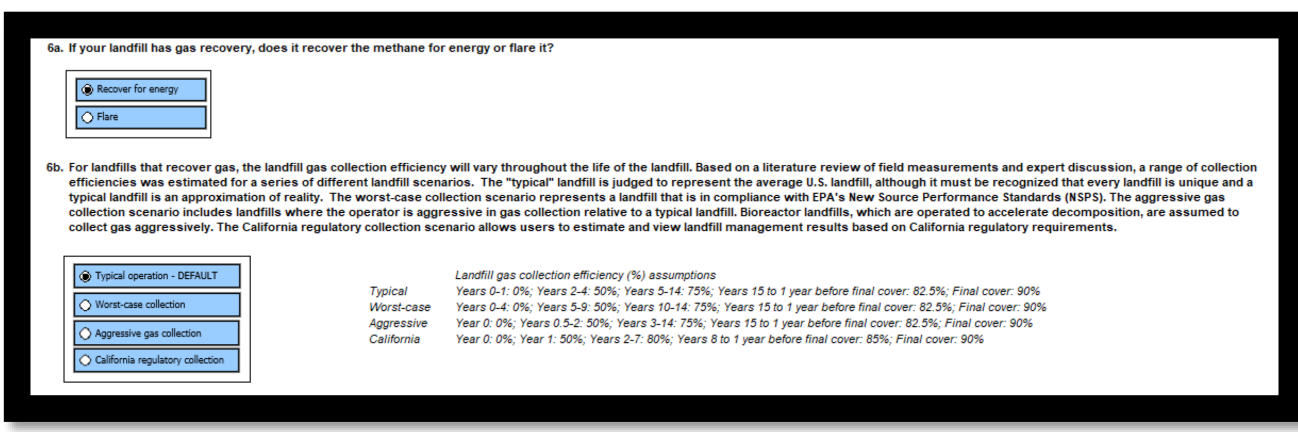


Figure 3.8: Step five of WARM analysis inputs (US EPA, 2016a)

The sixth step, which is operating under the assumption that the landfill has an LFG recovery system, allows for the user to choose moisture conditions, which is associated with the decay rate (Figure 3.9). The decay rate (k) defines the rate of change per year of organic waste decomposition. The higher the k value, the faster the decomposition of waste takes place in the landfill. The rates range from the default, national average of 0.01 to a bioreactor decay rate of 0.12.

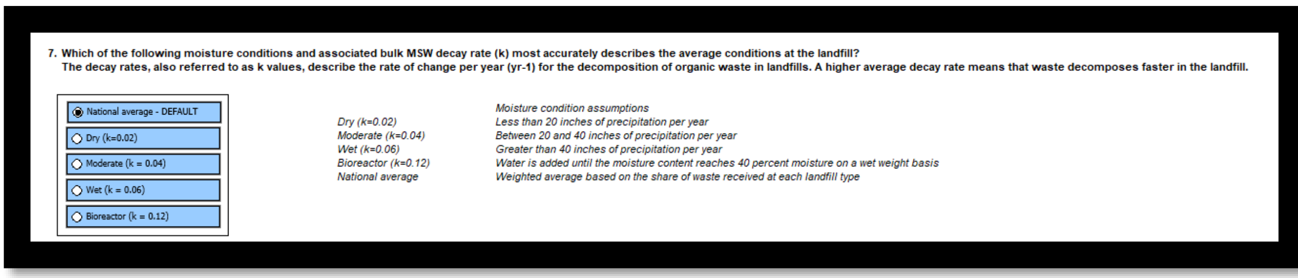
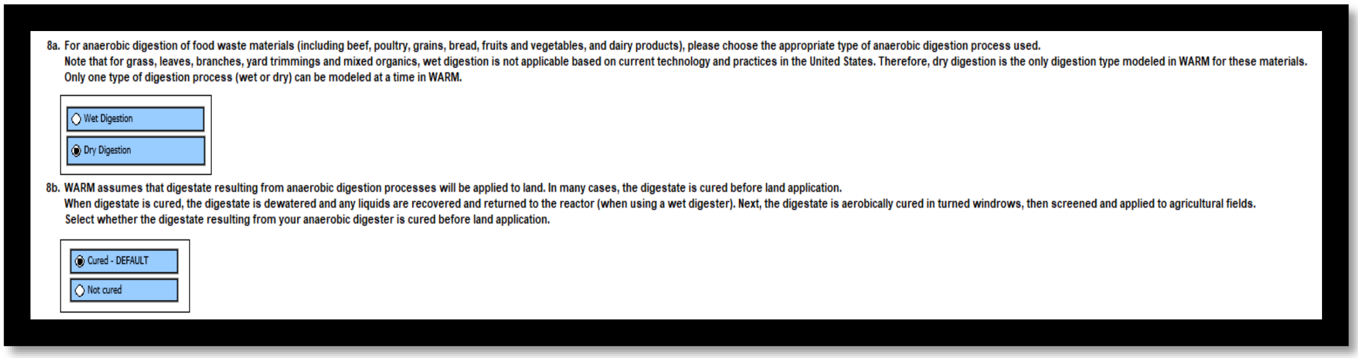


Figure 3.9: Step six of WARM analysis inputs (US EPA, 2016a)

The seventh step, or 8a, asks for the user to choose which process is to be utilized in the anaerobic digestion method (Figure 3.10). Due to current technology, the wet digestion process cannot be modeled for items such as leaves, grass, branches, yard trimmings, or mixed organics, due to that method not being in practice nor having the technology for it here in the United States. For the materials listed, WARM will only model dry digestion. Section 8b is utilized if there is an anaerobic digester utilized (Figure 3.10). The normal practice is that the digestate will be cured before applying it back to the land. The options for anaerobic digestion are either cured, which is the default, or not cured. This option is only available for food waste and yard trimmings.



8a. For anaerobic digestion of food waste materials (including beef, poultry, grains, bread, fruits and vegetables, and dairy products), please choose the appropriate type of anaerobic digestion process used.
Note that for grass, leaves, branches, yard trimmings and mixed organics, wet digestion is not applicable based on current technology and practices in the United States. Therefore, dry digestion is the only digestion type modeled in WARM for these materials.
Only one type of digestion process (wet or dry) can be modeled at a time in WARM.

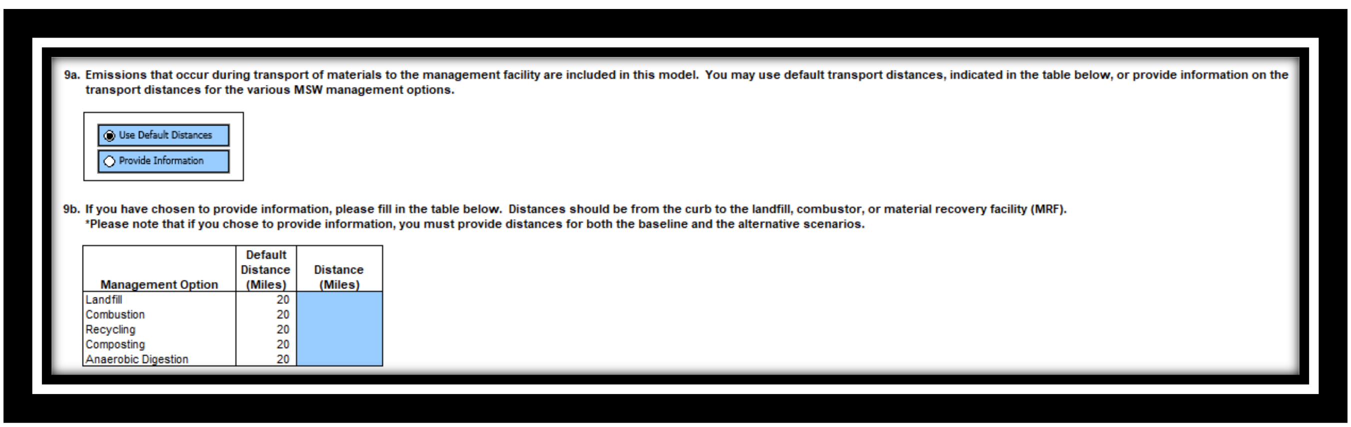
Wet Digestion
Dry Digestion

8b. WARM assumes that digestate resulting from anaerobic digestion processes will be applied to land. In many cases, the digestate is cured before land application.
When digestate is cured, the digestate is dewatered and any liquids are recovered and returned to the reactor (when using a wet digester). Next, the digestate is aerobically cured in turned windrows, then screened and applied to agricultural fields.
Select whether the digestate resulting from your anaerobic digester is cured before land application.

Cured - DEFAULT
Not cured

Figure 3.10: Step seven of WARM analysis inputs (US EPA, 2016a)

The eighth step, 9a, provides the input into the emissions that are generated during the transport of materials to the waste management facility (Figure 3.11). There are options to either use the default distance of twenty (20) miles, or proceed to step 9b, which is to provide the distance for each management option from curb to facility (Figure 3.11).



9a. Emissions that occur during transport of materials to the management facility are included in this model. You may use default transport distances, indicated in the table below, or provide information on the transport distances for the various MSW management options.

Use Default Distances
Provide Information

9b. If you have chosen to provide information, please fill in the table below. Distances should be from the curb to the landfill, combustor, or material recovery facility (MRF).
*Please note that if you chose to provide information, you must provide distances for both the baseline and the alternative scenarios.

Management Option	Default Distance (Miles)	Distance (Miles)
Landfill	20	
Combustion	20	
Recycling	20	
Composting	20	
Anaerobic Digestion	20	

Figure 3.11: Step eight of WARM analysis inputs (US EPA, 2016a)

3.3.2 WARM Model Analysis

Once the last step is completed, WARM has several tabs that provide information including summary reports on GHG emissions avoided, energy saved, labor, and wages. The avoided GHG emissions, energy savings, and a wage analysis page is created from the calculated data. The data is then placed in the spreadsheet for each scenario covered, which highlights the scenario which provided the most avoided GHG's, energy savings, and wage increases.

3.3.3 LandGEM Model

The Landfill Gas Emissions Model (LandGEM) first utilizes a series of inputs at the beginning of the modeling process to give an identity and size to the landfill. The items needed are landfill name, the open year, the closing year, which can be entered by the user or calculated by the model if closure year is not known, and waste design capacity (Figure 3.12).

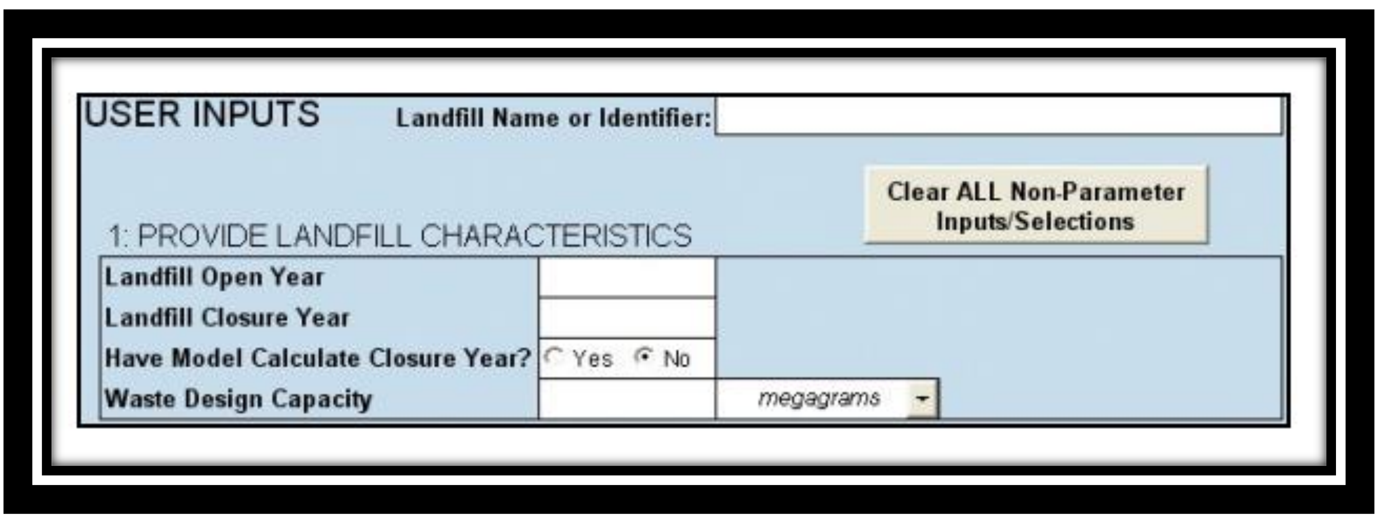


Figure 3.12: Step one of LandGEM model inputs (US EPA, 2005)

The next section of the model is to determine its parameters which include the methane generation rate (k), the potential methane generation capacity (L_0), the NMOC (non-methane organic compound concentration) concentration, and the methane content. The model parameters input is seen in figure 3.13.

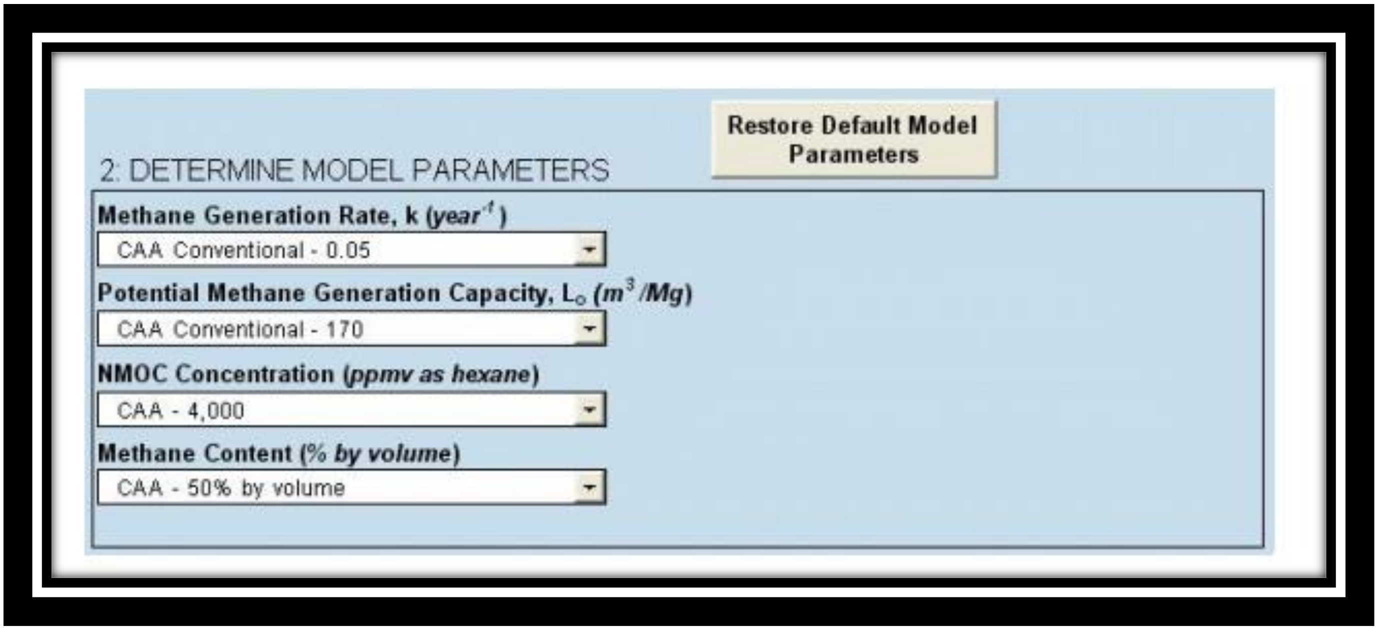


Figure 3.13: Step two of LandGEM model inputs (US EPA, 2005)

The third step in the LandGEM inputs is the choosing of gases or pollutants. When this section is being completed, up to four can be modeled at one time. For this study, the methane, carbon dioxide, total gases, and NMOCs were selected. Figure 3.14 displays this section of inputs.

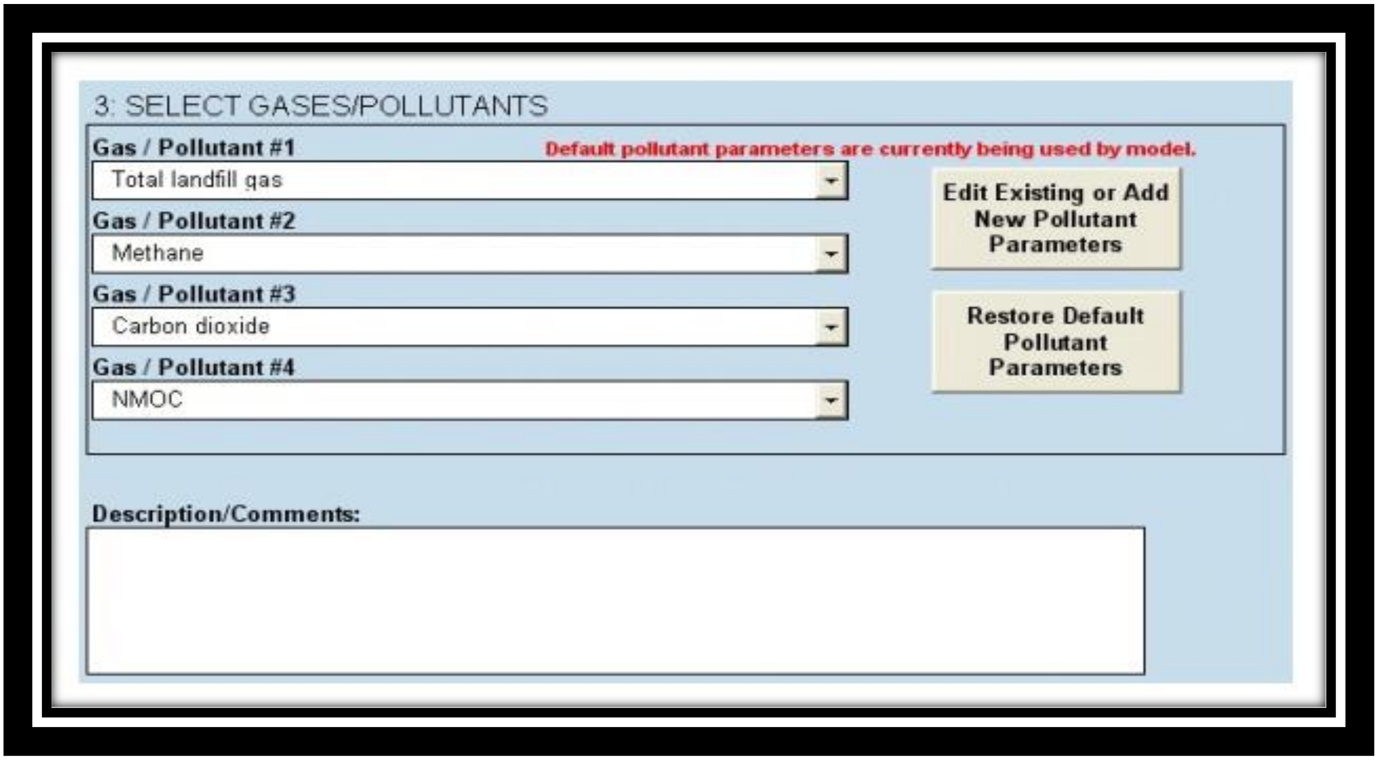


Figure 3.14: Step three of LandGEM model inputs (US EPA, 2005)

The fourth step in the LandGEM model input is the entering of the waste, which can be entered as either Megagrams per year or short tons per year. Once this data has been entered, a summary review of the inputs will appear (Figure 3.15).

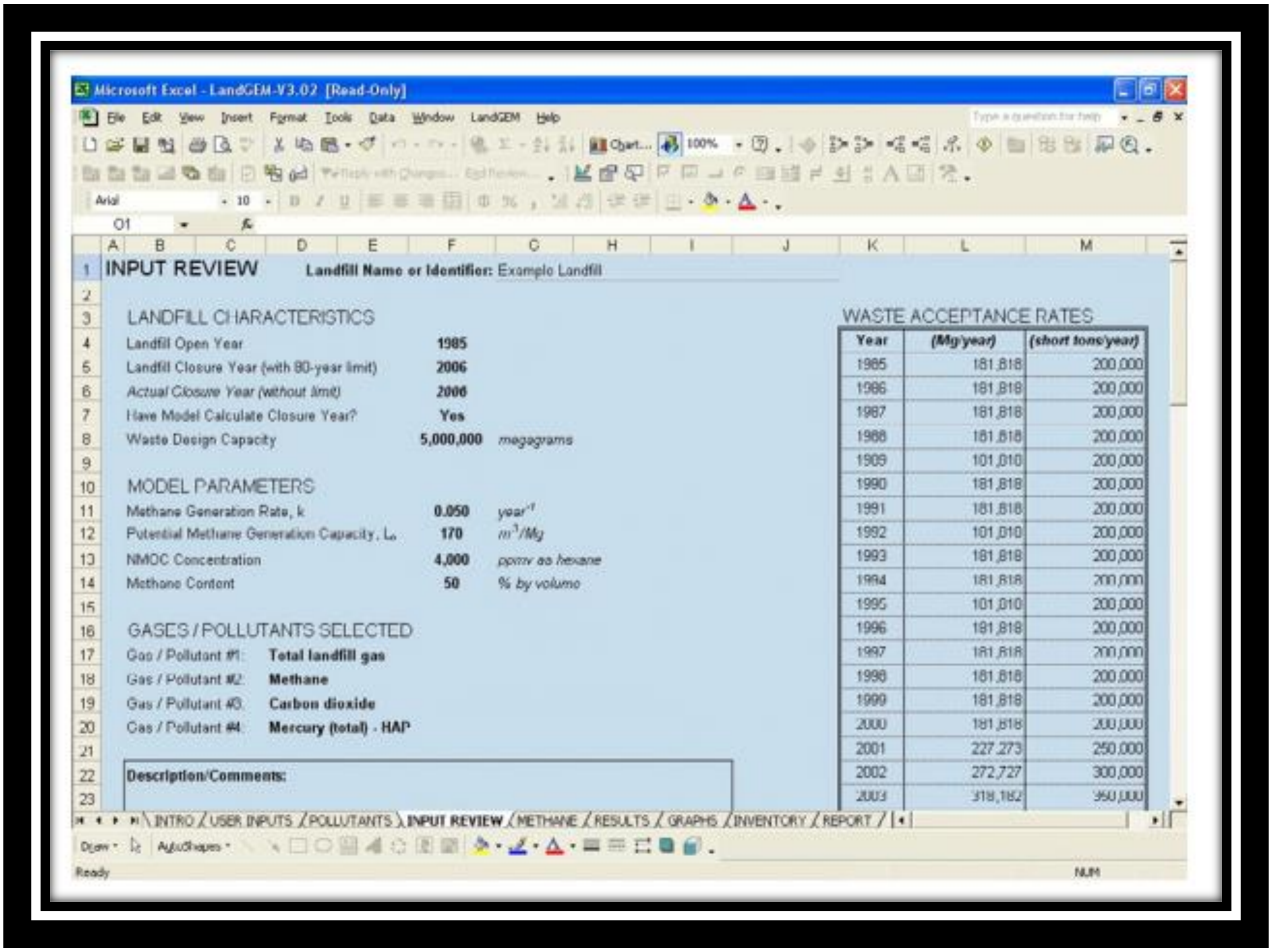


Figure 3.15: Step four of LandGEM model inputs (US EPA, 2005)

The final step of the model is the results page which gives the emissions estimates in the Excel spreadsheet format. The gases or pollutants that were selected in the third step are displayed on the results page as seen in Figure 3.16.

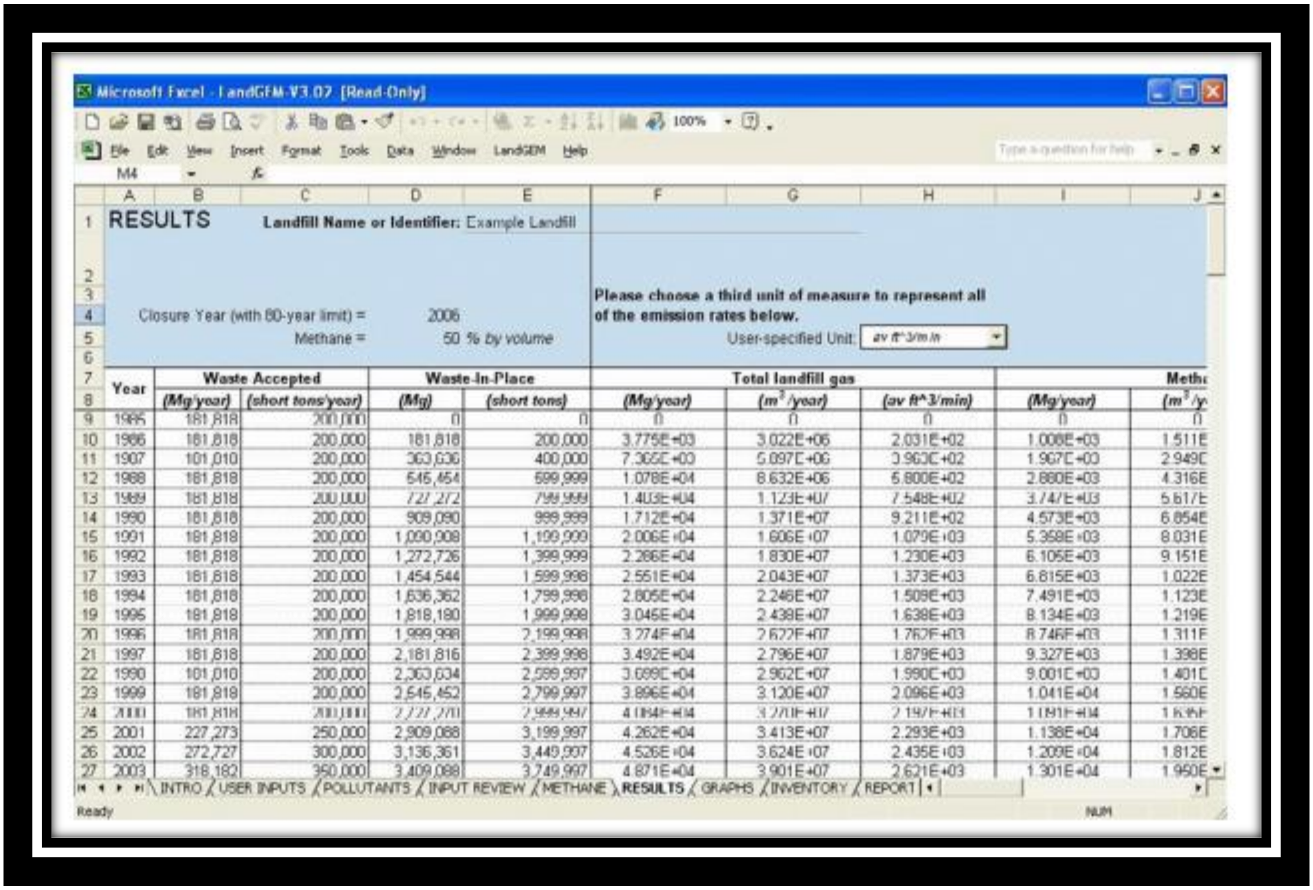


Figure 3.16: Step five of LandGEM model inputs (US EPA, 2005)

3.3.4 Energy Potential

Once the data from the results page in the LandGEM model has been obtained, the methane output will be used to attempt to quantify or calculate the potential energy from the landfill gas. A 2022 publication and study by Ramprasad and others researched the quantification of landfill gas emissions and energy production potential utilizing the LandGEM model. The study used landfill data for the years 2010 through 2019 and the emissions from the landfill were determined by the LandGEM model (Ramprasad et al., 2022). The energy potential equation is as follows:

$$E_p \text{ (kWh per year)} = \frac{LHV * Q_{rg} * E_e * E_r}{\gamma_i}$$ *Equation 3.1*

Where,

E_p is the energy potential that can be obtained by the methane gas in kWh per year

Q_{rg} is the quantity of recoverable methane gas emitted from the landfill site in cubic meter per year

LHV is the low heating value of the methane gas in MJ per cubic meter

E_e is the electrical combustion efficiency of the engine element (ICM) in percentage

E_r is the efficiency of the methane recovery in percentage

γ_i is the conversion factor from MJ into kWh (1 MJ is equal to 0.278 kWh)

(Ramprasad et al., 2022)

In the study by Ramprasad and others, they took the above equation and combined values from a study by Chandrasekaran and Busetty in 2022 to modify the equation to use a coefficient and constant value to convert from MJ to kWh. The new equation is,

$$E_p = \frac{0.9 * Q_{methane} * LHV_{methane} * \eta * \lambda}{3.6}$$ *Equation 3.2*

Where,

η is the combustion efficiency of the engine element (ICM) in percentage

λ is the efficiency of the methane recovery in percentage

3.6 is the conversion factor from MJ to kWh

0.9 is a constant value

3.4 Assumptions and Limitations

Landfill emissions and methane production are subjects that have been studied for quite some time in various fashions. However, in the United States, with the move to further reduce GHG emissions and produce cleaner energy, the need to perform additional studies to assist with these changes is needed. The research performed in this study made assumptions to generate reasonable data and conclusions.

Some of the assumptions that were made were regarding the research were:

- The percentages regarding the material distribution were pulled from EPA data (US EPA, 2018), as the makeup of material percentages within the studied landfill was unknown.
- In the theoretical modeling, an assumption was made that one hundred (100) percent of materials were utilized in each waste management scenario.
- In the actual modeling, an assumption was made that the landfill utilizes a typical gas collection efficiency due to that information not being published.
- In each WARM model analysis, the default distance was utilized instead of specific distances. In future research, specific distances would generate different outcomes for each pathway.
- The LandGEM model did not have the same corresponding k value, 0.06, as the WARM model, so the default value of 0.05, which is a conventional landfill, was used.
- The potential energy calculation used a combustion efficiency (η) of 40%, a methane recovery efficiency (λ) of 70%, and a lower heating value (LHV) of 18, following the same parameters as the study by Ramprasad and others.

There were a few limitations within the research and the modeling of the waste management which are as follows:

- The WARM model produced data one year at a time, compared to multiple year generation of data from the LandGEM model.
- Not knowing the exact makeup of the MSW could create possible problems with tonnage issues on both the generated side, depending on the makeup, and on the alternative side.

CHAPTER FOUR: MODELING RESULTS

4.1 Introduction

Chapter four will present the data that was computed from the insertion of the waste tonnage into the models, beginning with a theoretical calculation to determine the best waste management practice for certain materials. This step will correspond to research question number 1. The next step in the modeling phase will use the current waste management practices for the State of Alabama and Montgomery County, AL, while employing the waste tonnage from the landfill, to determine which waste management practice will correspond to research question number 2. The data will conclude with the energy potential production, corresponding to research question number 3.

The basis for the modeling was the Montgomery County Landfill located in Montgomery County, Alabama. This landfill accepts approximately 116,000 tons per year municipal solid waste as seen in Figure 4.1

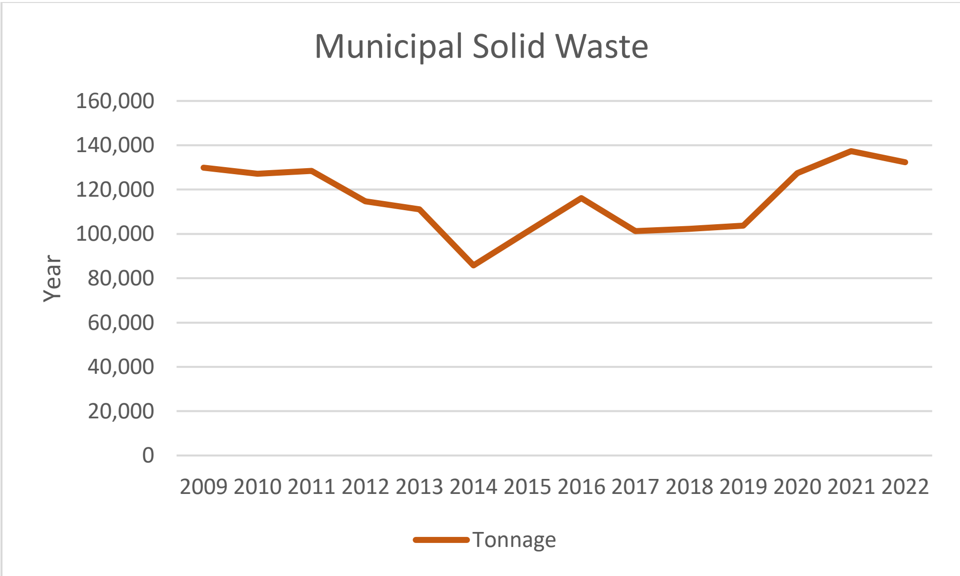


Figure 4.1: MSW annual tonnage - Montgomery County, AL landfill (M. Richburg 2023)

4.2 WARM Model Data

There are several technologies used to treat MSW, which include biochemical and thermochemical processes. While landfilling is a more cost-effective method of waste disposal, there can be impacts on water, soil, and air, particularly if there is no recovery for energy production occurring (Engelmann et al, 2022).

In the theoretical analysis of the MSW using the WARM model, the components were segmented into the type of material and the waste management scenario and its alternatives. Since the Montgomery County Landfill does not segregate and measure the quantities of each type of material it collects, as stated in Chapter 3, EPA data was used to estimate the various quantities of each type of material accepted into the landfill. Monthly averages for the year 2022 are given in Table 4.1. The impact of each material with regards to emissions avoided, energy potentially saved, and the wages associated with the waste management scenario was calculated for landfill with and without gas recovery. Baseline numbers for the current landfill operation without landfill gas recovery are presented in Table 4.2

Table 4.1: Montgomery County, AL landfill 2022 monthly average

Material	Current Landfill Tonnage (Tons)
Paper	2,644
Food Waste	2,743
Yard Trimmings	1,385
Mixed Plastics	1,396
Electronics	103
Metals	1,002

Glass	481
Carpet	132
Tires	252
Mixed MSW	1,683

Table 4.2: Current landfill conditions based upon WARM model calculations

	GHG Emission, MTCO2E	**Energy Use, MMBtu**	**Employment, USD**
Paper	3,750	709	122,025
Food Waste	3,446	663	114,106
Yard Trimmings	297	372	63,918
Mixed Plastics	28	375	64,425
Electronics	2	28	4,753
Metals	20	269	46,219
Glass	10	129	22,189
Carpet	3	35	6,073
Tires	5	68	11,621
Mixed MSW	2,138	451	77,652

4.2.1 WARM Model - Theoretical Calculation

This section will outline the data that was modeled in a theoretical manner to determine what would be the most impactful options, to achieve the maximum emissions avoidance, potential energy savings, and wage impact for various materials. During the modeling, some materials could not be managed in the manner as others. For example, the scenario of landfill to recycle could be performed for paper, however this scenario could not take place for food waste due to the material not being recyclable.

The first option of landfill to landfill describes the option of taking no alternative and not capturing or flaring any gas. From this scenario, a baseline waste management number was generated and each alternative was measured from this baseline number to the ending number for the alternative. The change between those numbers would determine the emissions avoidance and energy savings. Negative numbers indicate avoidance and savings, while positive numbers indicate actual emissions emittance and energy used.

4.2.2 Theoretical Paper Data

According to the paper analysis, each waste management alternative creates an avoidance of GHG emissions, except for keeping the material in the landfill, which causes no effect on emissions. There are three options for emissions avoidance with paper: landfilling, recycling, and combustion. Each alternative offers significant avoidance of emissions; however, the largest avoidance of emissions comes from the recycling of paper which is 12,158 MTCO2E as seen in Table 4.3. The change in emissions comes from calculating the number of emissions avoided of the alternative minus the emissions generated from the baseline method of waste generation. A positive number indicates that emissions are given off from the waste management method, while a negative number indicates that emissions are avoided with that method. A graphical representation of the chart is shown in Figure 4.2 which highlights the scenarios and the change in emissions between the alternative and baseline waste management numbers.

Table 4.3: Theoretical GHG emissions avoided - paper

Material	**Waste Management Scenario**	**Baseline Waste Management (MTCO2E)**	**Alternative Waste Management (MTCO2E)**	**Change (Alt. – Base) MTCO2E**	
Paper					
	Landfill to Landfill	3,750	3,750	0	
	Landfill to Recycle	3,750	(8,409)	(12,158)	
	Landfill to Combustion	3,750	(1,318)	(5,067)	
	Landfill (no gas rec) to Landfill (with gas rec)	3,750	(378)	(4,128)	

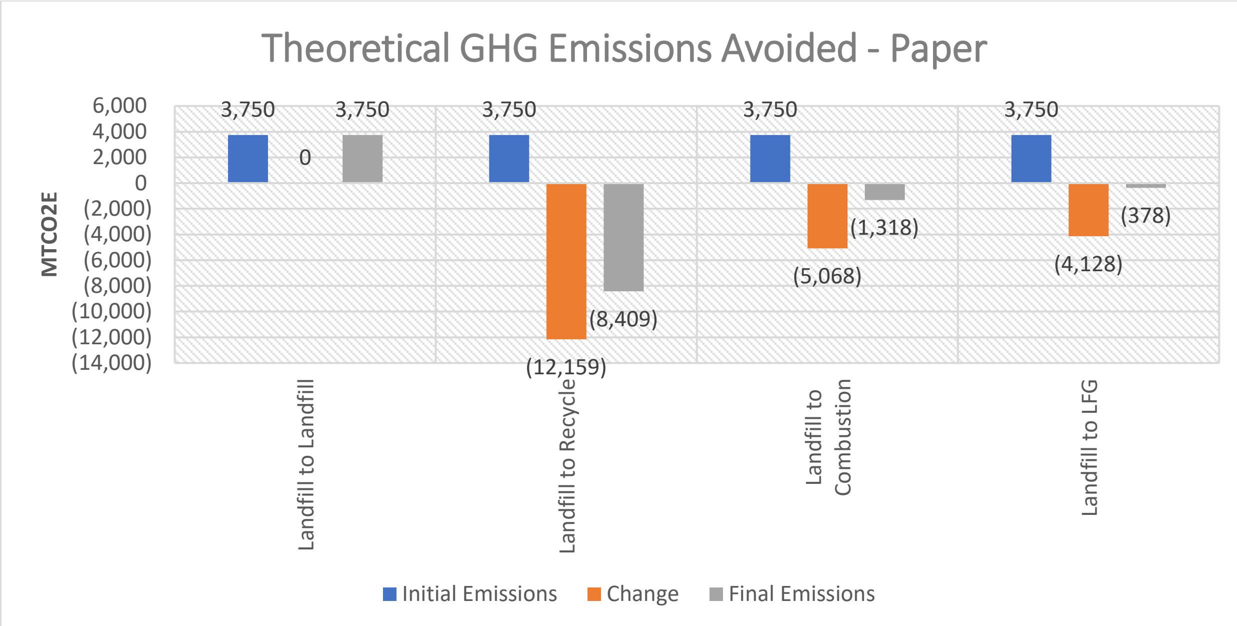


Figure 4.2: Theoretical GHG emissions avoided – paper (M. Richburg, 2023)

The energy savings analysis was performed the same as the emissions analysis, in that a baseline was created by performing a landfill-to-landfill calculation, which resulted in a change of zero (0) million BTU savings. The initial landfill scenario is used as the baseline to compare the alternatives to. As with the potential GHG emissions avoided, landfill-to-recycling represents the greatest potential of energy saved. In the calculation of the energy savings, it is shown in Table 4.4 and graphically represented in Figure 4.3. Utilizing recycling will result in a final energy savings or reduction of 40,079 million BTU.

Table 4.4: Theoretical energy savings - paper

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Paper					
	Landfill to Landfill	709	709	0	
	Landfill to Recycle	709	(40,079)	(40,788)	
	Landfill to Combustion	709	(17,893)	(18,602)	
	Landfill (no gas rec) to Landfill (with gas rec)	709	(647)	(1,356)	

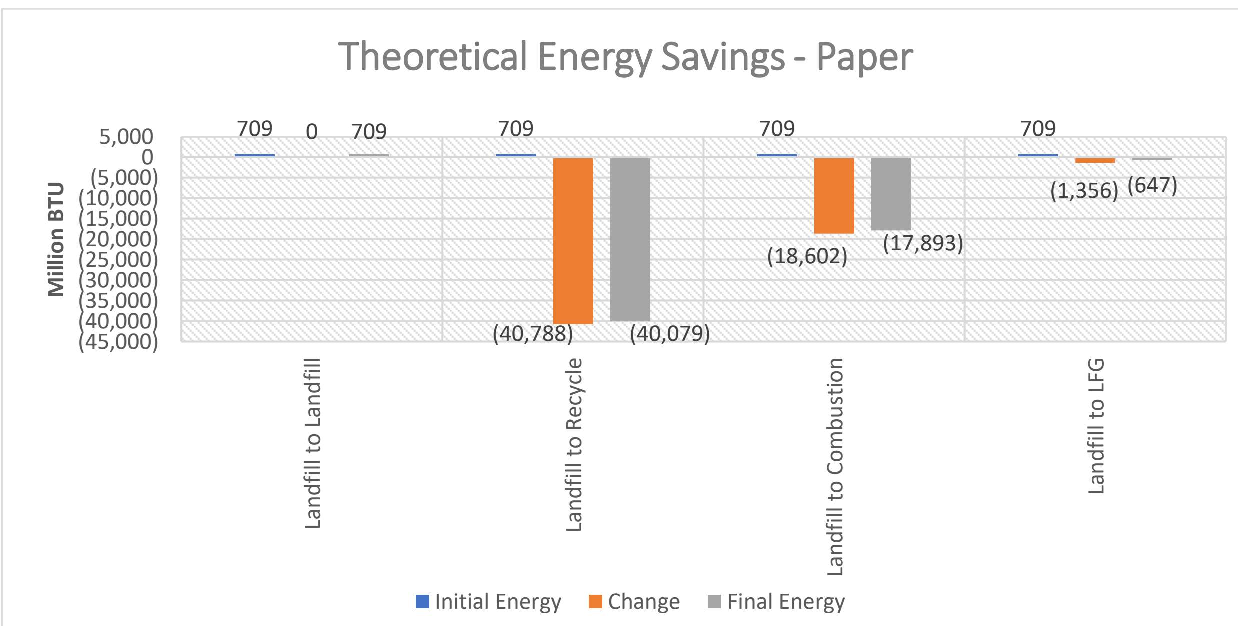


Figure 4.3: Theoretical energy savings – paper (M. Richburg, 2023)

The wage analysis section for paper created a uniform amount across the board, except for landfilling-to-recycling. In the EPA calculations of economic factors for waste disposal, the agency utilized a 2011 Tellus Institute study named "More Jobs, Less Pollution: Growing the Recycling Economy in the U.S." Landfilling and combustion creates smaller impacts on employment, wages, and taxes, as compared to the diversion of waste (US EPA, 2020). For the wage analysis, there are no savings involved in recycling, primarily due to its labor intensity as shown in Table 4.5 and Figure 4.4. In the analysis, recycling offers the only change in wages, an output amounting to $378,683, compared to no change in the other scenarios.

Table 4.5: Theoretical wages impact - paper

Material	**Waste Management Scenario**	**Wages from Baseline Waste Management US Dollar ($)**	**Wages from Alternative Waste Management US Dollar ($)**	**Change (Alt. – Base) US Dollar ($)**	
Paper					
	Landfill to Landfill	122,025	122,025	0	
	Landfill to Recycle	122,025	500,708	378,683	←
	Landfill to Combustion	122,025	122,025	0	
	Landfill (no gas rec) to Landfill (with gas rec)	122,025	122,025	0	

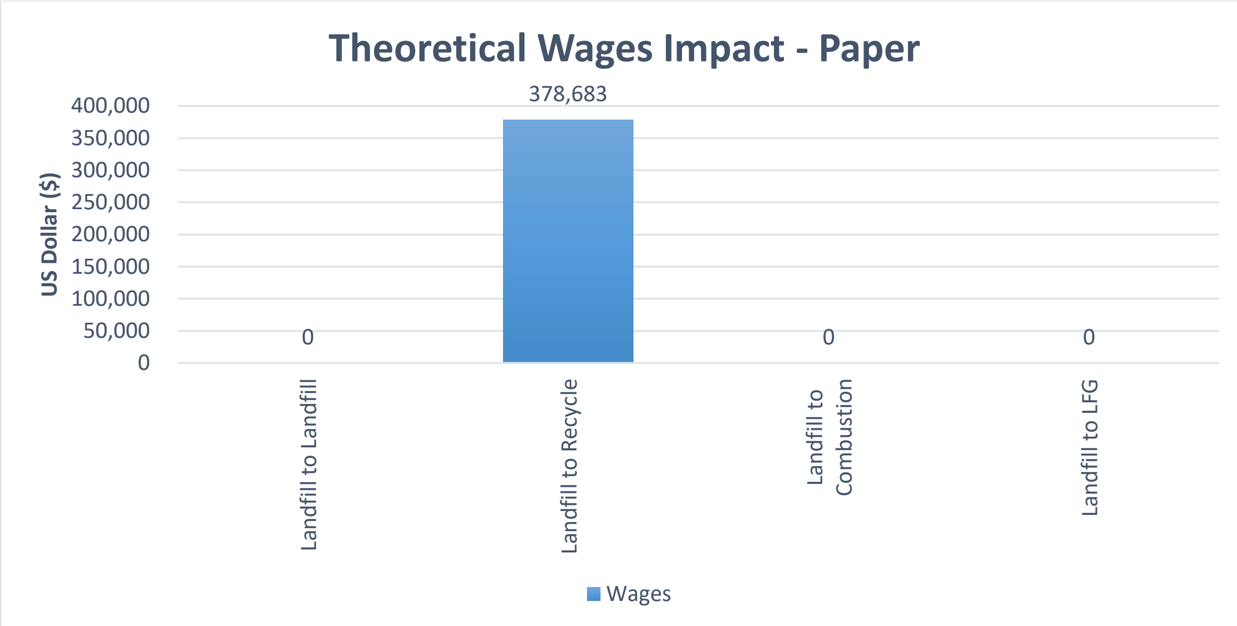


Figure 4.4: Theoretical wages impact – paper (M. Richburg, 2023)

4.2.3 Theoretical Food Waste Data

Food waste is one of the leading producers of methane emissions in landfills. This is due to the anaerobic digestion by bacteria of the waste (Sanciolo et al., 2022). The alternatives to landfilling food waste are combustion, composting, and anaerobic digestion. Another alternative for food waste management is to capture the gas if one of the other options is not chosen. In the analysis of GHG emissions each scenario, except for continuous landfilling with no gas recovery, offers emissions avoidance, however, even if landfilling with gas recovery is chosen, the emissions avoidance does not put the MTCO2E in the negative as compared to the other options. All three options are very similar in the avoidance of emissions, but landfill-to-combustion gives a slightly greater emission avoidance of 3,793 MTCO2E as seen in Table 4.6 and Figure 4.5.

Table 4.6: Theoretical GHG emissions avoided - food waste

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Food Waste					
	Landfill to Landfill	3446	3446	0	
	Landfill to Combustion	3446	(347)	(3,793)	
	Landfill to Compost	3446	(286)	(3,732)	
	Landfill to Anaerobic Digestion	3446	(115)	(3,561)	
	Landfill (no gas rec) to Landfill (with gas rec)	3446	1,000	(2,446)	

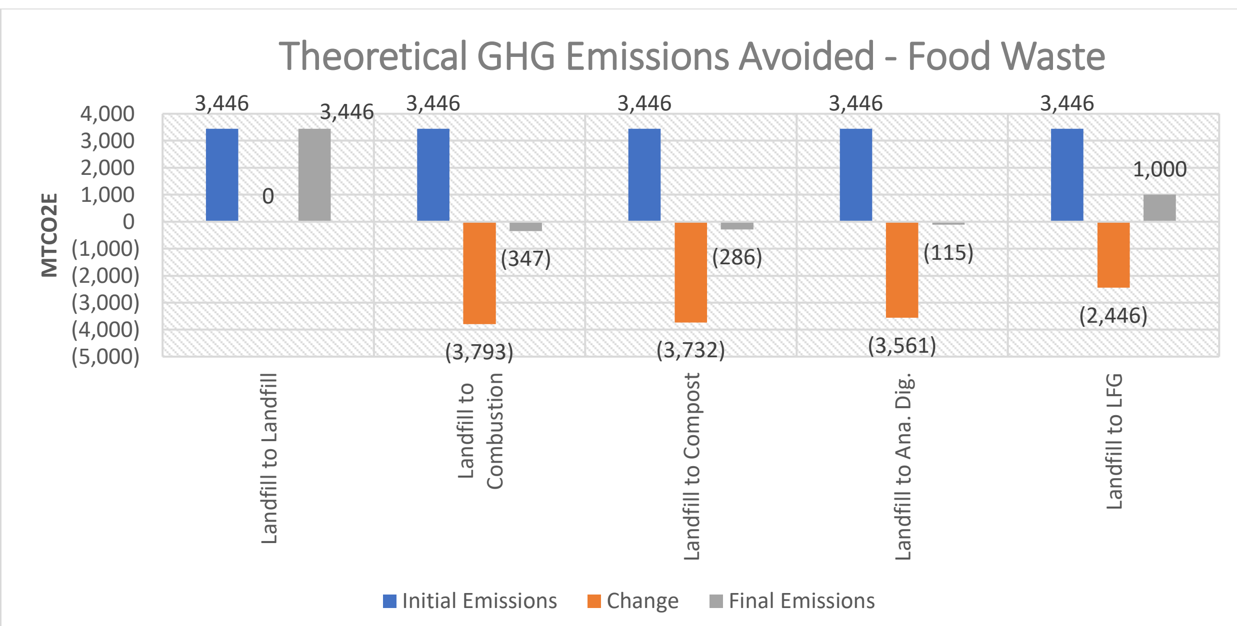


Figure 4.5: Theoretical GHG emissions avoided – food waste (M. Richburg, 2023)

The energy analysis calculations from the WARM model concluded similar results as the possible avoided emissions. Table 4.7 shows that each scenario except for composting, creates energy savings, with combustion having the greatest energy potential savings at 6,386 million BTU. The graphical representation for food waste is shown in Figure 4.6.

Table 4.7: Theoretical energy savings - food waste

Material	**Waste Management Scenario**	**Energy Use Baseline Waste Management Million BTU**	**Energy Use Alternative Waste Management Million BTU**	**Change (Alt. – Base) Million BTU**	
Food Waste					
	Landfill to Combustion	663	(5723)	(6,386)	
	Landfill to Compost	663	1798	1134	
	Landfill to Anaerobic Digestion	663	(3722)	(4385)	
	Landfill (no gas rec) to Landfill (with gas rec)	663	(122)	(785)	

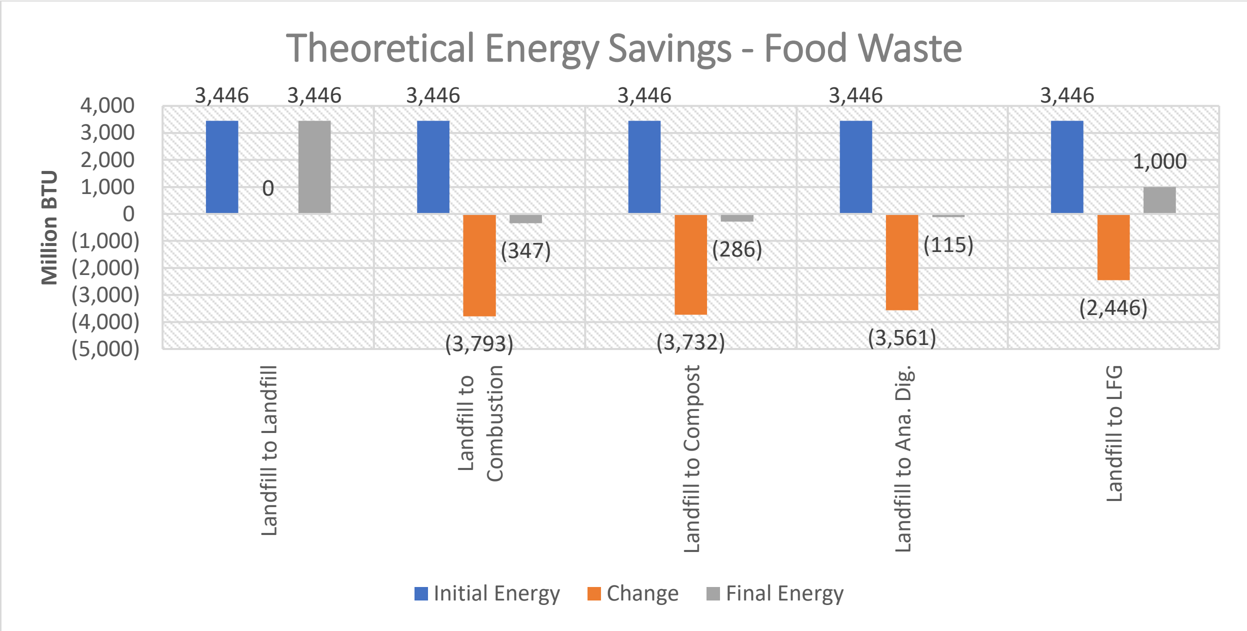


Figure 4.6: Theoretical energy savings - food waste (M. Richburg, 2023)

The wages associated to the waste management of food waste revolve primarily around those items that are not labor intensive. Both composting and anaerobic digestion are considered waste diversion, therefore WARM categorizes these activities as less labor intensive than landfilling and combustion. Both composting and anaerobic digestion do not need the amount of labor that is required for landfilling, thereby these two waste management practices create wage savings of $50,216 for composting and $29,044 for anaerobic digestion. Table 4.8 and Figure 4.7 show the savings and changes compared to each baseline.

Table 4.8: Theoretical wages impact - food waste

Material	**Waste Management Scenario**	**Wages From Baseline Waste Management US Dollar ($)**	**Wages From Alternative Waste Management US Dollar ($)**	**Change (Alt. – Base) US Dollar ($)**	
Food Waste					
	Landfill to Combustion	114,106	114,106	0	
	Landfill to Compost	114,106	63,889	(50,216)	
	Landfill to Anaerobic Digestion	114,106	85,062	(29,044)	
	Landfill (no gas rec) to Landfill (with gas rec)	114,106	114,106	0	

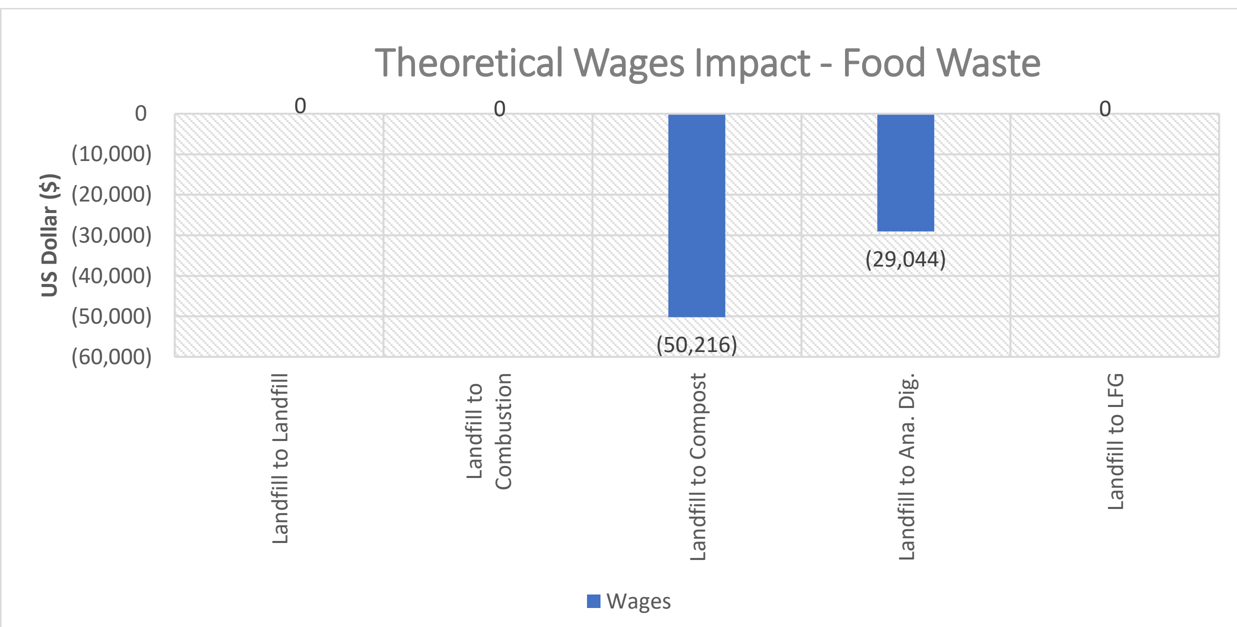


Figure 4.7: Theoretical wages impact – food waste (M. Richburg, 2023)

4.2.4 Theoretical Yard Trimmings Data

The handling of yard trimmings for waste management can be assessed in five different ways. Those ways are landfilling with no gas recovery (landfill-to-landfill), combustion, composting, anaerobic digestion, and landfilling with gas recovery. As it relates to GHG emissions, the methods used a baseline of 297 MTCO2E, which was determined by the WARM analysis of landfill-to-landfill, which is essentially a do-nothing method. When other alternatives are presented, they each provide similar avoidance of emissions as shown in Table 4.9, however, the most effective form of waste management treatment for yard trimmings would be to landfill the material with a gas recovery system. This method shows a change, or avoidance of emissions of 629 MTCO2E, resulting in a final emission of -332 MTCO2E. Figure 4.8 gives a graphical representation of the change in emissions.

Table 4.9: Theoretical GHG emissions avoided – yard trimmings

Material	**Waste Management Scenario**	**Baseline Waste Management (MTCO2E)**	**Alternative Waste Management (MTCO2E)**	**Change (Alt. – Base) MTCO2E**	
Yard Trimmings					
	Landfill to Landfill	297	297	0	
	Landfill to Combustion	297	(241)	(538)	
	Landfill to Compost	297	(74)	(371)	
	Landfill to Anaerobic Digestion	297	(125)	(422)	
	Landfill (no gas rec) to Landfill (with gas rec)	297	(332)	(629)	

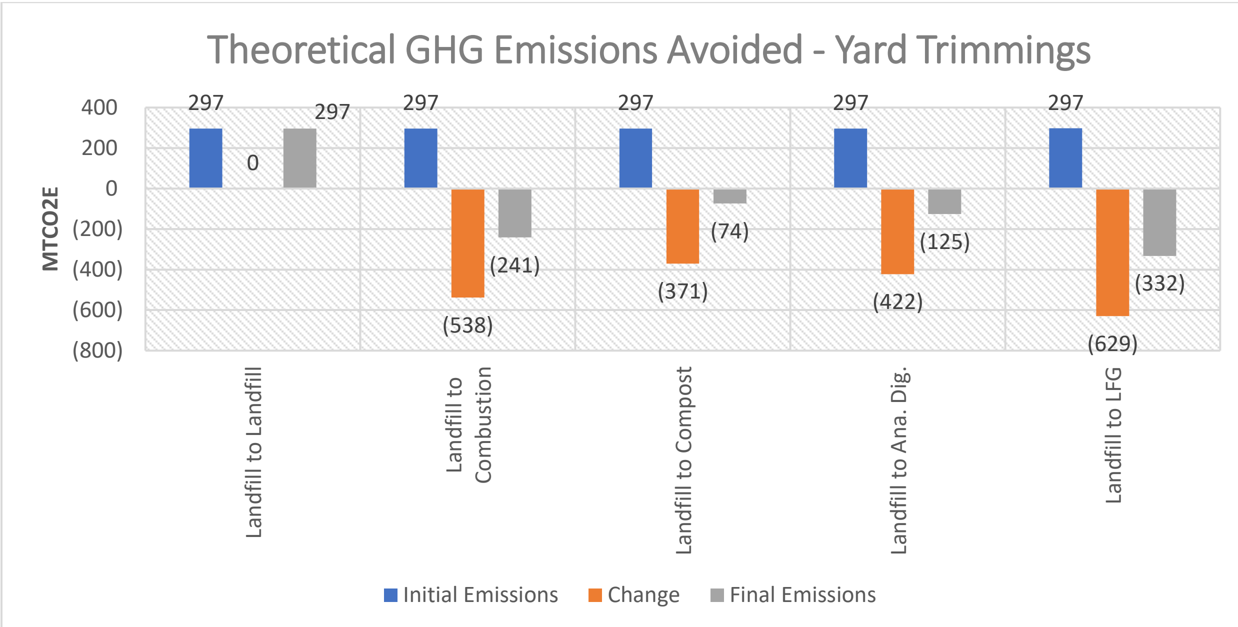


Figure 4.8: Theoretical GHG emissions avoided – yard trimmings (M. Richburg, 2023)

In the analysis of energy savings, the same five methods were used, but the landfill-to-landfill scenario produced a baseline of positive 372 Million BTUs. The WARM method calculated for the energy analysis that the landfill-to-combustion scenario provided the largest change or savings at 4,159 Million BTU. Each method provided an energy savings, but the combustion method proved to be the most significant as shown in Table 4.10 and Figure 4.9.

Table 4.10: Theoretical energy savings – yard trimmings

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Yard Trimmings					
	Landfill to Landfill	372	372	0	
	Landfill to Combustion	372	(3,787)	(4,159)	
	Landfill to Compost	372	358	(14)	
	Landfill to Anaerobic Digestion	372	(257)	(628)	
	Landfill (no gas rec) to Landfill (with gas rec)	372	176	(195)	

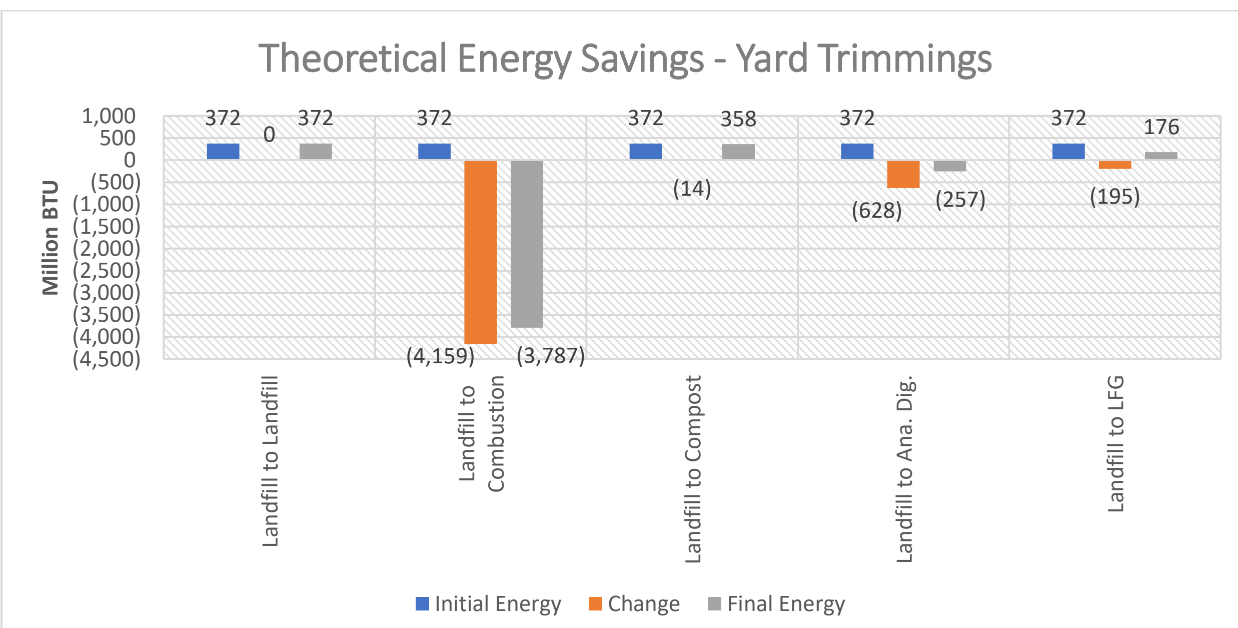


Figure 4.9: Theoretical energy savings – yard trimmings (M. Richburg, 2023)

As for the wage analysis, yard trimmings and the scenarios that are used to manage this type of waste act in the same manner as food waste. Composting and anaerobic digestion are the two waste management methods that provide changes in wages compared to the other methods. Composting provides the largest change in wages at $28,129, while anaerobic digestion provides a change of $19,550 as seen in Table 4.11 and Figure 4.10.

Table 4.11: Theoretical wages impact – yard trimmings

Material	**Waste Management Scenario**	**Wages From Baseline Waste Management US Dollar ($)**	**Wages From Alternative Waste Management US Dollar ($)**	**Change (Alt. – Base) US Dollar ($)**	
Yard Trimmings					
	Landfill to Landfill	63,918	63,918	0	
	Landfill to Combustion	63,918	63,918	0	
	Landfill to Compost	63,918	358	(28,129)	
	Landfill to Anaerobic Digestion	63,918	(257)	(19,550)	
	Landfill (no gas rec) to Landfill (with gas rec)	63,918	63,918	0	

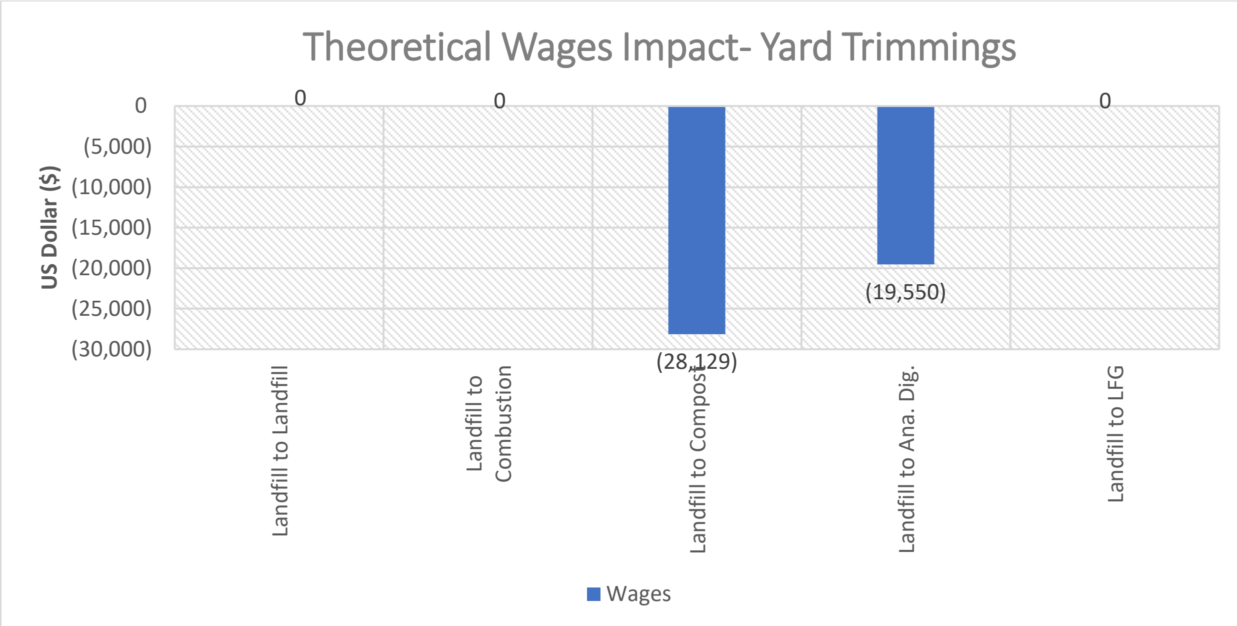


Figure 4.10: Theoretical wages impact – yard trimmings (M. Richburg, 2023)

4.2.5 Theoretical Mixed Plastics Data

Although plastics do not have the emitting values in terms of MTCO2E that paper and food waste have (they do not decompose in the landfill), they are the most common item that come up when emissions are mentioned. The waste management scenarios that are utilized for mixed plastics WARM analysis are landfilling, combustion, recycling/landfilling, recycling/combustion, and landfilling (with no initial gas recovery) to landfilling (with gas recovery). With the recycling/landfilling scenario, the waste was divided into plastics that could be recycled (high-density polyethylene (HDPE), polyethylene terephthalate (PET), polypropylene (PP), and mixed plastics), and ones that could not (low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polystyrene (PS), and polyvinyl chloride (PVC)). For the recycling/combustion scenario, the same plastics that could be recycled were disposed of in that method, while the other forms of plastics were combusted. In the GHG emissions analysis, the scenario that provides the largest avoidance of emissions is landfilling to recycling/landfilling. This scenario provides an avoidance of 822 MTCO2E of emissions. The recycling/combustion provides an avoidance as well, but combustion of plastics does not provide an avoidance of emissions. This data can be found in Table 4.12 and Figure 4.11.

Table 4.12: Theoretical GHG emissions avoided – mixed plastics

Material	**Waste Management Scenario**	**Baseline Waste Management (MTCO2E)**	**Alternative Waste Management (MTCO2E)**	**Change (Alt. – Base) MTCO2E**	
Mixed Plastics					
	Landfill to Landfill	28	28	0	
	Landfill to Combustion	28	1,733	1,705	
	Landfill to Recycle/Landfill	28	(794)	(822)	
	Landfill to Recycle/Combustion	28	(217)	(245)	
	Landfill (no gas rec) to Landfill (with gas rec)	28	28	0	

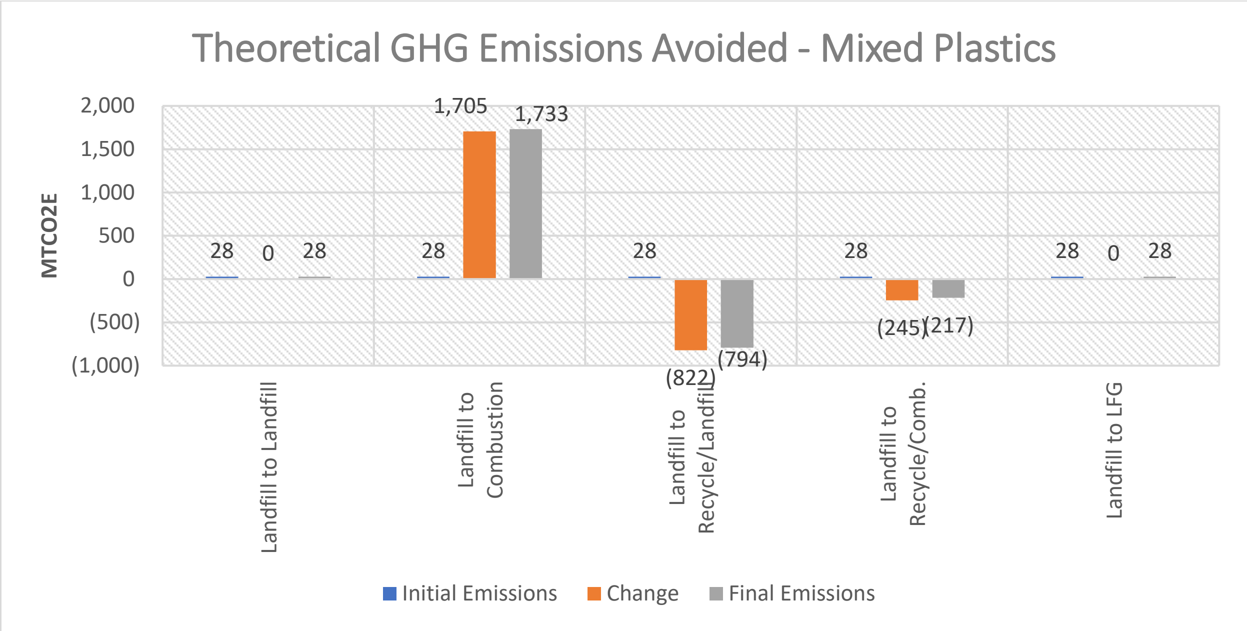


Figure 4.11: Theoretical GHG emissions avoided – mixed plastics (M. Richburg, 2023)

For the analysis of energy savings, only the landfill gas scenarios do not provide a form of energy savings. The combustion, recycling/landfill, and recycle/combustion scenarios provide a large energy savings when utilized. The recycle/combustion method provides the greatest energy savings of 45,606 Million BTU, while the recycle/landfill scenario provides a savings of 37,062 Million BTU, as shown in Table 4.13 and Figure 4.12.

Table 4.13: Theoretical energy savings – mixed plastics

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Mixed Plastics					
	Landfill to Landfill	375	375	0	
	Landfill to Combustion	375	(23,855)	(24,229)	
	Landfill to Recycle/Landfill	375	(36,688)	(37,072)	
	Landfill to Recycle/Combustion	28	(45,231)	(45,606)	←
	Landfill (no gas rec) to Landfill (with gas rec)	375	375	0	

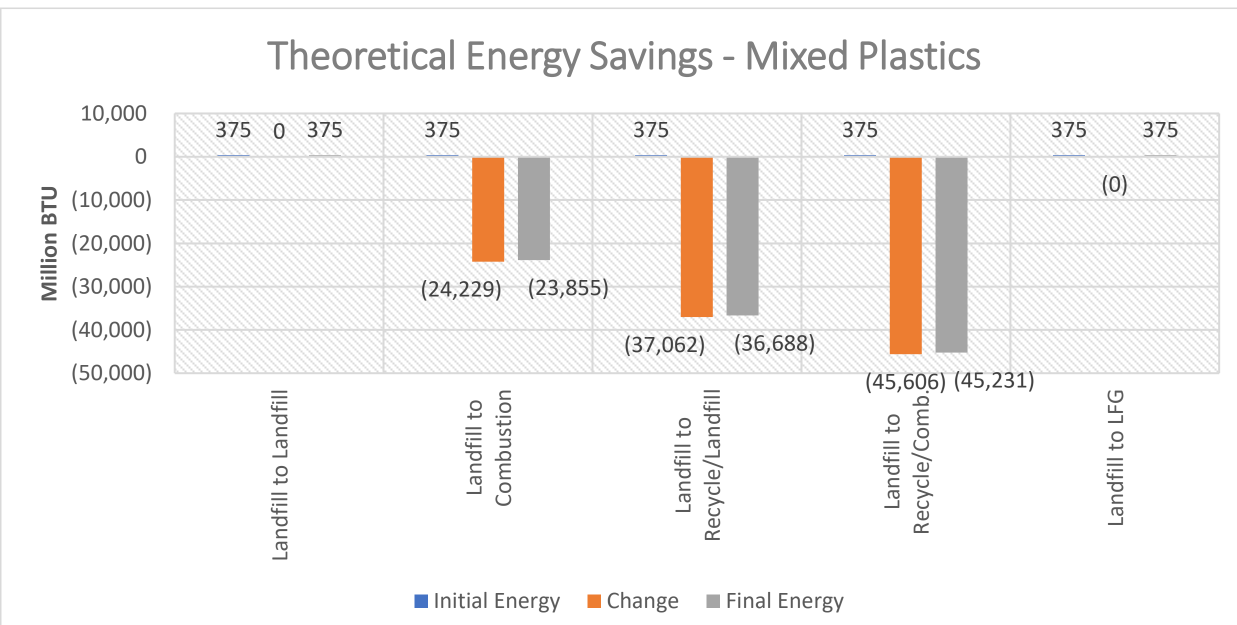


Figure 4.12: Theoretical energy analysis – mixed plastics (M. Richburg, 2023)

The finding of the wage analysis for mixed plastics reveals that the only scenarios which produce an impact are the ones that involve some form of recycling. The recycling/landfill scenario and the recycle/combustion scenario both provide a wage impact of $1,205,605. This is due to the labor involved with recycling. These values can be seen in Table 4.14 and Figure 4.13.

Table 4.14: Theoretical wages impact – mixed plastics

Material	**Waste Management Scenario**	**Wages From Baseline Waste Management US Dollar ($)**	**Wages From Alternative Waste Management US Dollar ($)**	**Change (Alt. – Base) US Dollar ($)**	
Mixed Plastics					
	Landfill to Landfill	64,425	64,425	0	
	Landfill to Combustion	64,425	64,425	0	
	Landfill to Recycle/Landfill	64,425	1,270,030	1,205,605	
	Landfill to Recycle/Combustion	64,425	1,270,030	1,205,605	
	Landfill (no gas rec) to Landfill (with gas rec)	64,425	64,425	0	

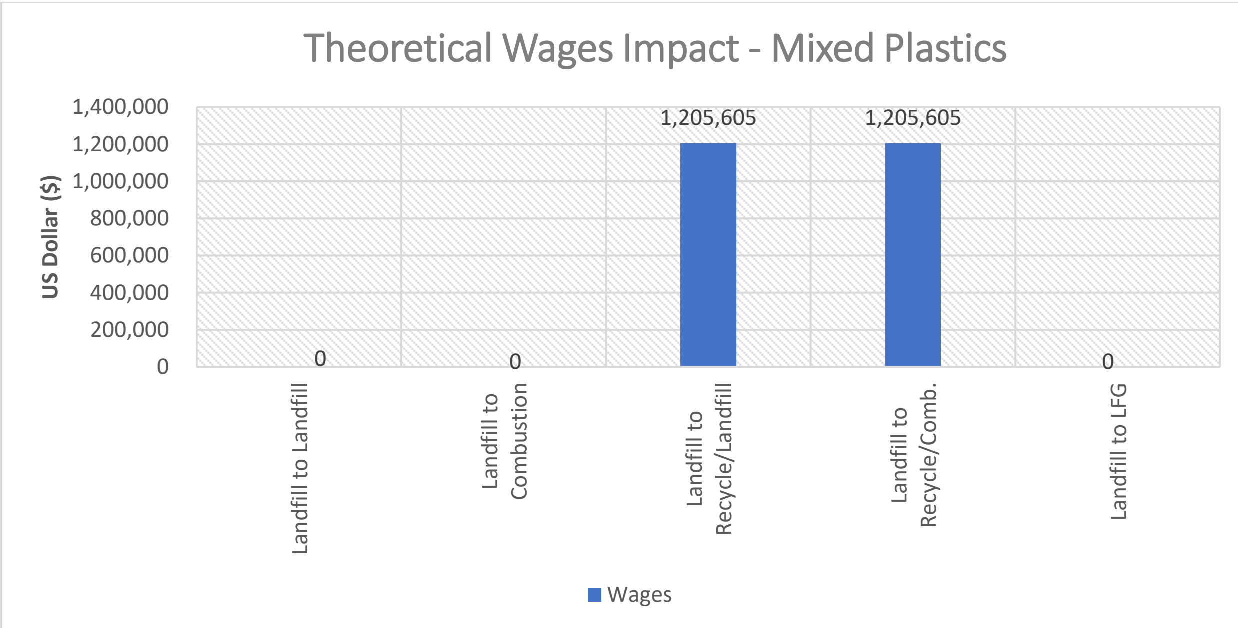


Figure 4.13: Theoretical wages impact – mixed plastics (M. Richburg, 2023)

4.2.6 Theoretical Electronics Data

There are four waste management scenarios that are utilized in the WARM analysis for electronics. Landfilling, no gas recovery, combustion, recycling, and landfilling with gas recovery make up the four options for electronics. In the GHG emissions analysis, it was seen that all scenarios for dealing with electronics had a negligible effect on GHG emissions. Recycling is the only option that has emissions avoidance. Recycling produces a change of -83 MTCO2E, compared to combustion at 37 MTCO2E. Landfilling has zero emissions avoidance. These values can be seen in Table 4.15 and Figure 4.14. It should be noted that although recycling of electronics has only a small effect on GHG emissions, recycling of electronics is very important for the recovery of the high-value metals contained in these materials.

Table 4.15: Theoretical GHG emissions avoided – electronics

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Electronics					
	Landfill to Landfill	2	2	0	
	Landfill to Combustion	2	39	37	
	Landfill to Recycle	2	(81)	(83)	⇐
	Landfill (no gas rec) to Landfill (with gas rec)	2	2	0	

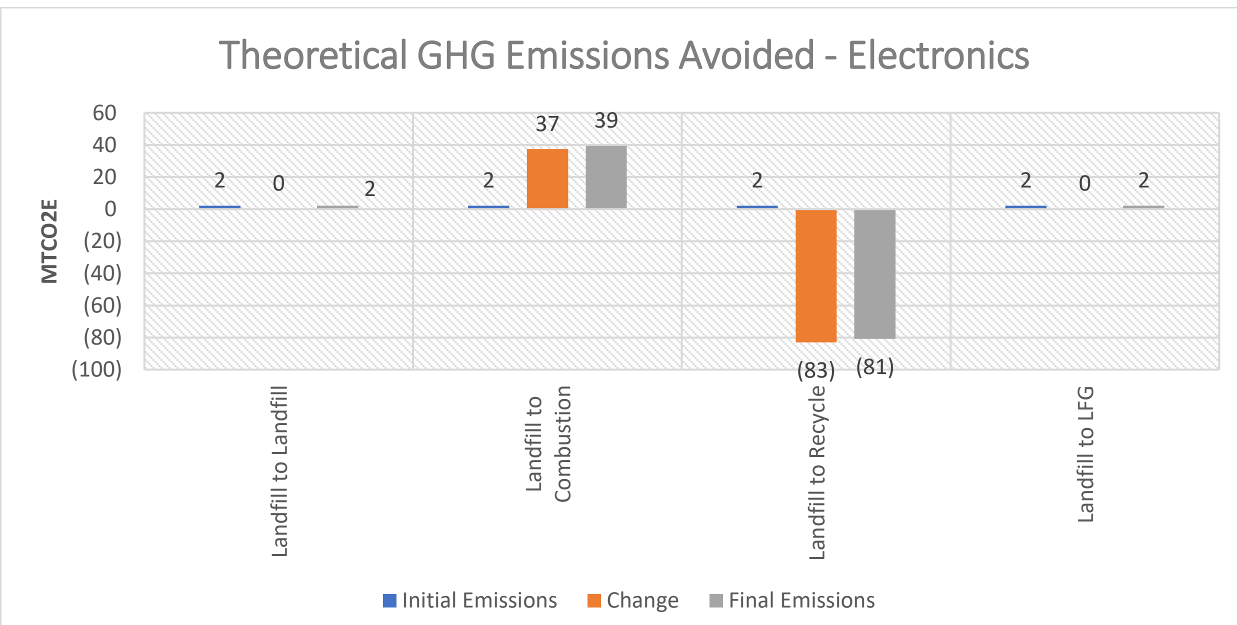


Figure 4.14: Theoretical GHG emissions avoided – electronics (M. Richburg, 2023)

With the analysis of energy savings for electronics, both combustion and recycling offer negative reductions in energy at -598 and 1,232 Million BTU, respectively. Neither option of landfilling offers an energy savings, whether gas recovery or not, as both have a zero change in Million BTU as shown in Table 4.16 and Figure 4.15.

Table 4.16: Theoretical energy savings – electronics

Material	**Waste Management Scenario**	**Energy Use Baseline Waste Management Million BTU**	**Energy Use Alternative Waste Management Million BTU**	**Change (Alt. – Base) Million BTU**	
Electronics					
	Landfill to Landfill	28	28	0	
	Landfill to Combustion	28	(570)	(598)	
	Landfill to Recycle	28	(1,204)	(1,232)	
	Landfill (no gas rec) to Landfill (with gas rec)	28	28	0	

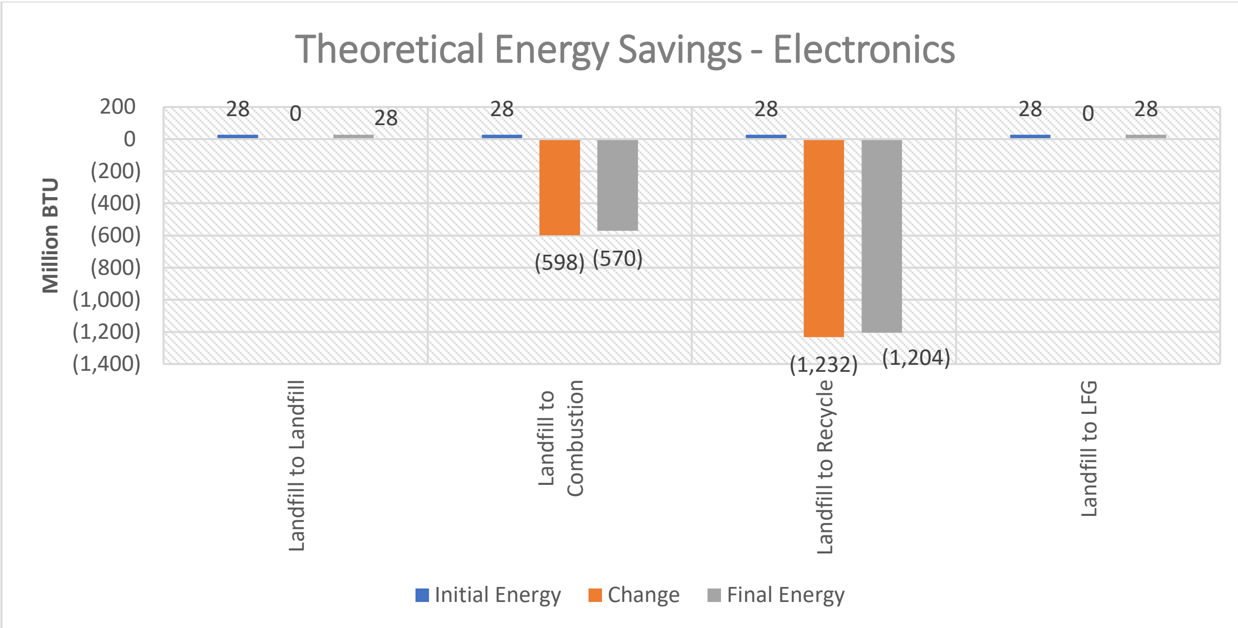


Figure 4.15: Theoretical energy savings – electronics (M. Richburg, 2023)

With the analysis of wages for electronics, recycling is the only waste management option that provides any impact or change, whether positive or negative. Recycling, due to its labor intensity, creates a $247, 220 impact on wages, as shown in Table 4.17 and Figure 4.16.

Table 4.17: Theoretical wages impact – electronics

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Electronics					
	Landfill to Landfill	4,753	4,753	0	
	Landfill to Combustion	4,753	4,753	0	
	Landfill to Recycle	4,753	251,973	247,220	⬅
	Landfill (no gas rec) to Landfill (with gas rec)	4,753	4,753	0	

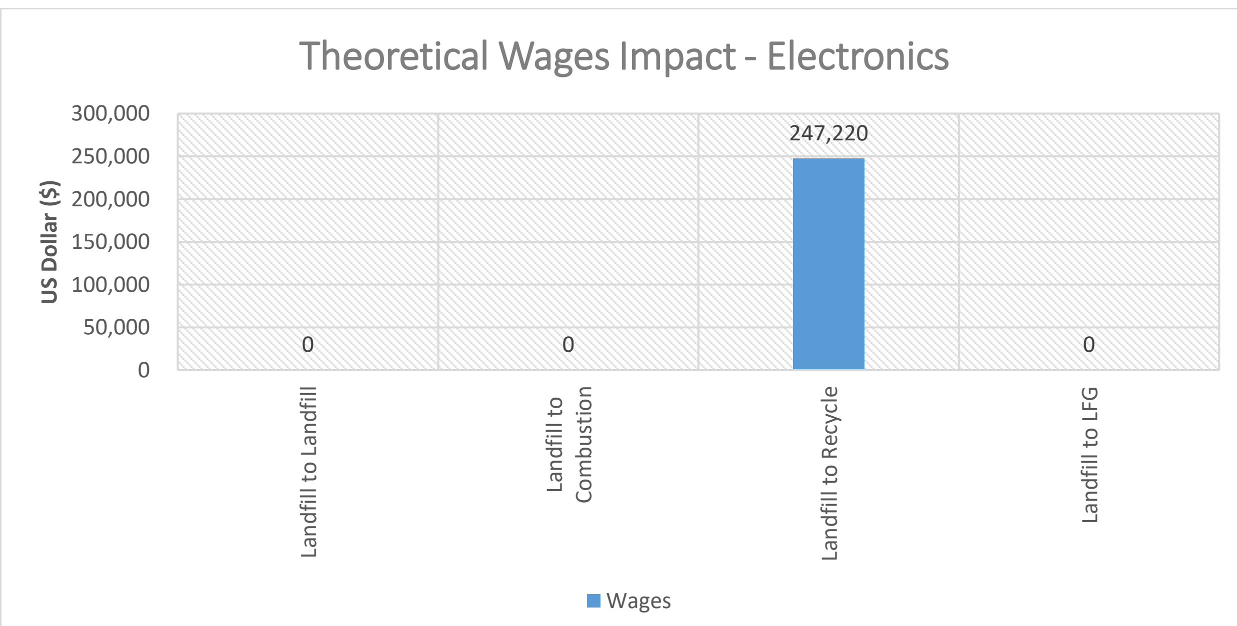


Figure 4.16: Theoretical wages impact – electronics (M. Richburg, 2023)

4.2.7 Theoretical Metals Data

The WARM model used the same scenarios for the metals calculations as it did for electronics, which is landfilling, combustion, recycling, and landfilling with gas recovery. The avoided emissions calculation yielded results like electronics, in that recycling is the best option for avoidance of emissions. The total MTCO2E avoided for metals is 4,520, which is more than 3,000 MTCO2E better than the next option of combustion. Landfilling with either no gas recovery or gas recovery yielded no change in emissions. Table 4.18 and Figure 4.17 show the initial, final, and change in MTCO2E.

Table 4.18: Theoretical GHG emissions avoided – metals

Material	**Waste Management Scenario**	**Baseline Waste Management (MTCO2E)**	**Alternative Waste Management (MTCO2E)**	**Change (Alt. – Base) MTCO2E**	
Metals					
	Landfill to Landfill	20	20	0	
	Landfill to Combustion	20	(999)	(1,019)	
	Landfill to Recycle	20	(4,500)	(4,520)	
	Landfill (no gas rec) to Landfill (with gas rec)	20	20	0	

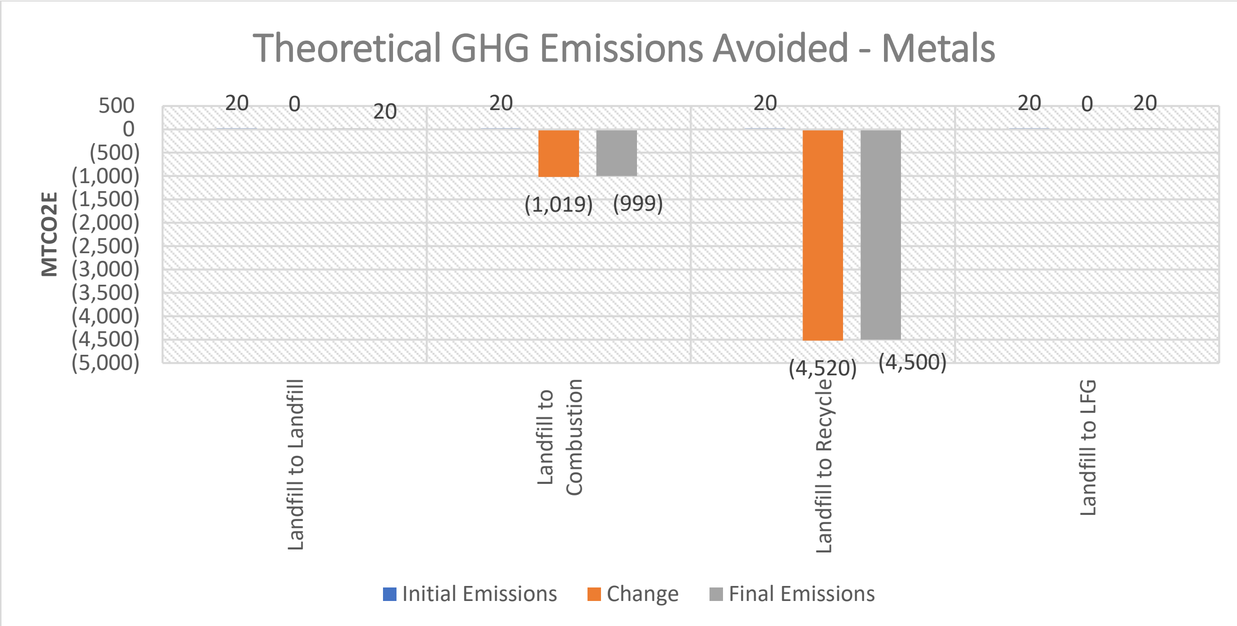


Figure 4.17: Theoretical GHG emissions avoided – metals (M. Richburg, 2023)

The WARM calculations determined that the best scenario for potential energy savings was to recycle any metals in waste management. In recycling metals, it was evaluated that a potential 68,773 BTUs could be saved utilizing this alternative or scenario. Combustion would also realize a savings of 11,223 BTUs, but this is over six times less than recycling metal. Landfilling does not provide any potential energy savings when utilized as shown in Table 4.19 and Figure 4.18.

Table 4.19: Theoretical energy savings – metals

Material	**Waste Management Scenario**	**Energy Use Baseline Waste Management Million BTU**	**Energy Use Alternative Waste Management Million BTU**	**Change (Alt. – Base) Million BTU**	
Metals					
	Landfill to Landfill	269	269	0	
	Landfill to Combustion	269	(10,954)	(11,123)	
	Landfill to Recycle	269	(68,504)	(68,773)	
	Landfill (no gas rec) to Landfill (with gas rec)	269	269	0	

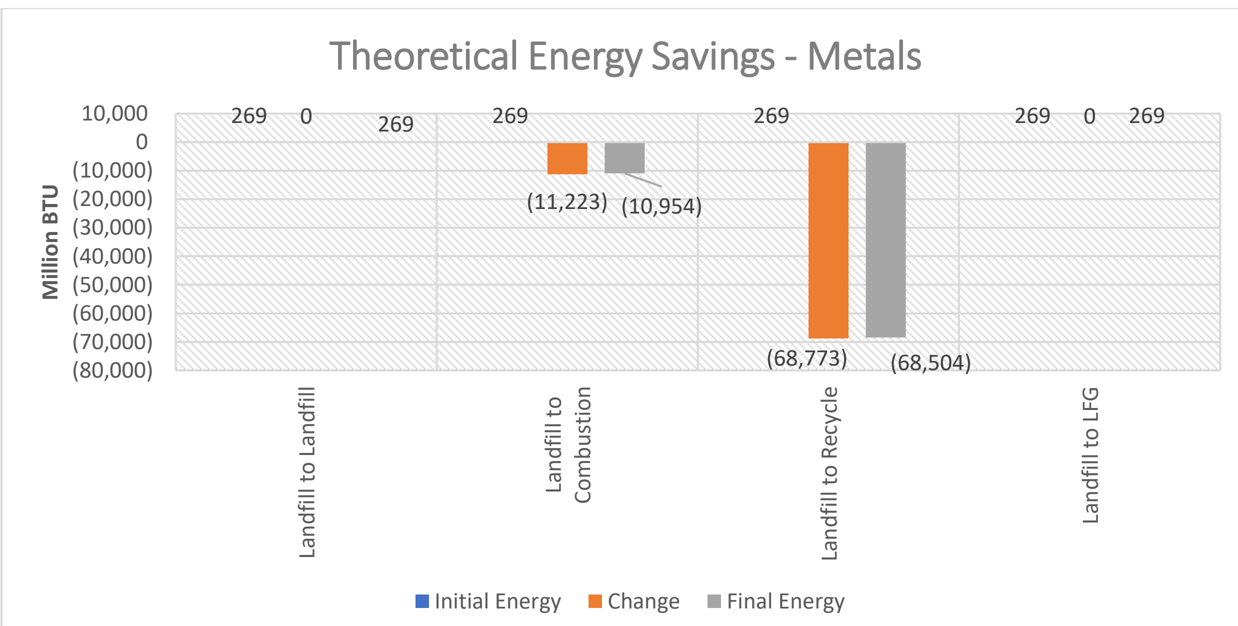


Figure 4.18: Theoretical energy savings – metals (M. Richburg, 2023)

The WARM model determined in the analysis of metals that recycling is the only alternative that creates some type of impact regarding wages in waste management. Metals create a wage impact of $1,462,262, compared to a zero change with the other alternatives or scenarios, as shown in Table 4.20 and Figure 4.19.

Table 4.20: Theoretical wages impact – metals

Material	**Waste Management Scenario**	**Wages From Baseline Waste Management US Dollar ($)**	**Wages From Alternative Waste Management US Dollar ($)**	**Change (Alt. – Base) US Dollar ($)**	
Metals					
	Landfill to Landfill	46,219	46,219	0	
	Landfill to Combustion	46,219	46,219	0	
	Landfill to Recycle	46,219	1,508,681	1,462,462	
	Landfill (no gas rec) to Landfill (with gas rec)	46,219	46,219	0	

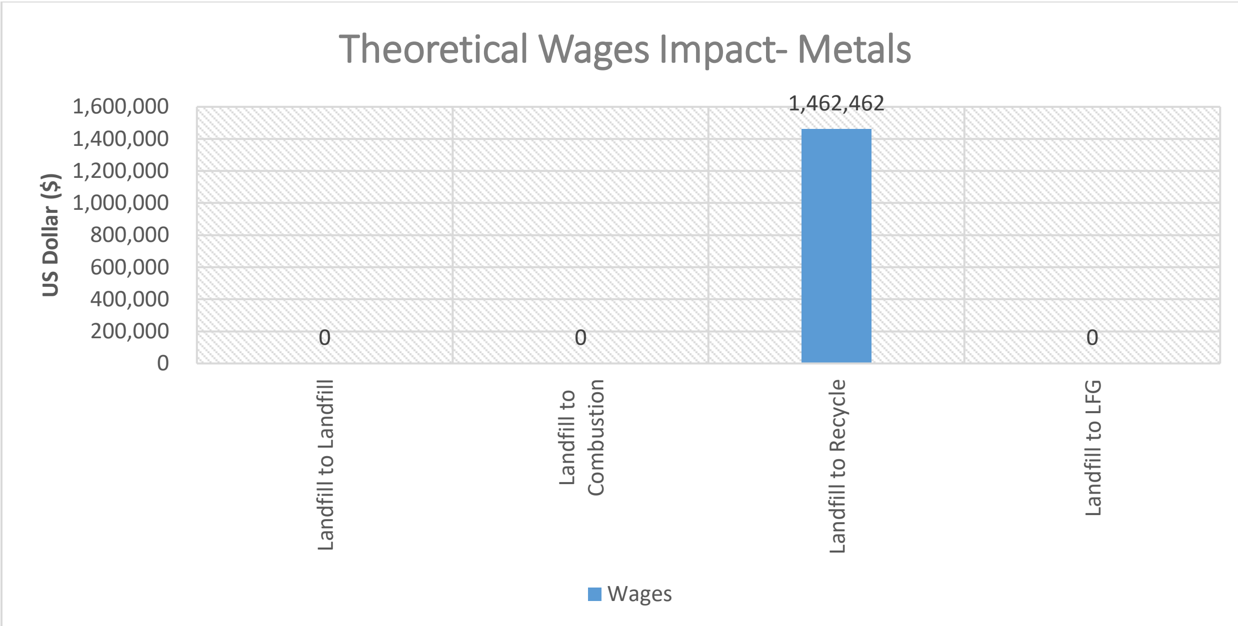


Figure 4.19: Theoretical wages impact – metals (M. Richburg, 2023)

4.2.8 Glass Data

In determining the emissions, energy, and wages within the WARM model, four scenarios were utilized to evaluate the best alternative for waste management. The four scenarios for the management of glass are landfilling, combustion, recycling, and landfilling with gas recovery. The emissions calculations determined that of the four options, recycling yields the best results with 142 MTCO2E of emissions avoided. The other alternatives produced little to no change, for instance, the emissions emitted from glass were very small, 3 MTCO2E, as seen in Table 4.21 and Figure 4.20.

Table 4.21: Theoretical GHG emissions avoided – glass

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Glass					
	Landfill to Landfill	10	10	0	
	Landfill to Combustion	10	13	3	
	Landfill to Recycle	10	(133)	(142)	
	Landfill (no gas rec) to Landfill (with gas rec)	10	10	0	

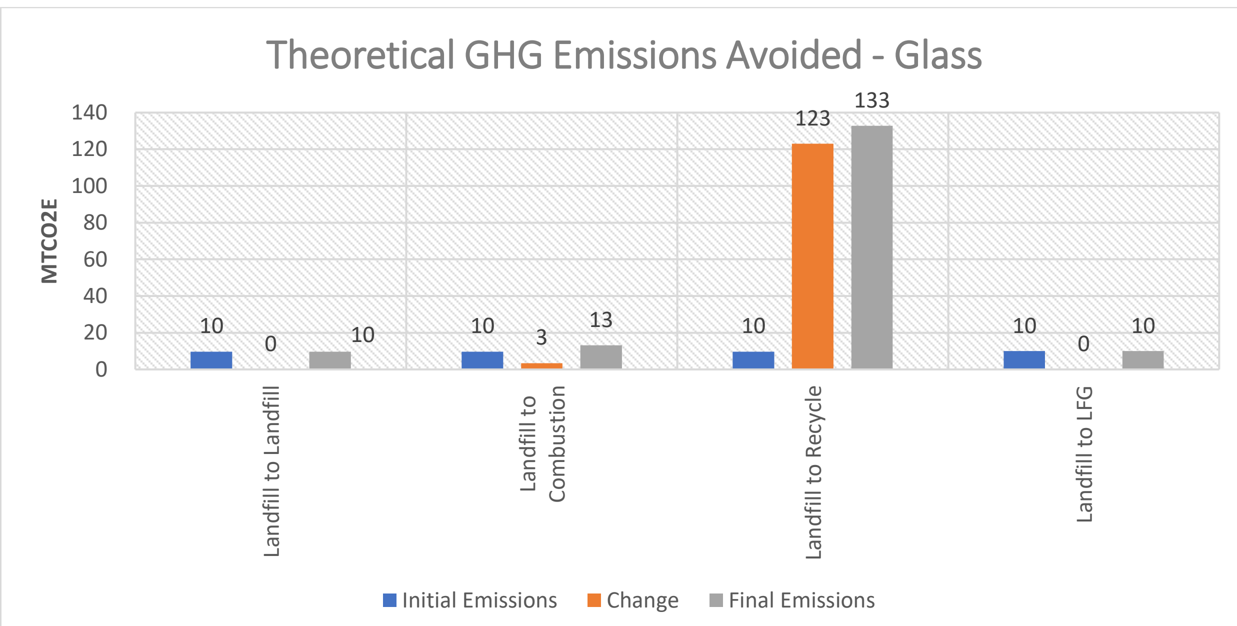


Figure 4.20: Theoretical GHG emissions avoided – glass (M. Richburg, 2023)

As with other materials and scenarios, the WARM model calculated that for energy savings, recycling is the best scenario for the waste management of glass. Applying the recycling alternative creates a potential energy savings of 1,151 Million BTUs, while combustion only creates a saving of 19 Million BTUs. The landfill options do not create any potential energy savings as seen in Table 4.22 and Figure 4.21.

Table 4.22: Theoretical energy savings – glass

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Glass					
	Landfill to Landfill	129	129	0	
	Landfill to Combustion	129	110	(19)	
	Landfill to Recycle	129	(1,022)	(1,151)	
	Landfill (no gas rec) to Landfill (with gas rec)	129	129	0	

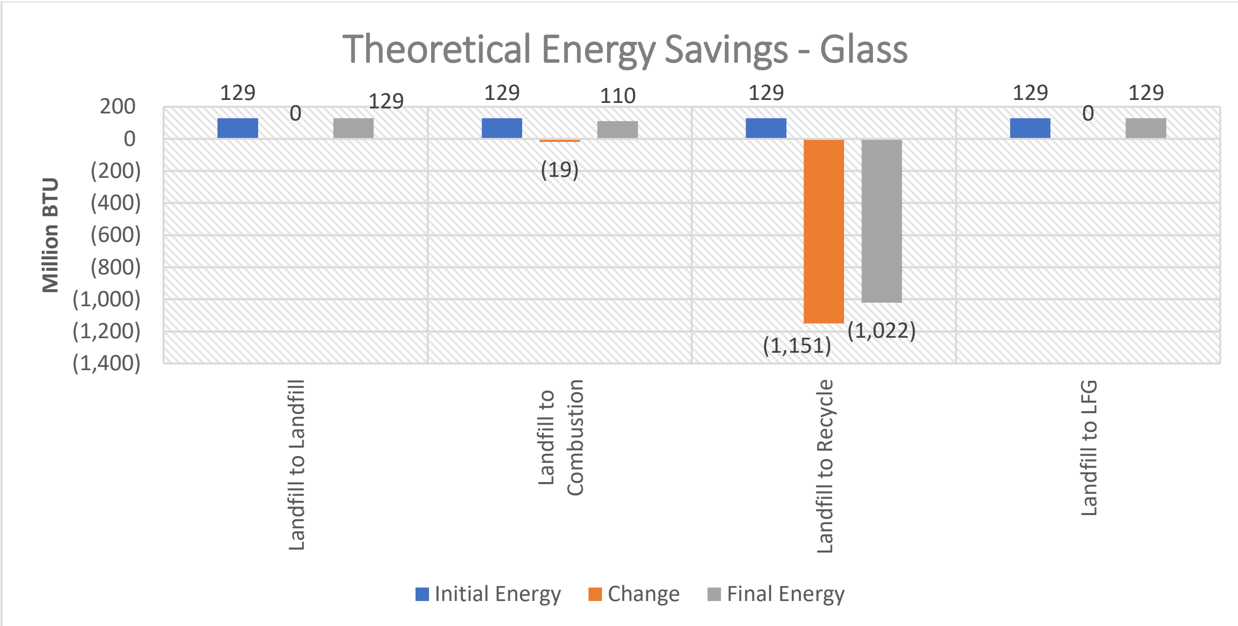


Figure 4.21: Theoretical energy savings – glass (M. Richburg, 2023)

For the wage analysis, the WARM model performed calculations that concluded that recycling is the best option for the waste management of glass. Glass creates a wage impact of $213, 231 compared to $0 impact for the other scenarios, as seen in Table 4.23 and Figure 4.22.

Table 4.23: Theoretical wages impact – glass

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Glass					
	Landfill to Landfill	22,189	22,189	0	
	Landfill to Combustion	22,189	22,189	0	
	Landfill to Recycle	22,189	235,420	213,231	⬅
	Landfill (no gas rec) to Landfill (with gas rec)	22,189	22,189	0	

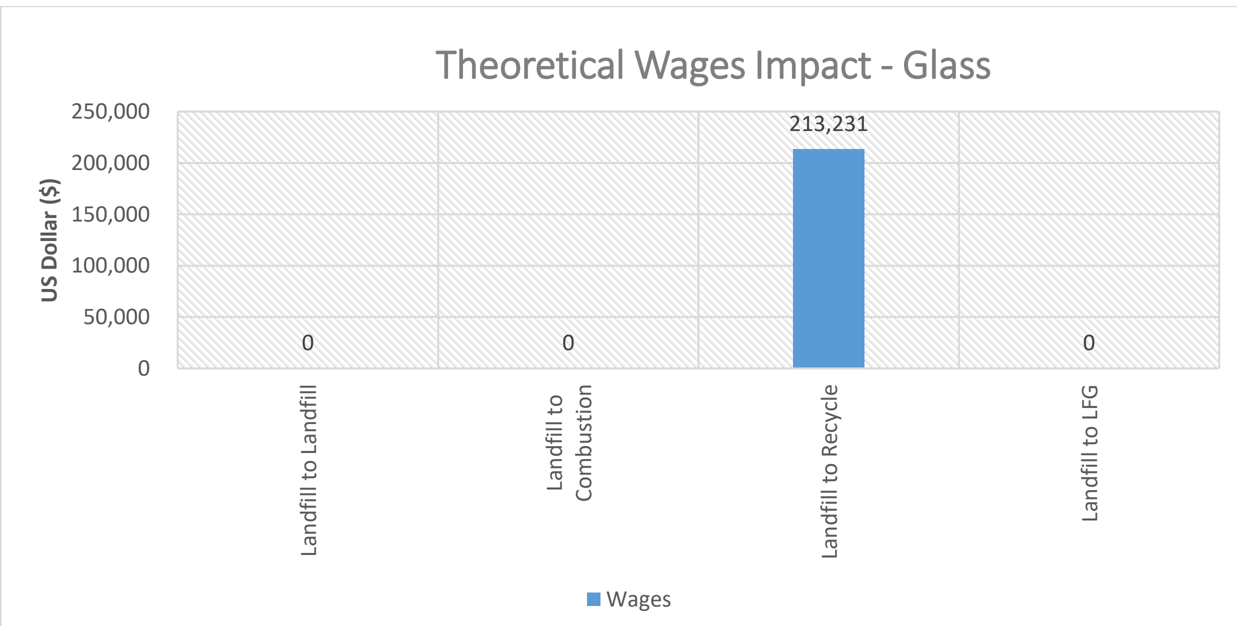


Figure 4.22: Theoretical wages impact – glass (M. Richburg, 2023)

4.2.9 Carpet Data

The WARM modeling for carpet was performed using the same four alternatives that were used for electronics, metals, and glass. Landfill options for carpet produced no avoided emissions, while the combustion alternative produced a non-savings of emissions at 139 MTCO2E. Recycling was once again the method that avoided emissions at 316 MTCO2E, as shown in Table 4.24 and Figure 4.23.

Table 4.24: Theoretical GHG emissions avoided – carpet

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Carpet					
	Landfill to Landfill	3	3	0	
	Landfill to Combustion	3	142	139	
	Landfill to Recycle	3	(313)	(316)	
	Landfill (no gas rec) to Landfill (with gas rec)	3	3	0	

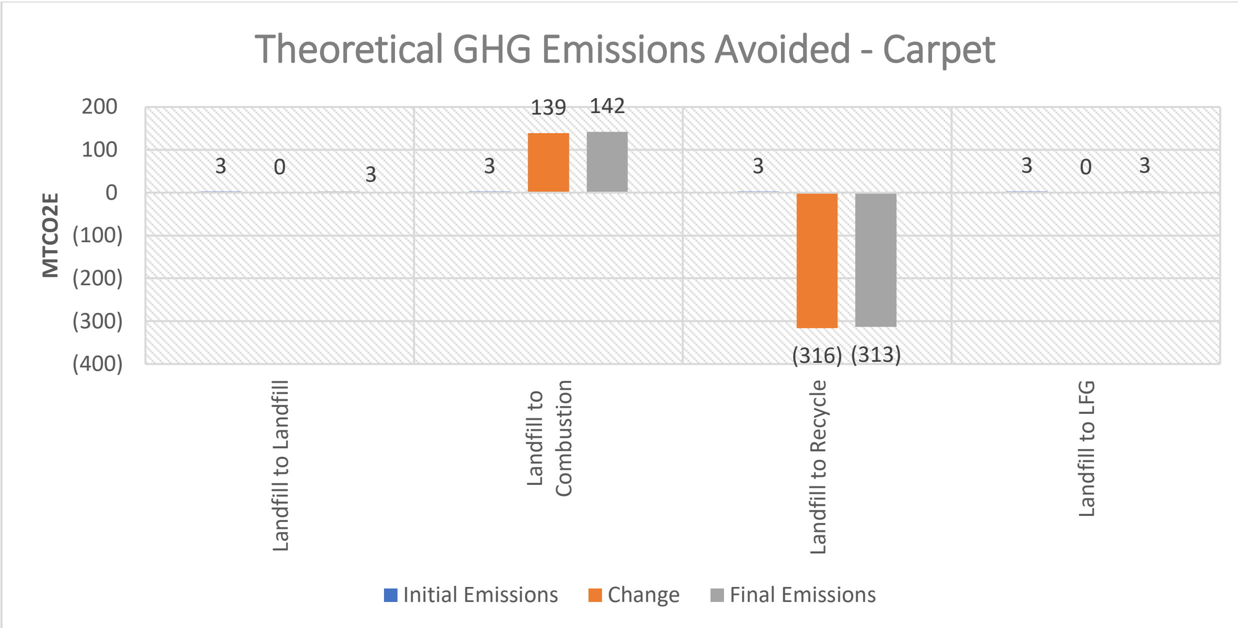


Figure 4.23: Theoretical GHG emissions avoided – carpet (M. Richburg, 2023)

The landfill to combustion and landfill to recycle alternatives both produced energy savings compared landfilling the material. The combustion alternative produced a savings of 1,012 BTUs, while the recycling alternative produced a savings of 2,860 BTUs. These numbers can be seen in Table 4.25 and Figure 4.24.

Table 4.25: Theoretical energy savings – carpet

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Carpet					
	Landfill to Landfill	35	35	0	
	Landfill to Combustion	35	(977)	(1,012)	
	Landfill to Recycle	35	(2,825)	(2,860)	
	Landfill (no gas rec) to Landfill (with gas rec)	35	35	0	

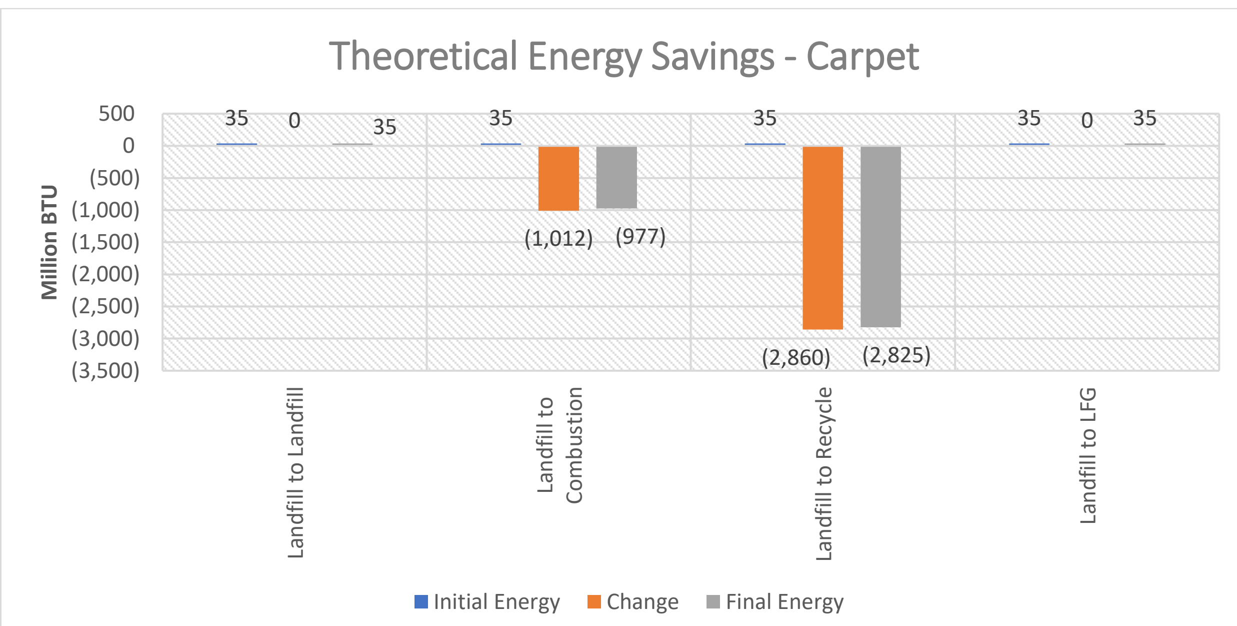


Figure 4.24: Theoretical energy savings – carpet (M. Richburg, 2023)

The recycling of carpet is the only alternative of the four used by WARM that will have a wage impact during the waste management process. The wage impact of recycling is $59,435 compared to the other alternatives, which produces no change in wages. The data can be seen in Table 4.26 and Figure 4.25.

Table 4.26: Theoretical wages impact – carpet

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Carpet					
	Landfill to Landfill	6,073	6,073	0	
	Landfill to Combustion	6,073	6,073	0	
	Landfill to Recycle	6,073	65,508	59,435	
	Landfill (no gas rec) to Landfill (with gas rec)	6,073	6,073	0	

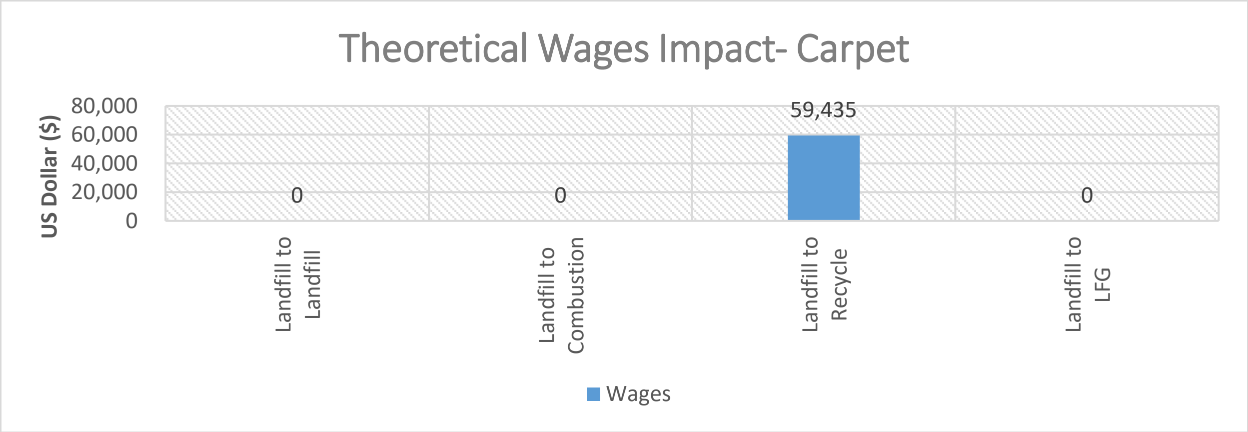


Figure 4.25: Theoretical wages impact – carpet (M. Richburg, 2023)

4.2.10 Tires Data

Recycling is the continuing trend when it comes to waste management and the WARM model. In modeling the best way to manage tire waste, landfilling, combustion, and recycling were the options presented. From the calculation of the waste stream, recycling was the only outcome that produced emissions avoidance. The calculation produced 100 MTCO2E compared to combustion, which produced a positive emissions impact of 100 MTCO2E, and landfilling, which produced no change. The data can be seen in Table 4.27 and Figure 4.26.

Table 4.27: Theoretical GHG emissions avoided – tires

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Tires					
	Landfill to Landfill	5	5	0	
	Landfill to Combustion	5	126	121	
	Landfill to Recycle	5	(95)	(100)	←
	Landfill (no gas rec) to Landfill (with gas rec)	5	5	0	

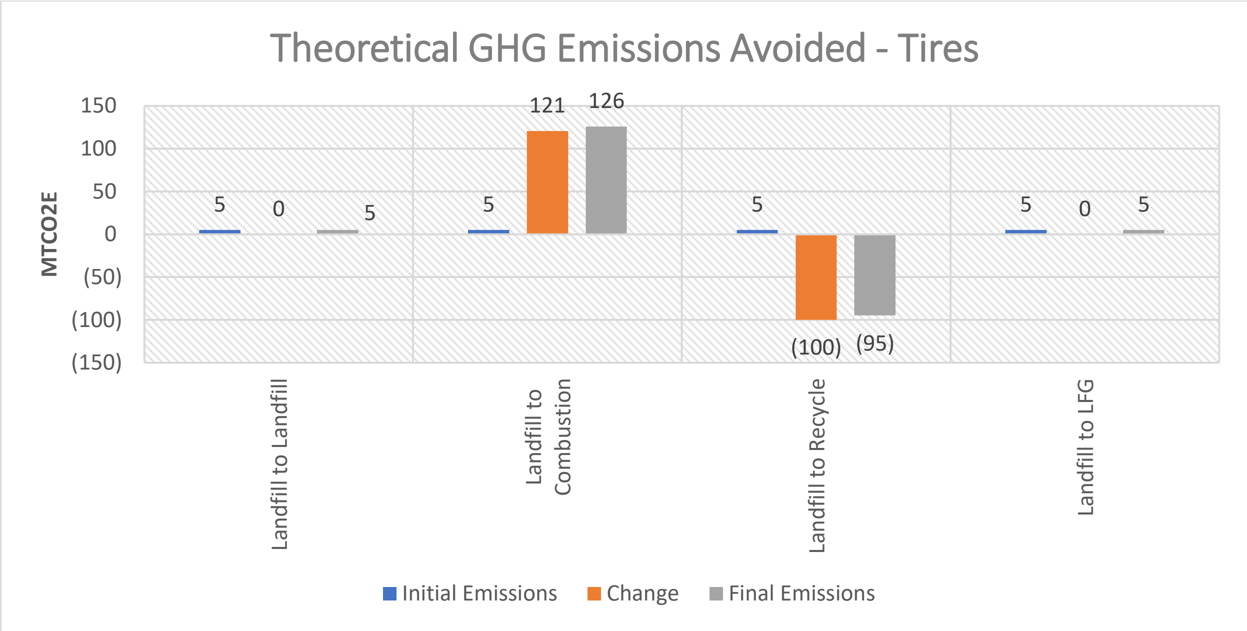


Figure 4.26: Theoretical GHG emissions avoided – tires (M. Richburg, 2023)

In the calculation of energy savings, combustion and recycling were the only two options out of the four that provided energy savings. The savings determined from the combustion of tires was 7,317 Million BTUs and 975 BTUs from the recycling tires. As seen in the previous materials in the WARM modeling, landfilling does not provide energy savings due to the change being zero (0). Table 4.28 and Figure 4.27 display the data from the tire calculations.

Table 4.28: Theoretical energy savings – tires

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Tires					
	Landfill to Landfill	68	68	0	
	Landfill to Combustion	68	(7,249)	(7,317)	
	Landfill to Recycle	68	(907)	(975)	
	Landfill (no gas rec) to Landfill (with gas rec)	68	68	0	

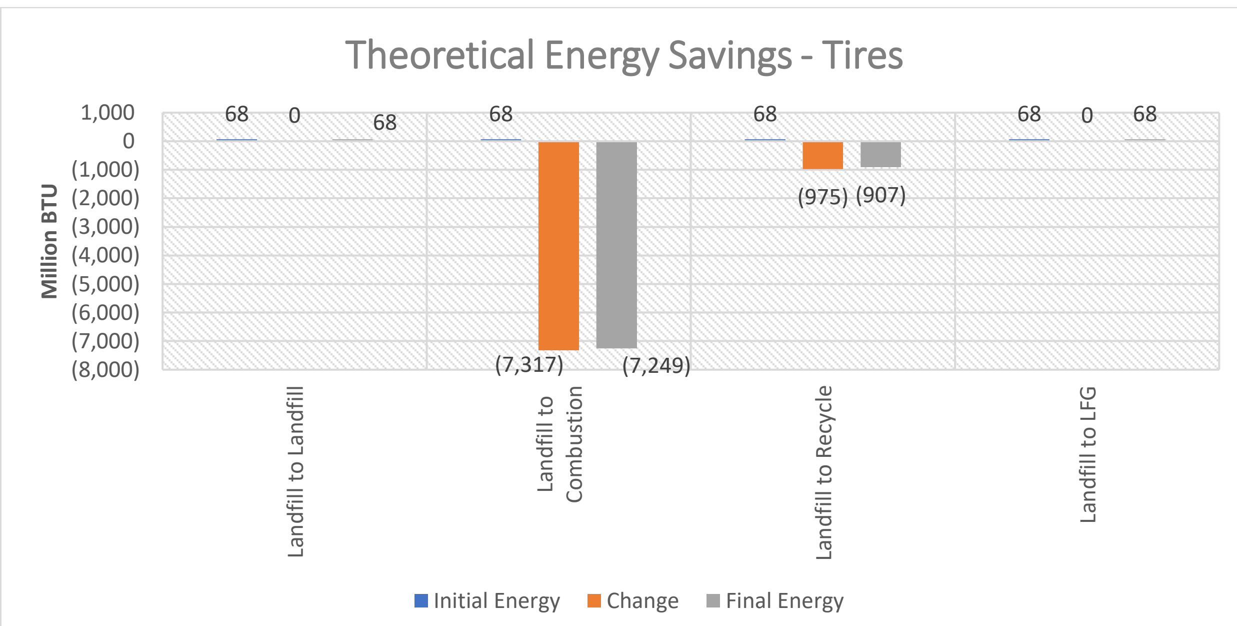


Figure 4.27: Theoretical energy savings – tires (M. Richburg, 2023)

The WARM model produced data that was consistent with the other materials and forms of waste management. Recycling is the scenario that will produce wage changes when utilized with materials such as tires, carpet, glass, and electronics. The wage change for recycling was calculated at $89,533, while the other forms of waste management yielded $0 change. The changes can be seen in Table 4.29 and Figure 4.28.

Table 4.29: Theoretical wages impact – tires

Material	**Waste Management Scenario**	**Wages From Baseline Waste Management US Dollar ($)**	**Wages From Alternative Waste Management US Dollar ($)**	**Change (Alt. – Base) US Dollar ($)**	
Tires					
	Landfill to Landfill	11,621	11,621	0	
	Landfill to Combustion	11,621	11,621	0	
	Landfill to Recycle	11,621	101,174	89,553	
	Landfill (no gas rec) to Landfill (with gas rec)	11,621	11,621	0	

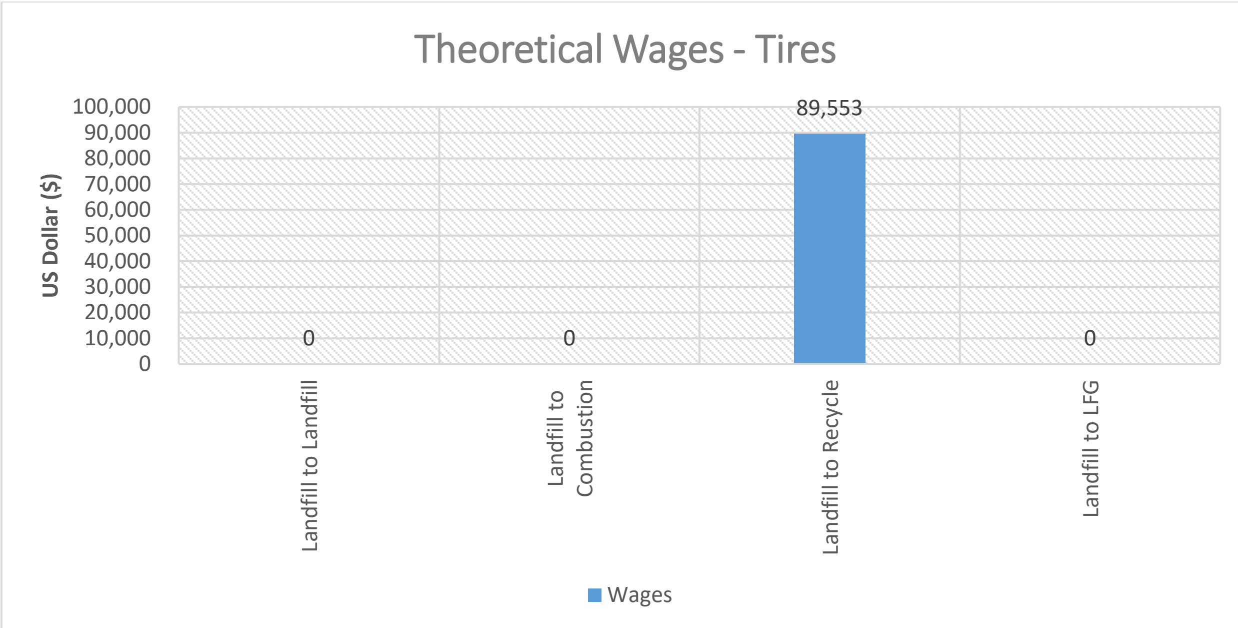


Figure 4.28: Theoretical wages impact – tires (M. Richburg, 2023)

4.2.11 Mixed MSW Data

Mixed MSW is seen as a catch all for the evaluation of materials in solid waste management. In the evaluation of emissions, energy, and wages, three alternatives are used to produce the values of those alternatives, which are landfill with no gas recovery, combustion, and landfill with gas recovery. In the analysis of GHG emissions avoided, both the combustion and landfill with gas recovery, produce an acceptable GHG emissions avoided number. Combustion has an emissions avoidance value of 2,144 BTUs and landfill with gas recovery has a value of 1,890 BTUs, while landfilling with no gas recovery does not produce an avoidance of emissions as seen in Table 4.30 and Figure 4.29.

Table 4.30: Theoretical GHG emissions avoided – mixed MSW

Material	**Waste Management Scenario**	**Baseline Waste Management (MTCO2E)**	**Alternative Waste Management (MTCO2E)**	**Change (Alt. – Base) MTCO2E**	
Mixed MSW					
	Landfill to Landfill	2,138	2,138	0	
	Landfill to Combustion	2,138	(6)	(2,144)	
	Landfill (no gas rec) to Landfill (with gas rec)	2,138	248	(1,890)	

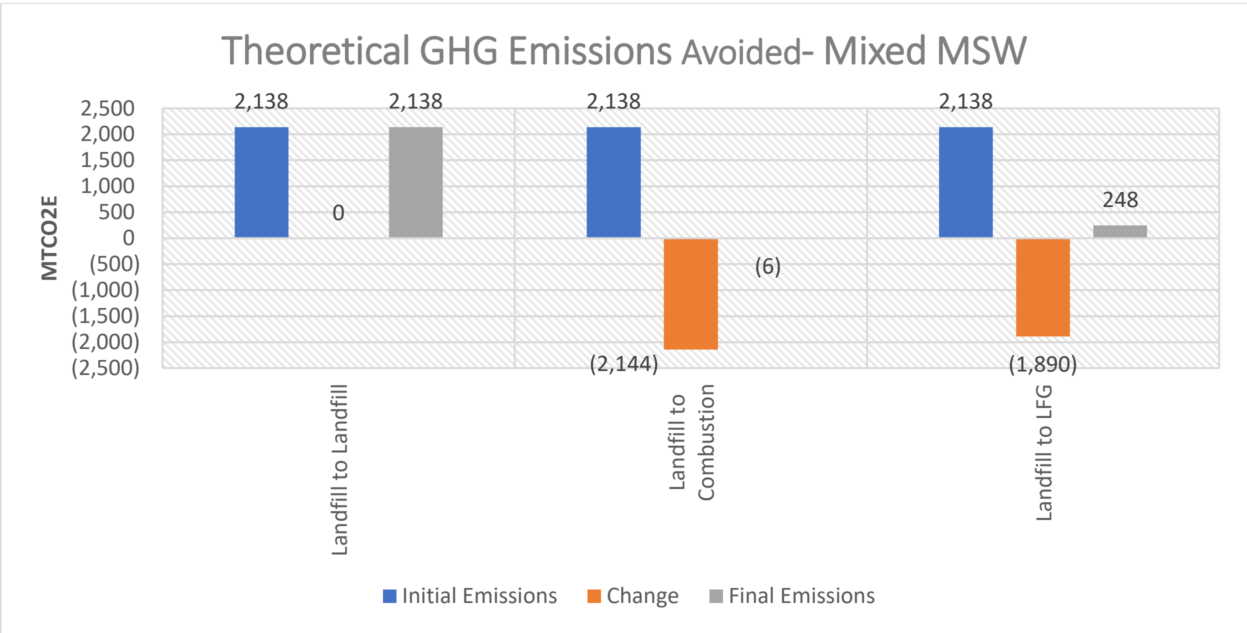


Figure 4.29: Theoretical GHG emissions avoided – mixed MSW (M. Richburg, 2023)

As in the previous analysis, landfilling with no gas recovery does not bring about any energy savings, but both combustion and landfilling with gas recovery bring about significant changes between the initial and final savings calculations. The combustion of the mixed MSW has an energy savings of 8,668 Million BTUs, while landfilling with gas recovery saves 637 BTUs. This data can be seen in Table 4.31 and Figure 4.30.

Table 4.31: Theoretical energy savings – mixed MSW

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Mixed MSW					
	Landfill to Landfill	451	451	0	
	Landfill to Combustion	451	(8,217)	(8,668)	⬅
	Landfill (no gas rec) to Landfill (with gas rec)	451	(186)	(637)	

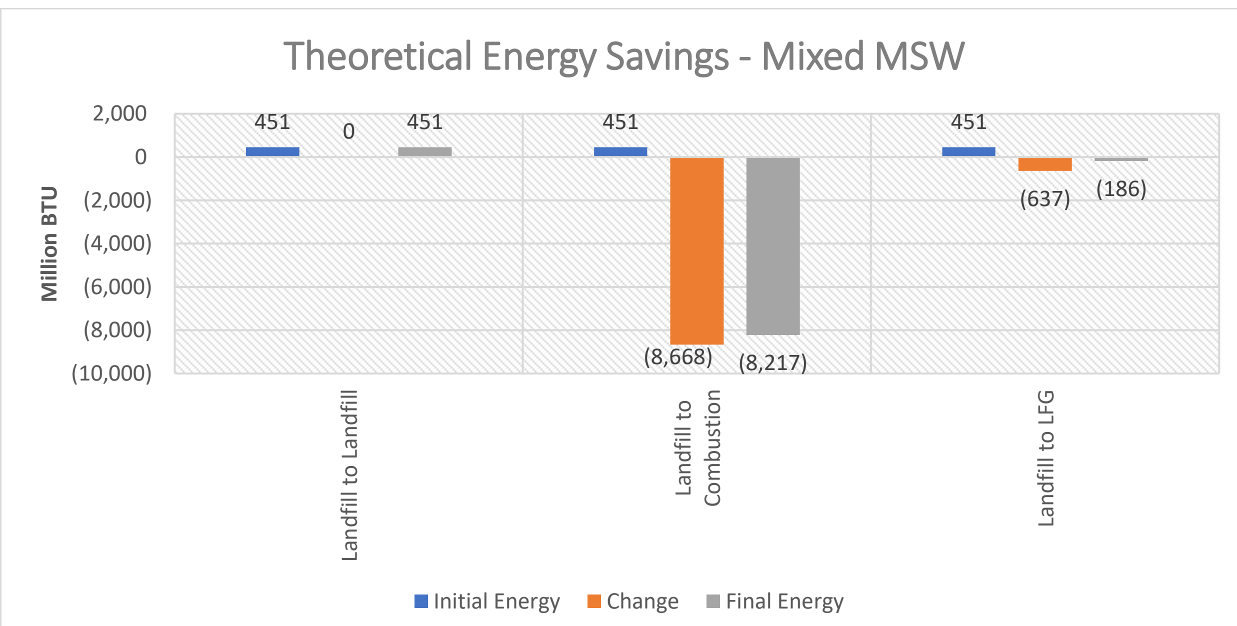


Figure 4.30: Theoretical energy savings – mixed MSW (M. Richburg, 2023)

Because of the inability to recycle mixed MSW, there are no wage changes when performing waste management for this material for any of the scenarios. As with the previous analysis of materials, landfilling nor combustion provides any changes as seen in Table 4.32. No figure was provided due to zero change in the wages.

Table 4.32: Theoretical wages impact – mixed MSW

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Mixed MSW					
	Landfill to Landfill	77,652	77,652	0	
	Landfill to Combustion	77,652	77,652	0	
	Landfill (no gas rec) to Landfill (with gas rec)	77,652	77,652	0	

4.2.12 Summary of Theoretical Calculations

Tables 4.33 – 4.35 provide a summary of WARM model calculations. As a reminder, these data are calculated based upon the monthly average of MSW delivered to the Montgomery County Landfill in 2021. The best treatment scenario for each waste segment can easily be seen from this data. Recycling is generally the best option for GHG emission reduction and energy saving, with combustion being a good option when recycling is not available. Recycling typically represents the largest impact on wages due to the labor intensity of most recycling operations. In terms of types of waste streams, effectively dealing with paper, food waste, metals, and mixed MSW are the most important for avoiding GHG emissions. Paper, plastics, metals and mixed MSW offer the greater potential for energy savings; however, significant energy savings can be realized from most of the waste streams. Recycling of metals, papers and electronics are the most labor intensive.

Table 4.33: Summary of GHG emissions for the theoretical case

	LFG	Recycle	Combustion	Compost	Anaerobic Digestion
Paper	(4,128)	(12,158)	(5,067)	N/A	N/A
Food Waste	(2,446)	N/A	(3,793)	(3,732)	(3,561)
Yard Trimmings	(629)	N/A	(538)	(371)	(422)
Mixed Plastics	0	See Note	1,705	N/A	N/A
Electronics	0	(83)	37	N/A	N/A
Metals	0	(4,520)	(1,019)	N/A	N/A
Glass	0	(142)	3	N/A	N/A
Carpet	0	(316)	139	N/A	N/A
Tires	0	(100)	121	N/A	N/A
Mixed MSW	(1,890)	N/A	(2,144)	N/A	N/A

Table 4.34: Summary of energy savings for the theoretical case

	LFG	Recycle	Combustion	Compost	Anaerobic Digestion
Paper	(1,356)	(40,788)	(18,602)	N/A	N/A
Food Waste	(785)	N/A	(6,386)	1134	(4,385)
Yard Trimmings	(195)	N/A	(4,159)	(14)	(628)
Mixed Plastics	0	See Note	(24,229)	N/A	N/A
Electronics	0	(1,232)	(598)	N/A	N/A
Metals	0	(68,773)	(11,123)	N/A	N/A
Glass	0	(1,151)	(19)	N/A	N/A
Carpet	0	(2,860)	(1,012)	N/A	N/A
Tires	0	(975)	(7,317)	N/A	N/A
Mixed MSW	(637)	N/A	(8,668)	N/A	N/A

Table 4.35: Summary of the wage impact for the theoretical case

	LFG	Recycle	Combustion	Compost	Anaerobic Digestion
Paper	0	378,683	0	N/A	N/A
Food Waste	0	N/A	0	(50,216)	(29,044)
Yard Trimmings	0	N/A	0	(28,129)	(19,550)
Mixed Plastics	0	See Note	0	N/A	N/A
Electronics	0	247,220	0	N/A	N/A
Metals	0	1,462,462	0	N/A	N/A
Glass	0	212,231	0	N/A	N/A
Carpet	0	59,435	0	N/A	N/A
Tires	0	89,553	0	N/A	N/A
Mixed MSW	0	0	0	N/A	N/A

4.3 WARM Model – "Business as Usual" Calculations

This section will outline the data that was modeled to the current waste management practices utilizing the same tonnage for the theoretical models. This modeling was performed to determine the emissions avoidance and energy savings for each material, in addition to wage impact, could be expected if the waste management alternatives such as recycling, combustion, composting, and anaerobic digestion are minimal to zero. The current recycling rate for the State of Alabama is sixteen (16) percent and assumptions were made as seen in Table 4.36 for the "Business as Usual" methodology.

Table 4.36: "Business as Usual" research methodology assumptions

	Landfill	Recycle	Combustion	Compost	Digestion
Paper	84%	16%	0%	0%	0%
Food Waste	100%	0%	0%	0%	0%
Yard Trimmings	100%	0%	0%	0%	0%
Mixed Plastics	84% | 100%	16%|0%	0%	0%	0%
Electronics	84%	16%	0%	0%	0%
Metals	84%	16%	0%	0%	0%
Glass	84%	16%	0%	0%	0%
Carpet	84%	16%	0%	0%	0%
Tires	84%	16%	0%	0%	0%
Mixed MSW	100%	0%	0%	0%	0%

4.3.1 "Business as Usual" Paper Data

The scenarios that will be used for the practical calculations are like those performed for the theoretical calculations, therefore a combination of landfill and recycling will be used. Each scenario for paper creates an emissions avoidance, however the highest emissions avoidance comes from the scenario of landfill/landfill with gas recovery at 4,128 MTCO2E. Table 4.37 and figure 4.31 display the scenarios and emissions avoidance numbers.

Table 4.37: "Business as Usual" GHG emissions avoided - paper

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Paper					
	Landfill to Landfill	3,750	3,750	0	
	Landfill to Landfill/Recycle	3,750	1,804	(1,945)	
	Landfill to Landfill (with gas recovery)	3,750	(378)	(4,128)	

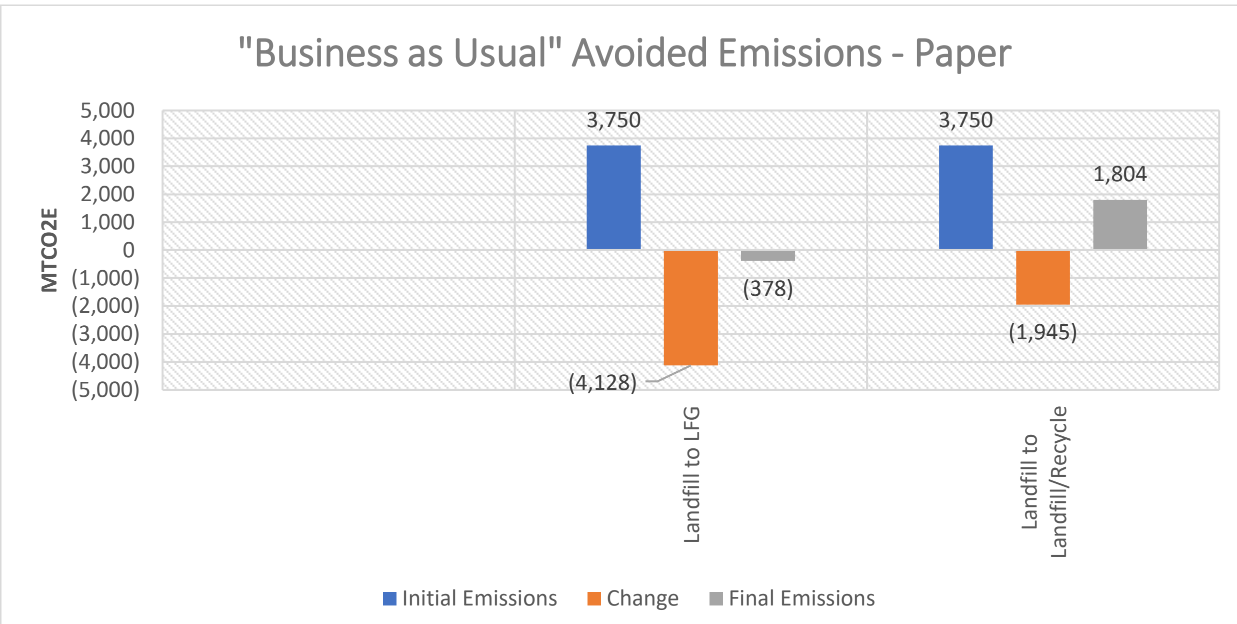


Figure 4.31: "Business as Usual" GHG emissions avoided – paper (M. Richburg, 2023)

The best scenario for energy savings from paper was the landfill/recycling option which created a savings of 6,526 BTUs as shown in table 4.38 and figure 4.32.

Table 4.38: "Business as Usual" energy savings – paper

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Paper					
	Landfill to Landfill	709	709	0	
	Landfill to Landfill/Recycle	709	(5,817)	(6,526)	
	Landfill to Landfill (with gas recovery	709	(647)	(1,356)	

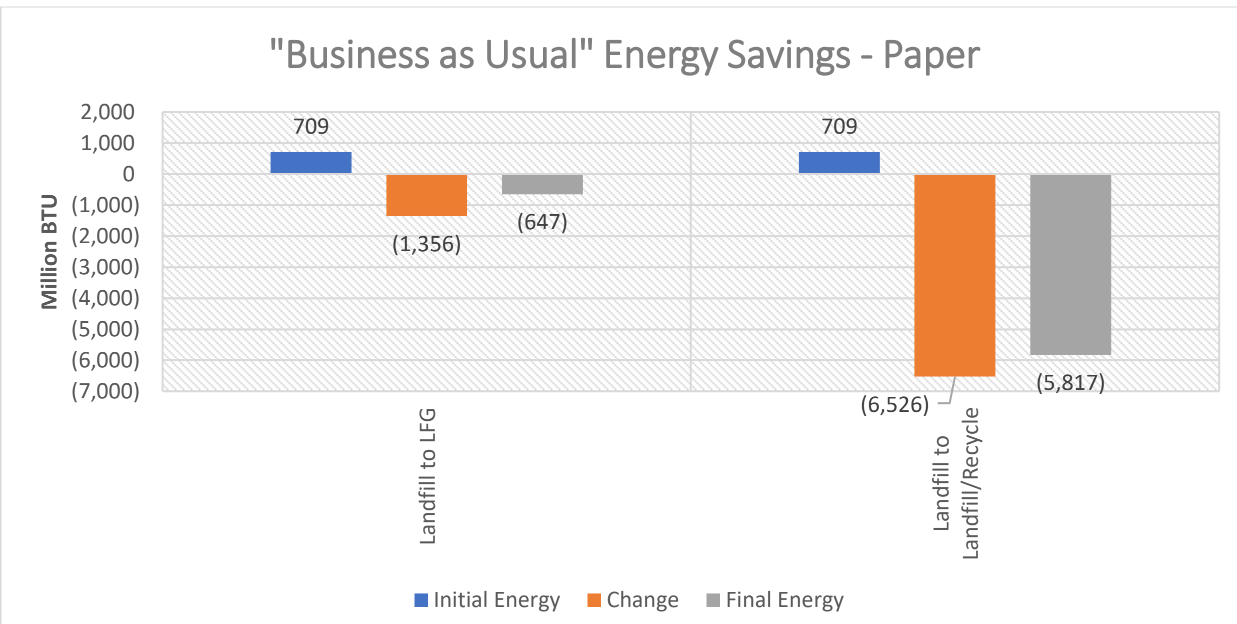


Figure 4.32: "Business as Usual" energy savings – paper (M. Richburg, 2023)

In calculating the wage impact, only the landfill/recycle method will have a wage change due to recycling being a labor-intensive process, as seen in table 4.39 and figure 4.33.

Table 4.39: "Business as Usual" wages impact – paper

Material	**Waste Management Scenario**	**Wages From Baseline Waste Management US Dollar ($)**	**Wages From Alternative Waste Management US Dollar ($)**	**Change (Alt. – Base) US Dollar ($)**	
Paper					
	Landfill to Landfill	122,025	122,025	0	
	Landfill to Landfill/Recycle	122,025	182,614	60,859	
	Landfill to Landfill (with gas recovery)	122,025	122,025	0	

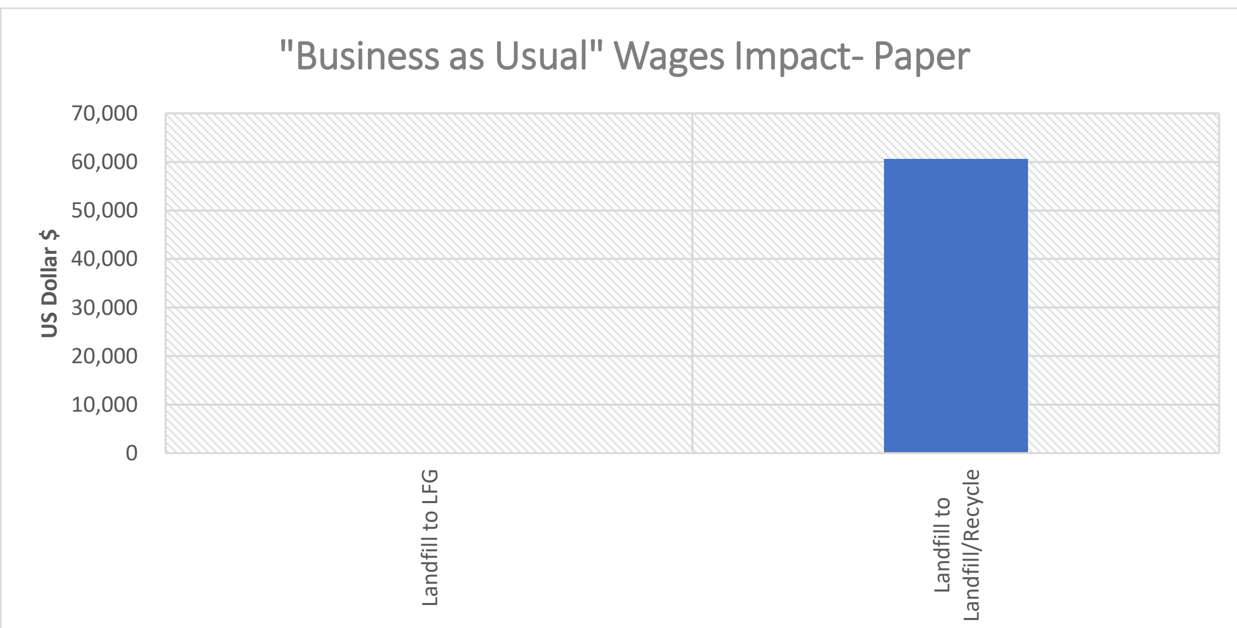


Figure 4.33: "Business as Usual" wages impact – paper (M. Richburg, 2023)

4.3.2 "Business as Usual" Food Waste Data

Food waste utilizes two scenarios in its modeling due to recycling not being applicable to this form of waste management. Within the management of food waste, landfill with gas recovery is the only method to have a change in emissions of 2,446 MTCO2E. Continual landfilling, with no gas recovery option, continually emits emissions to the atmosphere with no ability for avoidance. The data for food waste is shown in table 4.40 and figure 4.34.

Table 4.40: "Business as Usual" GHG emissions avoided - food waste

Material	**Waste Management Scenario**	**Baseline Waste Management (MTCO2E)**	**Alternative Waste Management (MTCO2E)**	**Change (Alt. – Base) MTCO2E**	
Food Waste					
	Landfill to Landfill	3,446	3,446	0	
	Landfill to Landfill/Recycle	n/a	n/a	n/a	
	Landfill to Landfill (with gas recovery)	3,446	1,000	(2,446)	⬅

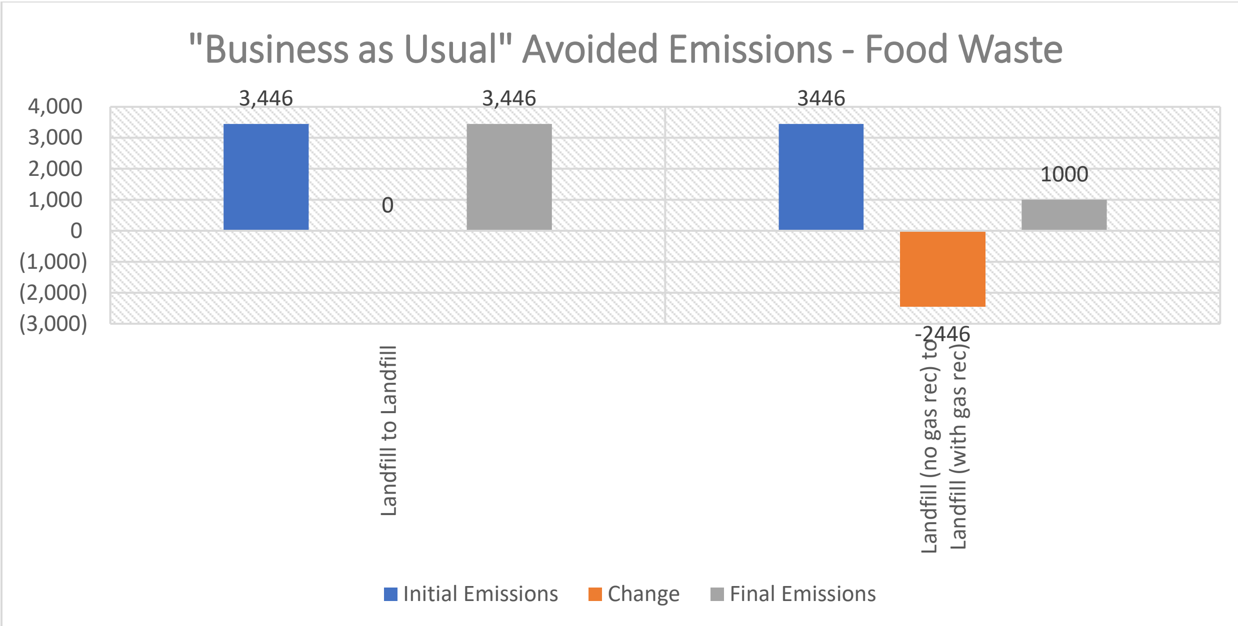


Figure 4.34: "Business as Usual" GHG emissions avoided – food waste (M. Richburg, 2023)

For "Business as Usual" food waste, landfilling with gas recovery produces an energy savings of 785 Million BTUs, while landfilling with no gas recovery has zero savings as shown in table 4.41 and figure 4.35.

Table 4.41: "Business as Usual" energy savings – food waste

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Food Waste					
	Landfill to Landfill	663	663	0	
	Landfill to Landfill/Recycle	n/a	n/a	n/a	
	Landfill to Landfill (with gas recovery)	663	(112)	(785)	⬅

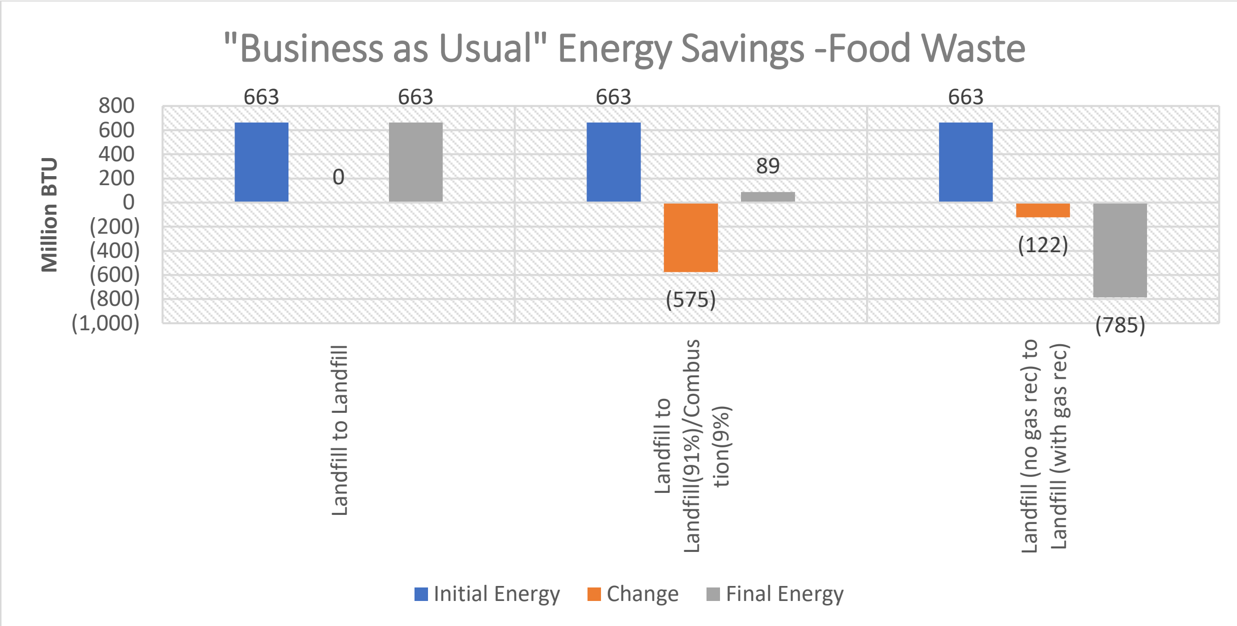


Figure 4.35: "Business as Usual" energy savings – food waste (M. Richburg, 2023)

Due to there not being any recycling associated with food waste, the wage impact for this material and its associated waste management scenarios is zero as shown in table 4.42.

Table 4.42: "Business as Usual" wages impact – food waste

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Food Waste					
	Landfill to Landfill	114,106	114,106	0	
	Landfill to Landfill/Recycle	n/a	n/a	n/a	

4.3.3 "Business as Usual" Yard Trimmings Data

Yard trimmings will perform in the same manner as food waste, in that the scenarios to be considered are landfilling and landfill with gas recovery. Table 4.43 and figure 4.36 shows the landfill gas recovery is the only scenario that has a change of emissions compared to no gas recovery which has zero change in emissions avoided.

Table 4.43: "Business as Usual" GHG emissions avoided – yard trimmings

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Yard Trimmings					
	Landfill to Landfill	297	297	0	
	Landfill to Landfill/Recycle	n/a	n/a	n/a	
	Landfill to Landfill (with gas recovery)	297	(332)	(628)	

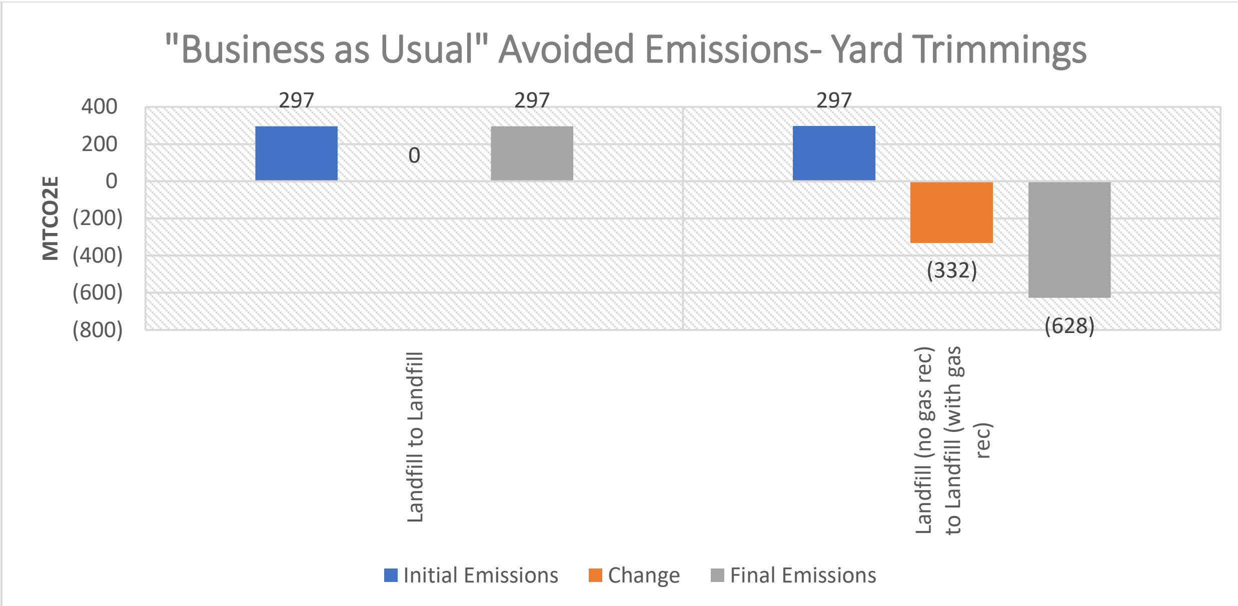


Figure 4.36: "Business as Usual" GHG emissions avoided – yard trimmings (M. Richburg, 2023)

Within the potential energy savings calculations, only the landfill with gas recovery had energy savings, which amounted to 196 Million BTUs. The data for the potential energy savings is displayed in table 4.44 and figure 4.37.

Table 4.44: "Business as Usual" energy savings – yard trimmings

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Yard Trimmings					
	Landfill to Landfill	372	372	0	
	Landfill to Landfill/Recycle	n/a	n/a	n/a	
	Landfill to Landfill (with gas recovery)	372	176	(196)	⬅

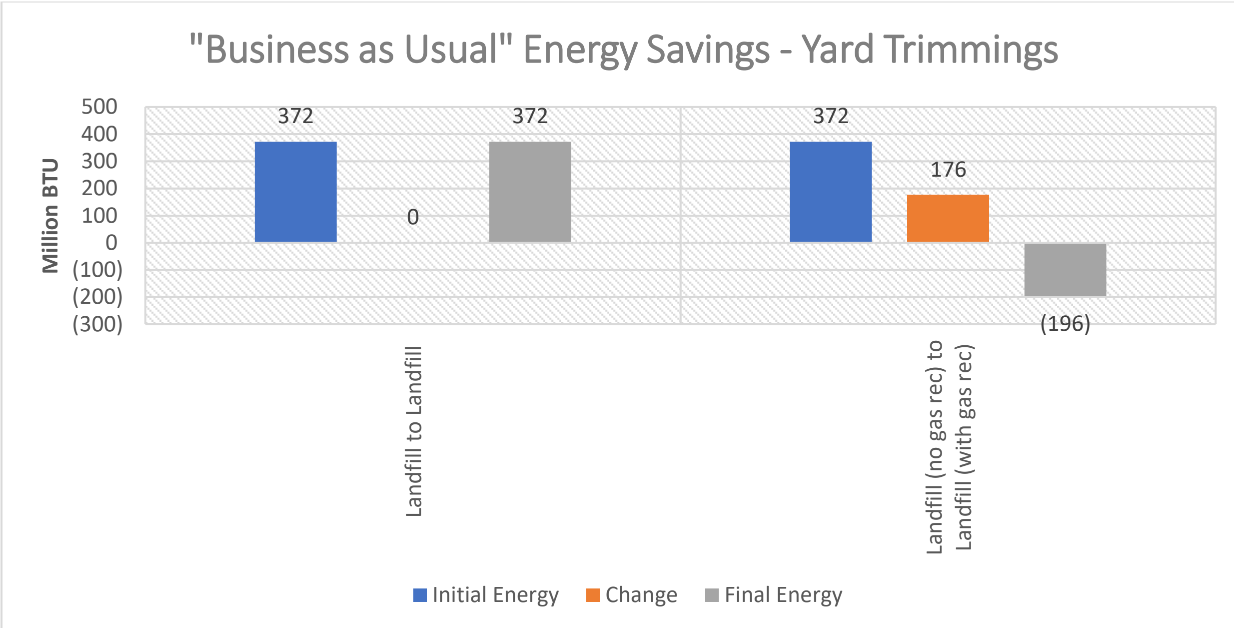


Figure 4.37: "Business as Usual" energy savings – yard trimmings (M. Richburg, 2023)

With no recycling taking place in the waste management options for yard trimmings, table 4.45 displays that there are no wage impacts for these scenarios and there is no graphical representation for the wage impact.

Table 4.45: "Business as Usual" wages impact – yard trimmings

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Yard Trimmings					
	Landfill to Landfill	63,918	63,918	0	
	Landfill to Landfill/Recycle	n/a	n/a	n/a	

4.3.4 "Business as Usual" Mixed Plastics Data

As previously stated, plastics do not have the emitting values in terms of MTCO2E that paper and food waste have (they do not decompose in the landfill), and they are the most common item that come up when emissions are mentioned. Landfilling/Recycling is the only scenario of mixed plastics that will have an emissions avoidance which is due to the recycling component, compared to the landfill option which has no emittance (see table 4.46 and figure 4.38).

Table 4.46: "Business as Usual" GHG emissions avoided – mixed plastics

Material	**Waste Management Scenario**	**Baseline Waste Management (MTCO2E)**	**Alternative Waste Management (MTCO2E)**	**Change (Alt. – Base) MTCO2E**	
Mixed Plastics					
	Landfill to Landfill	28	28	0	
	Landfill to Landfill/Recycle	28	(103)	(132)	⬅
	Landfill to Landfill (with gas recovery)	28	28	0	

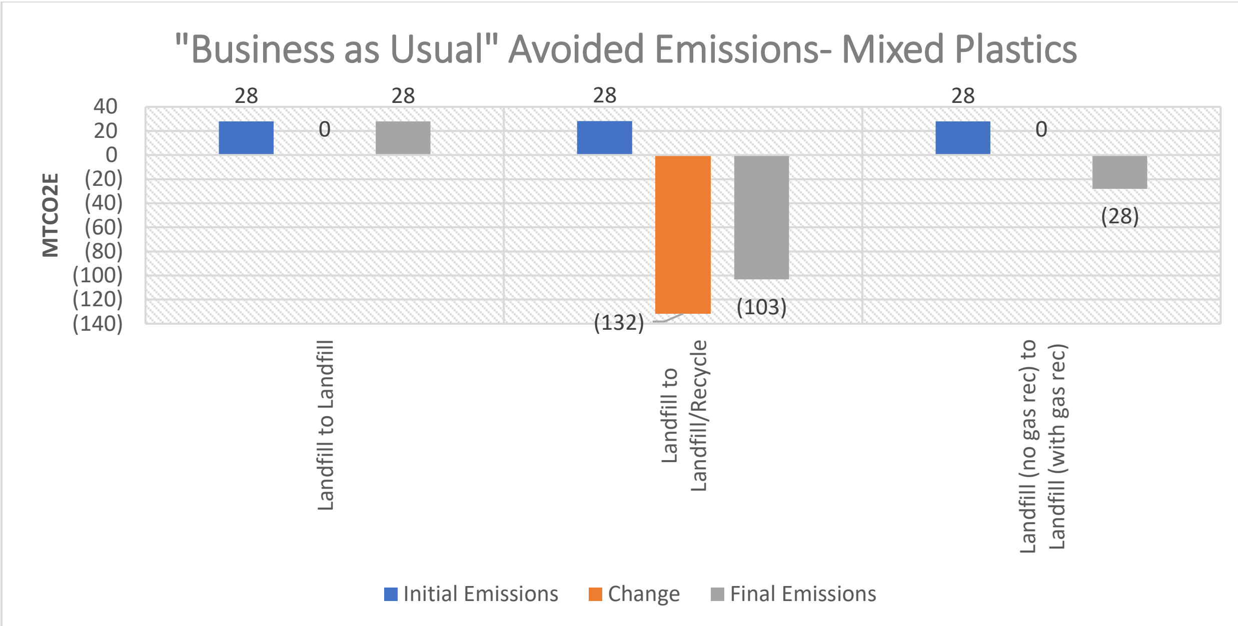


Figure 4.38: "Business as Usual" GHG emissions avoided – mixed plastics (M. Richburg, 2023)

With the potential energy savings, the landfill/recycle and landfill with gas recovery scenarios contribute energy savings for mixed plastics. The landfill/recycling scenario has an energy savings of 5,930 Million BTUs while the landfill with gas recycling has a potential savings of 199 BTUs. Table 4.47 and figure 4.39 show this data.

Table 4.47: "Business as Usual" energy savings – mixed plastics

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Mixed Plastics					
	Landfill to Landfill	375	375	0	
	Landfill to Landfill/Recycle	375	(5,555)	(5,930)	
	Landfill to Landfill (with gas recovery)	375	176	(199)	

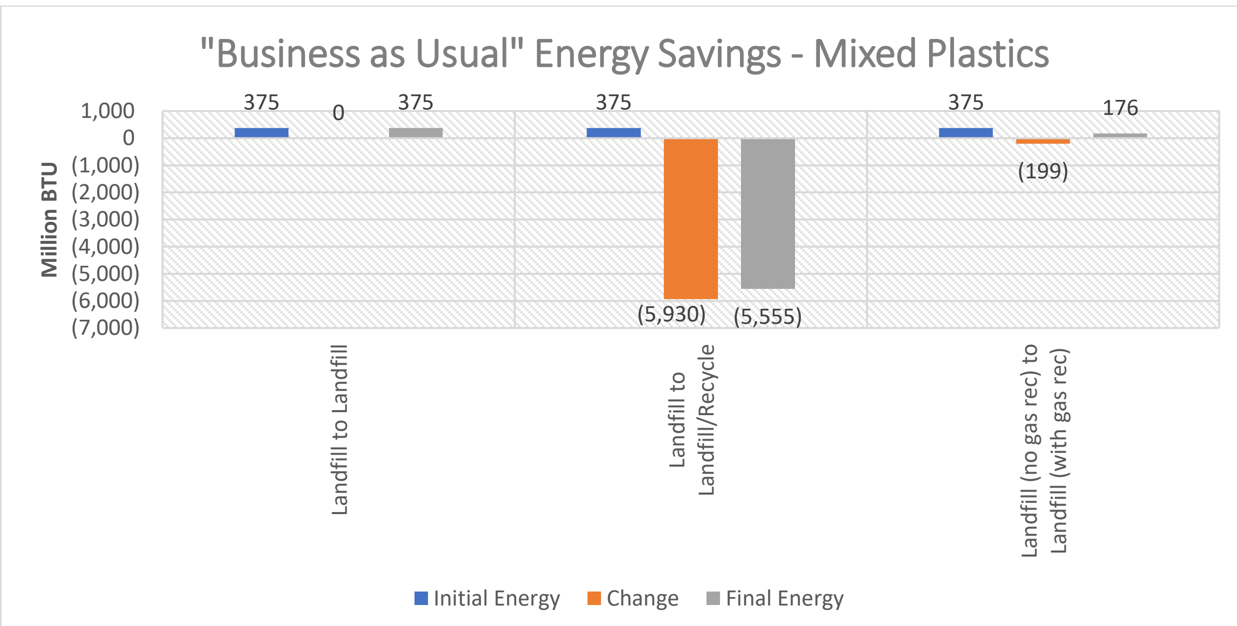


Figure 4.39: "Business as Usual" energy savings – mixed plastics (M. Richburg, 2023)

In the data calculations for mixed plastics, the wages impact is affected due to recycling being a part of two of the scenarios. Both landfill/recycling and landfill/recycling/combustion have a wages impact of $192,897, compared to the zero wages impact that the landfills with and without gas recovery, and combustion have. This data is shown in table 4.48 and figure 4.40.

Table 4.48: "Business as Usual" wages impact – mixed plastics

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Mixed Plastics					
	Landfill to Landfill	64,425	64,425	0	
	Landfill to Landfill/Recycle	64,425	257,322	192,897	
	Landfill to Landfill (with gas recovery)	64,425	64,425	0	

Figure 4.40: "Business as Usual" wages impact – mixed plastics (M. Richburg, 2023)

4.3.5 "Business as Usual" Electronics Data

Within the waste management scenarios for electronics, the landfill/recycling scenario is the only method to have emissions avoidance. The landfill/recycle option provides an emissions avoidance of 13 MTCO2E. The remaining options do not provide the emissions avoidance as seen in table 4.49 and figure 4.41.

Table 4.49: "Business as Usual" GHG emissions avoided – mixed electronics

Material	**Waste Management Scenario**	**Baseline Waste Management (MTCO2E)**	**Alternative Waste Management (MTCO2E)**	**Change (Alt. – Base) MTCO2E**	
Electronics					
	Landfill to Landfill	2	2	0	
	Landfill to Landfill/Recycle	2	(11)	(13)	⇦
	Landfill to Landfill (with gas recovery)	2	2	0	

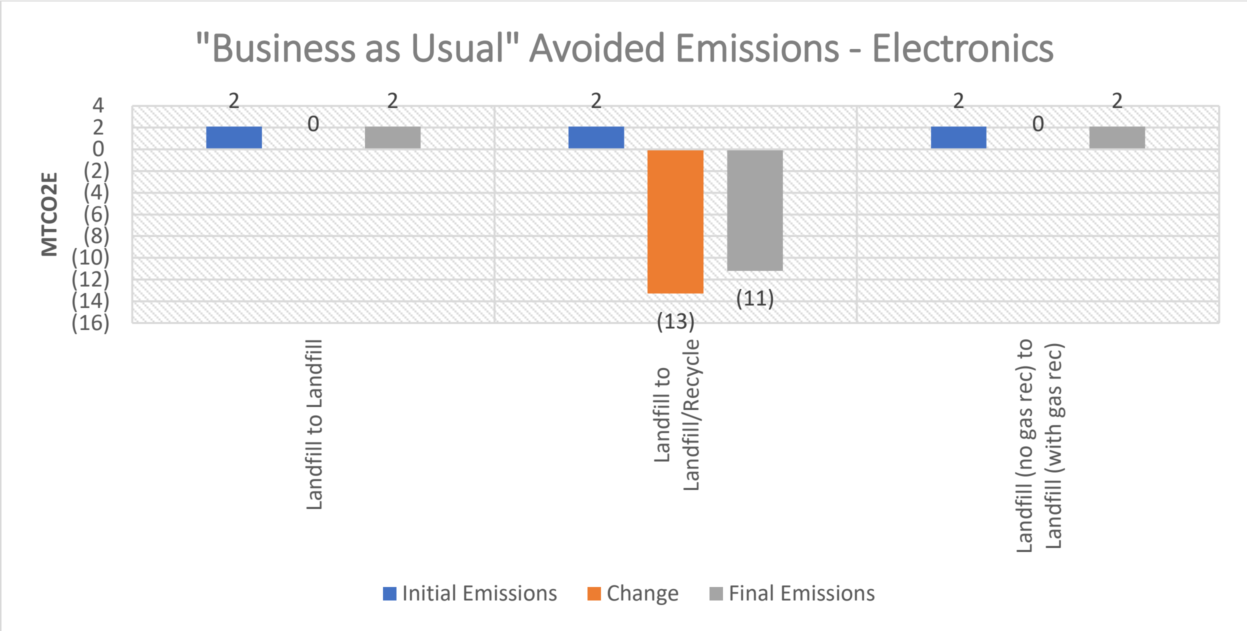


Figure 4.41: "Business as Usual" GHG emissions avoided – electronics (M. Richburg, 2023)

The recycling scenario provides an energy savings when disposing of electronics, primarily due to the materials within them having value. The scenario of landfill/recycling has a potential energy savings of 197 Million BTUs as shown in table 4.50 and figure 4.42.

Table 4.50: "Business as Usual" energy savings – electronics

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Electronics					
	Landfill to Landfill	28	28	0	
	Landfill to Landfill/Recycle	28	(169)	(197)	⬅
	Landfill to Landfill (with gas recovery)	28	28	0	

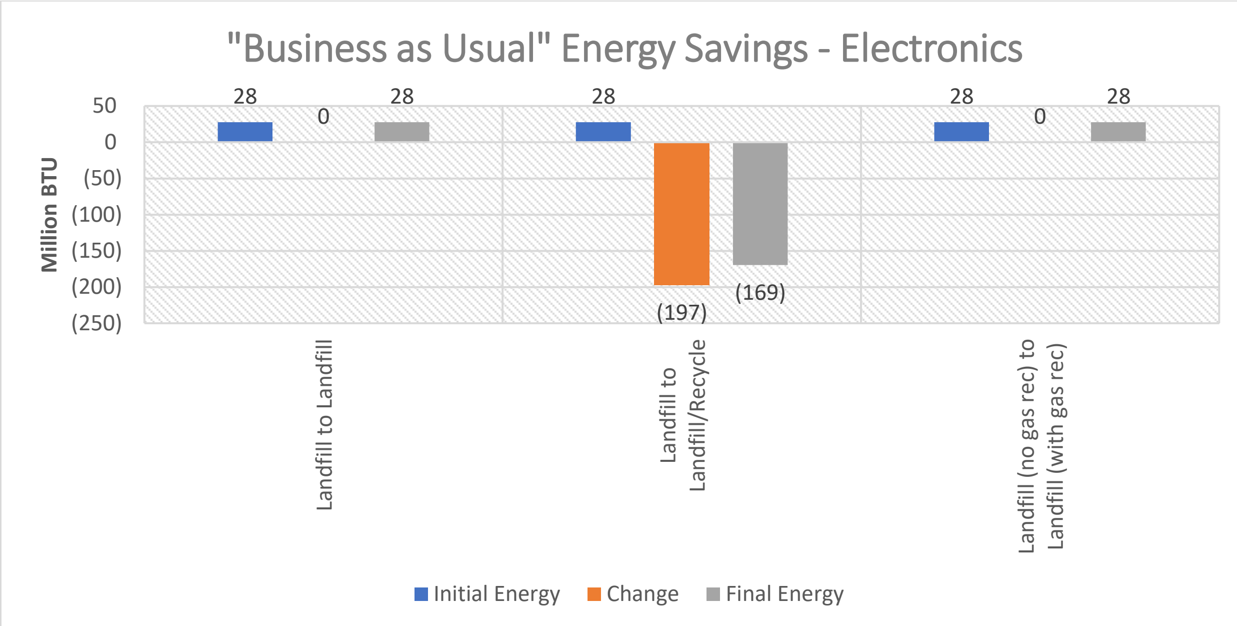


Figure 4.42: "Business as Usual" energy savings – electronics (M. Richburg, 2023)

Table 4.51 and figure 4.43 show that recycling is the only component that will produce a change in wages impacted. When combined with landfilling, the overall change for the waste management scenario is $39,555.

Table 4.51: "Business as Usual" wages impact – electronics

Material	**Waste Management Scenario**	**Wages From Baseline Waste Management US Dollar ($)**	**Wages From Alternative Waste Management US Dollar ($)**	**Change (Alt. – Base) US Dollar ($)**	
Electronics					
	Landfill to Landfill	4,753	4,753	0	
	Landfill to Landfill/Recycle	4,753	44,309	39,555	
	Landfill to Landfill (with gas recovery)	4,753	4,753	0	

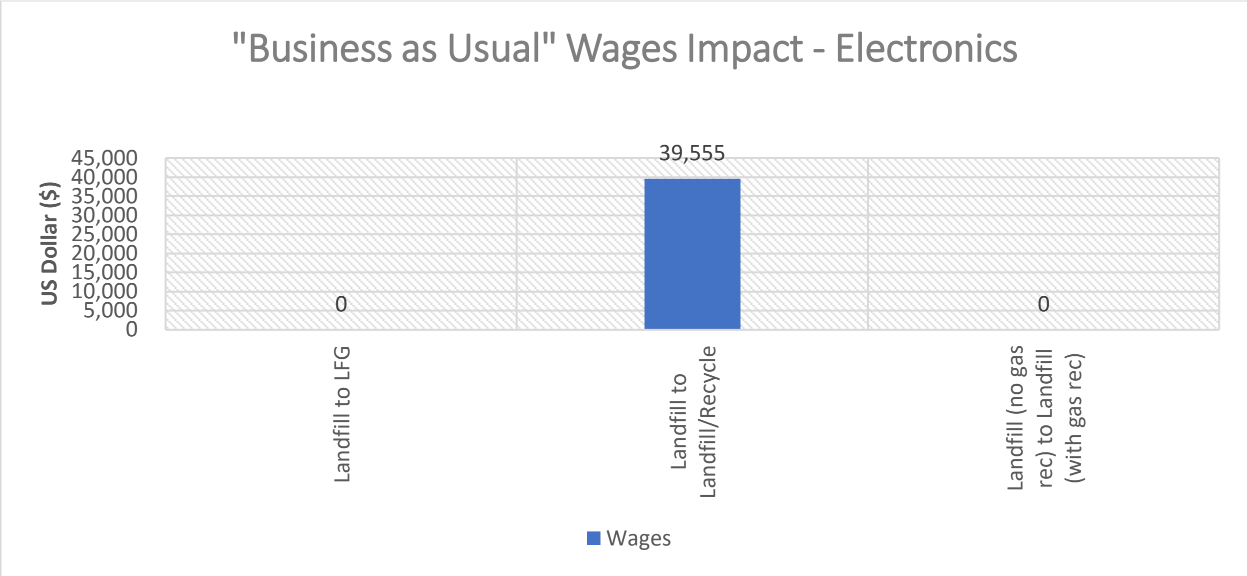


Figure 4.43: "Business as Usual" wages impact – electronics (M. Richburg, 2023)

4.3.6 "Business as Usual" Metals Data

For GHG emissions, the landfill/recycle combination provides the only opportunity for avoidance at 723 MTCO2E. Landfilling does not provide an emissions change or avoidance. The information can be seen in table 4.52 and figure 4.44.

Table 4.52: "Business as Usual" GHG emissions avoided – metals

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Metals					
	Landfill to Landfill	20	20	0	
	Landfill to Landfill/Recycle	20	(703)	(723)	⬅
	Landfill to Landfill (with gas recovery)	20	20	0	

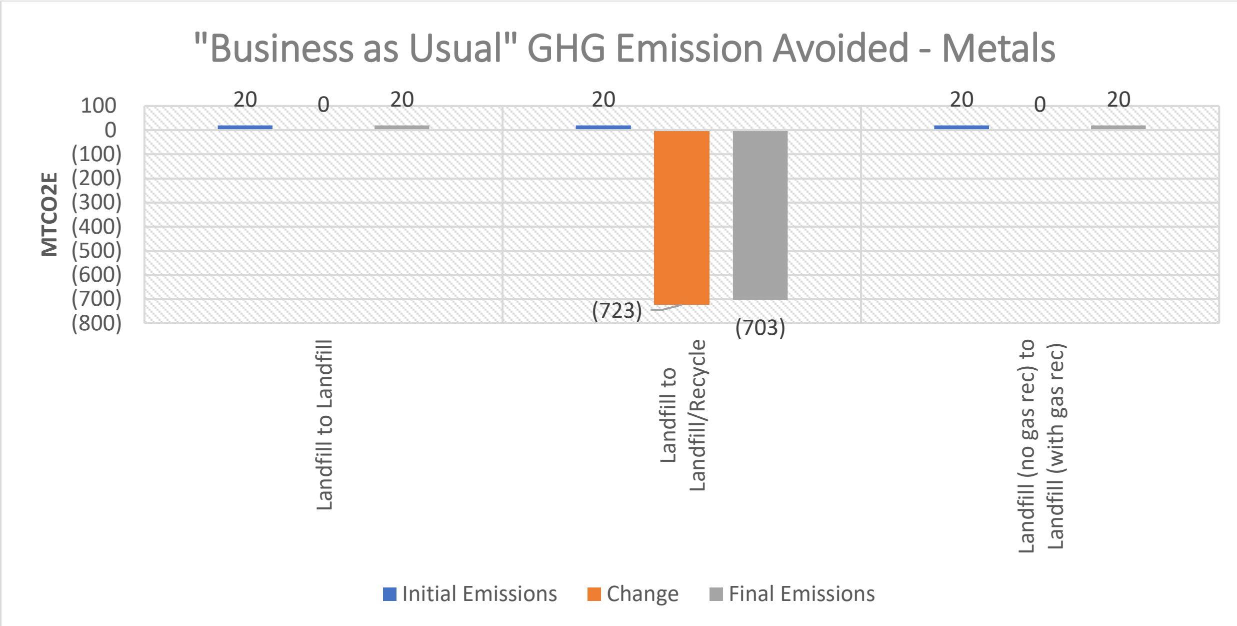


Figure 4.44: "Business as Usual" emissions avoided – metals (M. Richburg, 2023)

The opportunity for energy savings with the waste management of metal comes from utilizing the landfill/recycle scenario. Landfilling the materials solely does not produce an energy savings due to the production of metal being an energy intensive process. Landfilling/recycling has a potential for energy savings of 11,004 BUTs as seen in table 4.53 and figure 4.45.

Table 4.53: "Business as Usual" energy savings – metals

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Metals					
	Landfill to Landfill	269	269	0	
	Landfill to Landfill/Recycle	269	(10,735)	(11,004)	
	Landfill to Landfill (with gas recovery)	269	269	0	

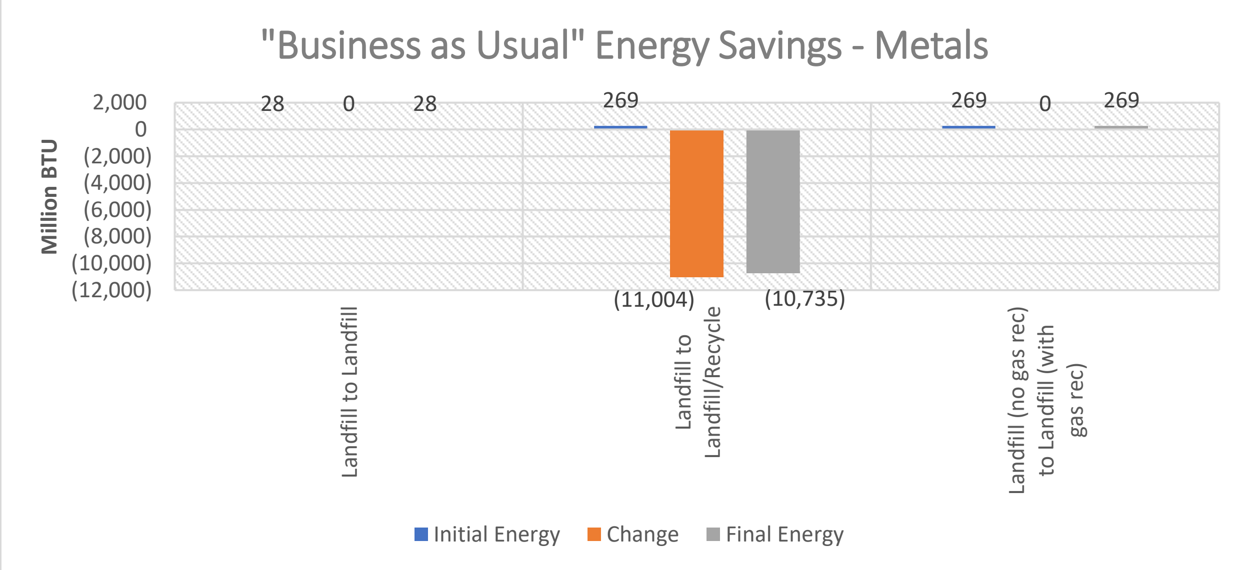


Figure 4.45: "Business as Usual" energy savings – metals (M. Richburg, 2023)

As some of the previous materials have shown, recycling must be involved for a wage impact to be seen. Table 4.54 and figure 4.46 display that a wage impact of $233,994 happens when recycling is tied into landfilling.

Table 4.54: "Business as Usual" wages impact – metals

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Metals					
	Landfill to Landfill	46,219	46,219	0	
	Landfill to Landfill/Recycle	46,219	280,213	233,994	
	Landfill to Landfill (with gas recovery)	46,219	46,219	0	

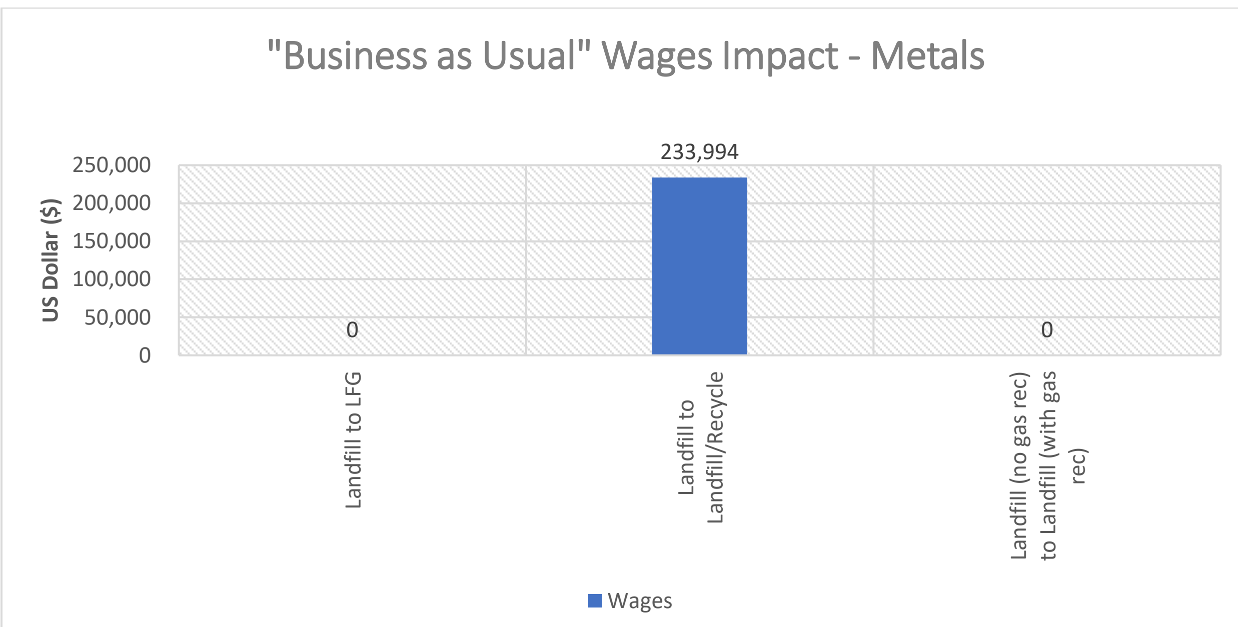


Figure 4.46: "Business as Usual" wages impact – metals (M. Richburg, 2023)

4.3.7 "Business as Usual" Glass Data

The waste management of glass has only one method that provides a small opportunity to have an emissions avoidance. Landfill/recycle has an avoidance of 23 MTCO2E, while landfilling solely does not provide emissions avoidance as seen in table 4.55 and figure 4.47.

Table 4.55: "Business as Usual" GHG emissions avoided – glass

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Glass					
	Landfill to Landfill	10	10	0	
	Landfill to Landfill/Recycle	10	(13)	(23)	
	Landfill to Landfill (with gas recovery)	10	10	0	

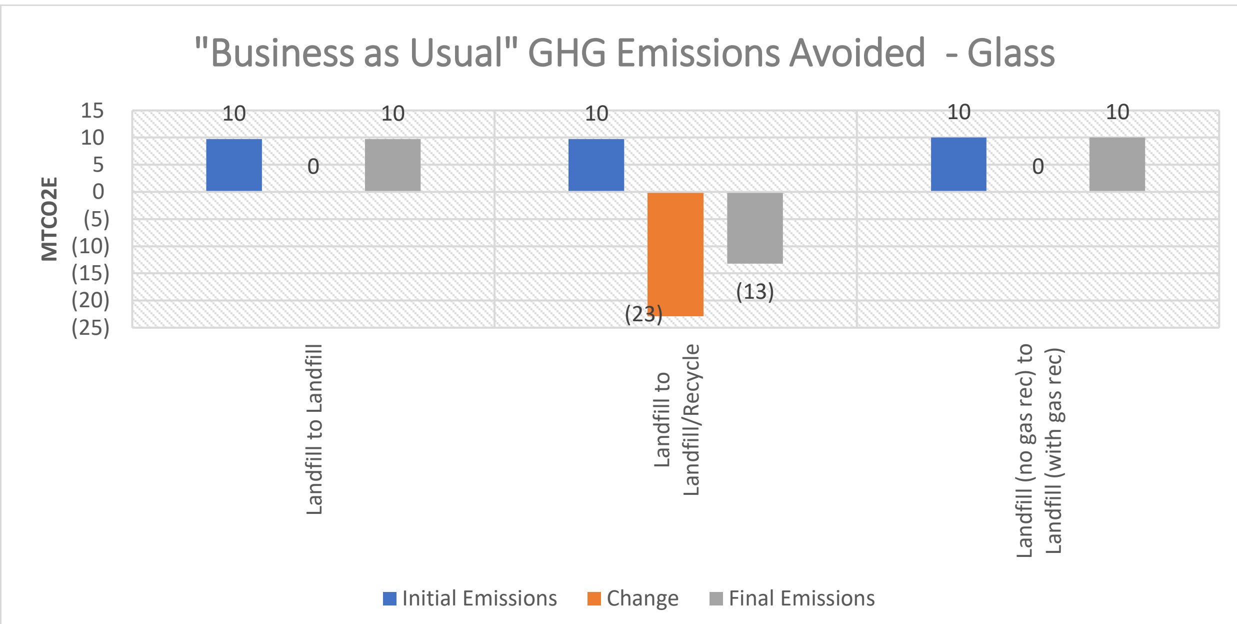


Figure 4.47: "Business as Usual" GHG emissions avoided – glass (M. Richburg, 2023)

Energy savings is seen through only one of the waste management scenarios for glass. Landfill/recycling provides an energy savings of 184 MTCO2E, while landfilling only provides no emissions avoidance (see table 4.56 and figure 4.48).

Table 4.56: "Business as Usual" energy savings – glass

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Glass					
	Landfill to Landfill	129	129	0	
	Landfill to Landfill/Recycle	129	(55)	(184)	
	Landfill to Landfill (with gas recovery)	129	129	0	

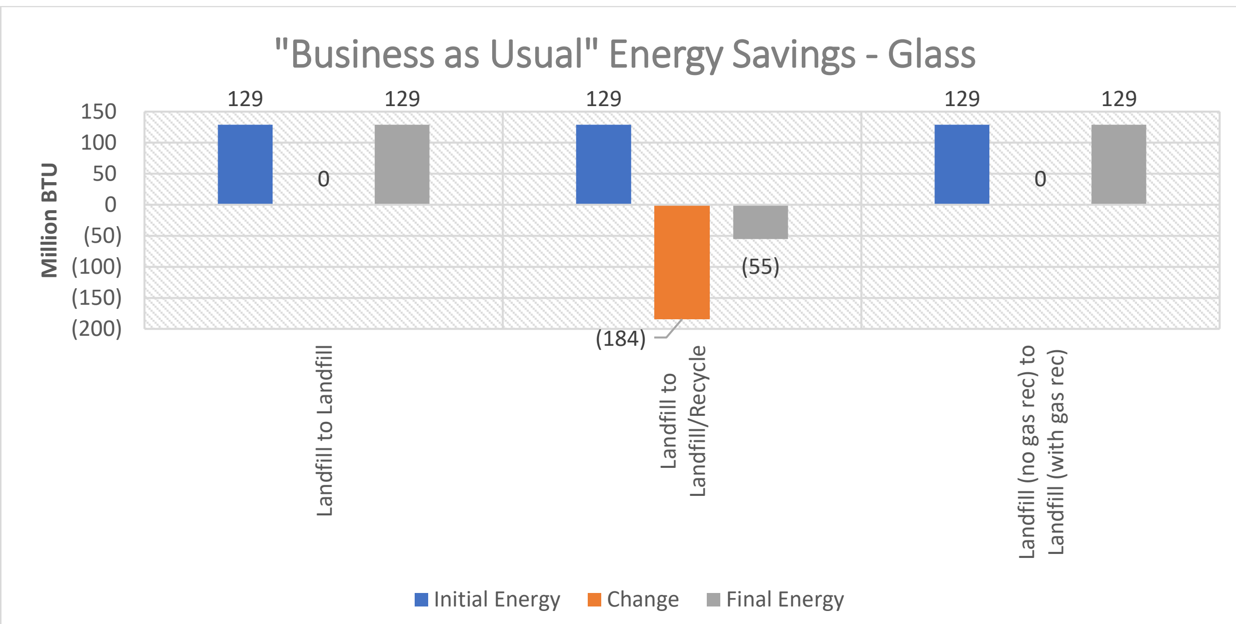


Figure 4.48: "Business as Usual" energy savings – glass (M. Richburg, 2023)

The wages in the waste management of glass are impacted by the scenario that has recycling involved with it. The landfill/recycle scenario impacts wages by $34,117 (see table 4.57 and figure 4.49) compared to zero impact when landfilling only.

Table 4.57: "Business as Usual" wages impact – glass

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Glass					
	Landfill to Landfill	22,189	22,189	0	
	Landfill to Landfill/Recycle	22,189	56,306	34,117	⬅
	Landfill to Landfill (with gas recovery)	22,189	22,189	0	

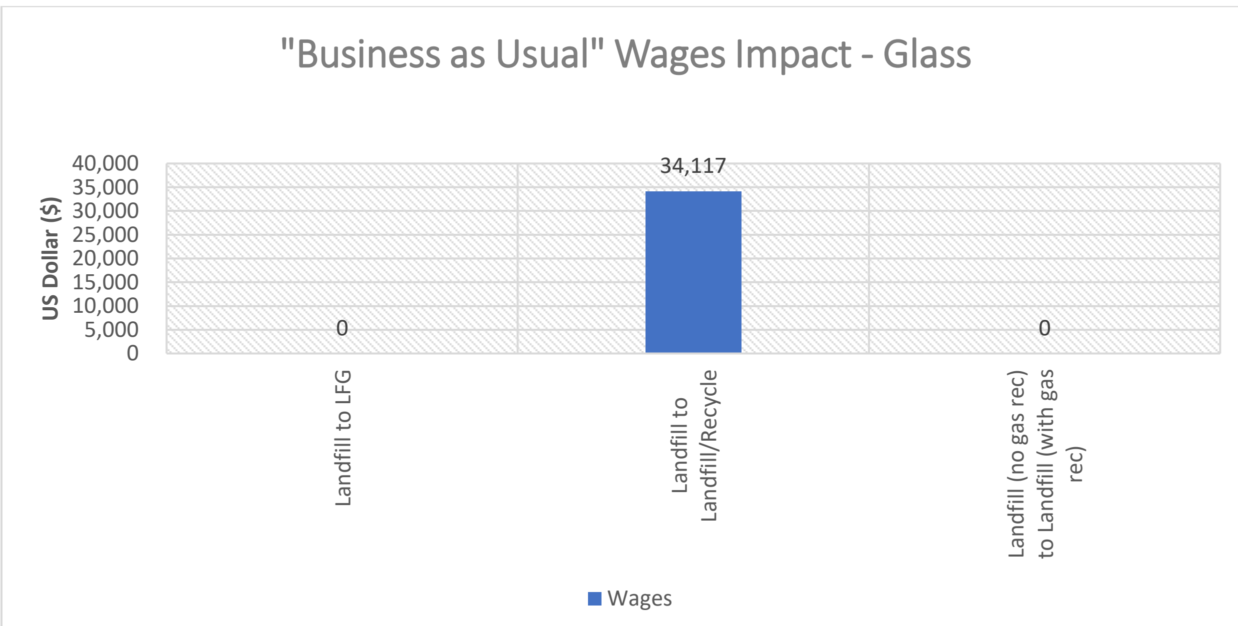


Figure 4.49: "Business as Usual" wages impact – glass (M. Richburg, 2023)

4.3.8 "Business as Usual" Carpet Data

The waste management of carpet has only one scenario that creates an opportunity for the avoidance of emissions which is the landfill/recycle scenario at 51 MTCO2E. Landfilling creates no change in emissions avoidance (see table 4.58 and figure 4.50).

Table 4.58: "Business as Usual" GHG emissions avoided – carpet

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Carpet					
	Landfill to Landfill	3	3	0	
	Landfill to Landfill/Recycle	3	(48)	(51)	
	Landfill to Landfill (with gas recovery)	3	(38)	0	

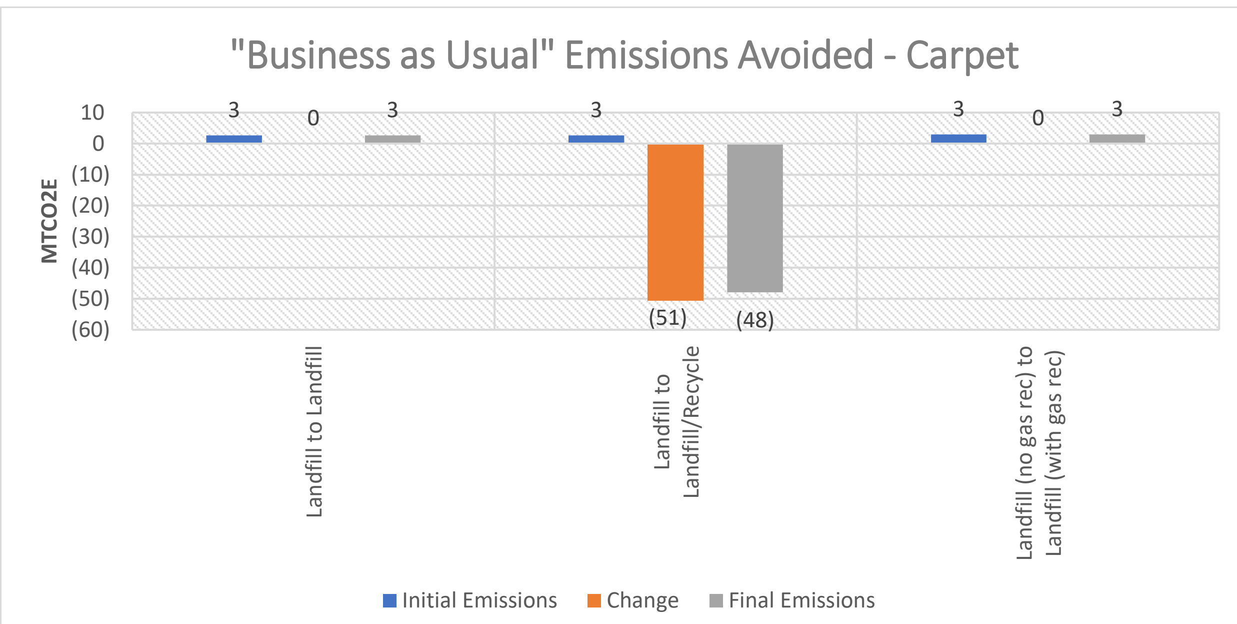


Figure 4.50: "Business as Usual" GHG emissions avoided – carpet (M. Richburg, 2023)

As with mixed plastics, electronics, metals, and glass, the recycling component is the only method, combined with landfilling, that provides an opportunity for energy savings. The landfill/recycle scenario has a savings of 458 Million BTUs, The landfill only options do not produce any change or savings in BTUs (see table 4.59 and figure 4.51).

Table 4.59: "Business as Usual" energy savings – carpet

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Carpet					
	Landfill to Landfill	35	35	0	
	Landfill to Landfill/Recycle	35	(422)	(458)	
	Landfill to Landfill (with gas recovery)	35	35	0	

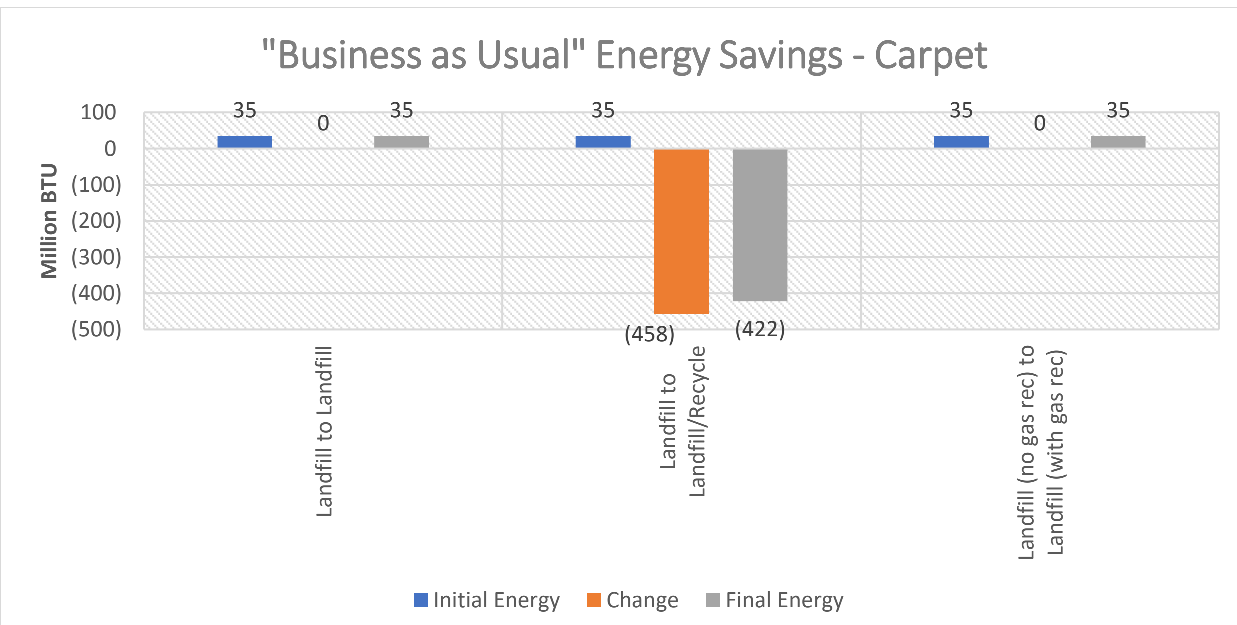


Figure 4.51: "Business as Usual" energy savings – carpet (M. Richburg, 2023)

The only scenario that will have an impact on wages is the landfill/recycle. This scenario has a wage impact of $9,510 whereas the landfill only option will see no change as shown in table 4.60 and figure 4.52.

Table 4.60: "Business as Usual" wages impact – carpet

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Carpet					
	Landfill to Landfill	6,073	6,073	0	
	Landfill to Landfill/Recycle	6,073	15,583	9,510	
	Landfill to Landfill (with gas recovery)	6,073	6,073	0	

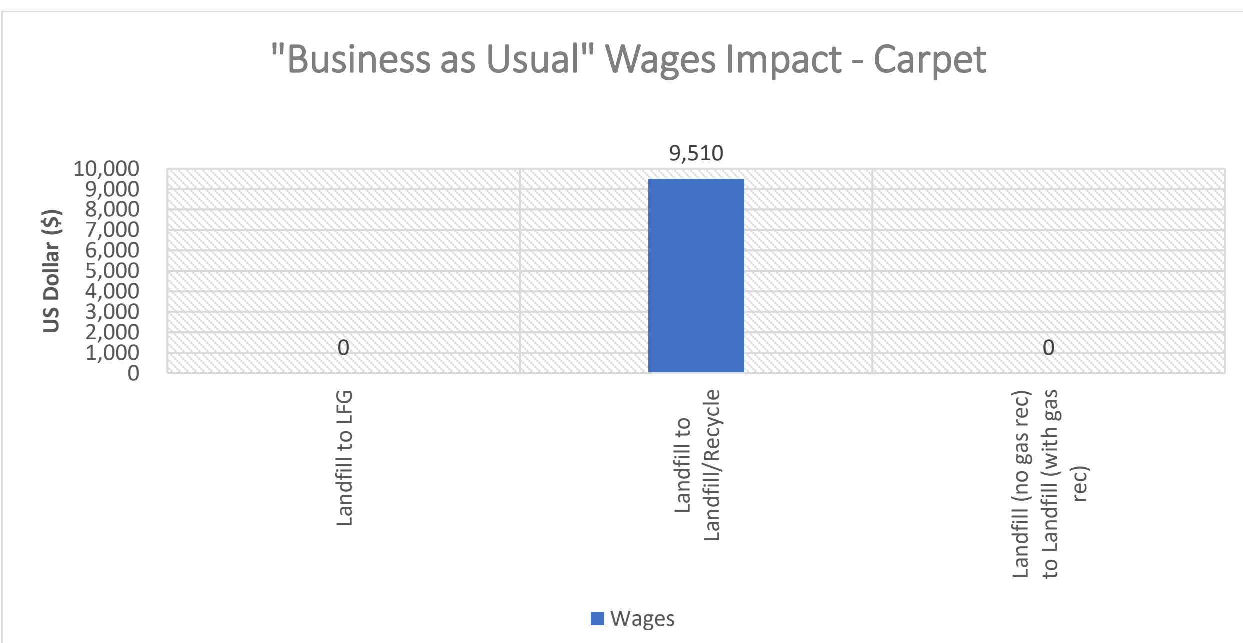


Figure 4.52: "Business as Usual" wages impact – carpet (M. Richburg, 2023)

4.3.19 "Business as Usual" Tires Data

Recycling is the main waste management method that will produce the opportunity for avoidance of emissions. Landfill/recycling has an emissions avoidance of 16 MTCO2E while the landfill only scenarios have zero change (see table 4.61 and figure 4.53)

Table 4.61: "Business as Usual" GHG emissions avoided – tires

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Tires					
	Landfill to Landfill	5	5	0	
	Landfill to Landfill/Recycle	5	(11)	(16)	
	Landfill to Landfill (with gas recovery)	5	5	0	

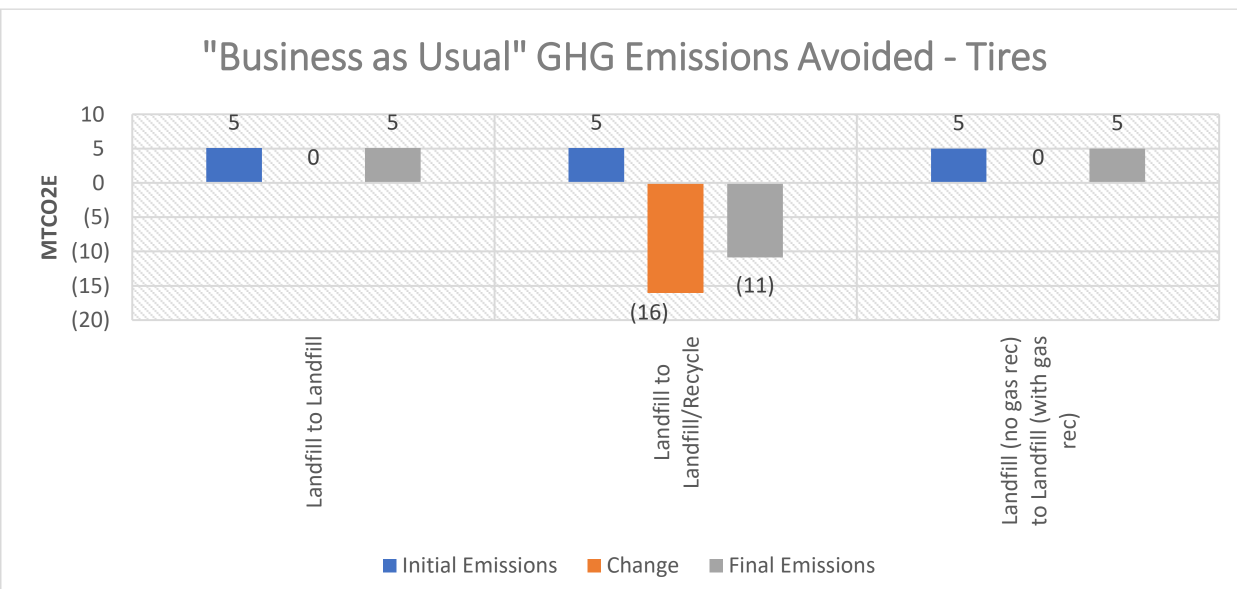


Figure 4.53: "Business as Usual" GHG emissions avoided – tires (M. Richburg, 2023)

The energy savings for tires is created by the landfill/recycling waste management scenario in which an energy savings of 156 BTUs is realized as seen in table 4.62 and figure 4.54 compared to zero for landfilling only.

Table 4.62: "Business as Usual" energy savings – tires

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
Tires					
	Landfill to Landfill	68	68	0	
	Landfill to Landfill/Recycle	68	(88)	(156)	
	Landfill to Landfill (with gas recovery)	68	68	0	

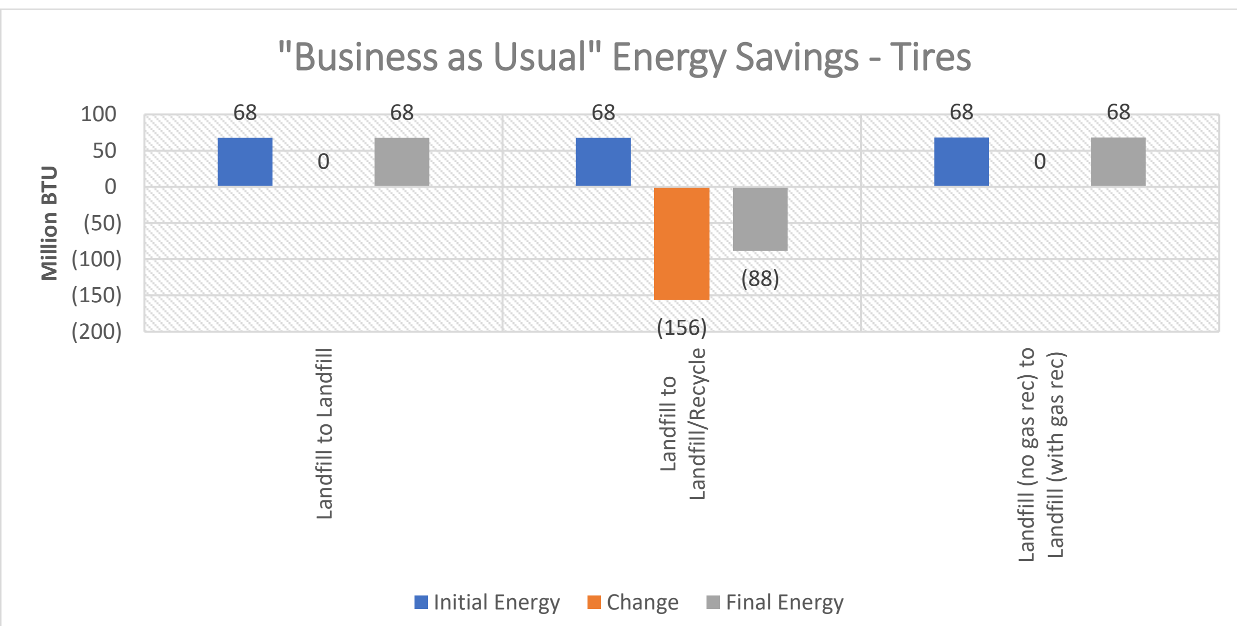


Figure 4.54: "Business as Usual" energy savings – tires (M. Richburg, 2023)

The wages impact for tires comes from the scenario that employs recycling as part of the waste management method. For tires, the landfill/recycle scenario has wages impacted of $14,328 (see table 4.63 and figure 4.55). Landfilling by itself produces no change or wages impacted.

Table 4.63: "Business as Usual" wages impact – tires

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Tires					
	Landfill to Landfill	11,621	11,621	0	
	Landfill to Landfill/Recycle	11,621	25,949	14,328	⬅
	Landfill to Landfill (with gas recovery)	11,621	11,621	0	

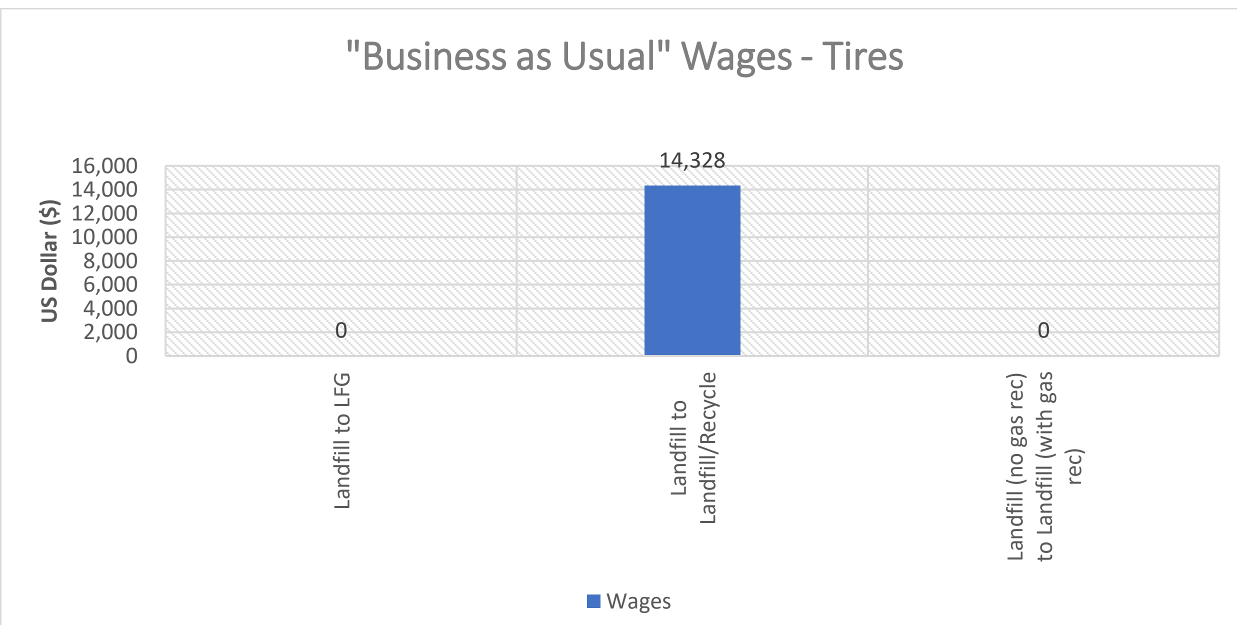


Figure 4.55: "Business as Usual" wages impact – tires (M. Richburg, 2023)

4.3.10 "Business as Usual" Mixed MSW Data

Mixed MSW only has two scenarios in its waste management to calculate emission avoided, energy savings, and wages impacted. The available options are landfill/landfill with no gas recovery and landfill/landfill with gas recovery. Only the landfill/landfill with gas recovery provides an emissions avoidance, which is 1,890 MTCO2E. The landfill/landfill (no gas recovery) has zero change in emission (see table 4.64 and figure 4.56).

Table 4.64: "Business as Usual" GHG emissions avoided – mixed MSW

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
Mixed MSW					
	Landfill to Landfill	2,138	2,138	0	
	Landfill to Landfill/Recycle	n/a	n/a	n/a	
	Landfill to Landfill (with gas recovery)	2,138	248	(1,890)	←

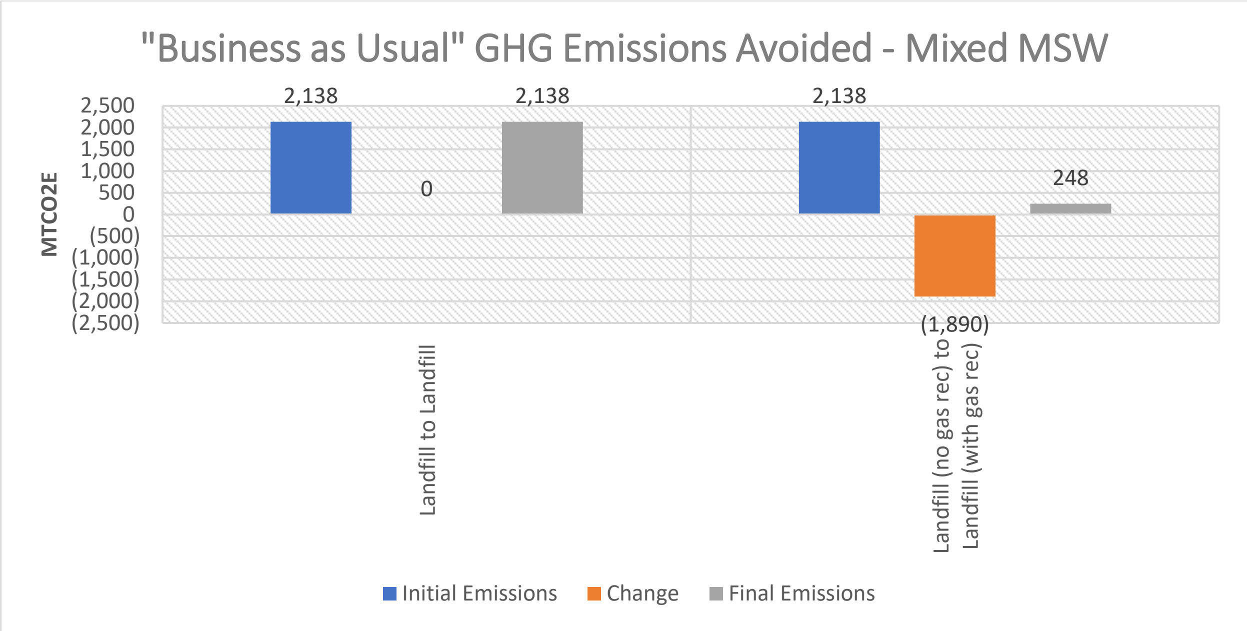


Figure 4.56: "Business as Usual" GHG emissions avoided – mixed MSW (M. Richburg, 2023)

The landfill with gas recovery scenario has the potential for energy savings in the waste management process of 637 Million BTUs (see table 4.65 and figure 4.57), while the landfill/recycle scenario cannot be utilized with mixed MSW.

Table 4.65: "Business as Usual" energy savings – mixed MSW

Material	**Waste Management Scenario**	**Energy Use Baseline Waste Management Million BTU**	**Energy Use Alternative Waste Management Million BTU**	**Change (Alt. – Base) Million BTU**	
Mixed MSW					
	Landfill to Landfill	451	451	0	
	Landfill to Landfill/Recycle	n/a	n/a	n/a	
	Landfill to Landfill (with gas recovery)	451	(186)	(637)	⇐

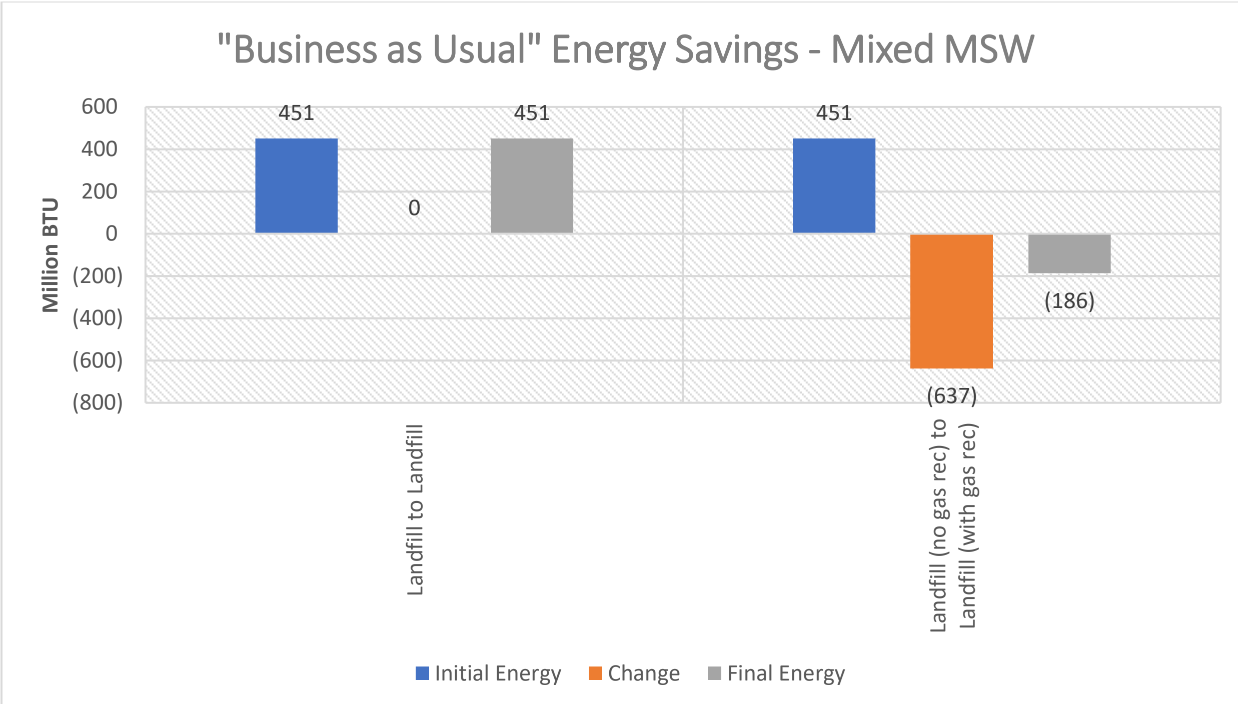


Figure 4.57: "Business as Usual" energy savings – mixed MSW (M. Richburg, 2023)

With there being no recycling involved in the handling of mixed MSW, there are no wages impacting waste management and all the scenarios involved have a change of zero (table 4.66).

Table 4.66: "Business as Usual" wages impact – mixed MSW

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
Mixed MSW					
	Landfill to Landfill	77,652	77,652	0	
	Landfill to Landfill/Recycle	n/a	n/a	n/a	
	Landfill to Landfill (with gas recovery)	77,652	77,652	0	

4.3.11 Summary of “Business as Usual” Calculations

Tables 4.67 – 4.69 provide a summary of WARM model “Business as Usual” calculations. As a reminder, these data are calculated based upon the monthly average of MSW delivered to the Montgomery County Landfill in 2021. The presented data displays avoided emissions, energy savings, and wages from the current waste management practices.

Table 4.67: Summary of GHG emissions for the “Business as Usual” case

	LFG (MTCO2E)	Recycle (MTCO2E)
Paper	(4,128)	(1,945)
Food Waste	(2,446)	N/A
Yard Trimmings	(629)	N/A
Mixed Plastics	0	(132)
Electronics	0	(13)
Metals	0	(723)
Glass	0	(23)
Carpet	0	(51)
Tires	0	(16)
Mixed MSW	(1,890)	N/A

Table 4.68: Summary of energy savings for the "Business as Usual" case

	LFG (Million BTU)	Recycle (Million BTU)
Paper	(1,356)	(6,526)
Food Waste	(785)	N/A
Yard Trimmings	(195)	N/A
Mixed Plastics	0	(5,930)
Electronics	0	(197)
Metals	0	(11,004)
Glass	0	(184)
Carpet	0	(458)
Tires	0	(156)
Mixed MSW	(637)	N/A

Table 4.69: Summary of the wage impact for the "Business as Usual" case

	LFG (US Dollar)	Recycle (US Dollar)
Paper	0	60,859
Food Waste	0	N/A
Yard Trimmings	0	N/A
Mixed Plastics	0	192,897
Electronics	0	39,555
Metals	0	233,994
Glass	0	34,117
Carpet	0	9,510
Tires	0	14,328
Mixed MSW	0	0

4.4 WARM Model – "Business as Usual" Full Generation Calculations

In the full generation "Business as Usual" calculation section, the full MSW tonnage for 2021 was applied to the entire WARM model, instead of by material isolation, to generate data to determine the total emissions avoided, potential energy savings, and the wages impact from the selected waste management method. The models that were run are in accordance with the current state of waste management in Alabama. The selected waste management methods are those that were presented in table 4.36. The scenarios for the full generation "Business as Usual" are landfill to landfill (no gas recovery), landfill to landfill (with gas recovery), and landfill to landfill/recycle (with gas recovery).

4.4.1 "Business as Usual" Full Generation Emissions Avoided

The landfill/recycle scenario with gas recovery provides an emissions avoidance of 11,583 MTCO2E, compared to that of landfilling with gas recovery, which has an emissions avoidance of 9,357 MTCO2E. Landfilling with no gas recovery provides no emissions avoidance, as seen in table 4.70 and figure 4.58.

Table 4.70: "Business as Usual" full generation GHG emissions avoided

Material	Waste Management Scenario	Baseline Waste Management (MTCO2E)	Alternative Waste Management (MTCO2E)	Change (Alt. – Base) MTCO2E	
	Landfill to Landfill (no gas recovery)	9,698	9,698	0	
	Landfill to Landfill/Recycle (gas recovery)	9,698	(1,885)	(11,583)	
	Landfill to Landfill (gas recovery)	9,698	341	(9,357)	

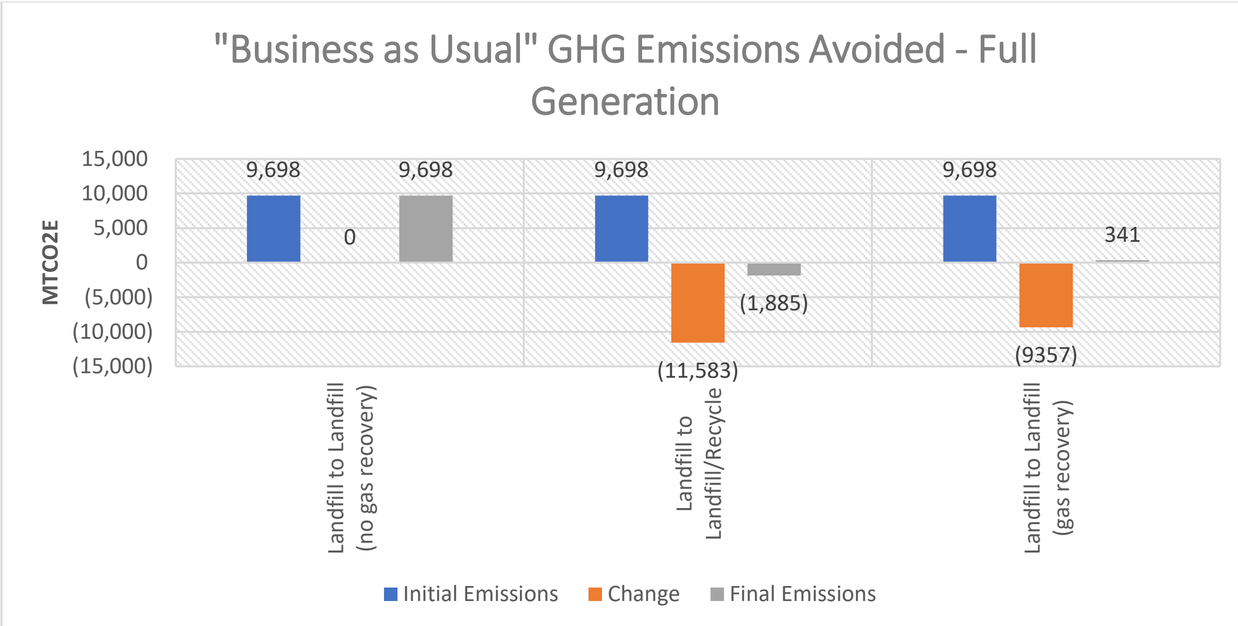


Figure 4.58: "Business as Usual" GHG emissions avoided – full generation (M. Richburg, 2023)

4.4.2 "Business as Usual" Full Generation Energy Savings

The landfill/recycle scenario provides an energy savings of 27,282 Million Btu, from which the large savings can be attributed to the recycling of metal. With the production of metals being energy intensive, recycling the metals can reduce the energy that is used early in the life cycle of the material. Landfill with gas recovery also provides an energy savings of 3,051 Million BTU, but landfill with no gas recovery does not provide an energy savings (see table 4.71 and figure 4.59).

Table 4.71: "Business as Usual" full generation energy savings

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
	Landfill to Landfill (no gas recovery)	3,098	3,098	0	
	Landfill to Landfill/Recycle (gas recovery)	3,098	(24,184)	(27,282)	
	Landfill to Landfill (gas recovery)	3,098	47	(3,051)	

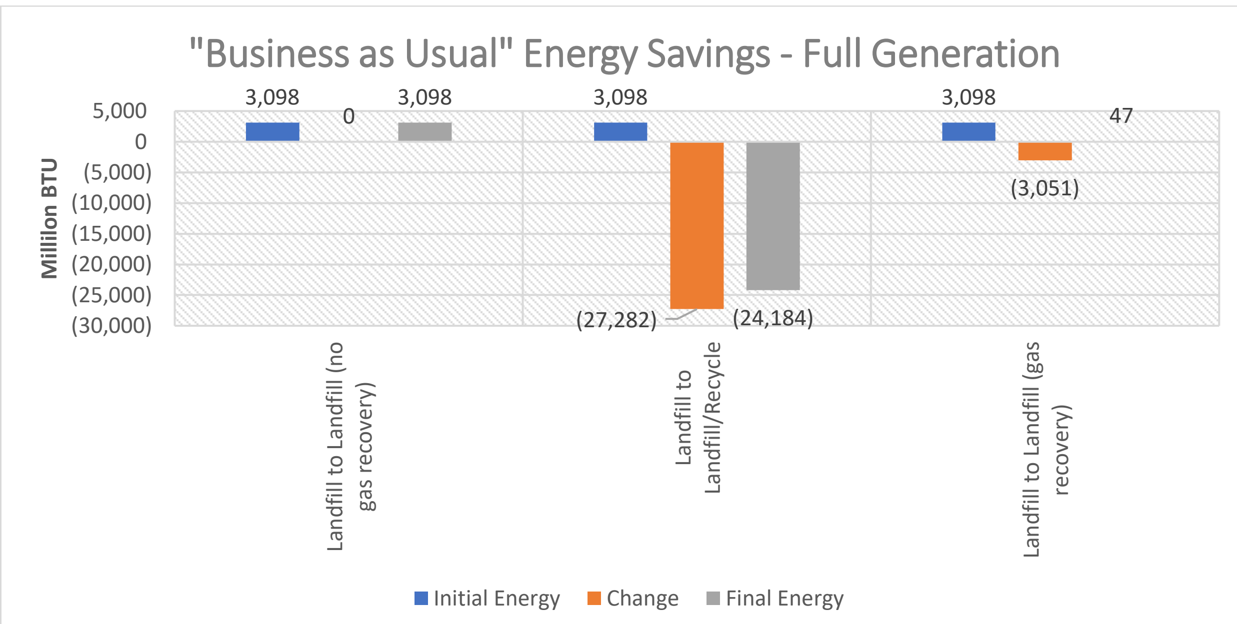


Figure 4.59: "Business as Usual" full generation energy savings (M. Richburg, 2023)

4.4.3 Full Generation Wages Impact

As it relates to the wages impact in the WARM model, recycling plays a major role in the calculation of wages in the waste management scenarios, whereas when there is no recycling, there are no changes between the baseline and the alternative, as seen with the landfill scenarios. Recycling, when combined with landfilling, produces a wage impact of $584, 990 (table 4.72 and figure 4.60).

Table 4.72: "Business as Usual" full generation - wages impact

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
	Landfill to Landfill (no gas recovery)	532,982	532,982	0	
	Landfill to Landfill/Recycle (gas recovery)	532,982	1,117,971	584,990	
	Landfill to Landfill (gas recovery)	532,982	532,982	0	

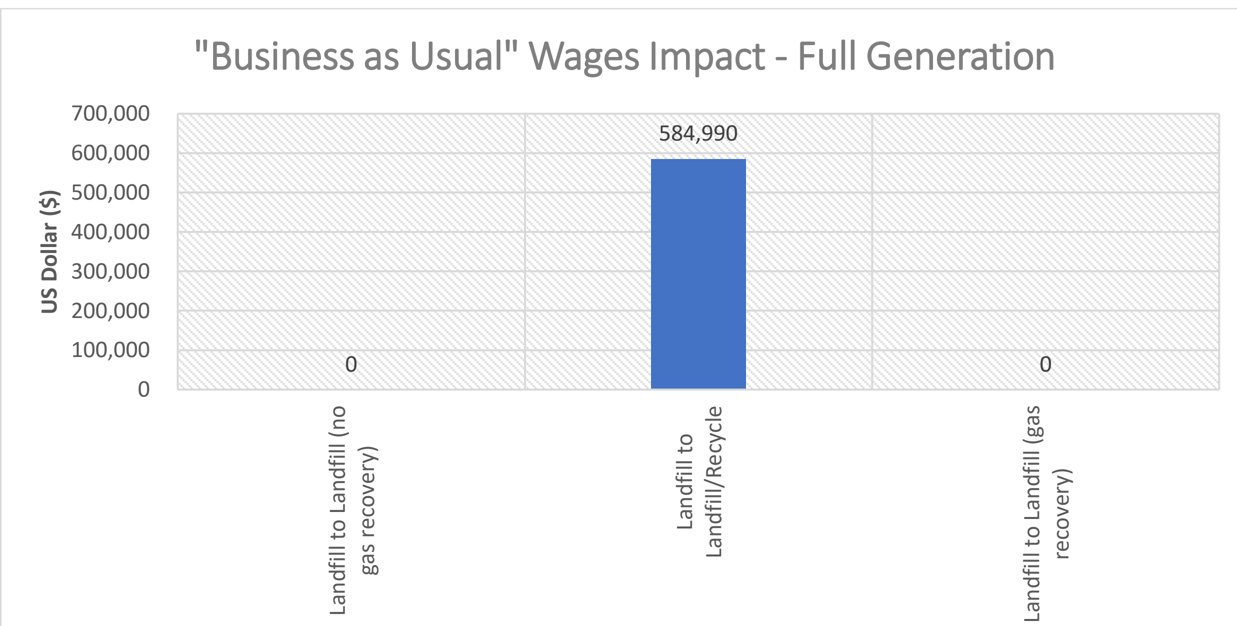


Figure 4.60: "Business as Usual" full generation wages impact (M. Richburg, 2023)

4.4.4 Summary of "Business as Usual" Full Generation Calculations

Table 4.73 provides a summary of WARM model "Business as Usual" full generation calculations. As a reminder, these data are calculated based upon the monthly average of MSW delivered to the Montgomery County Landfill in 2021. The monthly average for each material was input for the full waste management stream to generated data for avoided emissions, energy savings, and wages.

Table 4.73: Summary of "Business as Usual" full generation case

Waste Management Scenario	Emissions Avoided (MTCO2E)	Energy Savings (MTCO2E)	Employment (USD)
Landfill to Landfill (No Gas Recovery)	0	0	0
Landfill to Landfill/Recycle (Gas Recovery	(11,583)	(27,282)	584,990
Landfill to Landfill (Gas Recovery)	(9,357)	(3,051)	0

4.5 WARM Model - Practical Modeling

This section will utilize the average monthly tonnage data for 2021 from the Montgomery County, AL landfill and model the data in a practical methodology. The practical methodology will use assumptions based on current waste management methods, while assessing additional methods that will provide emissions avoidance, potential energy savings, and detail wage or employment impacts. In this analysis, it was assumed that a MRF could be added at the landfill site to separate the MSW into streams that could then potentially be recycled. Table 4.74 outlines the assumptions that are made for emissions avoidance and energy savings with additional details for each stream provided in the ensuring discussion.

Table 4.74: Practical research methodology assumptions

	Landfill	Recycle	Combustion	Compost	Digestion
Paper	10%	80%	10%	0	0
Food Waste	10%	0%	90%	0	0
Yard Trimmings	10%	0%	90%	0	0
Mixed Plastics	5% | 10%	90% | 0%	5% | 90%	0	0
Electronics	5%	90%	5%	0	0
Metals	5%	90%	5%	0	0
Glass	10%	90%	0	0	0
Carpet	5%	90%	5%	0	0
Tires	5%	90%	5%	0	0
Mixed MSW	10%	0	90	0	0

For the practical research method, percentages were assigned to each material and the selected waste management method. Recycling is the preferred waste management method, but in most scenarios, it will be combined with both landfilling and combustion. It is the primary goal to keep materials out of the landfill, therefore material percentages for landfilling will be kept at 10% or lower. Paper products were assigned its percentage due to the number of emissions avoided when this process takes place and the energy savings primarily shown during the theoretical research phase. Also, a greater than 80% recovery stream for paper was reported in the United States, but approximately 20% of the paper stream is still unable to be recycled (Sharma et al., 2019).

Food waste is unable to be recycled, therefore, to keep landfilling at a minimum, 90% of the material will be thermally converted, which is combustion for this research. Yard trimmings will be treated in the same manner as food waste. The theoretical research states that combustion is the best option for food waste and yard trimmings as it relates to emissions avoidance and energy savings.

Mixed plastics with its various types can be handled in two different ways. The first is when recyclable plastics are managed, which is at 90%, the other 10% is divided between landfilling and combustion. Some of the plastics will “slip through the cracks” and end up in either the landfill or combustion chamber. The plastics that cannot be recycled will primarily be combusted (90%) and the remaining landfilled (10%). The remaining materials, electronics, metals, glass, carpet, and tires will be recycled at a rate of 90%, with the remaining 10% split between landfill and combustion. The exception is glass, which the theoretical research states that there is no emissions avoidance and the energy savings is negligible. The remaining material is mixed MSW, in which there is no option for recycling. As previously stated, to reduce landfill capacity, the majority of MSW will be diverted, of which 90% will be combusted, while the remaining 10% will be landfilled.

4.5.1 **Practical Modeling – Emissions Avoided**

With the practical modeling, two scenarios are presented, which are landfill to landfill/recycle (no gas recovery) and landfill to landfill/recycle (with gas recovery). A baseline of landfill to landfill without recycling or gas recovery was created to determine and compare the change in emissions as shown in table 4.75 and figure 4.61.

Table 4.75: Practical model – emissions avoided

Material	**Waste Management Scenario**	**Baseline Waste Management (MTCO2E)**	**Alternative Waste Management (MTCO2E)**	**Change (Alt. – Base) MTCO2E**	
	Landfill to Landfill (no gas recovery)	9,698	9,698	0	
	Landfill to Landfill/Recycle (no gas recovery)	9,698	(11,208)	(20,907)	
	Landfill to Landfill/Recycle (gas recovery)	9,698	(12,144)	(21,842)	

.

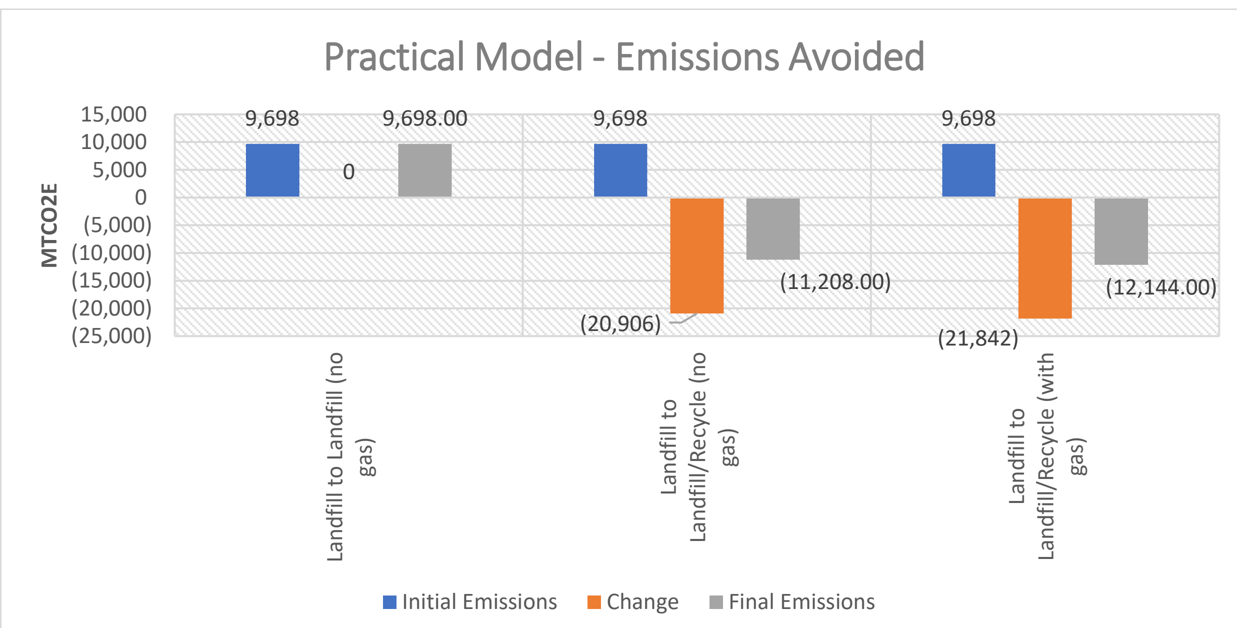


Figure 4.61: Practical model – emissions avoided (M. Richburg, 2023)

4.5.2 Practical Modeling – Energy Savings

The energy savings is calculated using two scenarios, with the landfill-to-landfill servings as the baseline method. Table 4.76 and figure 4.62 display that gas recovery at the landfill does not provide a distinct difference from not having a gas recovery system. Although there is not much difference between the two, the gas recovery system is still important for the landfill due to not being able to recycle materials such as food waste and yard trimmings.

Table 4.76: Practical research – energy savings

Material	Waste Management Scenario	Energy Use Baseline Waste Management Million BTU	Energy Use Alternative Waste Management Million BTU	Change (Alt. – Base) Million BTU	
	Landfill to Landfill (no gas recovery)	3,098	3,098	0	
	Landfill to Landfill/Recycle (no gas recovery)	3,098	(159,012)	(162,110)	
	Landfill to Landfill/Recycle (gas recovery)	3,098	(159,317)	(162,415)	

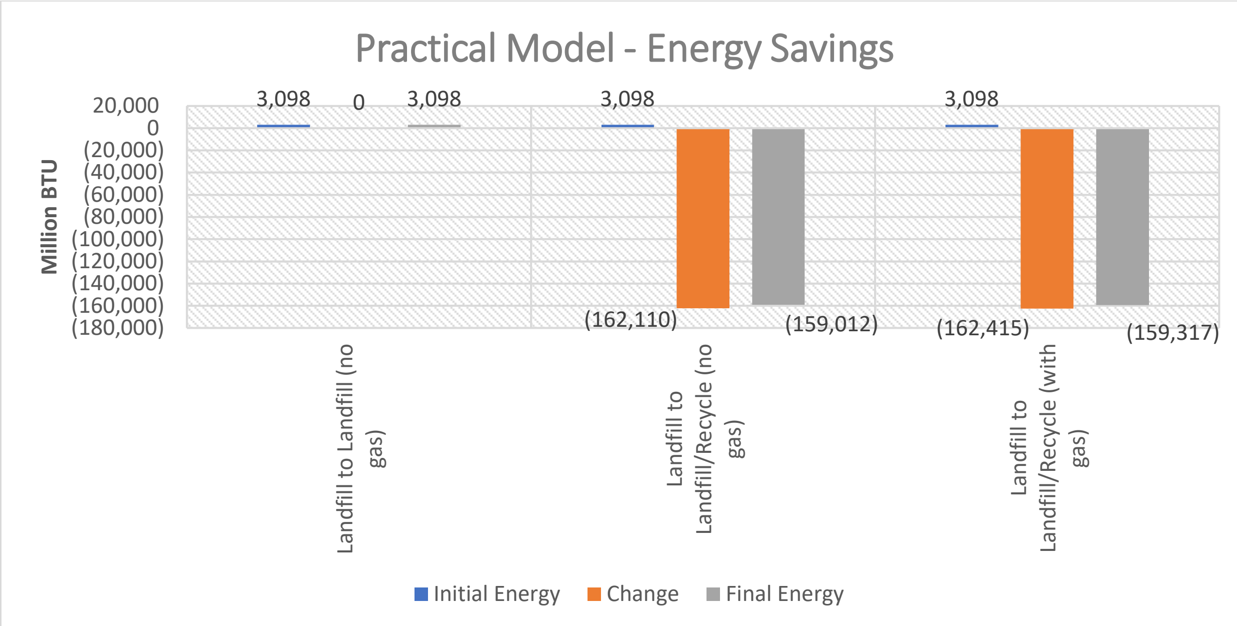


Figure 4.62: Practical model – energy savings (M. Richburg, 2023)

4.5.3 Practical Modeling – Wages Impact

In the practical modeling regarding wages or employment, recycling is a labor-intensive effort, which is the reasoning behind the large change from the baseline to the alternative method. Also, the addition of a MRF would cause an additional increase in wages or employment due to the labor involved in the process.

Table 4.77: Practical model - wages impact

Material	Waste Management Scenario	Wages From Baseline Waste Management US Dollar ($)	Wages From Alternative Waste Management US Dollar ($)	Change (Alt. – Base) US Dollar ($)	
	Landfill to Landfill (no gas recovery)	532,982	532,982	0	
	Landfill to Landfill/Recycle (no gas recovery)	532,982	3,785,683	3,252,701	
	Landfill to Landfill/Recycle (gas recovery)	532,982	3,785,683	3,252,701	

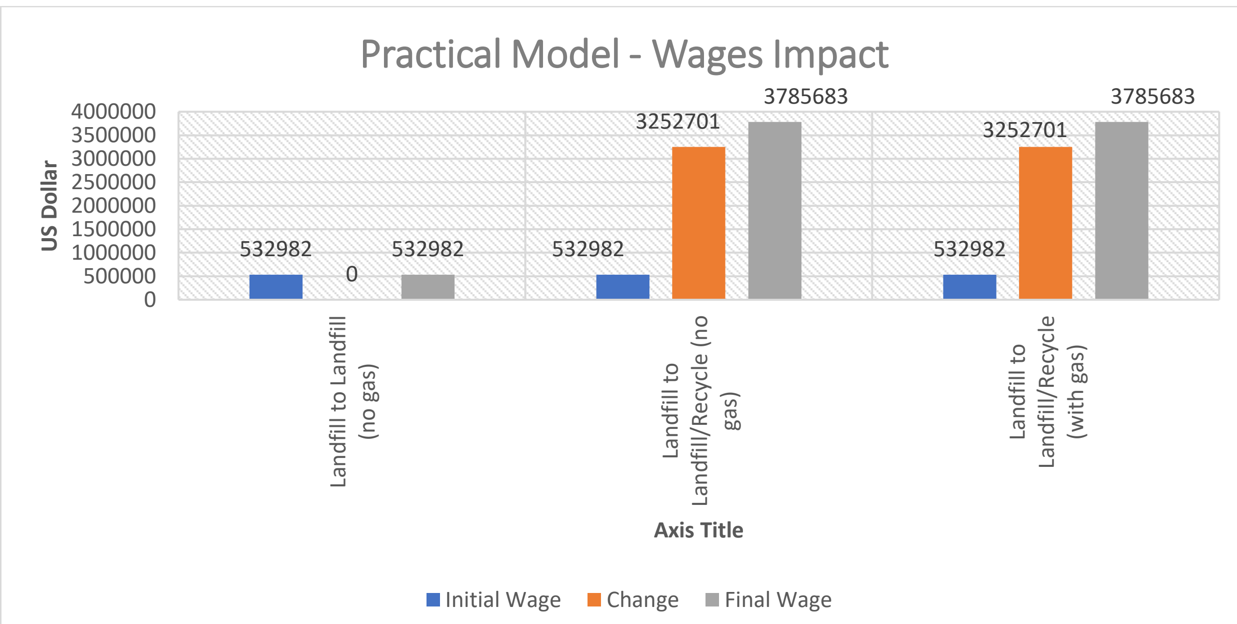


Figure 4.63: Practical model – wages impact (M. Richburg, 2023)

4.5.4 Practical Modeling – Summary

Table 4.78 displays the summary table for the Practical Modeling within the WARM model. As a reminder, these data are calculated based upon the monthly average of MSW delivered to the Montgomery County Landfill in 2021. The presented data displays avoided emissions, energy savings, and wages from the current waste management practices. The modeling shows that due to the shift from landfilling to recycling, there is only a small difference between employing and not employing a gas recovery system at the landfill. For the emissions avoided there is only a 936 MTCO2E difference and for the energy usage or savings, the difference is only 305 Million BTU. However, the gas recovery system is still important because of the materials that cannot be recycled such as food waste, yard trimmings, and non-recyclable plastics, although the plastics do not decompose, there would need to be another method of management for those plastics, which is why combustion was figured in.

Table 4.78: Practical model - summary

Waste Management Scenario	Emissions Avoided (MTCO2E)	Energy Usage (MMBTU)	(Employment) (USD)
Landfill to Landfill/Recycle (No Gas Recovery)	(20,906)	(162,110)	3,785,683
Landfill to Landfill/Recycle (with Gas Recovery)	(21,842)	(162,415)	3,785,683

The use of a MRF was significant in determining the recycling component. Although the life cycle does not factor in the use of a MRF, it was a factor in determining the recycling percentages for the Practical Modeling due to the recovery of recycled materials at the facility.

4.6 LandGEM Model Data

While the WARM model utilizes the life-cycle approach and presents the GHG emissions/avoidance across the whole life-cycle of each material, the LandGEM model can give an estimate of the actual direct emissions from the landfill. The first step in determining gas results within the LandGEM model was to input characteristics for the landfill. The landfill had an opening year of 1993 and it is to have a closing year of 2043, thereby giving it a fifty-year lifespan. The next step was to determine the parameters of the model. The landfill was assigned a k value of 0.05, which is the same as was given in the WARM model, the L_0 was assigned the Clean Air Act (CAA) conventional of 170, the methane content was assigned a CAA 50% volume, and the NMOC was given the inventory value of 600. Part 3, or the third step was to select the gases or pollutants, which the gases chosen were the total landfill gas, methane, carbon dioxide, and NMOC. The fourth step was to first select the units for the waste acceptance rates, which in this case is short tons/year, and the second part was to input the waste tonnage (table 4.79).

Table 4.79: Montgomery County Landfill waste acceptance per year

Year	Input Units ***(short tons/year)***
1993	317,499
1994	309,243
1995	397,178
1996	246,938

1997	212,338
1998	308,212
1999	370,605
2000	461,544
2001	439,021
2002	305,653
2003	249,322
2004	189,376
2005	326,520
2006	234,679
2007	231,402
2008	247,902
2009	129,955
2010	127,098
2011	128,427
2012	114,724
2013	111,102
2014	85,779
2015	100,955
2016	116,225
2017	101,336
2018	102,303
2019	103,668
2020	127,374
2021	137,359
2022	132,302

The landfill waste acceptance generated the total landfill gas, landfill methane, carbon dioxide, and NMOC which can be seen in figures 4.64 and 4.65, while figure 4.66 gives a graphical representation of the gases.

Year	Waste Accepted		Waste-In-Place		Total landfill gas			Methane		
	(Mg/year)	*(short tons/year)*	*(Mg)*	*(short tons)*	*(Mg/year)*	*(m^3/year)*	*(short tons/year)*	*(Mg/year)*	*(m^3/year)*	*(short tons/year)*
1993	288,635	317,499	0	0	0	0	0	0	0	0
1994	281,130	309,243	288,635	317,499	5.992E+03	4.798E+06	6.591E+03	1.601E+03	2.399E+06	1.761E+03
1995	361,071	397,178	569,765	626,742	1.154E+04	9.237E+06	1.269E+04	3.081E+03	4.619E+06	3.390E+03
1996	224,489	246,938	930,837	1,023,920	1.847E+04	1.479E+07	2.032E+04	4.933E+03	7.395E+06	5.427E+03
1997	193,035	212,338	1,155,325	1,270,858	2.223E+04	1.780E+07	2.445E+04	5.938E+03	8.900E+06	6.531E+03
1998	280,192	308,212	1,348,360	1,483,196	2.515E+04	2.014E+07	2.767E+04	6.718E+03	1.007E+07	7.390E+03
1999	336,913	370,605	1,628,552	1,791,407	2.974E+04	2.382E+07	3.272E+04	7.944E+03	1.191E+07	8.739E+03
2000	419,585	461,544	1,965,466	2,162,012	3.529E+04	2.826E+07	3.881E+04	9.425E+03	1.413E+07	1.037E+04
2001	399,110	439,021	2,385,051	2,623,556	4.228E+04	3.385E+07	4.650E+04	1.129E+04	1.693E+07	1.242E+04
2002	277,866	305,653	2,784,160	3,062,576	4.850E+04	3.884E+07	5.335E+04	1.295E+04	1.942E+07	1.425E+04
2003	226,656	249,322	3,062,027	3,368,229	5.190E+04	4.156E+07	5.709E+04	1.386E+04	2.078E+07	1.525E+04
2004	172,160	189,376	3,288,683	3,617,551	5.408E+04	4.330E+07	5.948E+04	1.444E+04	2.165E+07	1.589E+04
2005	296,837	326,520	3,460,843	3,806,927	5.501E+04	4.405E+07	6.051E+04	1.469E+04	2.203E+07	1.616E+04
2006	213,344	234,679	3,757,680	4,133,448	5.849E+04	4.684E+07	6.434E+04	1.562E+04	2.342E+07	1.719E+04
2007	210,365	231,402	3,971,024	4,368,126	6.007E+04	4.810E+07	6.608E+04	1.604E+04	2.405E+07	1.765E+04
2008	225,365	247,902	4,181,389	4,599,528	6.151E+04	4.925E+07	6.766E+04	1.643E+04	2.463E+07	1.807E+04
2009	118,141	129,955	4,406,755	4,847,430	6.318E+04	5.060E+07	6.950E+04	1.688E+04	2.530E+07	1.857E+04
2010	115,543	127,098	4,524,895	4,977,385	6.256E+04	5.009E+07	6.881E+04	1.671E+04	2.505E+07	1.838E+04
2011	116,752	128,427	4,640,439	5,104,482	6.190E+04	4.957E+07	6.809E+04	1.654E+04	2.478E+07	1.819E+04
2012	104,294	114,724	4,757,190	5,232,909	6.131E+04	4.909E+07	6.744E+04	1.638E+04	2.455E+07	1.801E+04
2013	101,001	111,102	4,861,484	5,347,633	6.048E+04	4.843E+07	6.653E+04	1.616E+04	2.422E+07	1.777E+04
2014	77,981	85,779	4,962,486	5,458,734	5.963E+04	4.775E+07	6.559E+04	1.593E+04	2.387E+07	1.752E+04
2015	91,777	100,955	5,040,466	5,544,513	5.834E+04	4.672E+07	6.418E+04	1.558E+04	2.336E+07	1.714E+04
2016	105,659	116,225	5,132,244	5,645,468	5.740E+04	4.596E+07	6.314E+04	1.533E+04	2.298E+07	1.687E+04
2017	92,123	101,336	5,237,903	5,761,693	5.679E+04	4.548E+07	6.247E+04	1.517E+04	2.274E+07	1.669E+04
2018	93,003	102,303	5,330,026	5,863,029	5.594E+04	4.479E+07	6.153E+04	1.494E+04	2.240E+07	1.644E+04
2019	94,243	103,668	5,423,029	5,965,332	5.514E+04	4.415E+07	6.065E+04	1.473E+04	2.208E+07	1.620E+04
2020	115,794	127,374	5,517,272	6,068,999	5.441E+04	4.357E+07	5.985E+04	1.453E+04	2.178E+07	1.599E+04
2021	124,871	137,359	5,633,067	6,196,373	5.416E+04	4.337E+07	5.957E+04	1.447E+04	2.168E+07	1.591E+04
2022	120,275	132,302	5,757,938	6,333,732	5.411E+04	4.333E+07	5.952E+04	1.445E+04	2.166E+07	1.590E+04
2023	120,275	132,302	5,878,213	6,466,034	5.397E+04	4.321E+07	5.936E+04	1.442E+04	2.161E+07	1.586E+04

Figure 4.64: LandGEM model data sheet – landfill gas & methane (M. Richburg, 2023)

Year	Waste Accepted		Waste-In-Place		Carbon dioxide			NMOC		
	(Mg/year)	(short tons/year)	(Mg)	(short tons)	(Mg/year)	(m^3/year)	(short tons/year)	(Mg/year)	(m^3/year)	(short tons/year)
1993	288,635	317,499	0	0	0	0	0	0	0	0
1994	281,130	309,243	288,635	317,499	4.391E+03	2.399E+06	4.831E+03	1.032E+01	2.879E+03	1.135E+01
1995	361,071	397,178	569,765	626,742	8.455E+03	4.619E+06	9.300E+03	1.987E+01	5.542E+03	2.185E+01
1996	224,489	246,938	930,837	1,023,920	1.354E+04	7.395E+06	1.489E+04	3.181E+01	8.874E+03	3.499E+01
1997	193,035	212,338	1,155,325	1,270,858	1.629E+04	8.900E+06	1.792E+04	3.828E+01	1.068E+04	4.211E+01
1998	280,192	308,212	1,348,360	1,483,196	1.843E+04	1.007E+07	2.028E+04	4.332E+01	1.208E+04	4.765E+01
1999	336,913	370,605	1,628,552	1,791,407	2.180E+04	1.191E+07	2.398E+04	5.122E+01	1.429E+04	5.634E+01
2000	419,585	461,544	1,965,466	2,162,012	2.586E+04	1.413E+07	2.845E+04	6.077E+01	1.695E+04	6.684E+01
2001	399,110	439,021	2,385,051	2,623,556	3.098E+04	1.693E+07	3.408E+04	7.281E+01	2.031E+04	8.009E+01
2002	277,866	305,653	2,784,160	3,062,576	3.554E+04	1.942E+07	3.910E+04	8.352E+01	2.330E+04	9.188E+01
2003	226,656	249,322	3,062,027	3,368,229	3.804E+04	2.078E+07	4.184E+04	8.938E+01	2.494E+04	9.832E+01
2004	172,160	189,376	3,288,683	3,617,551	3.963E+04	2.165E+07	4.360E+04	9.313E+01	2.598E+04	1.024E+02
2005	296,837	326,520	3,460,843	3,806,927	4.032E+04	2.203E+07	4.435E+04	9.474E+01	2.643E+04	1.042E+02
2006	213,344	234,679	3,757,680	4,133,448	4.287E+04	2.342E+07	4.716E+04	1.007E+02	2.810E+04	1.108E+02
2007	210,365	231,402	3,971,024	4,368,126	4.402E+04	2.405E+07	4.843E+04	1.034E+02	2.886E+04	1.138E+02
2008	225,365	247,902	4,181,389	4,599,528	4.508E+04	2.463E+07	4.958E+04	1.059E+02	2.955E+04	1.165E+02
2009	118,141	129,955	4,406,755	4,847,430	4.631E+04	2.530E+07	5.094E+04	1.088E+02	3.036E+04	1.197E+02
2010	115,543	127,098	4,524,895	4,977,385	4.585E+04	2.505E+07	5.043E+04	1.077E+02	3.006E+04	1.185E+02
2011	116,752	128,427	4,640,439	5,104,482	4.537E+04	2.478E+07	4.991E+04	1.066E+02	2.974E+04	1.173E+02
2012	104,294	114,724	4,757,190	5,232,909	4.493E+04	2.455E+07	4.943E+04	1.056E+02	2.946E+04	1.161E+02
2013	101,001	111,102	4,861,484	5,347,633	4.433E+04	2.422E+07	4.876E+04	1.042E+02	2.906E+04	1.146E+02
2014	77,981	85,779	4,962,486	5,458,734	4.370E+04	2.387E+07	4.807E+04	1.027E+02	2.865E+04	1.130E+02
2015	91,777	100,955	5,040,466	5,544,513	4.276E+04	2.336E+07	4.703E+04	1.005E+02	2.803E+04	1.105E+02
2016	105,659	116,225	5,132,244	5,645,468	4.207E+04	2.298E+07	4.628E+04	9.885E+01	2.758E+04	1.087E+02
2017	92,123	101,336	5,237,903	5,761,693	4.162E+04	2.274E+07	4.579E+04	9.781E+01	2.729E+04	1.076E+02
2018	93,003	102,303	5,330,026	5,863,029	4.100E+04	2.240E+07	4.510E+04	9.633E+01	2.688E+04	1.060E+02
2019	94,243	103,668	5,423,029	5,965,332	4.041E+04	2.208E+07	4.445E+04	9.496E+01	2.649E+04	1.045E+02
2020	115,794	127,374	5,517,272	6,068,999	3.987E+04	2.178E+07	4.386E+04	9.370E+01	2.614E+04	1.031E+02
2021	124,871	137,359	5,633,067	6,196,373	3.969E+04	2.168E+07	4.366E+04	9.327E+01	2.602E+04	1.026E+02
2022	120,275	132,302	5,757,938	6,333,732	3.966E+04	2.166E+07	4.362E+04	9.318E+01	2.600E+04	1.025E+02
2023	120,275	132,302	5,878,213	6,466,034	3.955E+04	2.161E+07	4.351E+04	9.294E+01	2.593E+04	1.022E+02

Figure 4.65: LandGEM model data sheet – carbon dioxide and NMOC (M. Richburg, 2023)

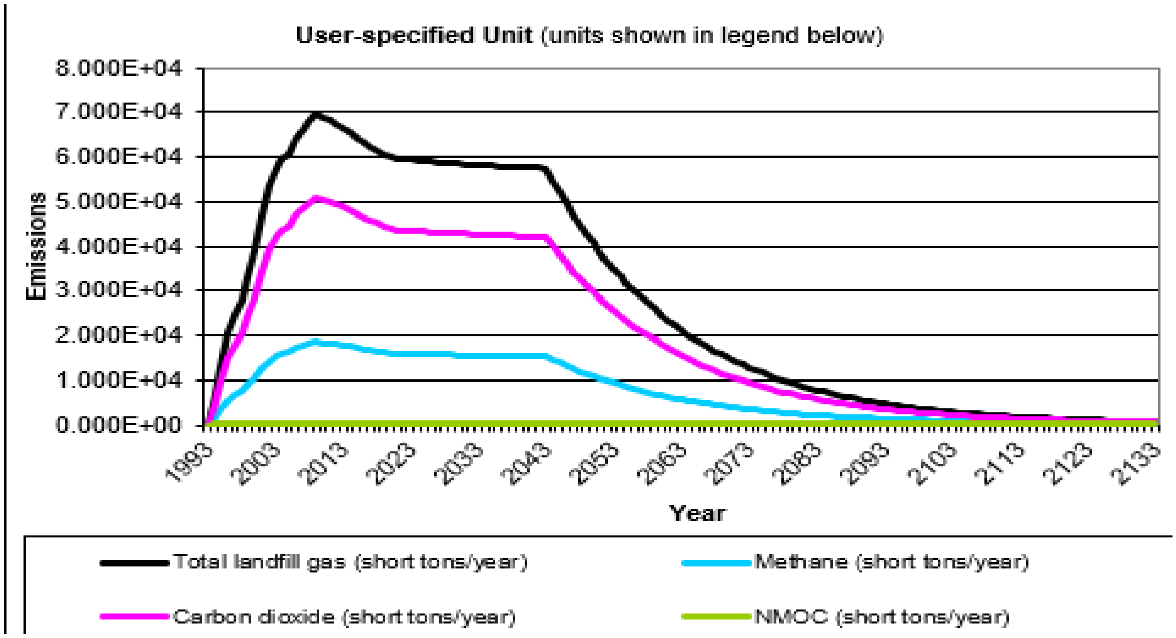


Figure 4.66: LandGEM model – gas emissions (M. Richburg, 2023)

4.7 Landfill Gas Energy Potential Data

The landfill gas energy potential was estimated based upon the amount of gas that could be produced from the landfill over a specific period, which for this study would be 2009 through 2022. As the LandGEM model provides an estimate of the direct methane emissions, as opposed to the life-cycle approach from the WARM model, results from the LandGEM model are used for the Landfill Gas Energy Potential calculations. For the calculation of energy potential, the assumed values made are in line with the EPA's Landfill Methane Outreach Program (LMOP), however, a comparison will be made to the research conducted for energy potential by Ramprasad et al. (2022).

- The Lower Heating Value (LHV) for methane ranges between 15-35 MJ/m^3. For the present research, a median LHV of 25 MJ/m^3 was considered. The Ramprasad et al. (2022) study chose a value of 18 MJ/m^3.

- The combustion efficiency (η) of the engines range between 30 and 40 percent, with a value of 30% chosen for this research. The Ramprasad et al. (2022) study chose a value of 40%.
- The methane recovery efficiency (λ) is 75% which is the average for LFG projects in the United States, with efficiencies ranging from 50 to 95 percent. The Ramprasad et al. (2022) study chose a value of 70%.

The LandGEM calculated the energy potential in kWh per year and to have a similar reference, the kWh was converted to BTUs. As the model calculates a methane decline over time, the energy potential equation determines that the energy potential will also decline over time, as shown in figure 4.67. Figure 4.68 shows the decline curve reaching a peak production in 2009 and then beginning its decline thereafter.

Year	Waste Accepted	Methane (short ton/yr)	Methane cubic meter	Energy Potential (E_p) (kWh/yr)	Energy Potential (E_p) (BTU/yr)
2009	129,955	20,718	28,231,152	39,700,058	135,456,596,492
2010	127,098	20,372	27,760,207	39,037,791	133,196,944,440
2011	128,427	20,028	27,290,895	38,377,821	130,945,125,805
2012	114,724	19,712	26,860,914	37,773,160	128,882,022,657
2013	111,102	19,324	26,332,271	37,029,756	126,345,529,118
2014	85,779	18,935	25,801,719	36,283,667	123,799,871,755
2015	100,955	18,401	25,073,473	35,259,572	120,305,659,386
2016	116,225	17,998	24,524,632	34,487,763	117,672,248,995
2017	101,336	17,720	24,145,598	33,954,747	115,853,597,087
2018	102,303	17,359	23,654,231	33,263,762	113,495,956,414
2019	103,668	17,026	23,200,209	32,625,294	111,317,504,148
2020	127,374	16,721	22,784,949	32,041,335	109,325,035,486
2021	137,359	16,591	22,607,868	31,792,314	108,475,376,833
2022	132,302	16,535	22,531,232	31,684,545	108,107,666,380

Figure 4.67: Energy potential - LandGEM (M. Richburg, 2023)

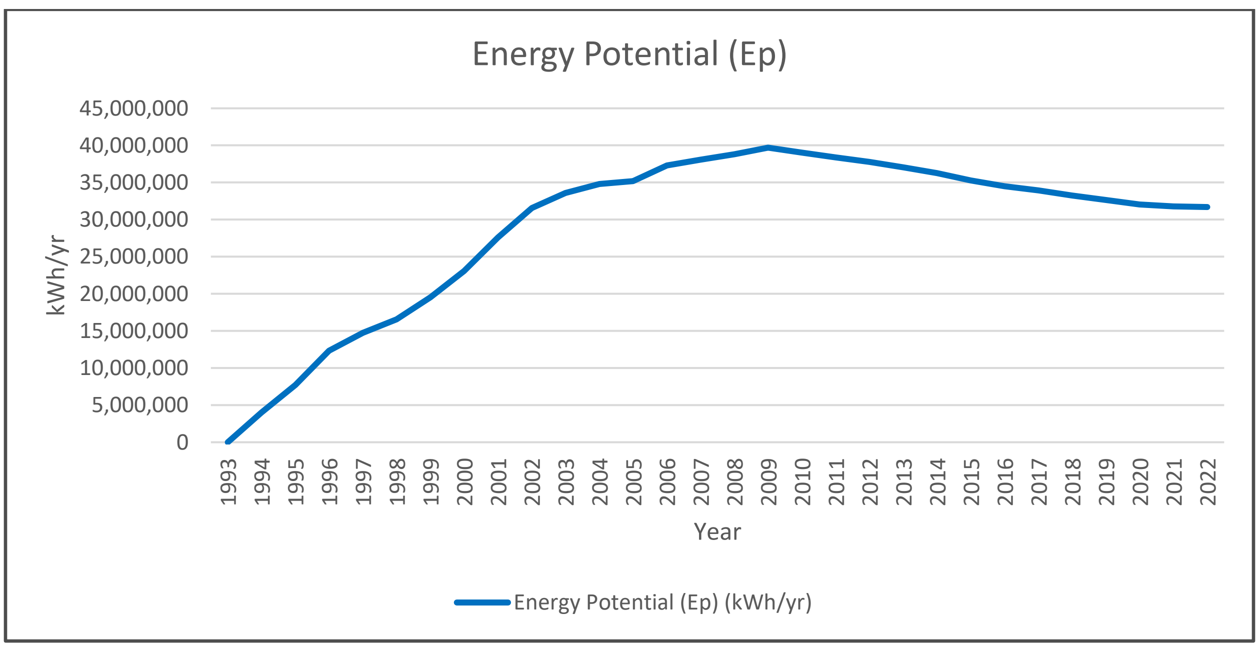


Figure 4.68: Energy potential decline curve -. LandGEM (M. Richburg, 2023)

CHAPTER FIVE: MODELING ANALYSIS & DISCUSSION

5.1 Introduction

Chapter four presented the raw data, to include the theoretical, practical, and full generation calculation from the application of the WARM model. In addition to the application of the WARM model, data generated by the LandGEM model was also presented, along with estimating energy potential from gases produced from the landfill. Chapter five will analyze and interpret the data that was computed. The objective of this chapter is to summarize the data to address the rationale for this research and answer the research questions posed in Chapter one.

5.2 Theoretical Modeling Analysis & Discussion

The theoretical work produced in the WARM model analyzed varied materials separately instead of the full MSW tonnage. The weight of each material was determined by percentages calculated from the EPA 2018 MSW National Overview: Facts and Figures on Materials, Wastes and Recycling. The collected data will assist in determining the best strategies for emissions avoidance and energy savings. Also, wages will be presented, analyzed, and discussed, although they were not part of the research question. The focus of this section will revolve around Research Question one.

5.2.1 Theoretical Emissions Avoided

The first Research Question presented in Chapter one asked "what combination of MSW strategies will result in the theoretical maximum GHG emissions avoided and energy savings?" In focusing on the emissions avoided, each material, beginning with paper, and ending with mixed MSW, was analyzed for its emissions avoidance by different waste management scenarios.

5.2.2 Theoretical Paper Emissions Avoidance

In Section 4.2.2, the theoretical data on paper emission avoidance was calculated, with four options in managing paper waste. The scenario of landfill-to-recycling is the waste management option that provides the largest number of emissions avoided at 12,158 MTCO2E. Paper products have a larger emissions avoidance in the landfill-to-recycling scenario due to recycling offsetting some GHGs in the manufacturing and transportation of virgin products, and it helps to increase carbon stored in forests. With recycling, the remanufactured product or material is considered a closed loop process with the final product being made into the same product also assists with the emissions avoidance.

5.2.3 Theoretical Food Waste Emissions Avoidance

The emissions avoidance for food waste was discussed in Section 4.2.3, in which there were five scenarios for managing food waste as displayed in Table 4.6. Each scenario for food waste management created an emissions avoidance, with combustion and composting having only an approximately 60 MTCO2E difference. Also, anaerobic digestion was very close in its emissions avoidance. Landfill-to-combustion had an emissions avoidance of 3,793 MTCO2E, while landfill-to-compost had an emissions avoidance of 3,732 MTCO2E. The emissions from combustion are estimated from those that occur from the manufacturing of the initial products, the transportation of products to the WTE facility, and non-biogenic CO_2 and N_2O combustion at the facility. This is offset by the avoidance emissions from electric utilities from the WTE and recovered steel at the WTE facility that can be recycled.

5.2.4 Theoretical Yard Trimmings Emissions Avoidance

Yard trimmings emissions avoidance has the same five waste management scenarios as food waste, in addition to each of the scenarios providing emissions avoidance to where any of the waste management scenarios could be utilized. The landfill-to-landfill with gas recovery is the scenario that provides the largest emissions avoidance at 629 MTCO2E due to two primary factors. The first factor is that the yard trimmings in the landfill are considered carbon storage, while the second factor is the avoided utility emissions because of the conversion of the landfill gas to energy.

5.2.5 Theoretical Mixed Plastics Emissions Avoidance

With the mixed plastics theoretical avoidance, there are five scenarios that can be considered; however, recycling is combined with landfilling and with combustion for these scenarios. As described in Section 4.2.5., there are plastics that can be recycled, such as HDPEs, PETs, PPs, and mixed plastics, and those that cannot such as LDPEs, LLDPEs, PSs, and PVC. Only the landfill-to-landfill/recycle and landfill-to-recycle/combustion scenarios have emissions avoidance. The landfill-to-recycle/landfill has the largest avoidance with 822 MTCO2E. This is due to those recyclable plastics being re-manufactured back into the same usable products and avoiding the manufacturing process of new materials. The plastics that cannot be recycled are landfilled with zero emissions which is what is seen with landfilling only.

5.2.6 Theoretical Electronics Emissions Avoidance

The theoretical electronics emissions avoidance in the WARM model used four methods or scenarios to manage the waste stream. From the WARM calculations, landfill-to-recycle is the scenario that will have the largest emissions avoidance, avoiding 83 MTCO2E. Electronic recycling is considered an open-loop process due to the recycled product being different than the initial product. The positive of recycling electronics to reduce GHGs is that the avoided emissions result from the avoidance of new (virgin) materials in the manufacturing of the secondary product from the recycled product. As seen in Table 4.15, landfilling electronics will not produce any emissions due to the electronics being of a non-carbon source, and combustion releases emissions during the process due to its non-carbon sources.

5.2.7 Theoretical Metals Emissions Avoidance

There are two scenarios that produce large emissions avoidance numbers, recycling, and combustion as seen in Table 4.18. The recycling of metals has an emissions avoidance of 4,520 MTCO2E, which provides the largest avoidance, while combustion avoids 1,019 MTCO2E of emissions. Recycling of metal is considered a closed-loop process due to the metal being processed back into the same product. The emissions avoidance comes from the avoidance of producing a new product equal to the secondary product using all virgin materials in the process.

5.2.8 Theoretical Glass Emissions Avoidance

The landfill-to-recycling scenario is the only waste management option for glass that has emissions avoidance. The emissions avoidance for glass is 142 MTCO2E. Glass is a close loop process due to glass being made into glass again from the recycling process.

5.2.9 Theoretical Carpet Emissions Avoidance

The landfill-to-recycling scenario, as with glass and electronics, is the only scenario for carpet that has emissions avoidance. The emissions avoidance for carpet is 316 MTCO2E, while combustion gives off 139 MTCO2E, as shown in Table 4.24. Carpet recycling is an open-loop process and the avoided emissions come from not manufacturing the secondary product with virgin materials but instead with the recycled products.

5.2.10 Theoretical Tire Emissions Avoidance

The waste management scenario of landfill-to-recycle at 100 MTCO2E is the selected method for emissions avoidance for tires. Combustion is the only other scenario that has a change in MTCO2E, however that change is an increase in emissions, not a reduction. Tires can be recycled into many other products; therefore, it is an open-loop process.

5.2.11 Theoretical Mixed MSW Emissions Avoidance

Mixed MSW emissions avoidance has three scenarios, but landfill-to-combustion is the option that provides the largest emissions avoidance at 2,144 MTCO2E, compared to the avoidance of 1,890 MTCO2E from landfill gas recovery as shown in Table 4.30. Mixed MSW is defined as normal or typical waste that is disposed of by households and collected curbside (US EPA - ICF, 2020). Mixed MSW is a compilation of the entire municipal solid waste stream, therefore it uses each of the materials in its calculation of emissions avoided with food waste and paper helping to offset much of the emissions, and the recycling of metals that occur before combustion. Landfill gas recovery provides a significant amount of emissions avoidance due to the recovery of emissions at the landfill site that is then provided for energy.

5.2.11 Theoretical Emissions Avoidance Summary

Each of the materials began with a landfill-to-landfill baseline for waste management, and then the optional scenarios were calculated to determine the maximum emissions avoided. Table 5.1 summarizes the materials and the scenario that provides the largest emissions avoided for each material.

Table 5.1: Theoretical MSW treatment by material for maximum emissions avoided

Material	Waste Management Scenario	Emissions Avoided (MTCO2E)
Paper	Landfill-to-Recycle	12,158
Food Waste	Landfill-to-Combustion	3,793
Yard Trimmings	Landfill-to-Landfill (gas recovery)	629
Mixed Plastics	Landfill-to-Recycle	822
Electronics	Landfill-to-Recycle	83
Metals	Landfill-to-Recycle	4,520
Glass	Landfill-to-Recycle	142
Carpet	Landfill-to-Recycle	316
Tires	Landfill-to-Recycle	100
Mixed MSW	Landfill-to-Combustion	2,144

Research Question number one posed the question, “what combination of MSW treatment strategies will result in the maximum GHG emissions avoided and energy savings?” The first part of the question regarding maximum GHG emissions avoided is a combination of treatment strategies as shown in Table 5.1. For this combination to occur, there must be either the infrastructure in place or the ability to develop the infrastructure, to manage the multiple ways that would be required to dispose of the waste so that the maximum number of emissions can be avoided. From the table, there are four methods required to reach the maximum number and it may or may not be feasible for some areas to develop all the required mechanisms necessary for this to occur. Of the ten materials listed, six state that recycling provides the largest number of emissions avoided. To achieve the goal of reducing or avoiding emissions, recycling is an alternative that must be put in place. Due to the sum of MTCO2E that are avoided between paper and metals, avoiding these items in landfills is highly recommended, however landfilling of paper can be substituted for recycling because there are emissions avoided, just not at the level of recycling.

5.3 Theoretical Energy Savings

The first Research Question presented in Chapter one asked "what combination of MSW strategies will result in the theoretical maximum GHG emissions avoided and energy savings?" In focusing on the energy savings, each material, beginning with paper, and ending with mixed MSW, was analyzed for the energy savings that occur by different waste management scenarios. Also, the equivalency of the savings to households' annual energy consumption, barrels of oil, and gallons of gasoline will be presented. Energy savings for the equivalency presentation is savings across many types of fuels to include petroleum, coal, electricity, and natural gas.

5.3.1 Theoretical Paper Energy Savings

The largest energy savings for paper is with the landfill-to-recycling scenario, in which 40,788 million BTUs are saved, as shown in Table 4.4. Each of the various components that fall under paper have different net energy impacts within the WARM model. The impact of the energy associated with the acquisition and production of raw materials to manufacture new paper products factors into the large number of BTUs saved when the alternative of recycling occurs. The processing of the recycled products back into the same products, or close-loop recycling, like the emissions avoided assists with producing the large savings. Figure 5.1 shows the conservation equivalency of 40,788 million BTUs saved because of recycling.

This is equivalent to...		
Conserving	**445**	Households' Annual Energy Consumption
Conserving	**7,020**	Barrels of Oil
Conserving	**338,625**	Gallons of Gasoline

Figure 5.1: Energy savings equivalency – paper (M. Richburg, 2023)

5.3.2 Theoretical Food Waste Energy Savings

Landfill-to-combustion for food waste produces an energy savings of 6,386 million BTUs, which is better than anaerobic digestion and landfilling with gas recovery, as seen in Table 4.7. Composting is the only scenario that does not have an energy savings. The landfill-to-combustion scenario has an energy savings due to either the energy produced being reused at the facility or being sold to the energy grid, which avoids other raw materials to be used in electrical generation. Figure 5.2 shows the conservation equivalency of 6,386 million BTUs saved from the combustion of food waste.

This is equivalent to...		
Conserving	**70**	Households' Annual Energy Consumption
Conserving	**1,099**	Barrels of Oil
Conserving	**53,019**	Gallons of Gasoline

Figure 5.2: Energy savings equivalency – food waste (M. Richburg, 2023)

5.3.3 Theoretical Yard Trimmings Energy Savings

Each of the scenarios for yard trimmings produces an energy savings, however, the landfill-to-combustion scenario produces the largest energy savings of 4,159 million BTUs as seen in Table 4.10. Yard trimmings perform like food waste in that the energy produced from combustion can either fuel the combustion system or be sold to the electrical grid. Figure 5.3 shows the conservation equivalency of 4,159 million BTUs saved from the combustion of food waste.

This is equivalent to...		
Conserving	**45**	Households' Annual Energy Consumption
Conserving	**716**	Barrels of Oil
Conserving	**34,528**	Gallons of Gasoline

Figure 5.3: Energy savings equivalency – yard trimmings (M. Richburg, 2023)

5.3.4 Theoretical Mixed Plastics Energy Savings

Each scenario with mixed plastics, except for landfilling, creates an energy savings. The largest savings comes from the landfill-to-recycle/combustion scenario. This scenario creates a savings of 45,606 million BTUs as shown in Table 4.13. This savings comes from recycling those items that can be recycled and re-made back into the same item, which saves from using energy to remake the same product, while combusting the non-recyclable plastics to produce energy. In the manufacturing of plastics, petroleum, which is a main ingredient of plastic, is considered as energy saved during the recycling process. Figure 5.4 shows the conservation equivalency of 45,606 million BTUs saved from the combination of recycling and combustion.

This is equivalent to...		
Conserving	**498**	Households' Annual Energy Consumption
Conserving	**7,850**	Barrels of Oil
Conserving	**378,623**	Gallons of Gasoline

Figure 5.4: Energy savings equivalency – mixed plastics (M. Richburg, 2023)

5.3.5 Theoretical Electronics Energy Savings

The landfill-to-recycling scenario creates the largest energy savings for the waste management of electronics at 1,232 million BTUs. The savings for electronics are small due to electronics being an open-loop recycling process, and the recycled materials are made into secondary items, not the primary item that originated. Some energy will have to go into the raw materials acquisition process as well as the manufacturing process, therefore a reduction in energy savings is realized. Figure 5.5 shows the conservation equivalency of 1,232 million BTUs saved from recycling.

This is equivalent to...		
Conserving	**13**	Households' Annual Energy Consumption
Conserving	**212**	Barrels of Oil
Conserving	**10,224**	Gallons of Gasoline

Figure 5.5: Energy savings equivalency – electronics (M. Richburg, 2023)

5.3.6 Theoretical Metals Energy Savings

The largest energy savings for metals comes from the landfill-to-recycling scenario. This scenario provides a savings of 68,773 million BTUs of energy as seen in Table 4.19. Recycling metals and manufacturing the same items is a less energy intensive process than producing metal from virgin inputs. Figure 5.6 shows the conservation equivalency of 68,773 million BTUs saved from recycling.

This is equivalent to...		
Conserving	**751**	Households' Annual Energy Consumption
Conserving	**11,837**	Barrels of Oil
Conserving	**570,953**	Gallons of Gasoline

Figure 5.6: Energy savings equivalency – metals (M. Richburg, 2023)

5.3.7 Theoretical Glass Energy Savings

To achieve substantial energy savings in the waste management of glass, the material must be recycled instead of landfilled. This scenario creates a savings of 1,151 million BTUs of energy as shown in Table 4.22. The recycling process of glass created a small savings due to the large energy component, electricity, which is needed to manufacture the product. Figure 5.7 displays the conservation equivalency of 1,151 million BTUs saved from recycling.

This is equivalent to...		
Conserving	13	Households' Annual Energy Consumption
Conserving	198	Barrels of Oil
Conserving	9,555	Gallons of Gasoline

Figure 5.7: Energy savings equivalency – glass (M. Richburg, 2023)

5.3.8 Theoretical Carpet Energy Savings

The largest energy savings for carpet comes from the landfill-to-recycle scenario, where 2,860 million BTUs of energy are saved (see Table 4.25). The recycled carpet provides substantial energy savings due to the energy required to manufacture the secondary products. Figure 5.8 shows the conservation equivalency of 2,860 million BTUs saved from recycling.

This is equivalent to...		
Conserving	31	Households' Annual Energy Consumption
Conserving	492	Barrels of Oil
Conserving	23,744	Gallons of Gasoline

Figure 5.8: Energy savings equivalency – carpet (M. Richburg, 2023)

5.3.9 Theoretical Tires Energy Savings

The waste management scenario that provides the largest energy savings for tires is the landfill-to-combustion method. This method produces a savings of 7,317 million BTUs as shown in Table 4.28. The energy savings comes from the use of petroleum products in tire manufacturing that could be avoided, plus the combustion of the tires produces fuel for operating cement kilns, boilers, and pulp and paper mills. This offsets energy that would be used from other energy sources. Figure 5.9 displays the conservation equivalency of 7,317 million BTUs saved from combustion.

This is equivalent to...		
Conserving	**80**	Households' Annual Energy Consumption
Conserving	**1,259**	Barrels of Oil
Conserving	**60,742**	Gallons of Gasoline

Figure 5.9: Energy savings equivalency – tires (M. Richburg, 2023)

5.3.10 Theoretical Mixed MSW Energy Savings

The largest energy savings for mixed MSW comes from the landfill-to-combustion scenario. This method provides a savings of 8,668 million BTUs as seen in Table 4.31. The savings is due to the make-up of the mixed MSW, which comprises normal household waste, and although some items are recycled or removed from the combustion process, the remaining items help to provide fuel that can be re-supplied to the system or sold to the grid. Figure 5.10 shows the conservation equivalency of 8,668 million BTUs saved from combustion.

This is equivalent to...		
Conserving	88	Households' Annual Energy Consumption
Conserving	1,382	Barrels of Oil
Conserving	66,668	Gallons of Gasoline

Figure 5.10: Energy savings equivalency – mixed MSW (M. Richburg, 2023)

5.3.11 Theoretical Energy Savings Summary

Table 5.2 as seen below, summarizes the materials and the scenario that provides the largest energy savings for each material.

Table 5.2: Theoretical MSW treatment by material for maximum energy savings

Material	Waste Management Scenario	Energy Savings (Million BTUs)
Paper	Landfill-to-Recycle	40,788
Food Waste	Landfill-to-Combustion	6,386
Yard Trimmings	Landfill-to-Combustion	4,159
Mixed Plastics	Landfill-to-Recycle/Combustion	45,606
Electronics	Landfill-to-Recycle	1,232
Metals	Landfill-to-Recycle	68,773

Glass	Landfill-to-Recycle	1,151
Carpet	Landfill-to-Recycle	2,860
Tires	Landfill-to-Combustion	7,317
Mixed MSW	Landfill-to-Combustion	8,668

Research Question number one posed the question, “what combination of MSW treatment strategies will result in the maximum GHG emissions avoided and energy savings?” The second part of the question regarding maximum energy savings is a combination of treatment strategies as shown in Table 5.2. To reach the maximum energy savings, the methods and infrastructure must be in place, such as recycling and combustion facilities, which will require significant investment to reach these savings.

5.4 “Business as Usual” Modeling Analysis & Discussion

This section will review and analyze the practical data that was presented beginning in Section 4.3. The methodology for this section made assumptions based on the current waste management practices in the State of Alabama and Montgomery County, AL. Table 4.36 displays that landfilling and recycling are the two current forms of waste management, therefore the two practices are considered “business as usual” and will addresses Research Question number two; “what combination of MSW treatment strategies can provide maximum GHG emissions avoidance and energy savings utilizing actual data if minimal to zero alternatives are available?”

5.4.1 Emissions Avoided, Energy Savings, and Wages Impact

For the "business as usual" section, the first step was to calculate the materials separately by the average monthly tonnage during the year 2021. Tables 4.67 through 4.69 display the emissions avoidance, energy savings, and wages impact for each material based on landfilling with gas recovery and a combination of landfilling and recycling, in which 84% of the material went to the landfill and 16% was recycled. When landfilling is the primary waste management method, an opportunity is missed to have a larger number of avoided emissions. Landfilling is the only option for food waste, yard trimmings, and mixed MSW due to those materials not being recyclable.

For the energy savings with the "business as usual" modeling, with landfilling comprising most of the waste management method, only lesser amounts of energy are saved compared to if recycling was the dominant waste management practice. The items that would contribute to larger amounts of energy saved if recycled such as paper, mixed plastics, and metals, require substantial amounts of energy in their production, but that energy would be saved if the process were not consistently repeated.

If recycling constituted a larger percentage of the waste management practice, the wages or employment would be higher but the percentage is weighted more towards landfilling which has a lower labor intensity than recycling.

Within the "business as usual" modeling, a full generation calculation is performed. The summary for the full generation is shown in table 4.73. The calculation is performed by distributing the data across the full model instead of isolating each material. Three scenarios are presented for the full generation; however, the landfill-to-landfill was used as a baseline for the landfill-to-landfill (with gas recovery) and landfill/recycling (with gas recovery). For the emissions avoided, the difference between the landfill (with gas recovery) and the landfill/recycling is small, however being able to recycle materials has a greater impact than landfilling only. With the energy savings, having a recycling component provides nine times greater energy savings than a 100% landfilling of the material.

Recycling has a significant impact on waste management as it relates to wages compared to landfilling solely. Recycling is a more labor-intensive component compared to landfilling; therefore, additional labor is needed to accomplish this task which nearly doubles that of landfilling.

5.5 Practical Modeling

The summary for the practical model is shown in section 4.5.4 and table 4.78. Two ideas can be deduced from the practical model are: 1) recycling must be included in waste management to reach significant avoided emissions and energy savings values and 2) with reducing landfilling to avoid emissions and achieve higher energy savings, there is little difference between having or omitting a gas recovery system at the landfill. Having a gas recovery system would only enhance the energy that can be recovered from the landfill and there is still opportunity to increase the avoidance of emissions. The relative impact of adding the MRF can be seen by comparing the Business-as-Usual Case with the Practical Case as shown in Table 5.3. Avoided GHG emissions are nearly double that realized using the current practices being implemented in Alabama today. In fact, by using a MRF to separate the MSW to allow for a combination of recycling and combustion, the GHG avoidance approaches the theoretical optimal. With regards energy usage, the potential saving in energy is 5 times higher when a MRF is added to the landfill and reaches 87% of the theoretical optimal. Achieving these significant improvements will result in an additional $3.2 million per month of employment to Montgomery County.

Table 5.3: Comparison of modeling results

Waste Management Scenario	Emissions Avoided (MTCO2E)	Energy Usage (MMBTU)	Wages Impact (USD)
Business as Usual - No Recycle (no Gas Recovery)	0	0	0
Business as Usual – w/Recycle (w/Gas Recovery)	(8,443)	(149,742)	4,189,169
Business as Usual - No Recycle (w/Gas Recovery)	(9,348)	(3,051)	0
Recommended Treatment (no Gas Recovery)	(20,906)	(162,110)	3,785,683
Recommended Treatment (w/Gas Recovery)	(21,842)	(162,415)	3,785,683
Theoretical (Optimal)	24,707	186,940	2,322,645

5.6 LandGEM and Landfill Gas Energy Potential

Research Question number three asked “what is the theoretical amount of energy that can be achieved from the landfill using the emissions produced?” The landfill gas energy potential equation attempts to answer the third research question using emissions data calculated by the LandGEM model. Historical tonnage data was input into the LandGEM model which estimated gases from the landfill to include methane and CO_2 which could then be incorporated into the energy potential equation, along with other parameters, to determine energy potential in kilowatts hours per year. The energy potential equation calculates that the methane from the tonnage at its peak in 2009 could have produced 135 MMBTU or nearly 40 million kWh per year. Energy potential would begin to experience a decline beginning in 2010, however by 2022, the potential would still be over 31.5 million kWh per year which is enough to meet the electrical demands for an average of 2900 households.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

Greenhouse gas emissions, or GHGs, as they have been addressed throughout this work, will continue to cause changes to our atmosphere if emission levels are not lowered. The climate change issue that we are dealing with is not just a individual nation issue, it is one that the global population must work to control if we do not want continued undesirable effects on the planet, to include our oceans, atmosphere, cryosphere, and biosphere. The global population must continue to survive, which means that food will continue to be grown, clothes will be worn, shelter will be built, items will be produced for purchase, and people will continue to travel, whether for work or pleasure. If these factors continue, then waste will continue to occur, and that waste must be disposed of in some manner. To most, landfills are the easiest way to dispose of MSW, however, landfills are major emitters of GHGs (14.5% of manmade U.S. methane emissions are from landfills) if there is not some form of gas recovery system in place. Also, the presence or absence of a gas recovery system affects energy savings. The presence of a gas recovery system provides the opportunity to produce renewable energy, while the absence of one causes a renewable energy source opportunity to be missed. The main objective of this dissertation was to determine the best treatment strategy for municipalities that would provide maximum emission avoidance while providing maximum energy savings. A secondary objective was to evaluate the theoretical potential energy of the landfill from the models and how the two models differ in their estimations, if any.

Approximately 60% of the global MSW is disposed in landfills and open dumps. Landfill MSW is third in anthropogenic methane emissions, behind fossil fuels and livestock (Y. Wang et al., 2020). With the global population expecting continued growth, MSW generation is projected to reach an estimated 9.5 billion tons by 2050. With this projected growth in MSW, Waste-to-Incineration (WtE) will be key in changing waste into a source to provide energy generation and conserving land (Sajid Khan et al., 2023). As stated in Section 2.2.2, the number of WtE facilities in the United States has decreased, but these facilities continue to grow worldwide. The concern of hazardous substances being emitted has been the major issue in the lack of development of new WtE facilities, however with new technologies to include multiple stage systems to reduce dioxins and other emissions, the opportunity to re-introduce and build new WtE plants, as other nations have done, should be reviewed.

The move to emissions reduction and energy savings, or energy from renewable sources, is studied from a waste management methodology whereas which methods will work in isolation or combination with other methods to achieve its stated mission. Landfills will be difficult to fully eliminate in the United States because of their low operating costs and the abundance of land space compared to other countries that have minimal space and have fully operational WtE facilities in operation. Landfills in conjunction with recycling operations and combustion operations will provide the maximum emissions avoided and energy savings. If the landfill is worked in conjunction with the other operations, gas recovery will add to the renewable source to provide a method for electrical generation, thereby reducing emissions and providing both energy savings and energy production. The landfill is still a lower cost operating mechanism compared to the recycling operation and combustion facility. The WARM model in the dissertation calculated that there will be a large increase in wage change when there is a recycling operation in effect, but the landfill and combustion facility will have flat wage changes in moving from the baseline to the alternative.

The type of combustion facility to be built would be determined by the entity choosing to build it. There are three types of technologies that are currently used for combustion, mass burn facilities, modular systems, and refuse derived fuel systems; however, there are several newer technologies including gasification and pyrolysis that appear to offer benefits over the conventional combustions systems. The cost to build a new combustion/gasification plant can range from the tens of millions of dollars for small systems (25 to 100 ton per day) to hundreds of millions for very large plants. The municipalities can offer other municipalities and contractors the use of the facility, which would bring in more revenue from additional tipping fees, while also receiving income from the sale of electricity that is sold to the grid by the utilities (US EPA, 2016b). A key factor in revenue generation would be as the sole Alabama facility has done is to find a partner in which a large portion of the steam is sold to that one entity for heating and cooling at their operation. A previous paper by LoRe and Oswald, 2009, stated that some WtE facilities have found large customers to sell a dedicated amount of steam to, which has decreased their gross electrical generation rates (LoRe & Oswald, 2009).

This dissertation and modeling was performed to study which methods will work best in combination to avoid emissions and provide energy savings. If governments are serious about climate change, which has been caused primarily by human activity, and fossil fuel reduction, investments must be made which can both change the emission levels and assist with production of renewable energy. The life cycle modeling of the landfills has determined that recycling, in addition to combustion, is the best alternative outside of source reduction to accomplish emissions avoidance, energy savings and production of energy.

REFERENCES

Abushammala, M. F., Qazi, W. A., Azam, M.-H., Mehmood, U. A., Al-Mufragi, G. A., & Alrawahi, N.-A. (2016). Economic and environmental benefits of landfill gas utilisation in Oman. *Waste Management & Research*, *34*(8), 717–723. https://doi.org/10.1177/0734242X16628983

Ahiduzzaman, Md., & Islam, A. K. M. S. (2011). Greenhouse gas emission and renewable energy sources for sustainable development in Bangladesh. *Renewable and Sustainable Energy Reviews*, *15*(9), 4659–4666. https://doi.org/10.1016/j.rser.2011.07.086

Ajasa, A. (2023, May 21). Why the recycling symbol could end up in the trash bin. *Washington Post*. https://www.washingtonpost.com/climate-environment/2023/05/18/recycling-labels-epa-consumers/

Alavosius, M. P., Gelino, B. W., & Pietras, C. J. (2022). Approaching 1.5 °C of Global Warming: Introduction to the Special Section on Behavior and Cultural Systems Analysis for Climate Change, Part I. *Behavior & Social Issues*, *31*(1), 366–372. https://doi.org/10.1007/s42822-022-00113-2

Al-Ghussain, L. (2019). Global warming: Review on driving forces and mitigation. *Environmental Progress & Sustainable Energy*, *38*(1), 13–21. https://doi.org/10.1002/ep.13041

Alluvione, F., Moretti, B., Sacco, D., & Grignani, C. (2011). EUE (energy use efficiency) of cropping systems for a sustainable agriculture. *Energy*, *36*(7), 4468–4481. https://doi.org/10.1016/j.energy.2011.03.075

Almer, C., & Winkler, R. (2017). Analyzing the effectiveness of international environmental policies: The case of the Kyoto Protocol. *Journal of Environmental Economics and Management*, *82*, 125–151. https://doi.org/10.1016/j.jeem.2016.11.003

Al-Salem, S. M., Antelava, A., Constantinou, A., Manos, G., & Dutta, A. (2017). A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). *Journal of Environmental Management*, *197*, 177–198. https://doi.org/10.1016/j.jenvman.2017.03.084

Amini, H. R., & Reinhart, D. R. (2011). Regional prediction of long-term landfill gas to energy potential. *Waste Management*, *31*(9), 2020–2026. https://doi.org/10.1016/j.wasman.2011.05.010

Aminzadegan, S., Shahriari, M., Mehranfar, F., & Abramović, B. (2022). Factors affecting the emission of pollutants in different types of transportation: A literature review. *Energy Reports*, *8*, 2508–2529. https://doi.org/10.1016/j.egyr.2022.01.161

Amornsamankul, S., Sirimangkhala, K., Pimpunchat, B., Nuttavut, N., & Triamp, W. (2019). A Review of Modelling and Computer Simulation of Landfill Gas. *International Journal of Simulation: Systems, Science & Technology*. https://doi.org/10.5013/IJSSST.a.20.04.09

Anderson, T. R., Hawkins, E., & Jones, P. D. (2016). CO2, the greenhouse effect and global warming: From the pioneering work of Arrhenius and Callendar to today's Earth System Models. *Endeavour*, *40*(3), 178–187. https://doi.org/10.1016/j.endeavour.2016.07.002

Andress, D., Nguyen, T. D., & Das, S. (2011). Reducing GHG emissions in the United States' transportation sector. *Energy for Sustainable Development*, *15*(2), 117–136. https://doi.org/10.1016/j.esd.2011.03.002

Arora, N. K., & Mishra, I. (2023). Responsible consumption and production: A roadmap to sustainable development. *Environmental Sustainability*, *6*(1), 1–6. https://doi.org/10.1007/s42398-023-00266-9

Barnes, P. W., Williamson, C. E., Lucas, R. M., Robinson, S. A., Madronich, S., Paul, N. D., Bornman, J. F., Bais, A. F., Sulzberger, B., Wilson, S. R., Andrady, A. L., McKenzie, R. L., Neale, P. J., Austin, A. T., Bernhard, G. H., Solomon, K. R., Neale, R. E., Young, P. J., Norval, M., … Zepp, R. G. (2019). Ozone depletion, ultraviolet radiation, climate change and prospects for a sustainable future. *Nature Sustainability*, *2*(7), 569–579.

https://doi.org/10.1038/s41893-019-0314-2

Bastianoni, S., Pulselli, F. M., & Tiezzi, E. (2004). The problem of assigning responsibility for greenhouse gas emissions. *Ecological Economics*, *49*(3), 253–257. https://doi.org/10.1016/j.ecolecon.2004.01.018

Benedick, R. E., & World Resources Institute (Eds.). (1991). *Greenhouse warming: Negotiating a global regime*. World Resources Institute.

Bhatt, K. P., Patel, S., Upadhyay, D. S., & Patel, R. N. (2022). A critical review on solid waste treatment using plasma pyrolysis technology. *Chemical Engineering and Processing - Process Intensification*, *177*, 108989. https://doi.org/10.1016/j.cep.2022.108989

Bhuvaneshwari, S., Hettiarachchi, H., & Meegoda, J. N. (2019). Crop Residue Burning in India: Policy Challenges and Potential Solutions. *International Journal of Environmental Research and Public Health*, *16*(5), Article 5. https://doi.org/10.3390/ijerph16050832

Bradfield, F. L. (2014). *Examination of the thermal properties of municipal solid waste and the scalability of its pyrolysis* [Thesis, Stellenbosch : Stellenbosch University]. https://scholar.sun.ac.za:443/handle/10019.1/86670

Brandt, U. S., & Svendsen, G. T. (2022). Is the annual UNFCCC COP the only game in town?: Unilateral action for technology diffusion and climate partnerships. *Technological Forecasting and Social Change*, *183*, 121904. https://doi.org/10.1016/j.techfore.2022.121904

Calma, J. (2021, November 15). *The US finally adopts a national recycling strategy*. The Verge. https://www.theverge.com/2021/11/15/22783450/recycling-united-states-epa-plastic-pollution-waste

Campos, J. L., Valenzuela-Heredia, D., Pedrouso, A., Val del Río, A., Belmonte, M., & Mosquera-Corral, A. (2016). Greenhouse Gases Emissions from Wastewater Treatment Plants: Minimization, Treatment, and Prevention. *Journal of Chemistry*, *2016*, e3796352. https://doi.org/10.1155/2016/3796352

Canada, E. and C. C. (2007, January 9). *Greenhouse gas emissions* [Research]. https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/greenhouse-gas-emissions.html

Castigliego, J. R., Pollack, A., Cleveland, C. J., & Walsh, M. J. (2021). Evaluating emissions reductions from zero waste strategies under dynamic conditions: A case study from Boston. *Waste Management*, *126*, 170–179. https://doi.org/10.1016/j.wasman.2021.02.026

Chai, X., Tonjes, D. J., & Mahajan, D. (2016). Methane emissions as energy reservoir: Context, scope, causes and mitigation strategies. *Progress in Energy and Combustion Science*, *56*, 33–70. https://doi.org/10.1016/j.pecs.2016.05.001

Chipperfield, M. P., Hossaini, R., Montzka, S. A., Reimann, S., Sherry, D., & Tegtmeier, S. (2020). Renewed and emerging concerns over the production and emission of ozone-depleting substances. *Nature Reviews Earth & Environment*, *1*(5), Article 5. https://doi.org/10.1038/s43017-020-0048-8

Cho. (2020, March 13). Recycling in the U.S. Is Broken. How Do We Fix It? *State of the Planet*. https://news.climate.columbia.edu/2020/03/13/fix-recycling-america/

Connolly, R., Connolly, M., Carter, R. M., & Soon, W. (2020). How Much Human-Caused Global Warming Should We Expect with Business-As-Usual (BAU) Climate Policies? A Semi-Empirical Assessment. *Energies*, *13*(6), Article 6. https://doi.org/10.3390/en13061365

Damgacioglu, H., Hornilla, M., Bafail, O., & Celik, N. (2020). Recovering value from single stream material recovery facilities – An outbound contamination analysis in Florida. *Waste Management*, *102*, 804–814. https://doi.org/10.1016/j.wasman.2019.11.020

Demirbas, A. (2009). Political, economic and environmental impacts of biofuels: A review. *Applied Energy*, *86*, S108–S117. https://doi.org/10.1016/j.apenergy.2009.04.036

Dengler, A., Shulman, J., & Fuller, R. (2022). *Greenhouse Gas Emissions from Waste: A Critique on the Data Inconsistencies for Reporting and Decision Making*. *5*(1).

Dincă, M., Ferdes, M., Zăbavă, B.-Ștefania, Ungureanu, N., Moiceanu, G., & Ionescu, M. (2018). *A REVIEW REGARDING MODELS WHICH PREDICT LANDFILL GAS GENERATION*.

EIA projects global energy-related CO2 emissions will increase through 2050. (n.d.). Retrieved April 27, 2023, from https://www.eia.gov/todayinenergy/detail.php?id=41493

Faour, A. A., Reinhart, D. R., & You, H. (2007). First-order kinetic gas generation model parameters for wet landfills. *Waste Management*, *27*(7), 946–953. https://doi.org/10.1016/j.wasman.2006.05.007

Feng, T., Yang, Y., Xie, S., Dong, J., & Ding, L. (2017). Economic drivers of greenhouse gas emissions in China. *Renewable and Sustainable Energy Reviews*, *78*, 996–1006. https://doi.org/10.1016/j.rser.2017.04.099

Fernández-González, J. M., Grindlay, A. L., Serrano-Bernardo, F., Rodríguez-Rojas, M. I., & Zamorano, M. (2017). Economic and environmental review of Waste-to-Energy systems for municipal solid waste management in medium and small municipalities. *Waste Management*, *67*, 360–374. https://doi.org/10.1016/j.wasman.2017.05.003

Florides, G. A., & Christodoulides, P. (2009). Global warming and carbon dioxide through sciences. *Environment International*, *35*(2), 390–401. https://doi.org/10.1016/j.envint.2008.07.007

Ganesh, P. R., & Webster, B. (n.d.). *Gasification as a Potential Technology Solution in the Integrated Approach to a Sustainable Circular Economy for Plastics in the US: Case Study*.

Ge, M., Friedrich, J., & Vigna, L. (2020). *4 Charts Explain Greenhouse Gas Emissions by Countries and Sectors*. https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors

Goers, L., Lawson, J., Tyrrell, M. L., Ashton, M. S., Spalding, D., & Gentry, B. (2009). *Forests and Carbon: A Synthesis of Science, Management, and Policy for Carbon Sequestration in Forests; Chapter 14: Economic Drivers of Tropical Deforestation for Agriculture*.

Gołasa, P., Wysokiński, M., Bieńkowska-Gołasa, W., Gradziuk, P., Golonko, M., Gradziuk, B., Siedlecka, A., & Gromada, A. (2021). Sources of Greenhouse Gas Emissions in Agriculture, with Particular Emphasis on Emissions from Energy Used. *Energies (19961073)*, *14*(13), 3784–3784. https://doi.org/10.3390/en14133784

Gupta, A. (2016). Chapter 1 - Climate Change and Kyoto Protocol: An Overview. In V. Ramiah & G. N. Gregoriou (Eds.), *Handbook of Environmental and Sustainable Finance* (pp. 3–23). Academic Press. https://doi.org/10.1016/B978-0-12-803615-0.00001-7

Hasan, M. M., Rasul, M. G., Khan, M. M. K., Ashwath, N., & Jahirul, M. I. (2021). Energy recovery from municipal solid waste using pyrolysis technology: A review on current status and developments. *Renewable and Sustainable Energy Reviews*, *145*, 111073. https://doi.org/10.1016/j.rser.2021.111073

How a Materials Recovery Facility Works. (n.d.). Retrieved July 27, 2023, from https://dakotavalleyrecyclingmn.gov/other-residential-recycling/330-how-a-materials-recovery-facilities-works

Huang, W. M., Lee, G. W. M., & Wu, C. C. (2008). GHG emissions, GDP growth and the Kyoto Protocol: A revisit of Environmental Kuznets Curve hypothesis. *Energy Policy*, *36*(1), 239–247. https://doi.org/10.1016/j.enpol.2007.08.035

Ismail, M. M., & Dincer, I. (2022). Development of an Integrated Waste to Energy Multigeneration System Based on Plastic Wastes for Sustainable Cities. *Sustainable Cities and Society*, *85*, 104079. https://doi.org/10.1016/j.scs.2022.104079

Jobson, T., & Khosravi, N. (2019). *Emissions from Washington State Compost Facilities: A Review of Volatile Organic Compound Data, and an Estimation of Greenhouse Gas Emissions*.

Johari, A., Ahmed, S. I., Hashim, H., Alkali, H., & Ramli, M. (2012). Economic and environmental benefits of landfill gas from municipal solid waste in Malaysia. *Renewable and Sustainable Energy Reviews*, *16*(5), 2907–2912. https://doi.org/10.1016/j.rser.2012.02.005

Johnson, J. M.-F., Franzluebbers, A. J., Weyers, S. L., & Reicosky, D. C. (2007). Agricultural opportunities to mitigate greenhouse gas emissions. *Environmental Pollution*, *150*(1), 107–124. https://doi.org/10.1016/j.envpol.2007.06.030

Karim, M., & Corazzini, B. (2019). The current status of MSW disposal and energy production: A brief review of waste incineration. *MOJ Ecology & Environmental Sciences*, *4*(1). https://doi.org/10.15406/mojes.2019.04.00129

Kaur, A., Bharti, R., & Sharma, R. (2021). Municipal solid waste as a source of energy. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2021.04.286

Khalida, A. (2018). A Review of The Climate Change Funding under the United Nations Framework Convention on Climate Change (UNFCCC) With reference to the case of Algeria. 295, *03*□□□□□□□ □□□□□□□□□□ □□□□□□ □□□□. https://doi.org/10.38170/1993-000-004-019

Khalifa, A. A., Ibrahim, A.-J., Amhamed, A. I., & El-Naas, M. H. (2022). Accelerating the Transition to a Circular Economy for Net-Zero Emissions by 2050: A Systematic Review. *Sustainability*, *14*(18), Article 18. https://doi.org/10.3390/su141811656

Kim, D.-G., & Kirschbaum, M. U. F. (2015). The effect of land-use change on the net exchange rates of greenhouse gases: A compilation of estimates. *Agriculture, Ecosystems & Environment*, *208*, 114–126. https://doi.org/10.1016/j.agee.2015.04.026

Kumar, A., & Samadder, S. R. (2017). A review on technological options of waste to energy for effective management of municipal solid waste. *Waste Management*, *69*, 407–422. https://doi.org/10.1016/j.wasman.2017.08.046

Kumar, S., Himanshu, S., & K.K., G. (2012). Effect of Global Warming on Mankind -A Review. *International Research Journal of Environment Sciences*, *1*, 2319–1414.

Kuyper, J., Schroeder, H., & Linnér, B.-O. (2018). The Evolution of the UNFCCC. *Annual Review of Environment and Resources*, *43*(1), 343–368. https://doi.org/10.1146/annurev-environ-102017-030119

Kyung, D., Kim, M., Chang, J., & Lee, W. (2015). Estimation of greenhouse gas emissions from a hybrid wastewater treatment plant. *Journal of Cleaner Production*, *95*, 117–123. https://doi.org/10.1016/j.jclepro.2015.02.032

Lamb, W. F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J. G. J., Wiedenhofer, D., Mattioli, G., Khourdajie, A. A., House, J., Pachauri, S., Figueroa, M., Saheb, Y., Slade, R., Hubacek, K., Sun, L., Ribeiro, S. K., Khennas, S., Can, S. de la R. du, … Minx, J. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters*, *16*(7), 073005. https://doi.org/10.1088/1748-9326/abee4e

Larson, S. L., Martin, W. A., Şengör, S. S., Wade, R., & Altamimi, F. (2021). Amendment for increased methane production rate in municipal solid waste landfill gas collection systems. *Science of The Total Environment*, *772*, 145574. https://doi.org/10.1016/j.scitotenv.2021.145574

Lee, D.-J. (2022). Gasification of municipal solid waste (MSW) as a cleaner final disposal route: A mini-review. *Bioresource Technology*, *344*, 126217. https://doi.org/10.1016/j.biortech.2021.126217

Leggett, J. (1998). A guide to the Kyoto protocol: A treaty with potentially vital strategic implications for the renewables industry. *Renewable and Sustainable Energy Reviews*, *2*(4), 345–351. https://doi.org/10.1016/S1364-0321(98)00004-5

Lenzen, M., Murray, J., Sack, F., & Wiedmann, T. (2007). Shared producer and consumer responsibility—Theory and practice. *Ecological Economics*, *61*(1), 27–42.

https://doi.org/10.1016/j.ecolecon.2006.05.018

Li, S., Yoo, H. K., Macauley, M., Palmer, K., & Shih, J.-S. (2015). Assessing the role of renewable energy policies in landfill gas to energy projects. *Energy Economics*, *49*, 687–697. https://doi.org/10.1016/j.eneco.2015.03.022

Li, X., & Lin, B. (2013). Global convergence in per capita CO2 emissions. *Renewable and Sustainable Energy Reviews*, *24*, 357–363. https://doi.org/10.1016/j.rser.2013.03.048

LoRe, A. M., & Oswald, K. J. (2009). Benchmarking Mass Burn WTE Facility Performance: How Does Your Facility Measure Up? *17th Annual North American Waste-to-Energy Conference*, 43–62. https://doi.org/10.1115/NAWTEC17-2335

Lou, X. F., & Nair, J. (2009). The impact of landfilling and composting on greenhouse gas emissions – A review. *Bioresource Technology*, *100*(16), 3792–3798. https://doi.org/10.1016/j.biortech.2008.12.006

Ma, F., Sha, A., Yang, P., & Huang, Y. (2016). The Greenhouse Gas Emission from Portland Cement Concrete Pavement Construction in China. *International Journal of Environmental Research and Public Health*, *13*(7), Article 7. https://doi.org/10.3390/ijerph13070632

Makarichi, L., Jutidamrongphan, W., & Techato, K. (2018). The evolution of waste-to-energy incineration: A review. *Renewable and Sustainable Energy Reviews*, *91*, 812–821. https://doi.org/10.1016/j.rser.2018.04.088

McMahon, J. (2021, May 22). *Three Reasons Recycling Is Failing*. Forbes. https://www.forbes.com/sites/jeffmcmahon/2021/05/22/three-reasons-recycling-is-failing/

Meijer, K. S. (2015). A comparative analysis of the effectiveness of four supply chain initiatives to reduce deforestation. *Tropical Conservation Science*, *8*(2), 583–597. https://doi.org/10.1177/194008291500800219

Michaels, T., & Krishnan, K. (2018). *Waste-to-Energy*. WTE Association. https://www.wte.org/waste-to-energy-101

Minter, S. (2013, January). *Saving the world one motor at a time: A new report says information and communications technology has the potential to drastically reduce greenhouse gas emissions in manufacturing—Document—Gale In Context: College*. https://go-gale-com.ezproxy.library.und.edu/ps/i.do?p=CSIC&u=ndacad_58202zund&id=GALE|A321056535&v=2.1&it=r

Mintzer, I. M. (1990). Energy, Greenhouse Gases, and Climate Change. *Annual Review of Energy*, *15*(1), 513–550. https://doi.org/10.1146/annurev.eg.15.110190.002501

Mirasgedis, S., Sarafidis, Y., Georgopoulou, E., & Lalas, D. P. (2002). The role of renewable energy sources within the framework of the Kyoto Protocol: The case of Greece. *Renewable and Sustainable Energy Reviews*, *6*(3), 247–269. https://doi.org/10.1016/S1364-0321(01)00011-9

Mitchell, R., & Gu, J.-D. (2009). *Environmental Microbiology*. John Wiley & Sons.

Mohammadi, A., Rafiee, S., Jafari, A., Keyhani, A., Mousavi-Avval, S. H., & Nonhebel, S. (2014). Energy use efficiency and greenhouse gas emissions of farming systems in north Iran. *Renewable and Sustainable Energy Reviews*, *30*, 724–733. https://doi.org/10.1016/j.rser.2013.11.012

Mohareb, E. A., MacLean, H. L., & Kennedy, C. A. (2011). Greenhouse Gas Emissions from Waste Management—Assessment of Quantification Methods. *Journal of the Air & Waste Management Association (Air & Waste Management Association)*, *61*(5), 480–493. https://doi.org/10.3155/1047-3289.61.5.480

Morrisette, P. M. (1991). The Montreal Protocol: Lessons for Formulating Policies for Global Warming. *Policy Studies Journal*, *19*(2), 152–161. https://doi.org/10.1111/j.1541-0072.1991.tb01890.x

Mukherjee, C., Denney, J., Mbonimpa, E. G., Slagley, J., & Bhowmik, R. (2020). A review on municipal solid waste-to-energy trends in the USA. *Renewable and Sustainable Energy Reviews*, *119*, 109512. https://doi.org/10.1016/j.rser.2019.109512

Muth, M. K., Birney, C., Cuéllar, A., Finn, S. M., Freeman, M., Galloway, J. N., Gee, I., Gephart, J., Jones, K., Low, L., Meyer, E., Read, Q., Smith, T., Weitz, K., & Zoubek, S. (2019). A systems approach to assessing environmental and economic effects of food loss and waste interventions in the United States. *Science of The Total Environment*, *685*, 1240–1254. https://doi.org/10.1016/j.scitotenv.2019.06.230

Nanda, S., Reddy, S. N., Mitra, S. K., & Kozinski, J. A. (2016). The progressive routes for carbon capture and sequestration. *Energy Science & Engineering*, *4*(2), 99–122. https://doi.org/10.1002/ese3.117

NASA. (n.d.). *Overview: Weather, Global Warming and Climate Change*. Climate Change: Vital Signs of the Planet. Retrieved April 6, 2023, from https://climate.nasa.gov/global-warming-vs-climate-change

Ni, P., Wang, X., & Li, H. (2020). A review on regulations, current status, effects and reduction strategies of emissions for marine diesel engines. *Fuel*, *279*, 118477. https://doi.org/10.1016/j.fuel.2020.118477

Niu, B., Peng, S., Li, C., Liang, Q., Li, X., & Wang, Z. (2020). Nexus of embodied land use and greenhouse gas emissions in global agricultural trade: A quasi-input–output analysis. *Journal of Cleaner Production*, *267*, 122067. https://doi.org/10.1016/j.jclepro.2020.122067

Oh, C. (2022). Evaluation of the UNFCCC Technology Mechanism's contribution to an international climate policy framework. *International Environmental Agreements: Politics, Law and Economics*, *22*(3), 527–542. https://doi.org/10.1007/s10784-021-09559-y

Olafasakin, O., Ma, J., Bradshaw, S. L., Aguirre-Villegas, H. A., Benson, C., Huber, G. W., Zavala, V. M., & Mba-Wright, M. (2023). Techno-Economic and life cycle assessment of standalone Single-Stream material recovery facilities in the United states. *Waste Management*, *166*, 368–376. https://doi.org/10.1016/j.wasman.2023.05.011

Ouikhalfan, M., Lakbita, O., Delhali, A., Assen, A. H., & Belmabkhout, Y. (2022). Toward Net-Zero Emission Fertilizers Industry: Greenhouse Gas Emission Analyses and Decarbonization Solutions. *Energy & Fuels*, *36*(8), 4198–4223. https://doi.org/10.1021/acs.energyfuels.2c00238

Paleologos, E. K., Caratelli, P., & Amrousi, M. E. (2016). Waste-to-energy: An opportunity for a new industrial typology in Abu Dhabi. *Renewable and Sustainable Energy Reviews*, *55*, 1260–1266. https://doi.org/10.1016/j.rser.2015.07.098

Pant, K. (2009). Effects of Agriculture on Climate Change: A Cross Country Study of Factors Affecting Carbon Emissions. *Journal of Agriculture and Environment*, *10*. https://doi.org/10.3126/aej.v10i0.2134

Pathak, H. (2015). Greenhouse Gas Emissions and Mitigation in Agriculture. *Greenhouse Gases: Science and Technology*, *5*(4), 357–358. https://doi.org/10.1002/ghg.1528

Pauw, W. P., Castro, P., Pickering, J., & Bhasin, S. (2020). Conditional nationally determined contributions in the Paris Agreement: Foothold for equity or Achilles heel? *Climate Policy*, *20*(4), 468–484. https://doi.org/10.1080/14693062.2019.1635874

Pendrill, F., Persson, U. M., Godar, J., Kastner, T., Moran, D., Schmidt, S., & Wood, R. (2019). Agricultural and forestry trade drives large share of tropical deforestation emissions. *Global Environmental Change*, *56*, 1–10. https://doi.org/10.1016/j.gloenvcha.2019.03.002

Pour, N., Webley, P. A., & Cook, P. J. (2018). Potential for using municipal solid waste as a resource for bioenergy with carbon capture and storage (BECCS). *International Journal of Greenhouse Gas Control*, *68*, 1–15. https://doi.org/10.1016/j.ijggc.2017.11.007

Prins, G., & Rayner, S. (2008). The Kyoto Protocol. *Bulletin of the Atomic Scientists*, *64*(1), 45–58. https://doi.org/10.2968/064001011

Psomopoulos, C. S., Bourka, A., & Themelis, N. J. (2009). Waste-to-energy: A review of the status and benefits in USA. *Waste Management*, *29*(5), 1718–1724. https://doi.org/10.1016/j.wasman.2008.11.020

Radwan, H. (2013). Carbon Footprint for Paddy Rice Production in Egypt. *Nature and Science*, *11*, 36–45.

Rajak, J. (2021). A Preliminary Review on Impact of Climate change and our Environment with Reference to Global Warming. *International Journal of Environmental Sciences*.

Ram, C., Kumar, A., & Rani, P. (2021). Municipal Solid Waste Management: A Review of Waste to Energy (WtE) Approaches. *BioResources*, *16*(2), 4275–4320. https://doi.org/10.15376/biores.16.2.ram

Ramprasad, C., Teja, H. C., Gowtham, V., & Vikas, V. (2022). Quantification of landfill gas emissions and energy production potential in Tirupati Municipal solid waste disposal site by LandGEM mathematical model. *MethodsX*, *9*, 101869. https://doi.org/10.1016/j.mex.2022.101869

Ranveer, A., Latake, P., & Pawar, P. (2015). The Greenhouse Effect and Its Impacts on Environment. *International Journal of Innovative Research and Creative Technology (IJIRCT)*, *1*, 333–337.

ResearchGate. (n.d.). Retrieved April 10, 2023, from https://www.researchgate.net/figure/World-Population-Growth-1950-2050-41_fig1_325002825/download

Rhodes, C. J. (2016). The 2015 Paris Climate Change Conference: Cop21. *Science Progress*, *99*(1), 97–104. https://doi.org/10.3184/003685016X14528569315192

Ritchie, H., Roser, M., & Rosado, P. (2020). CO_2 and Greenhouse Gas Emissions. *Our World in Data*. https://ourworldindata.org/emissions-by-sector

Rogoff, M., & Ross, D. (2016). The future of recycling in the United States. *Waste Management*

& Research, *34(3)*, 181–183. https://doi.org/10.1177/0734242X16629599

Rosa, E. A., & Dietz, T. (2012). Human drivers of national greenhouse-gas emissions. *Nature Climate Change*, *2*(8), 581–586. https://doi.org/10.1038/nclimate1506

Roy, H., Alam, S. R., Bin-Masud, R., Prantika, T. R., Pervez, M. N., Islam, M. S., & Naddeo, V. (2022). A Review on Characteristics, Techniques, and Waste-to-Energy Aspects of Municipal Solid Waste Management: Bangladesh Perspective. *Sustainability*, *14*(16), Article 16. https://doi.org/10.3390/su141610265

Sajid Khan, M., Cui, J., Ni, Y., Yan, M., & Ali, M. (2023). Techno-economic and exergo-economic evaluation of a novel solar integrated waste-to-energy power plant. *Applied Thermal Engineering*, *223*, 119929. https://doi.org/10.1016/j.applthermaleng.2022.119929

Sanciolo, P., Rivera, E., Navaratna, D., & Duke, M. C. (2022). Food Waste Diversion from Landfills: A Cost–Benefit Analysis of Existing Technological Solutions Based on Greenhouse Gas Emissions. *Sustainability*, *14*(11), Article 11. https://doi.org/10.3390/su14116753

Scarlat, N., Motola, V., Dallemand, J. F., Monforti-Ferrario, F., & Mofor, L. (2015). Evaluation of energy potential of Municipal Solid Waste from African urban areas. *Renewable and Sustainable Energy Reviews*, *50*, 1269–1286. https://doi.org/10.1016/j.rser.2015.05.067

Schmidhuber, J., & Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences*, *104*(50), 19703–19708. https://doi.org/10.1073/pnas.0701976104

Shahsavari, A., & Akbari, M. (2018). Potential of solar energy in developing countries for reducing energy-related emissions. *Renewable and Sustainable Energy Reviews*, *90*, 275–291. https://doi.org/10.1016/j.rser.2018.03.065

Sharma, D. K., Bapat, S., Brandes, W. F., Rice, E., & Castaldi, M. J. (2019). Technical Feasibility of Zero Waste for Paper and Plastic Wastes. *Waste and Biomass Valorization*, *10*(5), 1355–1363. https://doi.org/10.1007/s12649-017-0109-5

Siddiqua, A., Hahladakis, J. N., & Al-Attiya, W. A. K. A. (2022). An overview of the environmental pollution and health effects associated with waste landfilling and open dumping. *Environmental Science and Pollution Research*, *29*(39), 58514–58536. https://doi.org/10.1007/s11356-022-21578-z

Sun, W., Wang, X., DeCarolis, J. F., & Barlaz, M. A. (2019). Evaluation of optimal model parameters for prediction of methane generation from selected U.S. landfills. *Waste Management*, *91*, 120–127. https://doi.org/10.1016/j.wasman.2019.05.004

The Paris Agreement | UNFCCC. (n.d.). Retrieved April 13, 2023, from https://unfccc.int/process-and-meetings/the-paris-agreement

United States GDP 1990-2022. (2023, May 30). Statista. https://www.statista.com/statistics/188105/annual-gdp-of-the-united-states-since-1990/

US EPA. (2018). *Advancing Sustainable Materials Management: 2018 Fact Sheet*.

US EPA. (2020). *Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM)—Management Practices Chapters*.

US EPA. (2005). *Document Display | NEPIS | US EPA*. https://nepis.epa.gov/Exe/ZyNET.exe/P1009C8L.txt?ZyActionD=ZyDocument&Client=EPA&Index=2016%20Thru%202020%7C1991%20Thru%201994%7C2011%20Thru%202015%7C1986%20Thru%201990%7C2006%20Thru%202010%7C1981%20Thru%201985%7C2000%20Thru%202005%7C1976%20Thru%201980%7C1995%20Thru%201999%7CPrior%20to%201976%7CHardcopy%20Publications&Docs=&Query=600r05047&Time=&EndTime=&SearchMethod=2&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C00THRU05%5CTXT%5C00000026%5CP1009C8L.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-

&MaximumDocuments=15&FuzzyDegree=0&ImageQuality=r85g16/r85g16/x150y150g16/i500&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x

US EPA - ICF. (2020). *Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM)*.

US EPA, O. (2016a, January 7). *Waste Reduction Model (WARM)* [Collections and Lists]. https://www.epa.gov/warm

US EPA, O. (2016b, March 24). *Energy Recovery from the Combustion of Municipal Solid Waste (MSW)* [Overviews and Factsheets]. https://www.epa.gov/smm/energy-recovery-combustion-municipal-solid-waste-msw

US EPA, O. (2016c, April 15). *Basic Information about Landfill Gas* [Overviews and Factsheets]. https://www.epa.gov/lmop/basic-information-about-landfill-gas

US EPA, O. (2016d, June 27). *Climate Change Indicators: Global Greenhouse Gas Emissions* [Reports and Assessments]. https://www.epa.gov/climate-indicators/climate-change-indicators-global-greenhouse-gas-emissions

US EPA, O. (2016e, September 6). *Emissions Estimation Tools* [Data and Tools]. https://www.epa.gov/air-emissions-factors-and-quantification/emissions-estimation-tools

US EPA, O. (2017, October 2). *National Overview: Facts and Figures on Materials, Wastes and Recycling* [Overviews and Factsheets]. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

USDA. (2021). *What is Pyrolysis? : USDA ARS*. https://www.ars.usda.gov/northeast-area/wyndmoor-pa/eastern-regional-research-center/docs/biomass-pyrolysis-research-1/what-is-pyrolysis/

Vaish, B., Sharma, B., Srivastava, V., Singh, P., Ibrahim, M., & Singh, R. (2019). Energy recovery potential and environmental impact of gasification for municipal solid waste.

Biofuels, *10*, 87–100. https://doi.org/10.1080/17597269.2017.1368061

Verburg, R., Stehfest, E., Woltjer, G., & Eickhout, B. (2009). The effect of agricultural trade liberalisation on land-use related greenhouse gas emissions. *Global Environmental Change*, *19*(4), 434–446. https://doi.org/10.1016/j.gloenvcha.2009.06.004

Wackernagel, M., & Rees, W. (1998). *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society Publishers.

Wang, X., Nagpure, A. S., DeCarolis, J. F., & Barlaz, M. A. (2013). Using Observed Data To Improve Estimated Methane Collection from Select U.S. Landfills. *Environmental Science & Technology*, *47*(7), 3251–3257. https://doi.org/10.1021/es304565m

Wang, Y., Levis, J. W., & Barlaz, M. A. (2020). An Assessment of the Dynamic Global Warming Impact Associated with Long-Term Emissions from Landfills. *Environmental Science & Technology*, *54*(3), 1304–1313. https://doi.org/10.1021/acs.est.9b04066

Waste-to-energy (MSW)—U.S. Energy Information Administration (EIA). (2022, October 31). https://www.eia.gov/energyexplained/biomass/waste-to-energy.php

Weart, S. R. (2010). The idea of anthropogenic global climate change in the 20th century. *WIREs Climate Change*, *1*(1), 67–81. https://doi.org/10.1002/wcc.6

Weitz, K. A., Thorneloe, S. A., Nishtala, S. R., Yarkosky, S., & Zannes, M. (2002). The Impact of Municipal Solid Waste Management on Greenhouse Gas Emissions in the United States. *Journal of the Air & Waste Management Association*, *52*(9), 1000–1011. https://doi.org/10.1080/10473289.2002.10470843

Wimbadi, R. W., & Djalante, R. (2020). From decarbonization to low carbon development and transition: A systematic literature review of the conceptualization of moving toward net-zero carbon dioxide emission (1995–2019). *Journal of Cleaner Production*, *256*, 120307. https://doi.org/10.1016/j.jclepro.2020.120307

Wuebbles, D. J., & Jain, A. K. (2001). Concerns about climate change and the role of fossil fuel use. *Fuel Processing Technology*, *71*(1), 99–119. https://doi.org/10.1016/S0378-3820(01)00139-4

Zhang, C., Xu, T., Feng, H., & Chen, S. (2019a). Greenhouse Gas Emissions from Landfills: A Review and Bibliometric Analysis. *Sustainability*, *11*(8), Article 8. https://doi.org/10.3390/su11082282

Zhang, C., Xu, T., Feng, H., & Chen, S. (2019b). Greenhouse Gas Emissions from Landfills: A Review and Bibliometric Analysis. *Sustainability*, *11*(8), Article 8. https://doi.org/10.3390/su1108