## Residue-Derived Solid Recovered Fuel for Use in Cement Kilns

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## **Executive Summary**

#### Purpose

Single-stream recycling has helped divert millions of tons of waste from landfills in the U.S., where recycling rates for municipal solid waste are currently over 30%. However, material recovery facilities (MRFs) that sort the municipal recycling streams do not recover 100% of the incoming material. Consequently, they landfill between 5% - 15% of total processed material as residue. This residue is primarily composed of high-energy-content non-recycled plastics and fiber<sup>1</sup>. One possible end-of-life solution for these energy-dense materials is to process the residue into solid recovered fuel (SRF) that can be used as an alternative energy source capable of replacing or supplementing fuel sources such as coal, natural gas, petroleum coke, or biomass in many industrial and power production processes. This report addresses the energetic, economic, and environmental benefits and trade-offs of converting non-recycled post-consumer plastics and fiber derived from MRF residue streams into SRF for use in a cement kiln.

#### Methodology

This project consists of four components: 1) a global literature search of SRF projects, experiments, and production companies; 2) site visits to various MRFs, an SRF production facility, and a cement kiln; and 3) a pilot project involving the manufacture and test burn of residue-derived SRF; and 4) a life-cycle analysis of SRF production and use. The research team conducted the experimental test burn of 130 tons of SRF in the precalciner<sup>2</sup> portion of the cement kiln. The SRF was a blend of 60% MRF residue and 40% post-industrial waste products producing an estimated 60% plastic and 40% fibrous material mixture. A sample was sent to a lab for a 3rd party elemental analysis and to calculate the energy value of the fuel. The SRF was fed into the kiln at 1 ton/hr for 24 hours and then 2 ton/hr for the following 48 hours. The emissions data recorded in the experimental test burn were used to inform the life-cycle analysis portion of this study.

To elucidate the energetic, environmental, and economic trade-offs associated with using MRF residue as SRF at cement kilns instead of landfilling the energy-dense material, a life-

<sup>&</sup>lt;sup>1</sup>Fiber refers to paper, paperboard, cardboard, etc.

<sup>&</sup>lt;sup>2</sup>The precalciner is a special combustion chamber for cement kilns that serves to pre-heat and decarbonate raw materials before entering the kiln.

cycle analysis was conducted. This study considers transportation, landfill, and processing steps. The energy use and emissions at each step is tracked for the two cases: 1) The Reference Case, where MRF residue is disposed of in a landfill and the cement kiln uses coal as its fuel source<sup>3</sup>, and 2) The SRF Case, in which MRF residue is processed into SRF and used to offset some portion of coal use at the cement kiln. Three scenarios were developed to provide insight into the relative effect of certain assumptions used in the analysis of the SRF Case. The scenarios considered are: the Early Scenario, structured to approximate the experimental SRF test burn method and an early stage SRF infrastructure; the Near-Term Scenario, representative of a near-term infrastructure buildout with environmental and energy efficiency improvements at the landfill and power plants; and the Future Scenario, defined to be as energetically and environmentally advantageous as possible, representing a hopeful outlook on future infrastructure buildout and emissions reductions efforts.

#### Key Findings

- The experimental test was successful on a technical basis and proved that refusederived SRF can be used as an alternative fuel at a cement kiln. Based on the experimentally measured heating value, the SRF supplied roughly 10% of the total precalciner energy requirements during the 1 ton/hour test period and 20% during the 2 ton/hour period.
- The experimental data and independent testing showed an average SRF heating value of about 12,500 British thermal units per pound (Btu/lb), which is comparable to the bituminous coal the cement kiln uses. Therefore, every ton of MRF residue diverted from a landfill to make SRF for the test burn approximately displaced an equivalent ton of bituminous coal. When compared to other coal sources, potential replacement rates are higher: the SRF is 10% more energy dense than sub-bituminous coals at about 11,300 Btu/lb and 80% more than lignite coals at about 7,000 Btu/lb.
- Emissions data for sulfur dioxide  $(SO_2)$  from the cement kiln indicated that the use of SRF reduced the SO<sub>2</sub> emissions rate by roughly 50% compared to the Reference Case using coal alone. Results from the life-cycle analysis portion of the study revealed that the use of SRF at 1 ton/hour reduces SO<sub>2</sub> emissions by 19% 44%. These reductions, as with all emissions results presented here, are preliminary results based on limited experimental data and require further testing to verify.
- The nitrogen oxides (NO<sub>X</sub>) emissions rate increased by 25% when the SRF was used at 1 ton/hour and by 93% during the 2 ton/hour feed rate period compared to the Reference Case using coal. The total emissions were 40%, 50%, and 75% of the

<sup>&</sup>lt;sup>3</sup>Though coal was used for this analysis, in reality cement kilns often use several different fuel types depending on cost, availability, regulations, etc.

total permitted levels for the non-SRF, 1 ton/hour, and 2 ton/hour test periods, respectively. Results from the life-cycle analysis portion of the study revealed that the use of SRF at 1 ton/hour increased NO<sub>X</sub> emissions by 16% - 24%. However, follow-up discussions with cement kiln operators suggest that the spike in NO<sub>X</sub> was likely due to the lack of an efficient feeding system for the experimental fuel and that plant operators would normally adjust burn conditions to more effectively control combustion. No adjustments were made during this limited test run.

- The analysis showed that carbon dioxide  $(CO_2)$  emissions were reduced by about 1.5% in the SRF Case compared to the Reference Case (or about 13,780 tons/year in absolute reductions). The magnitude of these  $CO_2$  emissions reductions is comparable to making 1,800 homes carbon neutral or removing 2,800 cars from the road.
- This analysis concluded that the fuel use at the cement kilns offset by using SRF significantly outweighs the energy requirements of producing and transporting SRF. The production and transportation used 1% 11% of the heating value of the SRF: for every 10 million Btu (MMBtu) of SRF consumed, a total of 8.8 9.9 MMBtu of conventional fuel use is avoided.
- Replacing coal with SRF at a 1 ton/hour rate for an entire year at the cement kiln reduces fossil energy use by 5.5% 6.3%.
- These reductions translate to saving 8,500 9,600 tons of coal (enough to provide electricity to about 1,500 U.S. homes for a year), 32,400 36,200 barrels of oil (about 3,000 U.S. light-duty vehicles for a year), or 180 210 million cubic feet of natural gas (again, enough to provide electricity to 1,500 homes), and the reductions listed above would scale linearly with the amount of SRF used.
- For perspective, if just 5% of the total 2010 U.S. MRF throughput of 85 million tons per day is considered residue and converted to SRF in the same process studied in this report, the resulting coal displacement would be enough to power approximately 700,000 homes and an equivalent  $CO_2$  reduction of removing more than 1 million cars from the road.
- The preliminary economic analysis reveals that the cost of SRF as delivered to a customer has a strong dependence on local landfill tipping fees. However, to fully verify economic feasibility, costs such as amortized capital, labor, and technology-specific operations expenses need to be assessed, but are out of the scope of this report.

The experimental test burn and accompanying analysis indicate that using MRF residue to produce SRF for use in cement kilns is likely an advantageous alternative to disposal of the residue in landfills. The use of SRF can offset fossil fuel use, reduce  $CO_2$  emissions, and divert energy-dense materials away from landfills. Considering the total U.S. MRF

throughput and associated residue production rate, the potential fossil fuel and emissions reductions of widespread SRF use are substantial. Even with electricity consumption and additional transportation necessary for the SRF Case, SRF outperforms traditional fuels on an energetic basis, is able to provide benefits nationwide, and the margin of energy and emissions reductions is expected to increase if optimized facilities are developed. Colocation of MRFs, SRF production facilities, and landfills can increase the benefits of SRF use even further by reducing transportation requirements. Due to the unique characteristics of the combustion process used in cement kilns, serperate testing and analysis should be conducted in different combustion process such industrial boilers or power generation boilers to further realize the benefits of this novel use of MRF residue.

Finally, the handling of SRF on a policy basis will impact the economics and viability of this industry, as landfill avoidance incentives and  $\rm CO_2$  accounting could be important aspects in SRF economics. Overall, despite technical, social, political, and economic hurdles, our analysis indicates that harnessing the energy content of non-recycled plastics and paper from MRF residue diverted from landfills in the form of SRF offers environmental benefits. As recycling rates continue to increase and SRF production techniques are further refined, residue-derived SRF will be an important resource to consider as a possible solution to society's long-term energy usage and waste management strategies.

## Scope of Work

This report presents an evaluation of the energetic, environmental, and economic tradeoffs of converting non-recycled post-consumer plastics and fiber from material recovery facilities (MRFs) into solid recovered fuel (SRF) to be used as an alternative to coal in a cement kiln. Figure 1 details the system boundaries of the two cases considered for analysis, the Reference Case and the SRF Case. Through the participation of several industry partners a large-scale experimental test burn was conducted to verify technical feasibility. Accompanying systems analysis was conducted to assess whether non-recycled, non-marketable post-consumer plastic and fiber sourced from a single-stream MRF residue can be processed into a fuel that has environmental benefits including, but not limited to, landfill avoidance and reduced emissions compared to coal.



Figure 1: The process-flow with system boundaries is shown, highlighting material, emissions, and energy flows through the system. MSW stands for munisipal solid waste, MRF for material recovery facility, SRF for solid recovered fuel, and SRFF stands for SRF facility.

## 1 Background

Managing our waste has been an issue for thousands of years affecting sanitation and the use of land, water, and natural resources. Society's municipal solid waste (MSW) management solutions have evolved significantly over time due to public policy, public opinion, economics, and technological capability. Historic waste management (WM) methods include landfill disposal or incineration without energy recovery. More advanced techniques include recycling or direct incineration to produce power and advanced thermochemical processing to produce fuels. This chapter contains a brief background on generation, recycling, and energy recovery of MSW<sup>1</sup> from a U.S. and international perspective. Based on the subject of the report, a discussion of various waste-to-energy (WTE) technologies utilized by companies around the world is included, with an emphasis on how the technologies apply to handling non-recycled post-consumer plastic waste. Finally, some barriers to growth of the plastic waste-to-energy industry are identified and discussed.

## 1.1 Municipal Solid Waste Management Background

Waste management is a complex challenge informed by regional and seasonal waste composition, disposal and recovery technologies, local and national policies, and other economic factors such as the price of energy or the cost of landfilling. The harmful environmental effects of open burning and dumping of waste as well as our increasing understanding of the benefits of recycling and recovering energy from waste have led to complex and evolving regulations. In light of the inherent complexities, the EPA has developed a WM hierarchy to describe its regulatory policy preference for solid waste management (Figure 1.1). Under this framework, WM options that conserve resources, recycle material, and recover energy are preferred over simply landfilling waste. Preferentially, as much waste as possible is moved up the hierarchy to more useful and benign end-of-life pathways.

In recent history, society's waste generation rates have grown tremendously. Figure 1.2 shows the aggregate and per capita MSW generation in the U.S. from 1960 to 2009. In 2009, 243 million tons of MSW were generated in the U.S. with a per capita generation of 4.3 pounds per person per day [2]. For comparison, in the same year the E.U. produced 283 million tons of MSW, or 3.1 pounds per person per day. However, the European MSW situation varies dramatically from country to country. For example, in 2009 Poland and

<sup>&</sup>lt;sup>1</sup>MSW refers solely to waste generated by consumers and excludes hazardous, medical, construction, industrial, commercial, and demolition waste.



Figure 1.1: The Waste Management Hierarchy graphically represents the options of handling waste in the most desired ways [1].

the Czech Republic had per capita MSW generation rates on the low end at around 1.9 pounds per person per day, while Denmark had generation rates on the high end of around 5.0 pounds per person per day. The United Kingdom and Germany had MSW generation rates around the E.U. average at 3.2 and 3.5 pounds per person per day, respectively [3]. MSW generation rates will vary depending on the culture, industrialization, and policies of the country. Despite this variance in MSW production, end-of-life solutions besides landfilling have been pursued by the international community in the last century, namely recycling and energy recovery techniques.

Recycling of waste materials is a WM solution that recovers the material content of disposed wastes but is limited by the quality of the feedstock. Source separated recycling, where recyclables such as newspaper, plastic, and glass are placed in separate bins for collection, was the first wide spread recycling collection method. Later single-stream recycling became popular, a collection method where all recyclables are commingled and collected from a single bin and sorted at a materials recovery facility (MRF). The move to single-stream collection resulted in higher rates of material contamination. WTE is a method of energy recovery that, though not as preferred under the traditional waste management hierarchy as recycling, has the benefit of being less sensitive to contamination of the feedstock and is suitable for materials that cannot be economically recycled. Figure 1.3 shows the total recycling rates and recycling amounts as a percent of total MSW generation in the U.S. from 1960 to 2009. In 2009, 33.8% of the U.S. MSW was recycled, 54.3% was discarded and 11.9% was combusted for energy recovery [2]. The European Union as a whole has a higher recycling (including composting) and energy recovery rate than the U.S. at 40.6%and 16.1%, respectively. Again the rates vary dramatically by country, with Germany and Austria recycling or composting 63.6% and 69.9% of their MSW. Switzerland, Denmark, and Sweden are the leaders in energy recovery, using around 48% of their MSW for to produce heat or power [3]. The variations in end-of-life solutions for waste depend heav-



Figure 1.2: The total annual U.S. MSW generation rate has increased almost every year since 1960 but the per capita generation has plateaued since 1990 at around 4.5 lbs per person per day [2].

ily on social and policy drivers related to landfilling, composting, recycling, and energy recovery.

## 1.2 Waste-to-Energy Technology

Recovering energy from waste is an important option considering that some of MSW is considered too contaminated or expensive to recycle. Recovering energy from MSW is called waste-to-energy (WTE), a WM concept that has been in practice for many years.

#### 1.2.1 Traditional WTE

#### Mass Burn Incineration

One traditional method of converting solid waste into usable energy is through direct incineration. Direct incineration facilities typically truck and dump MSW at the facility



Figure 1.3: The total U.S. MSW recycling rate has increased almost every year since 1960 except between 2007 and 2009, but the per capita recycling has increased every year up to the 2009 rate of 33.8% [2].

storage site where materials that are easily segregated and undesirable are removed, such as furniture, appliances, or large batteries. The remaining material is directly combusted in a boiler producing heat to generate electricity. The remaining inert materials called ash are collected and landfilled, typically reducing the MSW by 90% of the initial volume and 75% of the original mass. Currently there are 86 WTE facilities totaling 2.6 GW of electricity generation capacity operating in the U.S. [4].

Mixed public opinion, feedstock reliability issues, and high costs have caused slow growth for the mass burn incineration WTE industry. Most WTE facilities were built over 25 years ago and were subject to claims of hazardous emissions, souring public opinion. A 1994 Supreme Court decision prohibiting municipalities from guaranteeing MSW deliveries to WTE plants forced operators to charge tipping fees low enough to compete with landfills, reducing revenue margins [5]. Updated emissions requirements in the 1990's required WTE facilities to have more advanced emissions control systems, reducing emissions rates enormously while driving up operations costs. As a consequence of these and other factors no new WTE facilities have been built since 1996. However, a modification to the 1994 ruling in 2007 and increased experience and expertise in emissions control systems are likely reasons why several new WTE are being planned around the U.S. [4].

#### Landfill Gas Capture

Another traditional method of waste-to-energy technologies is landfill gas capture. When compostable materials are buried in a landfill where no oxygen is present, they anaerobically break down and form methane. Methane gas in the landfill is buoyant and forces its way towards the surface where well-designed landfills can capture roughly 90% of the produced gas. This methane can then either be flared to produce  $CO_2$ , which is a less potent greenhouse gas than methane, or it can be used as a fuel in a engine to produce electricity. However, these systems are typically small and only recover the energy contained in the compostable materials that are buried, leaving the calorific-dense plastics unutilized.

#### 1.2.2 Emerging WTE Technologies for Plastics

#### Solid Recovered Fuels

The solid recovered fuel (SRF) process uses MSW to manufacture a fuel that can be engineered to meet customer specifications, while simplifying shipping and handling requirements compared to mixed MSW<sup>2</sup>. A typical SRF process requires that undesirable materials such as ferrous metal be removed before the feed is mixed and shredded. The feed is then densified into small pellets or cubes that provide a more consistent fuel supply than MSW. SRF can be used directly in a waste-to-energy facility, co-fired with traditional fuels, or used as feedstock to create higher quality fuels through gasification or pyrolysis. SRF facilities processing homogeneous industrial waste have been commercially successful in both the U.S. and internationally. However, the use of SRF with heterogeneous MSW or recycling waste streams as feedstocks is an undeveloped market that that has the potential to offset landfilling and move material up the WM hierarchy. A survey of companies pursuing SRF technology is found in Appendix A.

#### Thermal Processing

Plastic-to-fuel (PTF) is a set of nascent plastics-specific WTE technologies. PTF uses thermal processing techniques such as pyrolysis or gasification to convert scrap plastic to fuel sources such as syngas, oils, or liquid fuels [6]. These products are then upgraded to higher quality fuels that are more compatible with current fuel handling infrastructure designed for natural gas, gasoline, or diesel fuels. The primary difference between gasification and pyrolysis is the amount of energy required and the amount of oxygen included

<sup>&</sup>lt;sup>2</sup>SRF that is engineered and produced to consistently meet customer fuel specifications is sometimes referred to in the industry as "process engineered fuel" or simply "engineered fuel". For the purposes of this report the generic term SRF is used throughout.

in the system. Gasification typically requires more heat and drives the chemical reactions by controlling the amount of oxygen in the system to produce synthesis gas that can then be converted to methane. Pyrolysis operates at lower temperatures and in the absence of oxygen; the products from pyrolysis require more steps to refine into high quality fuels [7].

Pyrolysis systems using non-waste feedstocks have been successfully demonstrated on a commercial scale in Europe and Asia, but are still in the pilot stage in the U.S. Additionally, in the U.S. only pilot scale tests of gasification has been demonstrated. Agilyx, Climax Global Energy, Polyflow, Envion, GEEP, JBI, and Vadxx are a few of the companies with pilot scale pyrolysis facilities in the U.S. and are set out in Appendix A [6, 8]. Feedstocks for gasification technologies could be non-recycled plastics, food waste, biomass waste, or in some instances mixed waste streams. Pyrolysis requires a comparably more pure feedstock of only plastics.

We were unable to identify current commercial production of fuels created from MRF residue using any of the discussed technologies in the U.S. or Europe. The remainder of this report focuses on converting MRF residue into SRF. Investigation of other thermochemical conversion processes is out of the scope of this analysis.

### **1.3 SRF Industry Barriers and Issues**

Currently, a large amount of high-calorific value waste plastic, fiber, and biomass material is landfilled in the U.S. and elsewhere that could potentially be used as an alternative fuel. However, barriers must be overcome in order to economically divert these materials from a landfill to be used as SRF. Technical hurdles such as contamination and the consistency of feedstocks are regional and time-dependent. Economic variables are related to capital costs of waste-to-energy technologies, transportation expenses, tipping fees, and the cost of the fuels being displaced, all of which have geographic variability. Policy barriers also exist and can impede the growth of the solid recovered fuel industry. There are certainly other factors relevant to the waste-to-energy industry, but due to the limitations of scope will not be discussed here.

#### **1.3.1** Technical Barriers and Issues

Technical barriers exist for the introduction of any novel engineering process. For residuederived SRF<sup>3</sup>, there are several technical issues associated with consistency and predictability of feedstock. One cause of variability in residue is that incoming recycling streams to

<sup>&</sup>lt;sup>3</sup>Though SRF derived from MRF residue is the focus of this report, it is important to consider that SRF can be made from a variety of feedstocks including non-residual plastics.

MRFs differ regionally and seasonally. Regional variation in demographics, community participation, laws, and regulations ensure that no two MRFs will have identical incoming MSW streams. Seasonal changes can also change MRF feedstocks, resulting in variable moisture contents and MSW production rates. Even with identical feedstocks, MRFs are not certain to produce similar residue streams. Regional and time-dependent variation in commodity prices drive MRF operators to prioritize sorting of profitable materials, potentially changing their sort process to accommodate the market. In addition, different MRFs use different sorting equipment and techniques, which can cause varying quantity and quality of residue streams.

Impurities such as inert material, ferrous metal, PVC, and food scraps are detrimental to the SRF production process. Ferrous metal, in addition to being inert, can cause equipment damage and fires in the SRF production facility. PVC is known to produce chlorine when combusted, a chemical that is troublesome for the cement production process and can damage boilers in power plants, among other problems. Food attracts rodents and insects, complicating storage and handling logistics. Overcoming these technical hurdles typically requires more sophisticated and robust identification and sorting methods, at the expense of cost. Blending of residue sources can also alleviate some issues associated with minor contamination and to counteract variations in residue stream content.

#### **1.3.2** Cost Barriers and Issues

Several drivers of increased costs are synonymous with technical hurdles: to increase sorting and identification efficiency, additional labor or capital expenses must be incurred. Other factors including landfill costs, facility locations, time dependent fuel costs, and capital costs of new facilities are less directly related to technological barriers.

Landfilling costs, or tipping fees, are the fees that MRFs pay to dispose of their residue. It is a typical SRF production facility business model to take the tipping fee that the waste facility would normally pay to a landfill as a charge for accepting the material, generating a small stream of revenue. Therefore in areas where tipping fees are low, SRF facilities suffer by having a low cap on what they can charge as a disposal fee, cutting revenue. Distance between facility locations can increase costs associated with transportation, both based on mode of transportation available and distances traveled. Capital facility costs can be sizable and need to be considered closely, especially in light of the immaturity of the field and irregularity of residue supply.

Cost of conventional fuels is a clear barrier for residue-derived SRF. Coal, the fossil fuel studied as an alternative for this research, has a variable and time-dependent cost. When coal prices are high, the market for residue-derived SRF will be bolstered, while the opposite is true when coal prices are low. Despite frequent price fluctuations, coal prices have on

average risen in the last decade, implying a favorable coal-displacement market for SRF in the future.

#### **1.3.3** Policy and Regulation Considerations

There are a host of important legal issues related to using non-recycled post-consumer plastics as a fuel source. The legal handling of non-recycled post-consumer plastics has implications in the transportation, processing, storage, and combustion of the material. Furthermore, the rules that apply to the material can change from one step in the process to another as well as one state to another. Understanding the intricacies and implications of classification and federal vs. local policies and permitting is important for those interested in using non-recycled plastics as a fuel source.

One of the main issues is the classification of the non-recycled, post-consumer plastic itself. Classifying a material is an important process that has far-reaching implications on handling, processing, trading, manufacturing, transporting, using as fuel, or disposing of the material. For example, a material classified as hazardous has more stringent storage and disposal requirements than non-hazardous material. These distinctions can sometimes be subtle and non-obvious, with further complications arising from state and local laws. For example, some substances classified as hazardous waste in an industrial setting could be exempted from the classification when contained in municipal solid waste. These distinctions are also important when discussing emissions limits. For example, plants burning fuel classified as solid waste must meet Clean Air Act (CAA) section 129 emissions requirements while non-solid waste fuels must meet CAA section 112 requirements.

Another policy issue that has a large impact on the SRF industry is the classification of SRF as a renewable or alternative fuel. Many states are adopting policies that require certain portions of the electricity produced or energy consumed to come from preferred sources. These policies are typically called Renewable Portfolio Standards (RPS) but can have variations in the actual naming and for this paper will be referred to as simply RPS. Some states have not implemented formal standards but have policies that outline goals similarly structured to an RPS. Figure 1.4 shows the 30 states (plus Washington D.C.) that have adopted an RPS and the seven that have Renewable Portfolio Goals. Of the areas that have RPS policies, 14 of them include the use of MSW as a preferred resource (45%). Four of the seven areas with Renewable Portfolio Goals classify MSW as a preferable resource. Looking deeper into the RPS policies, some of the states (like Utah and Maine) initially did not include MSW but amended the bills to include MSW a few years later. While the overall picture of state policies suggests some state support of SRF technology, specifics vary greatly. For example, some states such as Illinois specifically reject any MSW-derived resource while others, such as New Mexico, Montana, and Virginia have general incentive policies in place that promote MSW as a renewable resource but MSW is not mentioned

as directly as it could be in their RPSs [9, 10].

Inspecting the state policies further for SRF-specific information reveals that only a few have addressed emerging waste-to-energy technologies, although none seem to address the full spectrum. California, for example, includes MSW waste-to-energy as an eligible technology but with the condition that it is not directly combusted. This classification is interesting from a SRF standpoint because it does not address whether the SRF processing steps might cause SRF to be classified differently than MSW. Missouri classifies pyrolysis and thermal depolymerization of waste materials as renewable energy production and provided tax incentives for traditional MSW facilities. Wisconsin, the only state to address SRF technology specifically, deems gasification and densified fuel pellets made from waste material that does not include garbage and contains less than 30% fixed carbon as eligible technologies in its RPS [11].

The current diversity of state policies is a disincentive for companies to invest in developing WTE conversion technologies. The lack of policies specifically addressing emerging technologies suggests an information gap between technology developers and policy makers. Fortunately, trends in updating RPSs for the inclusion of WTE facilities and alternative conversion processes as eligible technologies will lead to a better business environment for companies pursuing energy recovery from solid waste.



Figure 1.4: Most states have either a Renewable Portfolio Standard (RPS) or Goal (RPG). In all 14 of the 31 states with an RPS and 5 of the 7 with a RPG include MSW as an eligible resource [9, 10].

## 2 Material Recovery Facility

The role of a Material Recovery Facility (MRF) in a single-stream recycling system is to separate incoming mixed recyclable materials into individual streams of homogeneous material that can then be sent to end markets. Single-stream recycling refers to the system of recycling collection where all fiber, plastic, glass, and metal are collected in single containers yielding a commingled mixture of recyclables. As of 2009 there were 578 MRFs in the U.S. sorting single-stream recyclables, up from 480 facilities in 2000 [2].

Generally single-stream recycling programs are implemented alongside traditional MSW collection services, with distinct receptacles for recyclables and wastes. Once collected by trucks, the recyclables are taken from the consumer to an MRF, which separates individual components into various homogeneous material streams that are then baled and sold in the global recycling market [12]. Many sorting technologies are utilized depending on the application and include magnetic separators, eddy current separators, air-classifiers, optical sorters, and human sorting. After sorting valuable commodities from the stream, a certain amount of residue is created that has no market value. This residue can contain anything from PVC (which has no existing market), paper with food contamination (which reduces the value of the paper bales), or plastic PET bottles that get missed in the sorting (it is too expensive for a human labor to hand-pick each PET bottle that is missed by a mechanical sorter).

Moving to single-stream collection has been shown to increase the recycling rates of consumers with the drawbacks of increased processing costs and contamination that decreases the quality of recyclable goods and increases residue output. The move to single-stream recycling reduces the costs associated with the diversity and number of trucks needed to collect source-separated recycling, but increases the capital costs because of the need for MRFs to separate the material [13]. This chapter tracks some of those MRF-specific issues, as described below.

## 2.1 Canusa Hershman Material Recovery Facility

As part of this study, an on-site visit to Canusa Hershman Recycling Company's singlestream MRF in Manassas, VA was conducted on February 19, 2011. The Canusa MRF participates in the project by providing information about its operation and site specific recycling data, which are believed to be representative of a typical U.S. single-stream recovery facility.

### 2.2 Incoming Material

A general collection distance for most MRFs is estimated at 20-30 miles for curb collection and up to 70 miles for bulk transfer shipments<sup>1</sup>. The Canusa Hershman MRF processes about 17,000 tons of incoming material per month from a 15 mile radius surrounding the facility and approximately 40 miles for bulk material transfers. The facility pays its suppliers for materials from a service area that covers around 4 million people within the Baltimore/Washington D.C./Virginia market [12]. The average composition of incoming material between September 2010 and February 2011 is shown in Table 2.1. However, recycling stream composition is expected to vary both by location and season.

Table 2.1: The average composition of the Canusa Hershman MRF incoming material. The primary constituents are paper and glass. Residue includes contaminated fiber, organics, and recyclables that are missed during sorting [12].

Commodity	% by weight
Newspaper, other fiber	55.5
Corrugated	8.3
Glass	19.9
Aluminum Cans	0.6
Steel Cans	1.7
PET (#1)	2.6
HDPE Natural $(#2)$	0.7
HDPE Colored $(#2)$	0.9
Residue	9.8
	100.00

### 2.3 Material Separation

The incoming material is dumped, loaded into the material recovery system, separated, stored, baled, and finally sold and transported. The material recovery system is a continuous process that operates 20 hours per day five days a week, 10 hours on Saturdays, and is not operated on Sunday. The material recovery system consists of 30 manual sorters,

<sup>&</sup>lt;sup>1</sup>Bulk transfer shipments consist of material that had been collected by regional collection vehicles and consolidated at transfer stations for shipment to a landfill or MRF.

#### 2.3. MATERIAL SEPARATION

2 wheel loaders, 105 electric motors, 3 optical scanners, several separation screens, a vacuum system, a magnetic sorter, 2 balers (one variable and one fixed), and an eddy current sorter. The capital cost of this facility was roughly \$20 million broken up between the sorting process line (\$15 million) and other equipment such as the building, rolling stock, trucks, etc. (\$5 million). The throughput of the MRF is about 17,000 tons per month, or about 50 tons per hour of operation. The capacity could be increased by operating more hours or at an increased material flow rate. However the increased flow rate would cause a decrease in separation accuracy and possibly increase operating costs, primarily due to a need for additional manual sorters. The process flow diagram of the MRF is shown in Figure 2.1.



Figure 2.1: The Canusa Hershman process diagram shows the flow of material through the material recovery system [12]. (OCC Sort Screen: Old corrugated cardboard sort screen. Eddy Current: Separates aluminum from scrap using electromagnetic fields.)

### 2.4 Commodity Markets

The material recovery system at the Canusa Hershman MRF separates the incoming material into homogeneous material streams and stores them into respective bunkers prior to baling. MRF operators select which materials to separate from the incoming material based on the market value of each commodity. There are established markets for the following commodities (in decreasing order of value): aluminum, natural HDPE (#2), PET (#1), pigmented HDPE (#2), steel, corrugated cardboard, and old newspaper fiber. The MRF disposes of glass and residue at a cost [12]. The market prices for different commodities are constantly changing and are based on many outside factors.

This research focuses mainly on the MRF residue with the intent of converting it to SRF and using it as an alternative fuel at cement kilns. As seen in Figure 2.1 there are two residue streams. The two residue streams are typically combined when baled, but they can potentially be baled separately in order to have some control over the residue material used to create SRF. The average composition of the residue streams is currently unknown because there has been no need to determine it [12].

## 3 Fuel Processing Facility

The role of a fuel processing facility is to upgrade the combustion characteristics of waste materials through various processing techniques. Usual processing includes material sorting, shredding, and densifying. Additional processing steps are frequently included depending on facility capabilities and client needs. The steps and relevant issues of SRF processing are described in this chapter.

### 3.1 Balcones Resources Fuel Processing Facility

Balcones Resources owns a solid recovered fuel (SRF) manufacturing facility in Little Rock, Arkansas named Balcones Fuel Technology (BFT). BFT participated in the project by providing expertise in the SRF production field, as well as compressing and pelletizing MRF residue that was used in the cement kiln test burn. A site visit was conducted to gain detailed process data on April 4th, 2011.

### 3.2 Facility Operations

Balcones Fuel Technology charges companies a tipping fee (about 35/ton at the time of the site visit) to take their industrial waste, which amounts to less than 5% of total revenue. This waste is typically a consistent and predictable composition of manufacturing waste products (Figure 3.1). BFT then blends the various waste streams into specific plastic-to-fiber ratios depending on waste availability, process requirements, and customer needs. The blended waste is shredded before being fed at a controlled rate into two parallel fuel extruders with adjustable dies that control the extrusion dimensions, seen in Figures 3.2 – 3.4. The fuel extrusion process is primarily accomplished using pressure, though heat can be added using resistance heating elements. Once extruded, the fuel pellets fall onto a conveyor and are immediately stored in truck containers ready for delivery.

## 3.3 Manufacturing Variables and Challenges

There are numerous process challenges regarding unwanted materials being present in the SRF. Contaminants could cause undesirable emissions, metal materials can damage

#### 3.3. MANUFACTURING VARIABLES AND CHALLENGES



Figure 3.1: Post-industrial waste streams are mixed at BFT and used as feed for the solid recovered fuels.



Figure 3.2: The raw fuel feed is conveyed into a large container (beige container, top right) that is attached to the loading equipment (beige hoppers on either side of the container) that controls the feed rate into two parallel fuel extruders (circular red casings on the left and right).



Figure 3.3: The fuel extruder compresses the raw material before forcing it out radially through adjustable dies. Heat caused by compression and friction can fuse the material, and additional process heat can be added if needed. Shown here are various lengths of SRF being extruded through 1.25" by 1.25" dies with no heat added.



Figure 3.4: This figure is a close up shot of SRF being extruded out the bottom of the fuel extrusion equipment and onto a conveyor belt. The SRF either breaks apart in sections from the weight of the fuel itself or from being pulled along by the conveyor belt.

processing equipment, and food wastes can attract rodents if left in the facility for too long. Therefore, adequate sorting of the residue before it is processed into SRF is an important consideration for any SRF facility. For the BFT facility, sorting of incoming raw materials can be done on-site in some instances. However, there is limited on-site sorting space and sorting is done exclusively by hand. Therefore, any additional sorting is a time consuming and expensive operation [14].

One of the most important steps of SRF production is the shredding process. Often considered the bottleneck of the process, the shredding process poses many compositionbased challenges. Any large metallic objects that are fed to the shredders pose significant threats to the facility, including dulling and breaking of the shredder blades or causing fires. Small metallic objects (sizes smaller than a D-size battery) and aluminum cans and foil are not expected to cause significant problems. Large rigid plastics will be broken into large shards in the shredder. BFT is not affected by the large plastic shards, but they do not mix easily and are significantly larger and less malleable than other components, yielding a less consistent quality SRF. If BFT wants to produce a finer shredded feedstock, the size of the screen on the shredder can be reduced, though at the expense of energy costs, processing time, and increased equipment wear [14].

Water, heat, and additives are the three main variables that can be adjusted to increase the cohesion of the SRF. However, adding water to the material increases the production energy requirements and decreases the heat content of the SRF while heating the extrusion die increases electricity consumption and is accompanied by the threat of SRF combustion while being extruded [14].

## 3.4 Preliminary Energy Intensity and Cost of SRF

Each MRF residue stream will be different and therefore no exact answers can be given *a priori* about the quality of the SRF, the ease of the fuel making process, or the costs and energy associated with producing the SRF until the test material arrives and is processed. However, based on historic data provided during the BFT site visit, energy intensity and cost of SRF production has been estimated.

Based on an estimate of energy consumption of 215 - 320 MWh/month, monthly energy costs were calculated to be \$15,000 - \$16,000 /month at an electricity rate of 5 - 7 ¢/kWh. At a production rate of 3,000 tons per month, the energy intensity of producing SRF is estimated to be 72 - 106 kWh of electricity per ton of SRF produced while the energy cost is about \$5/ton of SRF. While these data represent estimates of a different fuel source and production process, it provides insight into the relative energy intensity and production cost of turning raw waste material into usable fuels using BFT's production process [14]. In addition to fuel costs, transportation, facility O&M, and capital recovery must be considered when calculating a total SRF production energy intensity and cost.

## 4 Cement Kiln

The main steps in the cement manufacturing process are the raw materials extraction, the precalcination of the raw materials (limestone, clay, sand) in the precalciner tower, and the clinking of the raw material in the kiln. The clinker is then cooled and mixed with calcium sulfate (typically gypsum) to achieve the desired setting qualities in the finished Portland cement product. Large energy inputs are required in the precalciner tower and at the end of the kiln. Figure 4.1 shows the cement manufacturing process diagram with emphasis on the fuel and material flows and the range of fuel types used. The precalciner tower energy requirements are the focus of this project because of the ability to use SRF more easily than in the kiln where precise control of the fuel is required [15].





### 4.1 TXI Hunter Cement Plant

The TXI Hunter Cement Plant, located in New Braunfels, TX, was built in the 1980s and currently has a cement production capacity of just less than 1 million tons per year. The TXI Hunter Cement Plant uses a dry kiln and a precalciner tower in its cement making process. TXI currently has over 100 employees operating the existing plant, which has an expected life of over 50 years [15]. The Hunter Cement plant's role in this project is to perform test burns of the SRF in the precalciner tower and to aid in information and data gathering. Emissions and process data were gathered during the test burn for use in the overall analysis. A site visit was conducted on February 26th, 2011.

### 4.2 Cement Kiln Fuel

There are two main energy input locations into the cement kiln (Figure 4.1). The *primary fuel* injected into the base of the cement kiln is required to be very stable and predictable from an energy content perspective in order to maintain a precise flame shape at a temperature around 2700 degrees Fahrenheit. The *secondary fuel* burned in the precalciner tower has less rigorous fuel specifications. Natural gas, petroleum coke, coal, chipped tires, wood chips, and nut shells have all been used as secondary fuels at this location in prior test burns. Multiple secondary fuels can be supplied to the precalciner simultaneously through an array of fuel injection methods. There are four fuel injection systems in the precalciner tower for the four categories of fuel: liquid fuels, gas fuels, pulverized fuels (coal and petroleum coke), and solid fuels (alternative fuels). The solid fuel feed system used to supply the SRF can achieve a feed rate of over 5 tons per hour [15].

#### 4.2.1 Energy Requirements

In the current line over 50% of the energy requirement is supplied by secondary fuel(s). The entire kiln system requires over 3 MMBtu per ton of cement. This energy requirement is met with a range of fuels depending on the current prices. The TXI plant has used coal (typically from Colorado for desired fuel specifications), natural gas, petroleum coke (shipped from Wyoming or other landlocked coke producers), tire chips, and biomass waste. At a heating value of 12,000 Btu per pound of SRF (an estimate equivalent to coal, see Section 5.4.2), a minimum flow rate of 11 tons of SRF per hour would be required to meet all of the energy needs of the precalciner tower. Because the solid fuel feed system as currently configured peaks around 5 tons per hour, SRF could only meet 45% of the precalciner energy needs during test burns unless the feed rate can be increased or additional equipment is added [15].

Alternative fuels such as tire chips, wood scraps, and nut shells are pursued by TXI for a variety of reasons. First, alternative fuels can sometimes be obtained at a lower price than coal, natural gas, or petroleum coke. Also, the TXI plant is regulated by a Texas Commission on Environmental Quality permit that restricts the kiln from obtaining more than 50% of its energy from petroleum coke [16]. Thus, after the 50% energy limit is reached with petroleum coke, alternative fuels only have to compete financially with coal and natural gas.

#### 4.2.2 Fuel Considerations

TXI is concerned with a fuel's elemental composition, physical characteristics, and energy content when determining if the fuel is a viable energy source. Making quality cement is the first priority of TXI and therefore the chemistry of the cement making process must be carefully monitored and considered. Therefore, predictable fuel specifications are essential. Chemical composition of the fuel is important because fuels are combusted within the cement making process, which means that the pre- and post-combustion constituents of the fuel can react chemically with the cement raw materials. Two elements that are of particular concern are sulfur and chlorine.

Excessive chlorine in the process can cause problems by increasing the viscosity of the material flow or by condensing and collecting on the tower walls. Chlorine restrictions due to process requirements keeps chlorine emissions below threshold levels that would trigger additional permitting. The cement making process has a predictable sulfur cycle that begins with the release of sulfur from the fuels and raw materials, followed by partial absorption by limestone. In order to produce consistent quality cement, the sulfur cycle within the cement process is regulated and balanced by plant operators. Because of the sulfur concerns, low-sulfur fuels would cause the least amount of process-related issues and could potentially be used at a higher rate than higher-sulfur fuels. Additionally, excess sulfur and chlorine can cause precipitate formation that can lead to clogging of internal systems in the kiln [15]. In addition to the chlorine and sulfur content, TXI is also interested in the metallic, potassium, and sodium content, as each can affect the cement making chemical process.

To ensure that the SRF would meet the fuel specification shown in Table 4.1, elemental testing was conducted and the results were sent to TXI before any fuel shipments were scheduled. The TXI fuel specifications are primarily to be used as a guideline and not definitive criteria because the amount of contaminant within the fuel will impact the operation based on both the flow rate of the fuel and the energy content of the fuel. Therefore, fuels that are out of spec for any one criterion can still be used in the kiln at reduced feed rates [15].

In addition to the elemental fuel specifications, TXI also has fuel preferences related to the

<b>TXI Hunter Cement Plant - Fuel Specifications</b>					
Heat of Combustion	Above	8,000	Btu/lb		
(prefer)		Above	$12,\!000$	Btu/lb	
Sulfur		Below	2	%	
Chlorine		Below	500	ppm	
Moisture		Below	5	%	
Sodium + Potassium		Below	1	%	
METALS:	METALS:				
Antimony	$\operatorname{Sb}$	Below	100	ppm	
Arsenic	As	Below	20	ppm	
Barium	Ba	Below	1,000	ppm	
Beryllium	Be	Below	20	ppm	
Cadmium	Cd	Below	5	ppm	
Chromium	$\operatorname{Cr}$	Below	1,000	ppm	
Cobalt	Co	Below	10	ppm	
Copper	Cu	Below	50	ppm	
Lead	Pb	Below	100	ppm	
Mercury	Hg	Below	5	ppm	
Nickel	Ni	Below	10	ppm	
Selenium	Se	Below	50	ppm	
Silver	Ag	Below	50	ppm	
Thallium	Tl	Below	100	ppm	
Vanadium	V	Below	1,000	ppm	
Zinc	Zn	Below	1,000	ppm	

Table 4.1: TXI's fuel specifications for SRF and other alternative fuels [15].

material handling portion of the test burn. Fuel handling issues that concern TXI are 1) jamming or clogging of hoppers due to inadequate rigidity of the fuel, 2) inability of the fuel to be transported via conveyor belts due to low density, and 3) long burn times or incomplete combustion of the fuel due to large diameter pellets. Qualitatively, SRF pellets that are more rigid than soft will be easier on the fuel handling equipment and are less likely to cause issues with higher feed rates. However, rigidity must be balanced with a pellet that is not so dense that it cannot be cut or burned quickly. TXI has stated that for its process, pellets with a diameter of 1/2 inch and less than 6 inches long would be ideal to ensure the pellets burn completely and does not collect on ledges within the precalciner or mix with the raw materials in the kiln [15].

Energy content of the fuels is important because it impacts feed rate. Lower energy contents would require a higher feed rate to supply the same amount of energy, so higher energy content SRF would facilitate higher fossil fuel displacement. It is useful to quantify the
chemical composition of the fuel before combustion not only as a percent per mass or per volume, but also to apply a simple conversion to quantify the chemical compositions as a mass per Btu content. Therefore, a SRF with higher energy content but with the same amount of undesirable impurities (such as chlorine or sulfur) would have a lower contaminant per energy ratio. For TXI, the SRF must supply consistent and predictable energy and chemistry to the process. TXI requires a minimum energy content variation from load to load of  $\pm 250$  Btu/lb with a seasonal variance of  $\pm 1000$  Btu/lb acceptable as long as it is predictable [15].

#### 4.2.3 Emissions Monitoring

The Hunter Cement Plant has an emissions permit (Appendix B) issued by the Texas Commission on Environmental Quality, which adheres to EPA guidelines for the performance of new stationary sources. The permit limits NO<sub>X</sub> production, for a 30-day rolling average, of 1.96 lbs NO<sub>X</sub>/ton of clinker from April 1 through October 31, and 390 lbs NO<sub>X</sub> per hour from November 1 through March 31. SO<sub>2</sub> emissions are regulated under the current permit and will also be restricted on a planned second kiln line at the facility. The restriction applied to the second line, a rate of 0.08 lbs SO<sub>2</sub>/ton of clinker over a twelve-month rolling average, will be used as a reference value in this report [16].

# 5 SRF Experimentation

# 5.1 Initial Experimentation Plan

The initial experimental approach established was to source MRF residue from a partnering MRF and ship it to the Balcones Fuel Technology SRF production facility to be processed into SRF. The next phase of the experimentation was to test and ensure the SRF met fuel specifications provided by TXI. After verification that the fuel meets the required specifications, it would then be shipped to the TXI Hunter Cement Plant for the test burn. An increasing feed rate approach was planned, starting at a 1 ton per hour feed rate for the first 24 hours. Following a successful first day of operation, TXI would approve an increase in flow rate to 2 tons per hour for another 24 hours. Initially, TXI suggested continuing to increase the flow rate up to 5 tons per hour over a 5 day span which would consume 360 tons of SRF if successful. During the test burn TXI would continuously monitor NO<sub>X</sub> and SO<sub>2</sub> emissions, the amount of various fuels being used, and internal measurements indicating combustion characteristics. The test was intended to determine the feasibility of using SRF as an alternative fuel at cement kilns, provide insight into changes in cement kiln emissions, and highlight any process and logistic issues for consideration.

# 5.2 SRF Feedstock Issues

The first-attempt nature of this experiment led to some unforeseen sourcing issues which required modifications to the original experimental plan. Material for the actual burn came from the fourth MRF that was contacted as a potential partner. Aside from business related issues out of the MRF's immediate control, the primary issue that arose while sourcing SRF feedstocks was metal contamination. Three possible changes that could address this issue are: 1) producing multiple residue streams that are separated, with one stream being largely metal free, 2) removing metal contaminants from the residue stream before it is bailed, and 3) adding pre-sort capabilities to the SRF production process. We conclude that some of these sourcing issues are a sign of the industry's relative immaturity rather than being an inherent or intractable hurdle for SRF production. We anticipate that as the sector grows, these supply chain issues are likely to sort themselves out.

# 5.3 Experiment Execution

A variety of events led to diversions from the initial experimentation plan. These diversions were valuable opportunities to understand and investigate problems along the supply chain involved in producing SRF for use at cement kilns. In addition to SRF feedstock sourcing issues, the amount of SRF used for the experiment was scaled back from 350 tons to 130 tons in response to logistics, costs, and experimental requirements. The materials used for production of the SRF consisted of a blend of 75 tons of MRF residue and 55 tons of industrial waste, each estimated to be a 60%/40% mixture of plastics and paper scraps with the plastic consisting of a polyethylene and polypropylene blend. The paper component of the industrial waste was a mixture of cardboard and fluff pulp. The reduction in total SRF production led to reduced burn rates at the TXI Hunter Cement Plant. The final experiment ran at a 1 ton per hour feed rate for the first 24 hours with no complications. The feed rate was then increased to 2 tons per hour for the following 48 hours.

# 5.4 Experimental Results

## 5.4.1 Elemental Analysis of MRF Residue

An elemental analysis was conducted on samples of residue from the second MRF. Because of sourcing issues related to volume availability, this residue was not used for the test burn. However, the samples tested are considered representative of common residue composition. The tests were performed by inductively coupled plasma analysis. Three composite samples were tested that contained a thoroughly mixed representation of all refuse constituents sent for testing, named Composite Samples 1, 2 and 3 in Table 5.1. These three composite samples had no problematic results for any of the elements tested. Samples of each paper material contained in the entire sample aggregate, labeled All Paper, were taken separately and analyzed with no problematic results for any test elements. Finally, samples of each plastic material contained within the aggregate sampling material were combined and tested, labeled All Plastic. The exclusively plastic sample analysis showed high cadmium (Cd) content. The high cadmium content came from a thick plastic bag contained within the aggregate sample material that was a thick PVC film bag, revealing the heterogeneous nature of MRF residue

#### 5.4. EXPERIMENTAL RESULTS

Flomont	Target	Comp	Composite Samples			e Samples
Liement	Target	1	2	3	All Paper	All Plastic
Sb	<100 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
As	$<\!20 \text{ ppm}$	<lod< td=""><td><lod< td=""><td>17.6783</td><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td>17.6783</td><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	17.6783	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Ba	<1000 ppm	10.3926	<lod< td=""><td>8.0427</td><td>15.4294</td><td>176.203</td></lod<>	8.0427	15.4294	176.203
Cd	<5  ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td>113.441</td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td>113.441</td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td>113.441</td></lod<></td></lod<>	<lod< td=""><td>113.441</td></lod<>	113.441
Cr	<1000 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Со	<10 ppm	1.434	2.7834	3.3332	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Cu	< 50  ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Pb	<100 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Hg	<5  ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Ni	<10 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Se	< 50  ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Ag	$<\!50 \text{ ppm}$	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Tl	<100 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
V	<1000 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>
Zn	<1000 ppm	15.0763	5.855	26.2955	17.3396	64.3867
Na	<1%	1111.26	1114.48	1214.05	1009.92	159.275
К	<1%	218.137	281.011	250.553	198.669	133.662

Table 5.1: MRF residue samples elemental analysis shows only one issue of high amounts of cadmium in the All Plastic sample. LOD is level of detection.

The chlorine and sulfur content of the second MRF's residue was tested separately by Intertek. Two samples taken from the heterogeneous mixture of paper and plastic were sent to Intertek, where they were then separated into four smaller (less than 20 mg) samples to be tested. The ASTM D7359 testing method was used for testing the total chlorine and sulfur in aromatic hydrocarbons and their mixtures by oxidative pyrohydrolytic combustion followed by ion chromatography detection.

Table 5.2 contains a summary of results from chlorine and sulfur testing in 4 pieces of 2 distinct samples, with the full report in Appendix C. Even within a single sample, the chlorine and sulfur content varied widely. For example, tests on different parts of Sample 2 showed anywhere between 158 and 1,690 mg of Chlorine per kg of material. These large variations highlight the need for thorough and representative testing of SRF to truly understand the overall composition and to apply regulations and certifications for fuels similar to SRF.

Table 5.2: Chlorine and sulfur analysis of MRF residue samples contains a large variation in results depending on the sample tested. This report highlights the heterogeneous nature of the residue and how a single contaminant can cause spikes in elemental analyses. For reference, TXI's recommended fuel specifications are <500 mg/kg for Chlorine and <20,000 mg/kg for Sulfur.

Sample ID	Number	Sulfur (mg/kg)	Chlorine (mg/kg)
	1	72.0	216
Sample 1	2	54.8	231
	3	70.6	138
	4	76.0	182
	1	88.3	158
Sample 2	2	108	752
	3	166	1690
	4	141	446

## 5.4.2 Analysis of SRF Material Tested

The samples of SRF sent for testing were taken to represent the diversity of material contained, and not as a representative sample of the entire SRF. More extensive testing on SRF would need to be conducted in order to accurately derive average compositions. Additionally, because the composition of MRF residue (and therefore the SRF) is transient, repeated sampling of material would need to be performed if the SRF was used over an extended period of time unless the residue material was guaranteed to be within certain composition ranges. Figures 5.1 and 5.2 show the material in bulk form that was sent to the testing facility. Figure 5.3 shows separated samples 1 through 4 that were actually tested.



Figure 5.1: The photo of the final SRF material that was analyzed that shows the heterogeneous nature of SRF (Photo credit: Total Petrochemicals & Refining USA, Inc.).



Figure 5.2: This photo is a close up of the final SRF material sent from TXI to be tested (Photo credit: Total Petrochemicals & Refining USA, Inc.).

The SRF had a low sulfur content of 0.07 wt %, or only 0.058 pounds per MMBtu. The sulfur content is low when compared to coal, which varies depending on if the coal is classified as low sulfur (less than 0.6 lb/MMBtu), medium sulfur (0.61 to 1.67 lb/MMBtu), or high sulfur (greater than 1.68 lb/MMBtu). A comparison of key fuel specifications for several common alternative kiln fuels is presented in Table 5.4. While the results of the tests in Table 5.3 are not necessarily a representation of the SRF as a whole, the test results agree with previous studies regarding SRF and with estimates based on typical contents of MRF residue [17, 15, 18].



Figure 5.3: Four samples were taken from the SRF material and tested individually (Photo credit: Total Petrochemicals & Refining USA, Inc.).

Test Method	Parameter	Units	As Received	Dry Basis
D 3302, 7582	Total Moisture	$\%  \mathrm{wt}$	4.27	-
D 5865	Calorific Value	Btu/lb (gross)	12,153	$12,\!695$
D 7582	Ash	$\%  \mathrm{wt}$	4.81	5.02
D 4239	Sulfur	$\%  \mathrm{wt}$	0.07	0.07
D 7359	Chlorine	$\%  \mathrm{wt}$	0.05	0.05

Table 5.3: Summary of SRF sample analysis [18, 19].

Table 5.4: Comparison of key specifications of several alternative kiln fuels [20, 21, 22, 23, 24, 25].

Specification	Units	Sub-bit.	As-Tested	Petroleum	Wood	Tire
		Coal	$\mathbf{SRF}$	Coke		Chips
LHV	Btu/lb	11,300	12,150	14,600	$7,\!300$	14,000
Ash	wt. %	4.04	4.81	0.48	2.82	1.61
Sulfur	wt. %	0.25	0.07	4.00	0.07	2.25
Chlorine	wt. %	0.04	0.05	0.00	0.09	0.50

Table 5.5 shows the final SRF elemental analysis conducted by Total Petrochemicals & Refining USA, Inc. Sample 2 in Table 5.5 contained a very high level of antimony (Sb) (possibly flame retardant material). The material containing antimony in the sample was visually estimated to make up much less than 1% of the overall SRF material. However, this analysis is an example of how thorough and proper testing needs to be done on heterogeneous solid fuels because small components can skew results if only a few samples are taken or testing methodologies are not rigorous. Such considerations are important when discussing potential future certifications for solid recovered fuels.

# 5.4. EXPERIMENTAL RESULTS

Table 5.5: The final SRF product elemental analysis had diverse results for the different samples, highlighting the difficulty of analyzing a heterogeneous solid fuel like SRF. LOD is level of detection.

Flowert	Townst	Extruded Waste Plastic (all units p				
Liement	Target	1	2	3	4	
Sb	<100 ppm	<lod< td=""><td><math>25,\!223</math></td><td>6</td><td><lod< td=""></lod<></td></lod<>	$25,\!223$	6	<lod< td=""></lod<>	
As	$<\!20 \text{ ppm}$	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Ba	<1000 ppm	19	<lod< td=""><td><lod< td=""><td>104</td></lod<></td></lod<>	<lod< td=""><td>104</td></lod<>	104	
Be	<20 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Cd	<5  ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Cr	<1000 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td>23</td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td>23</td></lod<></td></lod<>	<lod< td=""><td>23</td></lod<>	23	
Со	<10 ppm	<lod< td=""><td><lod< td=""><td>4</td><td>8</td></lod<></td></lod<>	<lod< td=""><td>4</td><td>8</td></lod<>	4	8	
Cu	<50 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Pb	<100 ppm	33	14	<lod< td=""><td>12</td></lod<>	12	
Hg	<5  ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Ni	<10 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Se	$<\!50 \text{ ppm}$	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Ag	$<\!50 \text{ ppm}$	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Tl	<100 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
V	<1000 ppm	<lod< td=""><td><lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Zn	<1000 ppm	48	9	28	208	
Na	<1%	5,880	32	240	3,099	
K	<1%	2,278	16	103	92	
Other Ele	ements Foun	d				
Al	None	1,995	266	183	$7,\!819$	
Ca	None	1,993	$3,\!677$	12,623	$23,\!867$	
Fe	None	1,189	30	185	225	
Li	None	6	5	2	4	
Mg	None	938	171	403	292	
Mn	None	29	<lod< td=""><td><lod< td=""><td><lod< td=""></lod<></td></lod<></td></lod<>	<lod< td=""><td><lod< td=""></lod<></td></lod<>	<lod< td=""></lod<>	
Р	None	1,262	42	52	213	
Si	None	562	189	66	<lod< td=""></lod<>	
Sn	None	<lod< td=""><td>52</td><td>118</td><td>159</td></lod<>	52	118	159	
Sr	None	8	<lod< td=""><td>8</td><td>22</td></lod<>	8	22	
Ti	None	669	171	2,952	5.847	

# 5.5 Cement Kiln SRF Test Burn

The final step in the process was to use the 130 tons of SRF in a live three day test burn at the TXI Hunter Cement Plant. The material was delivered successfully and trial scoops were successfully fed through the system as a logistical test in preparation for the full test burn. Figure 5.4 shows a hand sample of the SRF used at TXI. The full test burn commenced at 1 ton of SRF/hour being fed to the preheater system. The test began at 9am CST on November 14th, 2011.



Figure 5.4: This photo is of a hand sample of SRF taken from the on-site pile of 130 tons of SRF used for the test burn (Photo credit: Derek Thorington, TXI).

TXI reported that the initial SRF loads were around 80% pellets and 20% fluff while subsequent shipments were of increasing fluff amounts, with the final load (of 6 shipments) being around 10% pelletized. The SRF pellet size was small and not tightly packed, both of which are advantageous for combustion purposes. TXI found that the material properties of the SRF delivered for the test burn were adequate for burn rates up to about 4 to 5 tons per hour.

A logistical problem that was encountered at TXI was bridging, or clogging, in the feed bin. SRF material was getting stuck at the output neck of the feed bin causing material backup and inconsistent material feed rates. This problem was ameliorated by staffing an employee at the feed bin who could clear the bridging and keep the material flowing. This solution is not likely economical for a fully developed SRF system, but the problem could be solved technically by designing feed bins and feeders appropriate for SRF material. The TXI Hunter Cement Plant was burning coal and natural gas at the main burner of the kiln with natural gas and some liquid fuels in the precalciner tower. The plant was operating at roughly 80% capacity during the test, which provided additional flexibility for various logistical and process related systems that might not otherwise have been available. Such systems include fan power and raw material feed rate controls.

Plant operation data was supplied for the entire testing period as well as the day before the test began to provide baseline measurements. The plant was running using about 5 tons of coal per hour (around 100 MMBtu/hour) at the main burner, which accounts for roughly 88 - 90% of the main burner and 30 - 32% of the total energy requirements, respectively. Natural gas at around 11 - 14 KCF/hour<sup>1</sup> (around 11.5 - 14.4 MMBtu/hour) accounted for the remainder of the energy requirement for the main burner. The precalciner tower energy requirement was met by a combination of natural gas and liquid fuels. The liquid fuels were adjusted over the period of the testing, starting at 7 GPM<sup>2</sup> (roughly 41 MMBtu/hour) and fluctuation between 0 and 7 until the liquid fuels were temporarily cut off before the SRF test began. The liquid fuels at their highest rate supplied about 19% of the precalciner tower energy the remainder at all other times before the SRF test was started.

During the SRF test burn the SRF was fed into the precalciner tower at 1 ton per hour for the first 24 hour period, accounting for approximately 10% of the precalciner energy demand. During this time natural gas met the remaining energy requirement of the precalciner tower while the main burner remained at the same 80/20% mix of coal and natural gas. After a successful first 24 hours, the feed rate of SRF was increased to 2 tons per hour for the next 48 hours, supplementing about 20% of the precalciner energy demand. Liquid fuels were used during the final 21 hours of the test, offsetting some of the natural gas use while the SRF was unchanged. The  $NO_X$  and  $SO_2$  emissions from the test burn are used in the technical analysis for the cement kiln emissions, described in more detail in Section 6.2.3. Using the average Btu consumption per ton of clinker produced before firing with the SRF as a benchmark, the data indicate that for the 1 ton per hour test the SRF was contributing about 21 MMBtu per hour. When the test was ramped up to the 2 ton per hour level, the data indicate that the SRF contributed around 51 MMBtu per hour. The lab testing of the SRF gave a value of about 12,000 Btu/lb, or 24.3 MMBtu/ton, which compares well to 21 MMBtu/ton recorded during the 1 ton/hour test and 25.5 MMBtu/ton during the 2 ton per hour test. These heat content values derived from the TXI data fit with the SRF analysis within reasonable ranges. The inaccuracies are expected due to the heterogeneous nature of the SRF, the imprecise SRF feeding process, variable moisture content, and the effect of changing fuels and production levels by the cement kiln.

 $<sup>^{1}\</sup>text{KCF}$  = thousand standard cubic feet

 $<sup>^{2}</sup>$ GPM = gallons per minute

# 6 Technical Analysis

# 6.1 Analysis Methodology

The purpose of this research is to compare landfilling non-recycled post-consumer plastics sourced from MRF residue with an alternative energy recovery method in three scenarios. The proposed alternative method is to use the non-recycled plastics as a feedstock in producing solid recovered fuel to burn in cement kilns. The two pathways are compared on an energy consumption, emissions, landfill avoidance, and cost basis to provide a more thorough understanding of the various trade-offs. This method is a first-order life-cycle analysis comparison shown in Figure 6.1 with the various material, energy, and emission flows through the control boundaries indicated for this analysis.

## 6.1.1 System Boundaries and Flows

The system boundaries in Figure 6.1 were selected to include the energy, emissions, cost, and material flows of interest in this research. Selecting system boundaries can be done in many different ways to include more upstream effects or to highlight other areas of interest. In this research the system boundary was drawn to exclude any processes upstream of the MRF residue being transported under the assumption that the MRF does not operate any differently in the SRF Case than in the Reference Case.

The transportation of the MRF residue, SRF, and kiln fuel (for solid fuels only) were included in the system boundaries. The transportation of these components can add to the emissions, energy consumption, and cost of the different scenarios depending on the location of the MRF, SRF facility (SRFF), cement kiln, and fuel supply. Including the transportation within the system boundaries allows for a more flexible and robust analysis of the two scenarios.

The SRF facility in this analysis uses electricity to process the MRF residue into SRF. The electricity used at the SRF facility must be included in order to capture the effect of that energy consumption in order to produce SRF. However, the source of electricity varies spatially and temporally, which affects the amount of fuels consumed and emissions produced. The spatial variation in the source of electricity is included in the analysis by including the electric grid within the system boundaries. This inclusion allows the analysis to be more robust to factor in electricity generation from grids with various carbon intensities, emis-



Figure 6.1: Two scenarios are considered: 1) the Reference Case, with material recovery facility (MRF) residue being disposed of in a landfill and the cement kiln using fuel such as coal or natural gas (top panel) and 2) the Solid Recovered Fuel Case (SRF Case), where MRF residue is processed by the solid recovered fuel facility (SRFF) into SRF that is then used to offset fuel use at the cement kiln and to avoid landfilling the residue (bottom panel).

sion factors, and efficiencies. The temporal effect on electricity generation, which includes seasonal effects of renewable generation, is not included in this study but is not expected to add significant errors because the SRF facility is assumed to operate throughout the year, averaging out any temporal variation in fuel consumption or emissions.

## 6.1.2 Material Flows

The material flow of interest in this study is the MRF residue and its various pathways. The cement kiln materials are neglected on the assumption that the cement kiln produces the same amount and same quality cement irrespective of the type of fuel used in the system. This assumption is based on previous studies of the use of refuse-derived fuel at cement kilns, personal interviews with cement kiln industry experts, and because the main priority of the cement kiln is to produce as much cement as possible at a specified quality [26, 27]. In the Reference Case the MRF residue is transported directly to the landfill

and disposed of. In the SRF Case the MRF residue is first transported to the SRF facility where it is processed into SRF. The amount of SRF produced from a given amount of MRF residue depends on the composition of the MRF residue and the efficiency and capability of the SRF facility. The SRF produced is then transported to the cement kiln to be used as fuel and any material not converted to SRF is transported and landfilled.

#### MRF Residue Material Balance

The MRF residue material balance is done in both cases to determine the amount of SRF created and the amount of waste material that is disposed of. As previously mentioned, in the Reference Case the entire MRF residue is waste and the mass of the material disposed of in the landfill can be expressed as:

$$m_{res} = m_{lf, ref} \tag{6.1}$$

where  $m_{res}$  is the mass of the residue and  $m_{lf,ref}$  is the mass of the landfilled material in the Reference Case. The mass of the residue from the MRF remains constant in both the Reference Case and SRF Case, and therefore does not have a subscript for a specific case. This notation is used consistently in this research. The MRF residue and the SRF created from it are heterogeneous mixtures of materials. The composition of the incoming MRF residue will vary by location, time, demographics, and socio-economic factors. In the SRF Case some material may be removed from the MRF residue before or during the conversion to SRF. This removed material will most likely be disposed of in the landfill. The mass of material landfilled in the SRF case can therefore be defined as:

$$m_{res} - m_{SRF} = m_{lf,SRF} \tag{6.2}$$

where  $m_{SRF}$  is the mass of SRF created and  $m_{lf,SRF}$  is the mass of the landfilled material in the SRF Case. The amount of SRF created from the residue is found using the following expression:

$$m_{SRF} = m_{res} \times CR = m_{res} \times \left(1 - \frac{m_{lf,SRF}}{m_{res}}\right)$$
(6.3)

where CR is the mass conversion ratio of residue into SRF. The mass conversion ratio is dependent on SRF facility capabilities, residue composition, and end-use fuel specifications. Combining Equations 6.1 and 6.2 gives the landfill avoidance,  $m_{lf,avoided}$ , as:

$$m_{lf,avoided} = m_{lf,ref} - m_{lf,SRF} \tag{6.4}$$

#### 6.1.3 Energy Flows

Energy flows into the system are tracked by type to tally energy consumed at each step. The final analysis tracks the amount of total primary energy consumed in each scenario. Any renewable energy accounted for in the analysis, primarily hydro and wind used to generate electricity, was converted from electricity produced in kWh to Btu using a direct conversion factor but with no heat rate or any other adjustment. The SRF is not included in fuel flows in either scenario. The energy contained within the residue could be added to the primary energy accounting, but would be equal in both cases and is left off for clarity and to highlight the fuels that vary between the two scenarios.

#### Cement Kiln Energy Balance

The energy requirement at the cement kiln plays a vital role in the overall energy balance of this analysis. The amount of energy required at the cement kiln affects the amount of cement kiln energy transported and combusted at the cement kiln as well as the maximum amount of SRF that can be used at the cement kiln. Depending on the cement kiln and SRF specifications, there might be a maximum fractional amount of SRF that can be used to offset traditional kiln fuels such as coal, petroleum coke, or natural gas. The cement kiln energy requirement is simply the amount of energy the cement kiln requires to produce one ton of clinker. A value of 3.35 MMBtu/ton of clinker was used for this analysis [15, 26]. The cement kiln energy requirement is constant in both the Reference Case and the SRF Case because, as mentioned before, there is no significant change to the operation of the cement kiln due to a fuel switch [26, 27].

The amount of traditional cement kiln fuel that is displaced by SRF is dependent on the heating value and amount of SRF as well as the heating value of the displaced fuel. The mass of the displaced fuel can be expressed as:

$$m_{DF} = \frac{m_{SRF} \times HC_{SRF}}{HC_{KF}} \tag{6.5}$$

where  $m_{DF}$  is the mass of the displaced fuel and  $HC_{SRF}$  and  $HC_{KF}$  are the heat contents of the SRF and the displaced kiln fuel, respectively. Again, the SRF is a heterogeneous mixture of materials that have independent heat contents. Therefore, the heat content of the SRF can be calculated using a mass-weighted average of the individual components of the SRF, if known, as shown in the equation below:

$$HC_{SRF} = \frac{\sum_{i} m_i \times HC_i}{\sum_{i} m_i} \tag{6.6}$$

where  $m_i$  and  $HC_i$  are the mass and heat content of the component *i* of the SRF material.

## **Total Energy Balance**

Performing an energy balance on both scenarios shows the energetic trade-offs associated with using SRF to offset a fraction of the kiln fuel. The total balance between the two scenarios is expressed in the equation:

$$\Delta E = E_{total,ref} - E_{total,SRF} \tag{6.7}$$

where  $\Delta E$  is the difference in total primary energy used between the Reference Case,  $E_{total,ref}$ , and the SRF Case,  $E_{total,SRF}$ . The methodology of finding the total primary energy use in each scenario is described in the following sections.

#### **Reference Case Primary Energy Consumption**

The primary energy consumed in the Reference Case is the sum of the energy flows crossing the boundaries shown in Figure 6.1. The general equation is expressed as:

$$E_{total,ref} = E_{KF,ref} + E_{M \to L} + E_{KF \to K,ref} \tag{6.8}$$

where  $E_{KF,ref}$  is the total energy of the kiln fuel used in the Reference Case,  $E_{KF\to K,ref}$ is the total energy used in the transportation of the kiln fuel to the cement kiln in the Reference Case, and  $E_{M\to L}$  is the total energy used in the transportation of the MRF residue between the MRF and the landfill in the Reference Case. In the Reference Case, the total energy used in the form of kiln fuel ( $E_{KF,ref}$ ) is simply equal to the kiln energy requirement ( $E_{KR}$ ) because it is the only fuel used to supply the kiln. Calculating the transportation energy in Equation 6.8 relies on the transportation method, fuel type, amount of material transported, and the distance. A general expression was developed that applies to all transportation energy calculations in this research that can account for the variance in any of these factors:

$$E_{A \to B} = m \times d_{A \to B} \times EI_{TM} \tag{6.9}$$

where m is the mass of cargo being transported in tons (the MRF residue),  $d_{A\to B}$  is the distance in miles between point A and point B (example, the MRF and the landfill),  $EI_{TM}$  is the energy intensity of the transportation method in Btu per ton mile. The method for

determining the energy intensity of different transportation methods is discussed further in the Transportation Emission Rates section below (Section 6.2.2). Equation 6.9 assumes that each shipment occurs with the cargo mass equal to the transportation capacity, which minimizes transportation energy requirements.

#### SRF Case Primary Energy Consumption

The other main term in Equation 6.7 is the total primary energy consumed in the SRF Case,  $E_{total,SRF}$ . This term is described in Equation 6.10 below:

$$E_{total,SRF} = E_{KF,SRF} + E_e + E_{M \to S} + E_{S \to L} + E_{S \to K} + E_{KF \to K,srf}$$
(6.10)

where  $E_{KF,SRF}$  is the kiln fuel energy used in the SRF Case,  $E_e$  is the electrical energy required by the SRF facility to produce SRF (converted directly from kWh to Btu). The transportation terms for the following transportation steps: transportation between the MRF and the SRF facility  $(E_{M\to S})$ , transportation between the SRF facility and the landfill  $(E_{S\to L})$ , transportation between the SRF facility and the cement kiln  $(E_{S\to K})$ , and transportation of the kiln fuel to the cement kiln in the SRF Case  $(E_{KF\to K,srf})$ . The transportation terms are calculated using Equation 6.9. Because there are multiple transportation steps for this pathway, it is clear that co-location of facilities would likely yield some benefits.

The kiln energy consumption in Equation 6.10 is simply the amount of energy required at the cement kiln minus the fraction of that energy that is provided by the SRF. Therefore, this term is expressed as:

$$E_{KF,SRF} = E_{KR} - E_{SRF} \tag{6.11}$$

To calculate the electrical energy consumed, the amount of electricity used by the SRF facility must be calculated. The electricity consumption by the SRF facility is found by multiplying the mass of MRF residue processed by the energy intensity of the SRF facility (in Btu per ton of MRF residue processed). This expression is shown below:

$$E_{grid} = m_{res} \times EI_{SRFF} \tag{6.12}$$

where  $m_{res}$  is the mass of the MRF residue being processed and  $EI_{SRFF}$  is the energy intensity of the SRF facility, or the amount of energy required to per unit mass of residue processed. The energy intensity of the SRF facility is a function of the process equipment, MRF residue composition, and the final desired SRF consistency and therefore can be adjusted in this study independently. In order to determine the amount of energy used to produce the electricity more accurately, a grid-specific method was used to determine the fuel use. The grid-specific method in this study can compare the energy use from the following categories: U.S. average, the Electric Reliability Council of Texas (ERCOT), the Western Electricity Coordinating Council (WECC), and the Midwest Reliability Organization (MRO). These grids were chosen to represent a range of possible location-dependent electricity implications. The MRO grid represents a coal-heavy grid while the WECC grid has a significant fraction of hydro and little coal-based generation. The U.S. average is used as a moderate example and the ERCOT grid is included because of its applicability to this type of process because of Texas' large population to source MRF residue from and many cement kilns as potential SRF users. Additionally, Texas is the site of the experimental cement kiln test burn. The resource mix for each of the grids studied is from eGRID data maintained by the EIA and EPA for the year 2007, shown below [28].

Table 6.1: Year 2007 Grid Resource Mix Percentage from eGRID [28].

Grid	Coal	$\mathbf{NG}$	Nuclear	Hydro	Renewables	Other
U.S. Average	48.5	21.7	19.4	5.8	2.5	2.1
WECC	30.1	31.4	9.6	23.1	4.9	0.9
MRO	70.4	5.4	15.5	3.4	4.3	1.0
ERCOT	34.4	49.5	12.0	0.3	2.5	1.3

The data in Table 6.1 are from 2007, the most recent eGRID data set. While the exact percentages in each grid will be slightly different in 2011, the differences between the grid are illustrative of electric grids with vastly different resource mixes. For example, the amount of coal-based generation varies between 30 - 70% and the amount of natural gas-based generation varies between only 5.4% in MRO up to almost 50% in ERCOT. Additionally, the WECC is an example of a renewable energy heavy grid with more than one-fourth of its electricity production from hydro and non-hydro renewable energy sources [28].

## 6.1.4 Emissions

The landfilling of waste and the combustion of fuels both produce emissions. Landfill emissions occur in both the Reference Case and the SRF Case, though to differing degrees due to partial landfill avoidance. The landfill emissions are analyzed for each scenario using the same emission generation rate and landfill gas collection efficiency for consistency. Combustion emissions occur during fuel transportation, electricity generation, and cement production. The combustion emissions for transportation are dependent on the transportation method, amount of material transported, and the distance traveled. The emissions from the electricity generation in the SRF case are analyzed using average emission rates for the selected electricity grids of interest. For the details of how these emission rates were calculated see Section 6.2. Cement kiln nitrogen oxide (NO<sub>X</sub>) and sulfur dioxide (SO<sub>2</sub>) emissions data were taken from on-site emissions monitoring systems before (Reference Case) and during (SRF Case) the SRF trial burn. EPA average values of carbon dioxide (CO<sub>2</sub>), particulate matter (PM), total hydrocarbons (THC), mercury (Hg), and hydrogen chloride (HC $\ell$ ) production rates for cement kilns were used in conjunction with the measured NO<sub>X</sub> and SO<sub>2</sub> data [18].

#### **Total Emissions Balance**

The total amount of emissions avoided by using the SRF method is the difference between the total emissions in the SRF Case and the Reference Case. This comparison is done on a pollutant by pollutant basis. The term "Z" is used in place of particular emissions and can represent any of the tracked emissions:  $CO_2$ ,  $SO_2$ ,  $NO_X$ , PM, THC, Hg, and HC $\ell$ . The total emissions balance equation is:

$$\Delta Z = Z_{ref} - Z_{SRF} \tag{6.13}$$

where  $\Delta Z$  is the difference in total emissions between the two cases for each species of pollutant and  $Z_{ref}$  and  $Z_{SRF}$  are the total emissions for a particular species for the Reference Case (equation 6.14) and SRF Case (equation 6.15), respectively.

$$Z_{ref} = (Z_{CK} + Z_{M \to L} + Z_{KF \to CK} + Z_{lf})_{ref}$$

$$(6.14)$$

$$Z_{ref} = (Z_{CK} + Z_{M \to S} + Z_{S \to K} + Z_{S \to L} + Z_{KF \to CK} + Z_{lf} + Z_e)_{SRF}$$
(6.15)

where the terms represent the emissions from the cement kiln (subscript CK), transportation from the MRF to the landfill (M  $\rightarrow$  L), transportation of the kiln fuel to the cement kiln (KF  $\rightarrow$  CK), transportation from the MRF to the SRF facility (M  $\rightarrow$  S), transportation from the SRF facility to the cement kiln (SRFF  $\rightarrow$  CK), transportation from the SRF facility to the landfill (SRFF  $\rightarrow$  L), landfill (lf), and electricity used at the SRF facility (e).

#### **Quantifying Emissions**

In order to compare the emissions using equation 6.13 the values for each term must be calculated. Emissions from the cement kiln  $(Z_{CK})$  are experimentally derived. More detail

#### 6.1. ANALYSIS METHODOLOGY

Transportation	<b>Energy Intensity</b>
Method	[Btu/ton-mile]
Train (diesel)	347
Truck (diesel)	1455
Barge (diesel)	509
Barge (fuel oil)	513

Table 6.2: Energy intensity values for various transportation methods from NREL Life-Cycle Inventory [29].

of the cement kiln emissions data can be found in Chapter 5. The emissions from the transportation steps, landfill, and electricity are calculated using emissions rates and the energy information discussed previously.

The emissions associated with the transportation of material are dependent on the following: mass of material transported, distance traveled, and the efficiency, capacity, and emissions rate of the transportation method. The model can analyze transportation using diesel trucks, diesel rail, barge using fuel oil, or barge using diesel. Additionally, low-sulfur diesel fuel for trucking is a possibility but is not considered in this analysis. These terms are combined to form a generic transportation emissions term that can be applied to any of the transportation steps required. The equation below for the emissions from transportation can be simplified using Equation 6.9:

$$Z_{A \to B} = ER_{TM} \times m \times d_{A \to B} \times EI_{TM} = ER_{TM} \times E_{A \to B}$$
(6.16)

where  $\text{ER}_{TM}$  is the emissions rate for a specific transportation method (TM). The energy intensities of some major transportation methods were derived from the NREL Life-Cycle Inventory (LCI) Transportation Data and are shown in Table 6.2. The emission rates for the transportation methods were also gathered from the NREL LCI and are shown below in the emission rates section (Section 6.2.2) [29].

The electricity emissions  $(Z_e)$  are a result of the combustion of fuels at the power plants that produce the electricity. Below, a generic equation is used to express the amount of emissions from the production of electricity. The expression below is simplified by combining it with Equation 6.12:

$$Z_e = EI_{SRFF} \times m_{res} \times ER_{qrid} \tag{6.17}$$

$$Z_e = E_{grid} \times ER_{grid} \tag{6.18}$$

where  $ER_{qrid}$  is the emission rate for the electric grid where the electricity is produced.

Detail on the various grid emission rates can be found in Section 6.2 below. Additionally, emission rates vary on a diurnal and seasonal basis but assuming the SRF facility continually produces SRF, yearly grid averages are useful representations.

In both cases, some material might be disposed of in a landfill, leading to emissions from the breakdown of material. The main air emission from landfills is methane (CH<sub>4</sub>) and is the only one used in this research. The methane produced in the landfill could either escape directly into the atmosphere or be captured by the landfill. The captured methane is either flared and converted directly to  $CO_2$  or is used to produce electricity. The flaring of the methane is done for safety reasons and because methane has a much greater global warming potential (GWP) compared to  $CO_2$ . GWP is a relative term that compares the amount of heat that a certain mass of gas traps in the atmosphere compared to an equivalent mass of carbon dioxide. The 100-year global warming potential of methane is 25, according to Forster, et al., meaning that over a 100 year period, methane is 25 times as potent of a greenhouse gas compared to carbon dioxide [30]. The amount of methane emitted from a landfill is a function of the type of waste, the amount of waste, and landfill specifications. The  $CO_2$  equivalent emissions from the landfill is found using the following equation, using notation developed in [31]:

$$Z_{lf} = m_{lf} \times L_0 \times \rho_{CH_4} \times (1 - MC) \times (1 - \epsilon_{recovery}) \times GWP_{CH_4}$$
(6.19)

where  $L_0$  is the total methane yield of the waste in a landfill,  $\rho_{CH_4}$  is the density of methane, MC is the moisture content of the waste,  $\epsilon_{recovery}$  is the time-integrated landfill gas capture system recovery effectiveness, and  $GWP_{CH_4}$  is the global warming potential of methane. Again, the waste being disposed of in the landfill is a heterogeneous mixture of materials. To determine the total methane yield of the waste, a mass-weighted average of the total methane yield of each component can be conducted using the expression below [31]:

$$L_0 = \frac{\sum_i (m_i \times L_{0,i})}{\sum_i m_i}$$
(6.20)

where  $m_i$  and  $L_{0,i}$  are the mass and total methane yield of the component *i* of the waste material.

# 6.2 Emission Rates Data

#### 6.2.1 Electricity Emission Rates

Electricity is consumed in the SRF Facility in order to process the MRF residue into SRF. The source of the electricity is dependent on the location of the SRF Facility. Electricity generated in Texas is produced by burning a different mixture of fuels than electricity generated in California or Pennsylvania, for example. Even if the fuel mixture was the same at two different locations, different climates and different power plant efficiencies could lead to different fuel consumptions and emissions for every kilowatt-hour generated. For this study a range of emission rates are developed for the various grids chosen. Emission rates for carbon dioxide (CO<sub>2</sub>), nitrogen oxides (NO<sub>X</sub>), sulfur oxides (SO<sub>2</sub>), particulate matter (PM), total hydrocarbons (THC), mercury (Hg), and hydrogen chloride (HC $\ell$ ) are used to maintain consistency with emission rates from the cement kiln and transportation methods. Table 6.3 shows the emission rates calculated for the U.S. Average, WECC, MRO, and ERCOT.

Table 6.3	: Emission Rates	for Electricity	Generated in	Different	Regions of	the	United
States [32	2, 28, 33, 34].						

Pollutant	U.S. Average	WECC	MRO	ERCOT	Units
$CO_2$	1,190	850	$1,\!570$	1,030	(lbs/MWh)
NOX	1.4	1.1	2.0	0.4	(lbs/MWh)
$SO_2$	6.7	0.9	4.6	1.7	(lbs/MWh)
PM	0.31	0.15	0.29	0.17	(lbs/MWh)
THC (VOC)	24	23	34	20	(lbs/GWh)
Hg	0.020	0.009	0.035	0.030	(lbs/GWh)
$\mathrm{HC}\ell$	52	2.5	24	13	(lbs/GWh)

The values in Table 6.3 are projected emissions rates for 2011 using historical data from the EPA and EIA [32, 28, 33, 34]. A detailed discussion of how these rates were derived is included in Appendix D.

## 6.2.2 Transportation Emission Rates

The transportation emission rates were developed using data from the National Renewable Energy Lab's (NREL) Life-Cycle Inventory Database [29]. The database is maintained by NREL for use in life-cycle analyses such as this. Of the 7 pollutants tracked in this study, only Hg and HC $\ell$  were not accounted for by NREL. We expect these to be minimal, and are neglected in this portion of the study.

Emission	Rail <sup>3</sup>	Truck $^3$	Barge $^4$	Barge $^3$	$\mathbf{Units}$
$CO_2$	175.7	176.8	181.5	176.4	lb/MMBtu
NOX	4.6	1.2	2.2	2.2	lb/MMBtu
$SO_2$	0.039	0.039	0.57	0.039	lb/MMBtu
PM	0.12	0.020	0.056	0.056	lb/MMBtu
THC	0.17	0.058	0.083	0.083	lb/MMBtu

Table 6.4: The transportation emission rates were developed using the National Renewable Energy Lab's (NREL) Life-Cycle Inventory Database [29]. There are no mercury or hydrogen chloride emissions attributed to transportation.

## 6.2.3 Cement Kiln Emission Rates

The cement kiln emission rates (Table 6.5) were derived from two primary sources: 1) experimental results from the SRF test burn and 2) EPA emission rate data for cement kilns similar to the one used in the SRF test burn. Because emissions of PM, THC, Hg, and HC $\ell$  were not measured during the test burn, these emissions rates are assumed to be unchanged.

Table 6.5: The cement kiln emission rates were developed using the EPA and experimental data [18]

Emission	Reference Case	SRF Case	Units
$CO_2$	900,000.0	890,000.0	ton/year
$NO_X$	505.0	630.0	ton/year
$SO_2$	8.6	4.4	ton/year
PM	24.0	24.0	ton/year
THC	60.0	60.0	ton/year
Hg	0.11	0.11	ton/year
HCl	24.5	24.5	ton/year

The  $CO_2$  emission rate in Table 6.5 was calculated in a more complicated way to account for the fuel switch between coal and SRF between the two cases considered. In order to do this, EPA data for the  $CO_2$  emission rate for coal, refuse derived fuel, and similar cement kilns was used. Thus, the Reference Case  $CO_2$  emission rate was chosen to be equal to the average cement kiln  $CO_2$  emission rate. The SRF Case  $CO_2$  emission rate was calculated by subtracting the  $CO_2$  emissions from the replaced coal and adding the  $CO_2$  emissions from the SRF used, using the emissions rates for fuels mentioned above. The  $CO_2$  emission

<sup>&</sup>lt;sup>3</sup>Using diesel fuel.

<sup>&</sup>lt;sup>4</sup>Using fuel oil.

rate for SRF from the EPA was 110 lbs/MMBtu, based on data from a single refuse derived fuel combustion facility. The a  $CO_2$  emissions rate of 203 lbs/MMBtu was used for coal. While the SRF value is not representative of all SRF, it is a figure supported by the U.S. EPA and fits with the understanding that plastic waste typically has much lower carbon intensities than coal.

The NO<sub>X</sub> and SO<sub>2</sub> emissions are derived from experimental data taken during the SRF test burn. Due to the limited duration and scope of the experimental analysis, all emissions results discussed here should be considered preliminary and require extensive further testing to confirm. A summary of the recorded emissions relative to the permissible limits imposed by air quality standards can be seen in Table 6.6. During the experiment liquid fuels were used at certain times, adding complexity in determining the effect of SRF on the emissions of the cement kiln. For this reason, the SO<sub>2</sub> emission rate was calculated using data during times with no liquid fuel use. The data showed an SO<sub>2</sub> emission rate of 0.017 lbs SO<sub>2</sub>/ton of clinker when the SRF was being used at 1 and 2 ton/hr feed-rates. While these numbers are significantly lower than the EPA average for kilns of this type, the specific type of kiln fuel, raw materials, and efficiency of the pollution control systems can dramatically affect the SO<sub>2</sub> emission rate. Therefore, the 0.017 lb SO<sub>2</sub>/ton of clinker rate was used for the Reference Case and the 0.009 lb SO<sub>2</sub>/ton of clinker value was used for the SRF case.

The NO<sub>X</sub> emission rate was derived in a similar way to the SO<sub>2</sub> emission rate. Again, the times when liquid fuels were being used is neglected due to added complexity in determining the effect of SRF use. The NO<sub>X</sub> emissions average was 1.01 lb NO<sub>X</sub>/ton of clinker during the time period before SRF was used, 1.26 lb NO<sub>X</sub>/ton of clinker during the 1 ton/hr SRF test, and 1.96 lb NO<sub>X</sub>/ton of clinker during the 2 ton/hr SRF test. While the increased NO<sub>X</sub> emission rate was unexpected and is not consistent with previous studies, these values were used in the technical analysis [27]. It is possible that the method of injection caused higher temperatures within the precalciner tower, leading to higher NO<sub>X</sub> formation rates. It is also possible that outside factors such as raw-mill operation or the presence of ammonia (an NO<sub>X</sub> abatement chemical) were playing a role in the changed NO<sub>X</sub> emissions. It may also have simply been that the burn conditions within the kiln were not optimized to the SRF combustion characteristics due to lack of operators' experience with this fuel.

# 6.3 Analysis Scenarios

Three different scenarios were developed to study the energetic, environmental, and economic trade-offs associated with the proposed SRF pathway. The variables of interest in each scenario are: 1) the distances traveled for each transportation step, 2) the electric grid Table 6.6: Despite the increase of  $NO_X$  emissions measured during the test burn, the plant emissions remained well under permitted levels. Note that the permitted  $NO_X$  value was calculated as the quotient of a permitted emissions level of 390 lbs  $NO_X$ /hr divided by a clinker production rate of 150 tons/hr.

	SRF	Case	Base Case	Permitted	Units
SRF Feed-Rate	1	<b>2</b>			ton/hr
$SO_2$ Production	0.009	0.009	0.017	0.08	lbs/ton clinker
NO <sub>X</sub> Production	1.26	1.96	1.01	2.6	lbs/ton clinker

used to power the SRF facility, 3) the landfill recovery efficiency, 4) the landfill tipping fee, and 5) the use of an internal-combustion to provide energy from captured landfill gas. The scenarios are developed in a general way to highlight stark differences in possible ways this pathway could be developed. For all scenarios the analysis was conducted with the assumption that coal was replaced by SRF at a rate of 1 ton/hr. The first-order life-cycle nature of this study means that the results are useful on a macro scale and as a comparison to similar studies. The results should not be considered a tool for estimating energy consumption, emission amounts, or economic viability. Comparing the scenarios is useful in targeting the areas where the SRF pathway can improve on existing waste-management methods as well as highlighting concerns of using SRF that need to be studied further.

Table 6.7: The inputs for each scenario consist of transportation distances and methods, grid characteristics, landfill gas recovery efficiencies, landfill tipping fees, and landfill gas-to-energy use.

Parameter		Units		
	Early	Near Term	Future	
M2L Distance	50	50	0	miles
M2S Distance	1500	200	0	miles
S2L Distance	50	50	0	miles
S2K Distance	550	50	50	miles
KF2KR Distance	1300	200	200	miles
KF2KS Distance	1300	200	200	miles
Recovery Efficiency	55	75	90	%
Tipping Fee	23	38	70	\$/ton
LFG-to-Energy <sup>5</sup>	No	No	Yes	
Grid	MRO	U.S.	WECC	

<sup>&</sup>lt;sup>5</sup>LFG-to-energy: The use of an internal combustion engine to convert captured landfill gas to electricity.

## 6.3.1 Early Scenario

The Early Scenario is used to approximate the experimental SRF test burn method and an early stage SRF infrastructure. The inputs for the Early Scenario as well as the other two scenarios, Near-Term Scenario and Future Scenario, are shown in Table 6.7. In the Early Scenario the distances traveled are very high indicating an immature infrastructure for SRF use. The 50 mile distance between the SRF facility and the MRF to a landfill approximates the distance from a central metropolitan area to a remotely located landfill. The 1500 mile trip from the MRF to the SRF facility and the 550 mile trip between the SRF facility and the cement kiln are similar to the distances in the experimental test. Finally, the 1300 mile distance for the cement kiln fuel was chosen to approximate the use of Colorado coal at a central Texas cement kiln, again, similar to that of the experimental test. The transportation method was set as diesel truck for all shipping except for the fuel being sent to the cement kiln, which was designated as diesel rail. These transportation methods are the same in the other two scenarios as well. The MRO grid was chosen because of its high coal component and low renewable component. The landfill recovery efficiency of 55% was chosen on the low end of the typical range for landfills in the U.S. (typically between 55 - 90%, dependent upon landfill construction and waste composition) [31, 35]. The tipping fee was again chosen on the low end at 23/100, representing an economic environment not highly supportive of SRF use. Finally, no landfill gas-to-energy was used, reducing the benefits of the waste material further.

## 6.3.2 Near-Term Scenario

The Near-Term Scenario is developed with moderate considerations for energy efficiency, SRF infrastructure, and environmental impact in mind. In the Near-Term Scenario the distances traveled are reduced for the MRF to SRF facility to 200 miles, representing a distance from one major metropolitan area to another (such as Dallas to Austin). The landfill distances remained at 50 miles and the SRF facility to cement kiln distance was reduced to only 50 miles, with the same reasoning as the landfill distance. Finally, the fuel transportation distance to the cement kiln was reduced to 200 miles, representing an in-state fuel supply. U.S. average grid data were used as a moderate example of an electricity production fuel-mix. The landfill recovery efficiency was increased to a typically used average value of 75% [31, 35]. The tipping fee was chosen as a moderate current U.S. value of \$38/ton. Again, no landfill gas-to-energy was used.

### 6.3.3 Future Scenario

The Future Scenario was chosen to be as energetically and environmentally advantageous as possible within the realm of the current assumptions. The MRF, SRF facility, and landfill are assumed to be co-located and therefore there is no transportation required between any of these facilities. The distance between the co-located facilities and the cement kiln was maintained at 50 miles as it is expected the co-located facilities and a cement kiln are both in rural environments but not necessarily also co-located. Finally, the fuel transportation distance to the cement kiln was maintained at 200 miles. The WECC grid data were used due to WECC's low coal and high renewable fractions. The landfill recovery efficiency was increased to 90% [31, 35]. The tipping fee value of \$70/ton is near the highest in the country. Finally, landfill gas-to-energy was used.

# 6.4 Analysis Results

The three scenarios described above were analyzed and the environmental and energetic results are discussed here. The results of the preliminary economic analysis are discussed in Chapter 7. The environmental considerations in this study are seven air emissions: carbon dioxide (CO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), nitrogen oxides (NO<sub>X</sub>), particulate matter (PM), total hydrocarbons (THC), mercury (Hg), and hydrogen chloride (HC $\ell$ ). The emissions are compared in each scenario between the Reference Case and the SRF Case. Similarly, the energetic trade-offs between the Reference Case and the SRF Case are discussed for each of the scenarios considered.

## 6.4.1 Emissions Results

Figure 6.2 shows the emissions reductions (% basis) in the SRF Case compared to the Reference Case for PM, THC, Hg, and HC $\ell$ . In both the Near-Term Scenario and Early Scenario the emissions changes are all well below 1%. In the Future Scenario the PM emissions were reduced by 1.6% while the THC emissions were reduced by 2.2% in the SRF Case. However, the reduction in PM and THC comes from the small decrease in rail transportation of fuel to the cement kiln, which in the Future Scenario was chosen to be the longest distance. Therefore, the transportation effect of the SRF Case has only a minimal effect on the emissions in Figure 6.2. As mentioned previously, the cement kiln emissions rate for these pollutants was kept constant for both the Reference Case and the SRF Case. While this was done because insufficient data were gathered, further investigation into the effect of using SRF to replace coal should be analyzed in regard to the emissions of these pollutants at the cement kiln.



Figure 6.2: The percent reduction of emissions in the SRF Case is minimal for PM, THC, Hg, and HC $\ell$ . Because the cement kiln emission rate of these pollutants was the same in both Cases, further investigation into the effect of SRF on these emissions is recommended.

The SO<sub>2</sub> emission rate for the cement kiln is the driving factor in SO<sub>2</sub> emission reductions in the SRF Case, as seen in Figure 6.3. The SO<sub>2</sub> emissions reduction ranged from as low as 19% in the Near-Term Scenario to 44% in the Future Scenario. The reduction in SO<sub>2</sub> emissions at the cement kiln in the SRF Case are somewhat offset by the increased SO<sub>2</sub> emissions from transportation and electricity production. In the Near-Term Scenario the electricity production contributes roughly 20% of the total SO<sub>2</sub> emissions in the SRF Case, reducing the SO<sub>2</sub> reduction to only 19%, while the transportation for both the Reference Case and the SRF Case in the Near-Term Scenario contributes only a small fraction of the total. The large SO<sub>2</sub> emissions increase from the electricity production. As discussed previously in the emission rate of the U.S. average electricity production. As discussed than the U.S. average, leading to a smaller component of SO<sub>2</sub> emissions in the Early Scenario coming from electricity production. However, in the Early Scenario the much larger transportation distances contribute a much more significant fraction of the total  $SO_2$  emissions for both cases. However, the reduction of  $SO_2$  at the cement kiln is still enough to give a total reduction of 21% SO<sub>2</sub> in the Early Scenario for the SRF Case compared to the Reference Case.



Figure 6.3: The SO<sub>2</sub> emissions are lower in all 3 scenarios, between 19 - 44%. The reduction comes from the reduced cement kiln emissions which are large enough to offset any increase due to electricity consumption or increased transportation requirements.

The NO<sub>X</sub> emissions for each scenario increases in the SRF Case compared to the Reference Case due to the previously discussed increase in NO<sub>X</sub> at the cement kiln when using SRF. The NO<sub>X</sub> increase was 16% in the Future Scenario, 24% in the Near-Term Scenario, and 20% in the Early Scenario (Figure 6.4). In the Future Scenario some of the increase is offset by reductions in NO<sub>X</sub> emissions from the combustion of landfill gas, because less landfill gas is created in the SRF Case. This effect is not seen in the Near-Term Scenario or the Early Scenario because the landfill gas was flared in these cases, simply converting the captured landfill gas directly to CO<sub>2</sub>. The effect of transportation differences is minimal in all scenarios compared to the difference in NO<sub>X</sub> production at the cement kiln. However, it is important to note that there are about 13,000 tons more NO<sub>X</sub> emitted in the Early Scenario compared to the Future Scenario in both the Reference Case or the SRF Case, showing that co-location of facilities and the proximity of fuel to the cement kiln lead to large reductions in life-cycle emissions.



Figure 6.4: Emissions of  $NO_X$  increased slightly due to the higher emission rate of  $NO_X$  at the cement kiln during the SRF test burn. Total  $NO_X$  emissions remained below permitted levels.

The  $\text{CO}_2$  emissions in the SRF Case were lower in every scenario compared to the Reference Case, as seen in Figure 6.5. There are  $\text{CO}_2$  reductions from the cement kiln, which is the largest overall effect, but also from the landfill. The effect of the landfill reduction is more pronounced, as expected, in the Near-Term Scenario and even more so in the Early Scenario. These more pronounced reductions in  $\text{CO}_2$  are directly related to the landfill gas recovery efficiencies of the landfill, revealing that the use of SRF is even more beneficial where landfills are poorly designed or maintained. The transportation component of the  $\text{CO}_2$  emissions is the greatest in the Early Scenario where the SRF Case has nearly 50% more  $\text{CO}_2$  from transportation than the Reference Case. Finally, the electricity production in the SRF Case shows only limited contribution to the total  $\text{CO}_2$  emissions, showing that the amount of energy needed to produced SRF is only minimal compared to the amount it displaces.



Figure 6.5: The  $CO_2$  emissions were reduced by at least 1.4% or 12,000 tons over the course of the year using SRF compared to the Reference Case.

In addition to the  $CO_2$  emissions shown in Figure 6.5, it is important to remember the policy discussion on carbon related to the use of non-recycled materials. Depending on which policies are adopted in the future, it is possible that some or all of the  $CO_2$  from the SRF will be considered biogenic in nature. While the total  $CO_2$  emissions will not be changed, the accounting of  $CO_2$  emissions as biogenic or not has important implications in terms of renewable energy credits or any costs that are attached to  $CO_2$  emissions. Additionally, policies can treat the avoided emissions from the landfill as credits for the SRF producer or user. While these policies are still in discussion, they are important to keep in mind when thinking about the  $CO_2$  emissions in the context of using SRF as an alternative fuel [36].

## 6.4.2 Energy Results

The total energy use, not including SRF energy, was reduced by 5.5% in the Early Scenario, 6.2% in the Near-Term Scenario, and 6.3% in the Future Scenario, as seen in Figure 6.6. Including the large transportation distances in the Early Scenario, the use of SRF still reduced the total energy consumption by 5.5%, or by 188 billion Btu. In the Near-Term

Scenario and Future Scenario the reduction totaled 6.2% and 6.3%, or 208 and 210 billion Btu, respectively. The additional energy consumption from electricity is only a fraction of the total energy used in any of the scenarios and is barely visible in Figure 6.6. Table 6.8 shows the equivalent amount of coal, natural gas, or oil use that could be avoided using SRF under these assumptions.



Figure 6.6: The use of SRF offsets at least 5.5% of the total energy required in the Reference Case for all of the scenarios considered.

	Table $6.8$ :	The amount	of fuel us	se avoided	by using	SRF	under	the given	assumptions
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Fuel	Future Scenario	Near-Term Scenario	Early Scenario	Units
Coal	$9,\!596$	9,496	8,576	tons
Natural Gas	184	204	206	million scf $^{6}$
Oil	32,362	$35,\!827$	36,204	barrels

<sup>&</sup>lt;sup>6</sup>scf: standard cubic feet

# 7 Integrated Economics Analysis

A preliminary economic analysis was conducted to determine a first cut, order of magnitude estimate of the cost of fuel delivered (CoFD) of SRF. The CoFD is a theoretical cost that the SRF facility would incur by processing and delivering the SRF to the cement kiln. Computing this metric for SRF is useful because it can be compared to the delivered cost of other fuels such as natural gas, coal, petroleum coke, biomass alternatives, etc. Additionally, CoFD reveals the cost implications of several variables in this research such as transportation methods and distances, locations of facilities, processing, and the possibility of  $CO_2$  prices. Understanding which variables in the analysis affect the CoFD the most can direct further research targeting those areas in an effort to minimize costs.

# 7.1 Economic Model

The economic model was developed to use the data previously discussed in addition to estimated costs of relevant processes to develop a CoFD for the SRF as delivered to a cement kiln. Following the SRF from its origin as MRF refuse to the cement kiln as a processed fuel reveals the process steps where costs are accrued. The original flow chart shown in Figure 6.1 was reduced to only the SRF Case and green arrows were added to show relevant cost flows (Figure 7.1). The economic model can be simplified down further to focus on the SRF facility and the cement kiln. The SRF facility is considered first, tallying all incoming and outgoing payments required for each ton of residue to be shipped to the SRF facility and completely processed into usable SRF. The transportation and disposal of any waste is also considered as well as the transportation of SRF to the cement kiln. The operating and maintenance (O&M) costs of the SRF facility are factored in as shown below, with a dotted arrow linking the O&M cost node to the electric grid node signifying the link between operating costs and the cost of electricity for the SRF facility.

The economic model can be broken down into an equation that represents each of the financial inflows and outflows from the SRF facility. The equation is expressed on a dollar per ton basis as

$$C_{SRF facility} = OPEX + TRANS + TippingFee - Residue - Credits$$
(7.1)

where OPEX is the operating expenditures of the SRF facility on a per ton of residue processed basis. The operating expenditures of the SRF facility are based on the cost of



Figure 7.1: A graphic representation of financial flow for the SRF is shown with connections between the SRF facility (SRFF) and its relevant cash inflows and outflows. The money that the SRFF pays for electricity is included in O&M. The cost of fuel delivered (CoFD) for the SRF facility to the cement kiln is the sum of all the cash inflows and outflows from the SRF facility (along with other values not shown or considered in this analysis, such as carbon credits, labor costs, capital expenses, etc.).

electricity in that region as well as the typical labor, utilities, maintenance, and amortized costs. TRANS represents the transportation costs per ton of shipping the residue to the SRF facility, shipping any waste to the landfill, and shipping the SRF to its buyer (the cement kiln). These costs depend primarily on the type of transportation method used and the shipping distance. The *TippingFee* is the cost of disposing a ton of material at a landfill near the SRF facility. *Residue* is the income per ton of residue for the SRF facility. *Residue* is tracked as income because MRFs must pay someone to dispose of their residue, so the SRF facility can charge similar tipping fees as local landfills. If additional processing is done at the MRF to produce higher quality residue, these costs might be passed on to the SRF facility if the tipping fees near the MRF are very low and extensive additional sorting at the MRF is required. *Credits* encompass any greenhouse gas related credits that might be associated with the diversion of material from the landfill or the use/creation of alternative fuels. Credits were not considered in this CoFD analysis.
# 7.2 Operating Expenditures

Operation and maintenance (O&M) costs of an SRF facility are difficult to project because of the immature state of the industry. SRF can be created using a variety of technologies that would lead to various O&M costs. In addition, the location of the SRF facility plays an important role in energy, facility, shipping, and labor costs. Furthermore, the level of integration of an SRF facility with landfills or MRFs will also play an important factor in the cost of producing SRF. Finally, local, state, and federal policies can impact the economics of SRF and add complexity to the analysis. Therefore, due to the inability to provide comprehensive SRF production costs that would encompass the majority of real world implementations, we have outlined some of the primary parameters that will affect SRF production costs. Mainly, we highlight the differences in energy costs and landfill tipping fees that directly impact the O&M of the SRF facility as well as the transportation costs of shipping large amounts of material.

### 7.2.1 Transportation Costs

The TRANS value is the total of all shipping costs per ton of processed residue and is found using the following expression:

$$TRANS = TC_{M \to S} + \frac{m_{waste}}{m_{res}} \times TC_{S \to L} + \frac{m_{SRF}}{m_{res}} \times TC_{S \to CK}$$
(7.2)

Where  $TC_{M\to S}$  is the cost per ton of residue of transporting residue from the MRF to the SRF facility,  $TC_{S\to L}$  is the cost per ton of waste residuals of transporting the SRF processing residuals from the SRF facility to the landfill, and  $TC_{S\to CK}$  is the cost per ton of SRF of transporting the SRF from the production facility to the cement kiln,  $m_{res}$  is the mass of residue from the MRF,  $m_{waste}$  is the mass of discarded residuals from the SRF facility, and  $m_{SRF}$  is the mass of SRF. The mass of the residue from the MRF is equal to the mass of the discarded residuals plus the mass of the processed SRF. Because the ratio of the mass of waste residuals to mass of SRF vary with SRF conversion efficiency, the transportation costs of these steps is adjusted to a per mass of residue basis by considering the following constraint:

$$\frac{m_{waste}}{m_{res}} + \frac{m_{SRF}}{m_{res}} = 1 \tag{7.3}$$

Transportation costs from the Bureau of Transportation Statistics Research and Innovation Technology Innovation Administration (RITA) were used in this analysis. Transportation revenues on a per ton-mile basis were found for trucks, rail, and barges since the 1960s,

#### 7.2. OPERATING EXPENDITURES

shown in Figure 7.2. The average costs of the last three years for each transportation method were used for this analysis.



Figure 7.2: Transportation costs were found from the Bureau of Transportation Statistics for truck, rail, and barge. The average of the last three years costs were used as the base price point in this research [37].

### 7.2.2 Landfill Tipping Fees

The local landfill tipping fees near the MRF and SRF facility are used as a proxy for the amount the SRF facility will be paid to take the MRF residue. The SRF facility can charge the MRF competitive rates for taking their residue as long as no additional handling or processing is required at the MRF and there are no other logistical, technical, or regulatory hurdles in place. However, if an agreement is made that the MRF will process the residue further in order to increase the output quality of the SRF, the income the SRF facility will make for taking the residue will be lower than the local tipping fees. Additionally, the SRF facility might produce significant amounts of waste which they would have to pay to dispose of at the local tipping fee rates. Figure 7.3 shows typical local landfill tipping

#### 7.2. OPERATING EXPENDITURES

fees in different regions in the U.S. [38, 39]. The pink markers are MRF locations, which are more numerous near densely populated areas with high tipping fees and less available land for landfills. The high density of MRFs coincident with high tipping fees suggests the potential for a co-located SRF industry. The high tipping fees increase revenue for SRF producers while the large number of MRFs allow for more selective and robust sourcing of MRF residue.



Figure 7.3: Typical landfill tipping fees (shown in the boxes) can vary widely for different regions of the U.S. The pink markers show MRF facilities across the country. [38, 39].

### 7.2.3 Electricity Prices

Many densification technologies that SRF production facilities might employ use significant amounts of electricity to mix, shred, and/or compact the raw material into its final form. Similar to tipping fees, electricity prices vary geographically and will impact SRF facility economics. Average industrial electricity prices for every state in 2010 were taken from the U.S. Energy Information Agency and aggregated into similar regions and mapped in Figure 7.4 [40]. The full state-by-state breakdown of the average industrial electricity prices for 2010 can be found in Appendix E. Regions with higher than average landfill tipping costs also have high electricity prices: primarily the northeast Atlantic Coast and the West Coast regions. So while the higher landfill tipping fees will benefit SRF facilities, the higher-thanaverage electricity prices could possibly offset the advantages of operating in these regions. Therefore, it is hard to highlight specific regions where SRF facility are best suited without further investigation into local prices in addition to other important factors such as local policies, MRF and landfill locations, SRF market, and labor costs.



Figure 7.4: Average industrial electricity prices in the northeast are nearly double central U.S. prices. The pink markers show all MRFs listed by the Energy Information Administration [40].

### 7.2.4 Greenhouse Gas Credits

It is possible that state or national policies will be put in place that will regulate and price greenhouse gas (GHG) emissions. The handling of how SRF is treated in any GHG policy will impact the overall costs and the development of the SRF industry and any pending policy should be considered carefully before SRF commercialization efforts are pursued. While this research does not go into depth about how such policies would or should be structured, it is important to consider potential future regulations when discussing solid recovered fuels. Even if GHG emissions do become regulated, it is unclear how the regulations would affect an SRF industry. SRF is an engineered fuel that is created from waste material that would otherwise be landfilled, typically a mixture of fibrous material and fossil-fuel derived plastics. Therefore the diversity of materials comprising SRF and the fact that SRF production creates a second use for an energy-dense material that would otherwise have been buried convolute how SRF could be treated by potential GHG policies. SRF reduces the amount of waste buried in a landfill and therefore displaces some of the GHG emissions that would have been produced at the landfill site. However, when the SRF is combusted it releases  $CO_2$ , a GHG that may be priced in the future.

# 7.3 Illustrative Case Study

An illustrative case study was completed to show the relative impacts of each variable discussed above. The case study uses the Future Scenario values for transportation distances assuming that the SRF facility, landfill, and MRF are co-located at the same site and the distance between the SRF facility and the cement kiln is 50 miles. The transportation method used in both cases was diesel trucks with a cost of 0.16/ton-mile. Austin, TX and Boston, MA are compared to reflect location-dependent impacts on SRF costs. Austin, TX represents the low tipping fee, low cost electricity areas typical of the central U.S. and more rural areas. For Austin, the central U.S. value of a \$23/ton tipping fees from Figure 7.3 was used and the south-central U.S. value of \$0.06/kWh was used for the electricity prices [40, 38, 39]. Boston, MA is representative of the northeast coastal U.S. areas that lack abundant land resources and have high electricity costs. The north-east U.S. values for tipping fee and electricity prices were used for the Boston case at \$70/ton and 0.13/kWh, respectively. The electricity consumption to produce the SRF was estimated at 0.1 MWh/ton processed but could vary significantly based on the SRF densification method and technologies [14]. Table 7.1 shows the income from taking the MRF residue and the costs associated with disposing of waste material, transporting the SRF from the SRF Facility to the cement kiln, and the electricity required to produce the SRF.

Table 7.1: An example SRF cost analysis using Future Scenario transportation distances and Austin, TX and Boston, MA as case study cities. Numbers in black represent income for the SRF facility, while numbers in red are costs. All amounts are on a dollars per MMBtu of the produced SRF to compare costs of other fuels. Note that without considering production costs such as labor, capital, and technology specific expenses, the SRF has a net positive value.

Income/Expense Category	Austin, TX	Boston, MA	
Income from Accepting MRF Residue	1.02	3.11	
Waste Disposal	(0.10)	(0.31)	
Transportation	(0.32)	(0.32)	
Electricity	(0.27)	(0.58)	
Net Value of SRF (\$/MMBtu)	0.33	1.90	

The example case study shows the strong geographic dependence of the SRF delivered cost on the local tipping fees. The tipping fee had the largest impact on this simple analysis at about 2.00/MMBtu more in the Boston case than the Austin case. The regional dependence on electricity prices had less of an effect on the cost of producing SRF. While the costs associated with electricity in the Boston case are double that of the Austin case, the absolute increase was only 0.27/MMBtu. The transportation costs did not differ based on the location because the distances are constant in both cases. However, these costs could be extrapolated linearly to compare scenarios with larger distances between key facilities. Overall, Table 7.1 shows that SRF might expect to compete with other fuels such as coal (about 1.50/MMBtu) or natural gas (about 2/MMBtu) if the remaining costs are between 3.40 - 3.90 in Boston and between 1.80 - 2.30 in Austin. The other costs that must be considered are amortized capital costs, labor costs, and other overhead costs but are out of the scope of the research at this stage.

# 8 Conclusion and Recommendations

# 8.1 Key Findings

The analysis presented here elucidates the potential energetic and environmental trade-offs of using residue-derived SRF as an alternative fuel in a cement kiln. Key findings of the report include:

- The experimental test was successful on a technical basis and proved that refusederived SRF can be used as an alternative fuel at a cement kiln. Based on experimentally measured heating value, the SRF supplied roughly 10% of the total precalciner energy requirements during the 1 ton/hour test period and 20% during the 2 ton/hour period.
- The experimental data and independent testing showed an average SRF heating value of about 12,500 British thermal units per pound (Btu/lb), which is comparable to the bituminous coal the cement kiln uses. Therefore, every ton of MRF residue diverted from a landfill to make SRF for the test burn approximately displaced an equivalent ton of bituminous coal.
- Emissions data for sulfur dioxide  $(SO_2)$  from the cement kiln indicated that the use of SRF reduced the SO<sub>2</sub> emissions rate by roughly 50%. Results from the life-cycle analysis portion of the study revealed that the use of SRF at 1 ton/hour reduces SO<sub>2</sub> emissions by 19% – 44%. These reductions, as with all emissions results presented here, are preliminary results based on limited experimental data and require further testing to verify.
- The nitrogen oxides (NO<sub>X</sub>) emissions rate increased by 25% when the SRF was used at 1 ton/hour and by 93% during the 2 ton/hour feed rate period. The total emissions were 40%, 50%, and 75% of the total permitted levels for the non-SRF, 1 ton/hour, and 2 ton/hour test periods, respectively. Results from the life-cycle analysis portion of the study revealed that the use of SRF at 1 ton/hour increased NO<sub>X</sub> emissions by 16% – 24%. However, follow-up discussions with cement kiln operators suggest that the spike in NO<sub>X</sub> was likely due to the lack of an efficient feeding system for the experimental fuel and that plant operators would normally adjust burn conditions to more effectively control combustion. No adjustments were made during this limited

test run.

- Emissions of particulate matter (PM), total hydrocarbons (THC), mercury (Hg), and hydrogen chloride (HCℓ) are changed very little in the SRF Case compared to the Reference Case. No data could be taken on these pollutants at the cement kiln, so any change in these pollutants in the analysis results was the result of changes in transportation and electricity consumption. The changes of PM, THC, Hg, or HCℓ were greater than 1% from the Reference Case to the SRF Case in only two cases: in the Future Scenario PM emissions reduced by 1.6% and the THC by 2.2%.
- The analysis showed that carbon dioxide (CO<sub>2</sub>) emissions were reduced for all scenarios of the SRF Case, yielding reductions of 1.4%, 1.5%, and 1.6% in the Future Scenario, Near-Term Scenario, and Early Scenario respectively (or 12,172 tons/year, 13,780 tons/year, and 14,155 tons/year respectively in absolute reductions).
- This analysis concluded that offset fuel use at the cement kilns by using SRF significantly outweighs the energy requirements of producing and transporting SRF. The production and transportation used 1% 11% of the heating value of the SRF: for every 10 million Btu (MMBtu) of SRF consumed, a total of 8.8 9.9 MMBtu of conventional fuel use is avoided.
- Replacing coal with SRF at a 1 ton/hour rate for an entire year reduces fossil energy use by 5.5%, 6.2%, and 6.3% in the Early Scenario, Near-Term Scenario, and Future Scenario, respectively.
- The preliminary economic analysis reveals that the cost of SRF as delivered to a customer has a strong dependence on local landfill tipping fees. However, more indepth analysis is needed to determine an expected total cost of fuel delivered.

The experimental test burn and accompanying analysis indicate that using MRF residue to produce SRF for use in cement kilns is likely an advantageous alternative to disposal of the residue in landfills. The use of SRF can offset fossil fuel use, reduce  $CO_2$  emissions, and divert energy-dense materials away from landfills. Considering the total U.S. MRF throughput and associated residue production rate, the potential fossil fuel and emissions reductions of widespread SRF use are very substantial. Even with electricity consumption and additional transportation necessary for the SRF Case, SRF outperforms traditional fuels on an energetic basis, is able to provide benefits nationwide, and the margin of energy and emissions reductions is expected to increase if optimized facilities are developed. Colocation of MRFs, SRF production facilities, and landfills can increase the benefits of SRF use even further by reducing transportation requirements.

Finally, the handling of SRF on a policy basis will impact the economics and viability of this industry, as landfill avoidance incentives and  $CO_2$  accounting could be important aspects in SRF economics. Overall, despite technical, social, political, and economic hurdles, our

### 8.1. KEY FINDINGS

analysis indicates that harnessing the energy content of non-recycled plastics and paper from MRF residue diverted from landfills in the form of SRF offers environmental benefits. As recycling rates continue to increase and SRF production techniques are further refined, residue-derived SRF will be an important resource to consider as a possible solution to society's long-term energy usage and waste management strategies.

# 8.2 Recommendations

### 8.2.1 Experimental SRF Combustion

The analysis performed here was informed by data from literature review and experimental results. However, to improve accuracy and resolution of future analysis, more emphasis should be placed on obtaining experimental data, especially stack emissions monitoring. In addition, increasing the feed-rate and duration of the SRF experimental burn would help to stabilize any transient emissions effects, which would verify or disprove the unexpected increase in  $NO_X$  emissions measured during the SRF combustion period. During the experimental test burn presented in this report, the cement kiln displaced the combustion of supplementary fuels during the test burn. For a more accurate and appropriate test of coal-replacement feasibility, it is suggested that further tests be conducted with the intent of solely displacing coal.

### 8.2.2 SRF Production

Based on the first-cut approach of refuse-derived SRF production undertaken to perform the cement kiln experiments, several insights can be gleaned regarding the production process. First, sorting is an important priority and further experimentation and potential commercialization efforts need to consider it closely. There are several possible solutions to dealing with inadequately sorted MRF residue. One is that the SRF manufacturer can draft specifications for residue sourced from MRFs, placing the burden of adequate sorting on the MRF. Another tactic is for the SRF manufacturer to have its own sorting line, allowing full control over the final constituents of the residue stream bound for SRF production. A financial analysis of the added cost of sortation at the MRF and the SRF facility would need to be conducted to determine appropriate pricing schemes. A second issue encountered during the first production attempt was the consistency of the SRF delivered to the cement kiln, with the delivered loads becoming predominantly fluff, as opposed to the initial loads of pellets. This issue can again be addressed by defining fuel specifications, this time between the SRF manufacturer and the end user.

#### 8.2.3 Sensitivity Analysis

Three scenarios were analyzed in this report. Though they reveal the aggregate effects of several parameters on the overall emissions and energy consumption of SRF use, the scenarios do not reveal how individual variables affect the overall outcome, but rather they reveal how sets of variables change the results. An in-depth sensitivity analysis is more suited to high-resolution understanding of how individual variables affect the overall outcome. It is recommended that future work includes a sensitivity analysis, which would help shed light onto the extent that certain variables influence the emissions, energy, and economic results.

# 8.3 Future Work

Moving forward, the project team believes that further testing in different scenarios would reveal the non-obvious trade-offs of residue-derived SRF. This examination can be accomplished through more detailed combustion in cement kilns as well as testing new combustion facilities such as coal-fired boilers at industrial facilities and power plants. In light of the recommendation to consider additional sorting processes for SRF production, costs associated with these facility upgrades should be analyzed. These costs include capital costs as well as potential operating and maintenance expenses. Future cost analysis could reveal economic feasibility of facility upgrades for SRF producers or MRF residue providers.

A more detailed economic analysis should be conducted, considering all of the variables brought to light in Integrated Economic Analysis portion of the report. This analysis should include real and assumed costs of production, seeking to find an economic environment favorable to SRF production and use.

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Glossary

Biodiesel Biomass-based diesel fuel.

- **Biogas** Gas produced by the biological breakdown of organics in an oxygen-free environment.
- **Btu** British thermal unit, 1 Btu = 1055 Joules.
- **Bulk Material Transfer Station** An interim storage facility used for transfering waste or recyclables from small collection vehicles to large transportation vehicles in route to its final destination.
- Clean diesel Ultra Low Sulfur Diesel fuel.
- **Clinker** Small lumps of sintered limestone and alumino-silicate formed during the cement kiln stage. A primary ingredient for Portland cement production.
- **Clinking** The process of sintering limestone and alumino-silicate to form clinker.
- CoFD Cost of Fuel Delivered.
- Eddy Current Seperater An electro-mechanical device used in MRFs to seperate nonferrous metals from the recycling stream.
- EIA United States Energy Information Administration.
- EPA United States Environmental Protection Agency.
- **ERCOT** Energy Reliability Council of Texas.
- **Fibrous Material** Paper and paperboard found in MSW.
- **Flash Pyrolysis Process** A pyrolysis process that that is conducted very quickly to optimize the production of certain commodities.
- Fluidized Bed Waste Incineration An inceneration technique that utilizes strong airflow up through a sand bed and combustion products in the furnace, keeping the sand and waste in a fluid-like state during combustion.
- **Gasification** A process used to convert organics into syngas using very high temperatures and a reduced oxygen environment.
- **HDPE** High-density polyethylene, a thermoplastic made from hydrocarbons, mostly natural gas and natural gas liquids. Recycling #2.

- **Heat Content** A measure of the total energy available for combustion in a given fuel. This can be expressed as LHV or HHV.
- **HHV** Higher heating value; A property of a fuel determined by combusting a specific quantity of fuel and returning the products of combustion to the orignal temperature. This value assumes tha all water vapor in the combustion process is condensed to water.
- Landfill Gas A gas created from the microbeal breakdown of material within a landfill, often captured and flared or combusted for energy recovery.
- **LDPE** Low-density polyethylene, a thermolastic made from hydrocarbons, mostly natural gas and natural gas liquids. Recycling #4.
- LHV Lower heating value; A property of a fuel determined by combusting a specific quanity of fuel and returning the products of combustion to 150° Celsius. This value takes into acount the amout of latent heat required to evaporate any water contained in the fuel.
- Mixed Rigids A mixture of plastics #3-7, sometimes bailed at an MRF and sold as a commodity, and other times considered residue.
- MMBtu One million British thermal units.
- **MRF** Material Recovery Facility.
- **MRF Residue** All materials that enter an MRF but are not sorted and sold as a commodity. Usually the residue is disposed of in a landfill.
- MRO Midwest Reliability Organization.
- **MSW** Municipal Solid Waste.
- Municipal Sludge Semi-liquid product of treating municipal water and wastewater.
- **Off-the-Curb Collection** A waste collection scheme in which collection vehicles collect waste directly at the consumer's residence.
- **PET** Polyethylene terephthalate, a plastic resin often used for consumer packaging. Recycling #1.
- **Petroleum Coke** A carbon-rich solid biproduct of oil refinery cracking processes.
- **Polyolefins** A family of polymers including polypropylene and polyethylene often used for applications requiring material flexibility.
- **Portland Cement** The most common type of cement used around the world, comprised primarily of clinker, with some calcium sulfate and additives to control final product characteristics.

- **Precalciner** A special combustion chamber for cement kilns that serves to pre-heat and decarbonate the clinker before entering the kiln.
- **PVC** Polyvinyl chloride, a plastic made from hydrocarbons, mostly natural gas and natural gas liquids. Recycling #3.
- **PTF** Plastic-to-fuel, a thermal processing technology that uses pyrolysis or gasification to convert plastics into singas, oils, or other fuels.
- **Pyrolysis** A process of thermal degradation process used to convert feedstocks into gas, pyrolysis oil, and char. This process is similar to gasification but is conducted at lower temperatures.
- **RDF** Refuse Derived Fuel.
- **Single-Stream** A scheme for recycling, wherein the consumer places all recyclable material into one receptical to be delivered to a MRF.
- **SRF** Solid Recovered Fuel.
- **SRFF** Solid Recovered Fuel Facility.
- Syngas/Synthesis Gas A gas mixture that consists primarily of carbon monoxide and hydrogen, created through a synthetic conversion process of carbon-rich feedstock.
- **Tipping Fee** The fee paid by waste collectors to landfill operators in order to dispose of their loads into the landfill.
- **Ton** Called a short ton. 1 ton = 2,000 pounds.
- **Tonne** Called a metric ton. 1 tonne = 1,000 kilograms.

**TRI** United States Environmental Protection Agency's Toxic Release Inventory.

**WECC** Western Electricity Coordinating Council.

**WM** Waste Management.

**WTE** Waste-to-Energy.

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# **A Survey of WTE Companies**

Waste-to-energy encompasses a wide range of energy recovery solutions. Some companies offering WTE services are privately held waste reprocessing facilities that produce fuels from industrial and commercial waste contracts. Other companies supply complete waste management services to municipalities that provide collection, separation, disposal, and energy recovery solutions. A range of international companies were evaluated to show the broad range of possible WTE solutions with a focus on those that use non-recycled plastic (NRP) as a fuel source. This survey is not intended to be a complete representation of the industry but to highlight the promising avenues and the potential roadblocks related to energy recovery on the road to zero waste.

## Remondis AG & Co. KG

Remondis is one of the world's largest water, waste, and environmental services companies with over 500 locations in 28 countries. Remondis processes over 27 million tonnes per year and recycles 25 million tonnes of the waste coming from MSW, construction waste, commercial waste, and many other sources. Remondis produces biodiesel, biogas, landfill gas, and SRF and produces heat or power from biomass-fired plants, hazardous and nonhazardous incineration plants, and a sewage sludge incinerator. Remondis produces around 80,000 tonnes of SRF each year in the form of soft pellets. The SRF is sold to the cement industry and power plants as alternative fuels. Remondis is part of the extensive German SRF industry that produces between 1.7 and 2.2 million tons per year, nearly half of the European total [41, 42].

## HTL Recycling and Waste Management Services

HTL Recycling and Waste Management Services, located in London, U.K., is another example of the more developed European waste management industry compared to the U.S. HTL has an integrated waste management service with an MRF that can separate incoming mixed recyclables. HTL also has a Refuse Derived Fuel (RDF) processing facility located at its Deptford Recycling Centre, which can process 200,000 tonnes of general waste each year. The processing facility has systems that remove inert and compostable materials before pulverizing the material to create feedstock for RDF. The feedstock can be used in pyrolysis and gasification systems, burned directly in WTE facilities, or co-fired in power plants or industrial combustion processes such as cement kilns. The material that is removed, including some rigid plastics, is recycled whenever possible. HTL's RDF consists mostly of fibrous material such as paper and low grade polyolefins such as LDPE film that would normally go to landfill as MRF residue [43].

#### Kent Enviropower

Kent Enviropower is another example of an integrated waste management facility in Europe. In December of 2008 the facility opened in Kent in the U.K. Up to 500,000 tonnes of mixed waste and up to 65,000 tonnes of sorted material can be processed every year. The sorted material is separated into streams of recyclable and non-recyclable goods. The non-recycled goods are then added to the mixed waste, metals are removed, and the waste is burned in a fluidized bed waste incinerator [44].

### VEXOR Technology, Inc.

Located in Medina, Ohio, VEXOR Technology started a waste services company in 1999 and entered the waste-to-fuel production industry in 2001. VEXOR has produced solid fuel for WTE incinerators and precalciner and other coal-burning cement kilns. VEXOR Engineered Fuel® uses non-hazardous industrial waste from commercial and industry customers. While VEXOR has been commercially successful overall, it is unclear what level of production it has achieved compared to the more developed European companies. Similar to Balcones Fuel Technology (discussed later in Chapter 3), VEXOR has proven there is a U.S. market for commercial and industrial waste-to-fuel facilities [45].

### Interstate Waste Technologies

Interstate Waste Technologies (IWT) designs and owns waste processing facilities in countries throughout the world with offices in multiple U.S. states. IWT's process is controlled gasification of multiple waste streams, including MSW, commercial, industrial, medical, tires, E-waste, and municipal sludge. IWT's process outputs synthesis gas, or "syngas," which can be used to create electricity or cleaner burning fuels, such as "clean diesel." While IWT does not first separate out recyclable plastics from its MSW, their process could presumably be used in a waste management system with the MSW first going to a MRF and the MRF residue then being processed into syngas. The process also outputs aggregate material such as metals, sulfur, industrial salts, and zinc concentrate. While these output streams can be recycled or reused, they must be appropriately managed. IWT quoted a \$186/ton processing cost for 300 tons of waste per day in a Los Angeles (L.A.) County report for possible conversion technologies to be used with L.A. MSW [8, 46].

# Primenergy LLC

Primenergy LLC is one of the leading gasification companies in the U.S. with six completed biomass-to-energy facilities in Arkansas, Missouri, Georgia, Pennsylvania, and Rossano, Italy. While Primenergy LLC currently does not gasify MRF residue, they have demonstrated the technological feasibility of its gasification process works with rice hulls, corn fiber, waste carpet, medium density fiberboard (MDF) dust, sewage sludge, and olive waste. The waste carpet and MDF dust facility, the only Primenergy facility that accepts waste plastic material, can process around 80 tons per day to produce 50,000 pounds of process steam per hour. Primenergy currently has an alliance with CR&R MRF and Community Recycling to test residue from its facilities in Southern California. Primenergy quoted an estimate of \$87/ton for processing 100 tons of MSW per day in the L.A. county report [8, 47].

### Graveson Energy Management America

Graveson Energy Management (GEM) Limited is a WTE company that uses a flash pyrolysis process to convert pre-treated waste into a synthetic gas that can be used to create electricity, fuels, or industrial gases. GEM has demonstrated its process on a pilot and commercial scale but does not seem to have any commercial scale operations currently underway. GEM claims they can use MSW, biomass, animal by-products, waste water treatment sludge, or industrial waste as a process feedstock. In the L.A. county report, GEM America quoted a price of \$105/ton for 100 tons of MSW per day [8, 48].

# B TXI Hunter Cement Plant Emissions Permit

Contained in the following pages is the TXI permit pertaining to  $NO_X$  and  $SO_2$  emissions issued by the Texas Comission on Environmental quality in 2006.

# SPECIAL CONDITIONS

# Permit Numbers 5933 and PSD-TX-63M3

# EMISSION STANDARDS, FEDERAL APPLICABILITY, AND OPERATIONAL LIMITS

- 1. This permit covers only those sources of emissions listed in the attached table entitled "Emission Sources - Maximum Allowable Emission Rates," and those sources are limited to the emission limits and other conditions specified in that attached table. Compliance with the annual emission limits is based on a rolling 12-month year rather than the calendar year. This permit authorizes start-up, shutdown, and maintenance (SSM) emissions which comply with the emission limits in the maximum allowable emission rates table (MAERT).
- 2. Emission limits are based upon the permit application representations dated February 3, 2006, and subsequent submittals dated June 19, 2006; July 5, 2006; August 24, 2006; September 29, 2006; and October 18, 2006.
- 3. These facilities shall comply with the applicable requirements of the following regulations:
  - A. The U.S. Environmental Protection Agency Standards of Performance for New Stationary Sources (NSPS) promulgated in Title 40 Code of Federal Regulations Part 60 (40 CFR Part 60):
    - (1) Subpart A General Provisions;
    - (2) Subpart F Portland Cement Plants;
    - (3) Subpart Y Coal Preparation Plants; and
    - (4) Subpart OOO Nonmetallic Mineral Processing Plants.
  - B. The EPA regulations on National Emission Standards for Hazardous Air Pollutants (NESHAPS) for Source Categories promulgated in 40 CFR Part 63:
    - (1) Subpart A General Provisions; and
    - (2) Subpart LLL Portland Cement Manufacturing Industry.
  - C. Kiln and Precalciner No. 1 (Kiln Line 1), identified as Emission Point No. (EPN) 1-DE-3, shall comply with the TCEQ regulations in Title 30 Texas Administrative Code Chapter 117 (30 TAC Chapter 117), Division 4 - Cement Kilns.
  - D. If any condition of this permit is more stringent than the regulations so incorporated, then for the purposes of compliance, the permit shall govern and be the standard by which compliance shall be demonstrated.

# SPECIAL CONDITIONS Permit Numbers 5933 and PSD-TX-63M3 Page 2

- 4. The following contaminants and sources are subject to the federal Prevention of Significant Deterioration (PSD) rules as adopted in 30 TAC § 116.160:
  - A. Particulate matter (PM), including particulate matter equal to or less than 10 microns in diameter (PM/PM<sub>10</sub>), and sulfur dioxide (SO<sub>2</sub>) from all sources at site; and
  - B. Carbon monoxide (CO), nitrogen oxides (NO<sub>x</sub>), and volatile organic compounds (VOC) from Kiln and Precalciner No. 2 (Kiln Line 2), identified as EPN 2-DE-3.
- 5. Stack emissions shall meet the following:
  - A. Kiln Line 1 NO<sub>x</sub>, 30-day rolling average,
    - (1) 1.95 lbs NO<sub>x</sub>/ton clinker, from April 1 through October 31; and
    - (2) 390 lbs per hour, from November 1 through March 31.
  - B. Kiln Line 2,
    - (1) NO<sub>x</sub> 1.95 lbs/ton clinker, 30-day rolling average;
    - (2) SO<sub>2</sub> 0.08 lbs/ton clinker, 12-month rolling average;
    - (3) PM 0.007 grain per dry standard cubic foot (gr/dscf), front half;
    - (4) Total Hydrocarbons/VOC 0.10 lb/ton clinker; and
    - (5) CO 1.58 lb/ton clinker.
  - C. No. 2 Clinker Cooler, identified as EPN 2-DE-4, PM 0.005 gr/dscf, front half.
  - D. Finish Mill No. 3, identified as EPN 2-GE-1, PM 0.00137 grain/actual cubic foot (gr/acf), front half.
- 6. Opacity of emissions shall not exceed the following limitations, averaged over a six-minute period, except for those periods, as applicable, described in EPA regulations in 40 CFR Part 60, Subpart A, § 60.11(c):

# **C** Intertek Analysis Results

Contained in the following pages are the results of the Intertek SRF analysis reports.



December 12, 2011

Total Petrochemicals / American Chem Council PO Box 1200 Deer Park, TX 77536 Attn: Brad Stiles

#### **REPORT OF ANALYSIS**

File Number:US150-0026750Lab Number:001Sample Description:Submitted Sample - Extruded Plastic WasteSample Identification:2011-0575Sampled By:UnknownDate Received:12/6/2011Date Analyzed:12/12/2011

ASTM <u>Test Method</u>	Parameter	UOM	AS RECEIVED	DRY BASIS	MAF
D 3302, 7582	Total Moisture	% wt	4.27		
D 7582	Ash	% wt	4.81	5.02	
D 4239 D 5865	Sulfur Calorific Value	% wt Btu/lb (Gross)	0.07 12153	0.07 12695	13366

Respectfully Submitted,

Melanie McMahon Intertek

> 725 Oakridge Drive - Romeoville, IL 60446 Telephone 815-221-5002 Fax 815-221-5008





**INTERIM** 

Client: Total Petrochemicals, Inc. Job Location: Deer Park, TX, USA

Our Reference Number: US785-0026585

Client Reference Number:

4500857225

Sample ID: 2011-DRPK-007849-001 Sample Designated As: Paper Vessel/Location: DCS Representing: Rep 1,Total 24.8704g,60/40 Plastic/Paper		Date Taken: 01-June-2011 Date Submitted: 01-June-2011 Date Tested: Drawn By: Client		
Method	Test	Result	Units	
ASTM D7359	Total Eluorine Chlorine and Sulfur in Aromati	orine and Sulfur in Aromatic Hydrocarbons and Their mixtures by Oxidative Pyrobydrolytic		

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# D Electricity Emissions Generation Rates

The  $CO_2$ ,  $NO_X$ , and  $SO_2$  emission rates in Table D.1 are taken from eGRID [28, 33, 34].

Table D.1: Emission Rates for Electricity Generated in Different Regions of the United States [32, 28, 33, 34].

Pollutant	U.S. Average	WECC	MRO	ERCOT	$\mathbf{Units}$
$CO_2$	1,190.0	850.0	1,570.0	1,030.0	(lbs/MWh)
$NO_X$	1.4	1.1	2.0	0.4	(lbs/MWh)
$SO_2$	6.7	0.9	4.6	1.7	(lbs/MWh)
$\mathbf{PM}$	0.31	0.15	0.29	0.17	(lbs/MWh)
THC (VOC)	24.0	23.0	34.0	20.0	(lbs/GWh)
Hg	0.020	0.009	0.035	0.030	(lbs/GWh)
$\mathrm{HC}\ell$	52.0	2.5	24.0	13.0	(lbs/GWh)

eGRID has emission rates for the years 1996 - 2000, 2004, 2005, and 2007. The years 2004, 2005, and 2007 are used in this study because they are the most recent and do not have any significant gaps in time between them. As seen in Figures D.1, D.2, and D.3, the emission rates from 2004, 2005, and 2007 show a nearly linear decreasing trend for all emission rates in all regions (as well as the U.S. average) except for a single case. The single case where the data points do not agree with a linear decreasing trend is the U.S. average for SO<sub>2</sub> emissions rate. Because the U.S. average SO<sub>2</sub> emission rate does not show a recognizable trend and does not follow the trend of the three regions of study (slightly decreasing or nearly constant), the highest value of 6.72 lbs/MWh was used as an estimate for 2011.

The particulate matter (PM) and total hydrocarbon (THC) emissions are provided by EPA national and state summaries of PM and THC emissions by sector source. The PM emissions of interest are particulates under 10 micrometers ( $\mu$ m), also called PM10. PM10 includes any particles less than 2.5  $\mu$ m, which are referred to as PM2.5. The EPA emissions data for both THC and PM is for the year 2005 [32]. The THC emissions data are derived from the volatile organic compound (VOC) emission data from the EPA, at a one-to-one ratio, based on the EPA Conversion Factors for Hydrocarbon Emission Components report where VOC = THC for all non-tailpipe emissions [19]. The emissions data are combined



Figure D.1: The carbon dioxide  $(CO_2)$  emission rate has dropped over the past 8 years for the U.S. as a whole and within each region of study [34, 33, 28].

with state specific electricity generation data from the EIA for 2005 to produce an emission rate [49]. The emissions and electricity generation data were collected on a state-by-state basis to make up the WECC, MRO, and ERCOT grids. A small error is expected because the regions include only portions of some states while the emissions data are based on the entire state. However, this error is not expected to cause a dramatic difference in results and offers the highest level of resolution with the data available.

The HC $\ell$  and mercury emissions are taken from the EPA's Toxic Release Inventory and projected for the year 2011 as shown in Figures D.4 and D.5 [32, 34, 33, 28]. There is a noticeable difference in HC $\ell$  emissions between the U.S. average and the three regions being studied. This difference is in large part due to significant state-by-state differences in HC $\ell$  emissions. Data from the EPA Toxic Release Inventory confirm that some states have extremely high HC $\ell$  emissions, such as Maryland with 663 lb/GWh in 2007, while most states are between 10 – 30 lbs/GWh. Additionally, the WECC contains some of the states with the lowest HC $\ell$  emissions rates, primarily California, Washington, and Oregon [32].

The mercury emission rates from the EPA Toxic Release Inventory (TRI) and state generation data from the EIA were validated using the EPA's Mercury Study Report to Congress.


Figure D.2: The nitrogen oxide  $(NO_X)$  emission rate has dropped over the past 8 years for the U.S. as a whole and within each region of study [34, 33, 28].

In the study, the EPA found that U.S. mercury emissions from utility boilers in 1995 was 51.8 tons. The EIA reports that 3,353 billion kWh of electricity were generated in the U.S. in 1995, giving a mercury emission rate of around 0.3 lbs Hg/GWh for the U.S., very near the expected value of 0.28 lbs Hg/GWh for 1995 using the U.S. data in Figure D.5 [50]. The mercury emissions from the TRI were also compared against mercury emissions rates from the eGRID data for the year 2004 (the only year since 1999 mercury emissions were available from eGRID [34]). The eGRID mercury emission rate values match the TRI values closely for the U.S. average and the ERCOT and WECC regions but are only moderately close to the MRO values. Because the values from TRI agree with the EPA Mercury Study Report and the eGRID values, they are considered reliable and used in this research.



Figure D.3: The sulfur dioxide  $(SO_2)$  emission rate has dropped over the past 8 years within each region of study but the U.S. as a whole shows no obvious trend in this data set [34, 33, 28].



Figure D.4: The hydrogen chloride emission rate has dropped over the past 8 years for the U.S. and MRO, but has remained low in the ERCOT and WECC grids. The U.S. average rate is significantly higher than the other regions considered because of some states with high emission rates that are not included in any of the regions studied [32].



Figure D.5: The mercury emission rate has not changed significantly over the past 8 years in any of the regions studied [32]. The X marks represent eGRID 2004 values.

## **E** State Electricity Prices

The following page contains a state-by-state breakdown of electricity prices in the U.S.

## Table 4. Average Retail Price for Bundled and Unbundled Consumers by Sector, Census Division, and State, 2010 (Cents per kilowatthour)

Census Division	Residential	Commercial	Industrial	Transportation	All Sectors
State					
New England	16.24	14.72	12.98	8.45	14.89
Connecticut	19.25	16.45	14.50	11.46	17.39
Maine	15.71	12.51	9.17	-	12.84
Massachusetts	14.59	14.53	13.71	6.46	14.26
New Hampshire	16.32	14.26	12.75	-	14.84
Rhode Island	15.92	13.11	11.82	13.86	14.08
Vermont	15.57	13.44	9.53	-	13.24
Middle Atlantic	15.81	13.93	8.40	12.35	13.60
New Jersey	16.57	13.89	11.81	11.91	14.68
New York	18.74	16.31	8.78	13.74	16.41
Pennsylvania	12.70	10.10	7.66	7.92	10.31
East North Central	11.41	9.36	6.53	6.93	9.08
Illinois	11.52	8.88	6.82	6.71	9.13
Indiana	9.56	8.38	5.87	9.21	7 67
Michigan	12.46	9.81	7.08	10.65	9.88
Ohio	11 32	9.73	6.40	8.62	9.14
Wisconsin	12.65	9.18	6.85	0.02	9.78
West North Central	9.64	7.87	5.86	6.05	7.03
lowa	9.04	7.07	5.00	0.95	1.33
Kansas	10.42	1.91	5.30	-	1.00
Minneete	10.03	ö.25	0.23		ö.35
Minnesota	10.59	8.38	6.29	1.11	8.41
Missouri	9.08	7.50	5.50	6.14	7.78
Nebraska	8.94	7.63	6.00	-	7.52
North Dakota	8.13	7.21	5.81	-	7.11
South Dakota	8.97	7.55	6.07	-	7.82
South Atlantic	10.96	9.29	6.66	9.38	9.61
Delaware	13.80	11.36	9.57	-	11.97
District of Columbia	14.01	13.42	7.78	11.04	13.35
Florida	11.44	9.76	8.85	8.58	10.58
Georgia	10.07	9.06	6.22	7.46	8.87
Maryland	14.32	11.75	9.57	9.78	12.70
North Carolina	10.12	8.16	6.17	7.09	8.67
South Carolina	10.50	8.90	5.74	-	8.49
Virginia	10.45	7.65	6.66	7.70	8.69
West Virginia	8.79	7.66	5.86	8.33	7.45
East South Central	9.58	9.34	5.83	11.09	8.16
Alabama	10.67	10.18	6.01	-	8.89
Kentucky	8.57	7.88	5.05	-	6.73
Mississippi	9.87	9.32	6.32	-	8.59
Tennessee	9.23	9.66	6.58	11.09	8.61
West South Central	10.67	8.78	6.12	9.78	8.74
Arkansas	8.86	7.31	5 44	11.33	7 28
Louisiana	8.98	8 50	5.84	9.46	7.80
Oklahoma	Q 14	7 45	5 35		7.50
Texas	11 60	0 10	6.44	0 83	0.24
Mountain	10.40	9.19 Q 75	0.44 6.10	0.10	9.34 8 FO
Arizona	10.49	0.75	0.13	9.10	0.09
Colorado	11.97	9.47	6.00	0.24	9.09
Idaba	7.04	9.13	0.90	9.34	9.15
Montono	7.99	0.64	5.15	-	0.54
Nevede	9.16	8.55	5.49	-	7.88
	12.36	9.78	1.37	9.40	9.73
	10.52	8.57	6.01	-	8.40
Utan	8.71	7.15	4.93	8.69	6.94
Wyoming	8.77	7.42	4.98	-	6.20
Pacific Contiguous	12.31	11.58	7.47	8.23	10.92
California	14.75	13.10	9.80	8.27	13.01
Oregon	8.87	7.59	5.41	6.99	7.56
Washington	8.04	7.37	4.07	7.42	6.66
Pacific Noncontiguous	23.22	20.45	19.88	-	21.14
Alaska	16.26	13.95	14.14	-	14.76
Hawaii	28.10	25.93	21.94	-	25.12
U.S. Total	11.54	10.19	6.77	10.57	9.83