Lesser Known Energy Sources: A Study of Biogas and Tire-based Fuel

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ABSTRACT

The objective of this article is to investigate two reasonably uncommon energy sources: biogas and scrap tire-based fuel and their potential use in industry. The article will discuss germane background information about the energy sources, such as current and potential uses, operational constraints, advantages, and disadvantages. In addition, this article will explore each fuel source's potential capacity for energy generation and fuel savings. The quantitative section on biogas analyzes the amount of power biogas digesters can provide based off on varying types and numbers of farm animals and generation methods. The scrap tire fuel section analyzes potential fuel savings with cement kilns, explores these values using several examples, and conducts cursory financial analysis of tire fuel projects. Lastly, this article concludes that there exists great potential for fuel and cost savings with these types of alternative energy sources.

INTRODUCTION

It is well known that motors use about 50% of the total electric energy used in industry, which in turn consumes about 35% of the energy used in U.S. The relevance on efficiency motors estimation is based on the impact that this metric has over energy management analysis, which includes the evaluation of data and systems performance in current or future energy utilization. Certainly, it is known that the motor efficiency can be understood by everyone in the industry as the ratio of its useful power output to its total power input.

However, the approach taken to estimate these terms may vary significantly based on the standard used. According to previous research [1], the difference among European standard and American standard could be up to 2.5% for motors in the 1-100 hp range. This situation has been recognized and now the International Electro Technical Commission (IEC 34-2) is looking to improve its deficiencies according to real values.

Today, it is recognized that efficiency estimation coming from IEEE-12-B and NEMA provides the most accurate information among the generally world-wide accepted standards; therefore the need to have a pragmatic and reliable approach to apply this standard in our energy analysis arises.

In this work we show how from basic motor efficiency concepts supported on reliable experiments results [2], the electric-efficiency behaviors can be predicted. We develop a simple but useful procedure to facilitate the motor efficiency estimation based on very little data collection.

In the next section we review some useful motor efficiency concepts. Then a current widely used standards background is presented. To start our derivations we show some previous results found in the literature. At this point we present our analysis through some curves and equations development. We then discuss our results and present three-dimensional efficiency surfaces for motors under known working conditions. Finally, in the last section we present our conclusions.

BIO-GAS

Biogas is a product resulting from the anaerobic digestion of organic waste products. In an environment devoid of oxygen, anaerobic bacteria break down the carbohydrates that are in the waste products. This process of digestion releases several gasses and two of the most prevalent ones include carbon dioxide (CO_2) and methane (CH_4). The gas mixture can then be collected and use it as a fuel (Figure 1). The chemical equation for this digestion is shown in the following equation [6]:

$$C_xH_yO_z + (x-y/4-z/2)H_2O \rightarrow (x/2-y/8+z/4)CO_2 + (x/2+y/8-z/4)CH_4$$

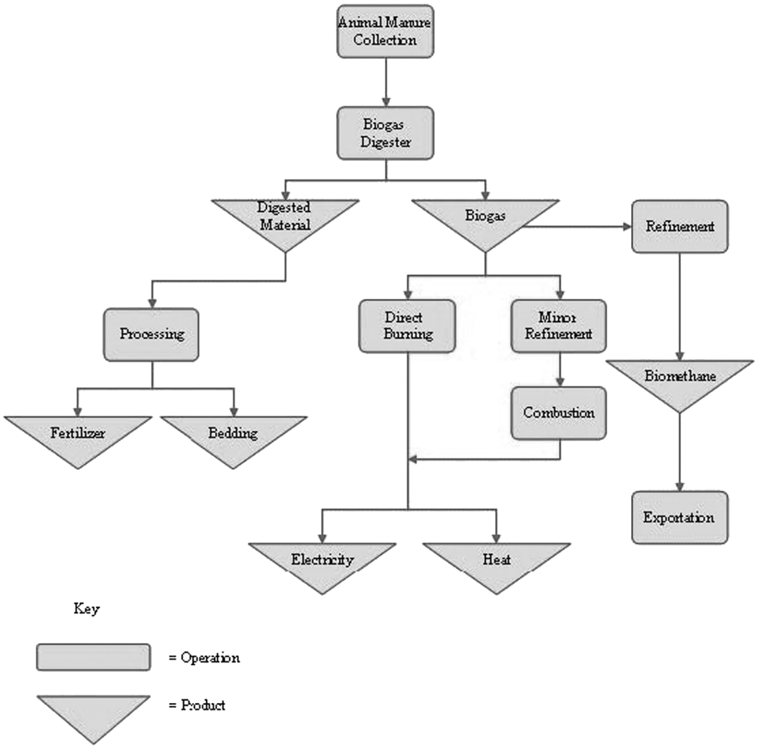

Figure 1. Biogas Flow Diagram

One can create biogas from a variety of sources and, depending on the source of the biogas, it may be termed differently. Some of the sources of biogas and its variants include animal slurries, slaughterhouse wastes, sewer systems, and landfills. This article will focus on biogas that results from the digestion of animal wastes as opposed to other sources, such as human waste. [6]

Biogas primarily consists of CO_2 and CH_4, but it also contains some moisture, and may contain trace quantities of compounds such as H_2 and H_2S. Typically, the maximum amount of methane found in biogas is about 70% and the minimum amount of carbon dioxide in biogas is about 30%. Often, an acceptable approximation for the composition of average biogas is between 50% and 60% methane. Typically, there are between 525 and 750 Btus of energy per cubic foot of biogas, depending on its methane composition and quality. [6]

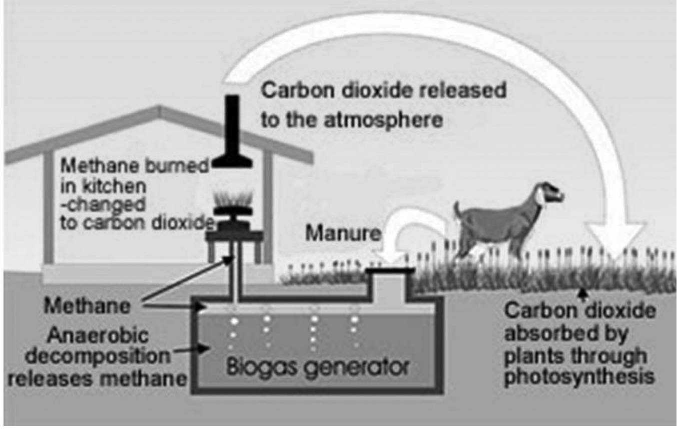

Figure 2. Biogas Cycle

Farms that generate biogas can use it for a myriad of applications. On smaller farms, the gas may be primarily burned to provide heat for the digesters (Figure 2). For digesters to produce biogas, certain temperatures must be maintained. Typically, the requisite temperature is about 100°F. Because of these temperature maintenance constraints, smaller farms will frequently have to use the produced biogas for digester warming applications. Consequently they will not gain any energy related benefits from digesters. [6]

GENERAL USES OF BIOGAS

Larger farms often burn the biogas and generate electricity from its combustion (Figure 3). Farms generally use this electricity to offset current electrical costs, but in cases where electricity is plentiful, farms can sell the electricity back to the utility company. In addition to generating power, farms can also use the heat from combustion to warm the digester, to heat water, or to provide heating. The most common uses of biogas are classified as on-farm uses and electricity is not commonly sold back to utility companies.[9]

In addition to heating and power generation applications, one can also refine biogas for use as a substitute to natural gas. This requires that CO_2 be removed from biogas to augment energy content. In addition, it is imperative to remove corrosive impurities such as H_2S and water.

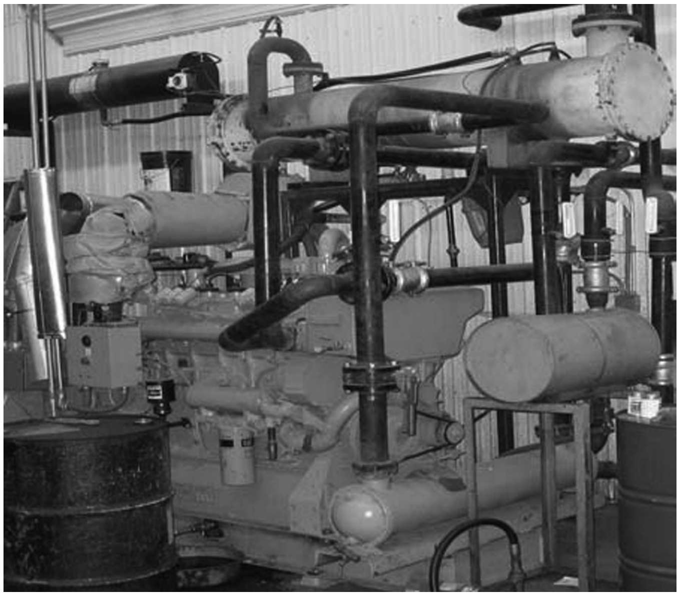

Figure 3. Biogas-rated Generator.

When all of these undesirable compounds are removed from the biogas, the CH_4 content becomes very high and the compound is commonly known as biomethane. Only after these upgrading procedures is the gas generally of sufficient quality to be exported off the farm and sold. In addition, once one completes the purification and refinement steps, one can distribute biomethane via normal natural gas pipelines.[9]

USAGE CONSTRAINS

Currently, a great number of constraints exist that make the usage of biogas somewhat difficult and expensive. To setup a biogas digester, considerable effort may be necessary to move animal excrement to the digester. Unfortunately, this extra effort can greatly augment the cost of a biogas digester project and ultimately lead to abandonment of the project. Consequently, it is important for biogas digesters to be placed in the steam of waste materials that currently exists because if these waste streams are heavily dispersed and not concentrated, the collection of wastes will require too much effort.[6]

In general, many typical burners cannot directly substitute biogas in place of natural gas. This is not merely because biogas contains compounds such as water and H_2S, but also because biogas has a large CO_2 content and posses a much lower energy per volume value when compared to natural gas. Because the CO_2 content lowers the energy density, there will not be sufficient flame stability if burners maintain current fuel-to-air ratios and pressures as used for natural gas. [9]

Another significant usage constraint of biogas involves the processing of raw biogas. There are methods to remove water and unwanted gasses, and it is possible to improve the quality of biogas to levels comparable to that of pipeline natural gas; however, these steps add additional cost. H_2S, or hydrogen sulfide, is highly corrosive and often needs to be removed. This can be the case even if the biogas is not purified and upgraded to biomethane quality. When one runs equipment using raw biogas, this results in elevated maintenance requirements and decreased reliability because of corrosion. Commonly, one of the many negative effects of using biogas with high H_2S concentrations is an increase in the frequency of oil changes and corrosion.[9]

To distribute biogas off site, one must first purify the biogas to the level of biomethane, removing unwanted compounds such as CO_2, water, and H_2S. Then one must either pipe the biomethane through dedicated biomethane gas lines or regular natural gas pipelines. If these pipelines do not exist and the pipeline construction cost is exorbitant, then some other options exist. One option is to compress the biomethane and transport it in the same fashion that one transports compressed natural gas (CNG). However, experts believe that a superior method for transporting biomethane is shipping the gas while it is in its liquefied form. This form is called liquefied biomethane (LBM) and is essentially equivalent to liquid natural gas (LNG). The primary advantage for transporting biomethane in liquefied form is that there already exists demand for liquid natural gas, as well as means for its transportation. Unfortunately, one significant problem with liquid biomethane is that it needs to be consumed rapidly after processing.[9]

Lastly, to provide a meaningful amount of biogas to be used as fuel in place of natural gas or to be burned and converted into electricity requires a farm with a substantial herd. Although smaller farms can still benefit from having a digester, the primary benefits would be odor reduction and elimination of potentially hazardous waste.

POTENTIAL APPLICATIONS

The potential for selling biogas appears to be fairly limited at this time. Most large farms that generate substantial quantities of biogas use the gas for internal purposes such as offsetting electricity costs and for heating. However, it is possible to export biogas off the farm. To achieve this, the gas first must be upgraded in quality to the level of biomethane. Afterwards, the gas may be shipped out via pipeline, compressed or liquefied and trucked out.[7,9]

Because of shipping and processing expenses and the reduction in on farm availability, the attractiveness of liquefying biomethane and exporting it off-farm is not particularly high. However, in certain areas of the country this could theoretically prove to be commercially viable. For businesses that do not have access to natural gas pipelines but are in close proximity to large farms, slaughterhouses, or any potential biogas source, a partnership could be formed. The proximity between the source and customer would reduce shipping expenses and make a project of this type more appealing. In addition, as natural gas prices rise, the profitability of producing and selling biomethane will grow and this may increase opportunities for biogas creating digesters.

ADVANTAGES AND BENEFITS OF BIOGAS AND BIOGAS PRODUCTION

Currently, there exist many advantages associated with biogas and its production. While many of the principal positive aspects of biogas are energy related, there also exists a plethora of additional benefits. First, the digested waste products that result from the process of biogas creation are considerably less harmful and toxic than the waste in its original form. There is a sharp reduction in the quantity of parasites and harmful germs. Although the digestion process does not destroy all pathogens and parasites, the risk of disease diminishes drastically.[6]

Another excellent, non-energy related benefit of biogas digesters is that they can help combat odor problems. On some smaller farms, the primary purpose of a biogas digester is the management of odor because small farms cannot produce meaningful quantities of biogas to support power generation. Furthermore, new farms may be required to implement odor control procedures to operate. Finally, in some situations residential areas may be encroaching on well established farm territory and demanding odor control practices to be initiated. Although the odor reduction benefits of digesters are difficult to quantify, biogas digesters can provide an effective solution to odor problems resulting in improved community relations.[7,8]

In certain situations, one can recover the digested solids and use them as bedding material. The digested solids generally need to be well dried before use, and as long as this occurs, the bedding should be of good quality. According to the agricultural biogas casebook, some farms have reported savings between $30,000 and $75,000 from using digested solids as bedding.[7,9]

Considerable savings can also arise from using digested material as fertilizer. The fertilizer can be sold, but in all likelihood, it will be used as a replacement for commercial fertilizers and result in offset costs. The digested manure is generally richer in nutrients, with more optimal levels of nitrogen, phosphorus, and potassium. Lastly, fertilizer provides cost savings that are often more valuable than bedding cost savings in terms of savings per cow.[7]

While there clearly are many non-energy related benefits of biogas and its production, the primary purpose of most large biogas digesters is to create energy and fuel. These digesters can provide large quantities of renewable energy that can be burned for heating uses, refined and sold, or directly burned for the generation of electricity. In addition, there exists much potential for combined heat and power applications because larger generators will output copious amounts of waste heat. Overall, the principal biogas related energy benefits are potential streams of electricity, biomethane, and heat energy [7,9].

DISADVANTAGES AND DRAWBACKS OF BIOGAS AND BIOGAS PRODUCTION

There are several drawbacks related to biogas and its production; however these negatives are generally minor. One of these negatives is that biogas creation requires warm, wet, and dark conditions. For colder environments, the yield of biogas production is sharply reduced because an elevated level of gasses needs to be burned to maintain the necessary temperatures conducive to anaerobic digestion. In addition, this presence of lignin reduces the generation of biogas in a digester.[6]

In addition, the initial cost to setup a biogas digester and generator that can provide significant amounts of energy is very expensive, and a large biogas project will require continuous maintenance. Some of the primary pieces of capital equipment required for power generation from biogas include the digesters, biogas rated generators, biogas fired boilers to warm the digesters, and a great deal of supporting and transporting equipment.[7, 9]

Lastly, one intrinsic disadvantage of biogas is that it is usually of a much lower quality than natural gas. It is often between 30-50% CO_2, which reduces the energy per cubic feet by up to a factor of 2 when compared to natural gas. In addition, water and other unwanted gasses such as H_2S are components of biogas, which frequently need to be removed.[6]

POTENTIAL POWER OF BIOGAS PRODUCTION

This section will investigate the ability of biogas to generate continuous thermal power and electrical power. Tables 1 through 8 explore the various amounts of power that biogas plants can generate. Tables 1 through 8 occur in related pairs, with Tables 1 and 2 being related, 3 and 4 being related, and so on. Also, the first table in each pair displays the values of the parameters used in the larger table. The larger table is the one that holds all of the calculations. In each example case, there is only one type of animal per farm and the animal is a pig, beef steer, or dairy cow. The first three sets of tables assume that the biogas generates steam which can drive a turbine to create power. The last set of tables, Tables 7 and 8, assumes that the biogas powers a biogas rated reciprocating generator. For the reciprocating generator case, the example will only focus on the dairy cow values. Note that many value tiers in the table are either not practical or unfeasible. For example, a farm with only 250 pigs would not generate enough biogas to power a steam driven turbine. These values are in the table for illustrative purpose only. Although slightly adapted for each case in the tables, the underlying formula is as follows:

$$E = \mu \times H \times f \times \upsilon$$

Where,

E = Energy output

μ = Efficiency

H = Heat of combustion for methane, 28 MJ/m^3
f = Fraction of methane in biogas
υ = Biogas volume

And

$$\upsilon = C \times m$$

Where,

C = Biogas yield per kg of solid excrement
m = Total mass of the solid excrement input

For example, power output in the stream case with 500 diary cows is as follows:

$$E = (70\%) \times (28\ \mathrm{MJ/m^3}) \times (60\%) \times (0.3\ \mathrm{m^3/kg}) \times (500\ \mathrm{cows}) \times (4.5\mathrm{kg/cow/day})$$

Where,

$$E = 7{,}938\ \mathrm{MJ/day}$$

Note that,

$$\begin{aligned} m &= (500\ \mathrm{cows}) \times (4.5\mathrm{kg/cow/day}) \\ &= 2{,}250\ \mathrm{kg/day} \end{aligned}$$

Converting to thermal power (TP),

$$\begin{aligned} TP &= E/(3.6\ \mathrm{MJ/kWh}) \\ &= 2{,}205\ \mathrm{kWh/day} \\ &= 91.88\ \mathrm{kW\ (continuous)} \end{aligned}$$

Multiplying by the generator efficiency, the electrical power (EP) is:

$$\begin{aligned} EP &= (91.88\ \mathrm{kW}) \times (40\%) \\ &= 36.75\ \mathrm{kW} \end{aligned}$$

The power output in the reciprocating generator case with 500 diary cows is as follows:

$$E = \mu \times H \times f \times \upsilon$$

$$E = (35\%) \times (28\ \mathrm{MJ/m^3}) \times (60\%) \times (0.3\ \mathrm{m^3/kg}) \times (500\ \mathrm{cows}) \times (4.5\mathrm{kg/cow/day})$$

Where,

$$E = 3{,}969\ \mathrm{MJ/day}$$

Note that,

m = (500 cows) × (4.5kg/cow/day) = 2,250 kg/day
μ = Reciprocating generator efficiency

Converting to electrical power (EP),

$$\begin{aligned} EP &= E/(3.6\ \text{MJ/kWh}) \\ &= 1{,}102.5\ \text{kWh/day} \\ &= 45.94\ \text{kW (continuous)} \end{aligned}$$

Table 1. Pig Data [6]

Pig (60 kg)			
		Units	**Approximate Ranges (if highly variable)**
Manure	3.3	Wet kg/animal/day	
Mass of Solids	0.3	Solid kg/animal/day	
Approximate Burner Efficiency	70%		0.5 to 0.8
Biogas Yield	0.3	Cubic meter/kg	0.2 to 0.4
Combustion Energy from Methane	28	MJ/cubic meter	
Density of Manure Solution	50	kg/cubic meter	
Retention Time	20	days	8 to 20
Percentage of Methane in Biogas	60%		50% to 70%
Approximate Generator Efficiency	40%		25% to 45%

Table 2. Steam Case with Pig Waste

Number of Pigs	**Mass of Solids**	**Volume of Digester Fluid**	**Approximate Digester Volume**	**Volume of Biogas Generated**	**Thermal Energy Output**	**Thermal Energy Output**	**Thermal Power**	**Electrical Power**
	kg/day	**m^3/day**	**m^3**	**m^3/day**	**MJ/day**	**kWh/day**	**kW**	**kW**
250	75	1.5	30	22.5	265	74	3.06	1.23
500	150	3.0	60	45.0	529	147	6.13	2.45
750	225	4.5	90	67.5	794	221	9.19	3.68
1,000	300	6.0	120	90.0	1,058	294	12.25	4.90
1,250	375	7.5	150	112.5	1,323	368	15.31	6.13
1,500	450	9.0	180	135.0	1,588	441	18.38	7.35
1,750	525	10.5	210	157.5	1,852	515	21.44	8.58
2,000	600	12.0	240	180.0	2,117	588	24.50	9.80
2,250	675	13.5	270	202.5	2,381	662	27.56	11.03
2,500	750	15.0	300	225.0	2,646	735	30.63	12.25
2,750	825	16.5	330	247.5	2,911	809	33.69	13.48
3,000	900	18.0	360	270.0	3,175	882	36.75	14.70
3,250	975	19.5	390	292.5	3,440	956	39.81	15.93
3,500	1,050	21.0	420	315.0	3,704	1,029	42.88	17.15
3,750	1,125	22.5	450	337.5	3,969	1,103	45.94	18.38
4,000	1,200	24.0	480	360.0	4,234	1,176	49.00	19.60
4,250	1,275	25.5	510	382.5	4,498	1,250	52.06	20.83
4,500	1,350	27.0	540	405.0	4,763	1,323	55.13	22.05
4,750	1,425	28.5	570	427.5	5,027	1,397	58.19	23.28
5,000	1,500	30.0	600	450.0	5,292	1,470	61.25	24.50
5,250	1,575	31.5	630	472.5	5,557	1,554	64.31	25.73
5,500	1,650	33.0	660	495.0	5,821	1,617	67.38	26.95
5,750	1,725	34.5	690	517.5	6,086	1,691	70.44	28.18
6,000	1,800	36.0	720	540.0	6,350	1,764	73.50	29.40
6,250	1,875	37.5	750	562.5	6,615	1,838	76.56	30.63
6,500	1,950	39.0	780	585.0	6,880	1,911	79.63	31.85

Table 3. Beef Steer Data [6]

Beef Cow (300 kg)			
		Units	**Approximate Ranges (if highly variable)**
Manure	25	Wet kg/animal/day	
Mass of Solids	3.2	Solid kg/animal/day	
Approximate Burner Efficiency	70%		0.5 to 0.8
Biogas Yield	0.3	Cubic meter/kg	0.2 to 0.4
Combustion Energy from Methane	28	MJ/cubic meter	
Density of Manure Solution	50	kg/cubic meter	
Retention Time	20	days	8 to 20
Percentage of Methane in Biogas	60%		50% to 70%
Approximate Generator Efficiency	40%		25% to 45%

Table 4. Steam Case with Beef Steer Waste

Number of Beef Cattle	**Mass of Solids**	**Volume of Digester Fluid**	**Approximate Digester Volume**	**Volume of Biogas Generated**	**Thermal Energy Output**	**Thermal Energy Output**	**Thermal Power**	**Electrical Power**
	kg/day	**m^3/day**	**m^3**	**m^3/day**	**MJ/day**	**kWh/day**	**kW**	**kW**
100	320	6.4	128	96	1,129	314	13.07	5.23
200	640	12.8	256	192	2,258	627	26.13	10.45
300	960	19.2	384	288	3,387	941	39.20	15.68
400	1,280	25.6	512	384	4,516	1,254	52.27	20.91
500	1,600	32.0	640	480	5,645	1,568	65.33	26.13
600	1,920	38.4	768	576	6,774	1,882	78.40	31.36
700	2,240	44.8	896	672	7,903	2,195	91.47	36.59
800	2,560	51.2	1,024	768	9,032	2,509	104.53	41.81
900	2,880	57.6	1,152	864	10,161	2,822	117.60	47.04
1,000	3,200	64.0	1,280	960	11,290	3,136	130.67	52.27
1,100	3,520	70.4	1,408	1,056	12,419	3,450	143.73	57.49
1,200	3,840	76.8	1,536	1,152	13,548	3,763	156.80	62.72
1,300	4,160	83.2	1,664	1,248	14,676	4,077	169.87	67.95
1,400	4,480	89.6	1,792	1,344	15,805	4,390	182.93	73.17
1,500	4,800	96.0	1,920	1,440	16,934	4,704	196.00	78.40
1,600	5,120	102.4	2,048	1,536	18,063	5,018	209.07	83.63
1,700	5,440	108.8	2,176	1,632	19,192	5,331	222.13	88.85
1,800	5,760	115.2	2,304	1,728	20,321	5,645	235.20	94.08
1,900	6,080	121.6	2,432	1,824	21,450	5,958	248.27	99.31
2,000	6,400	128.0	2,560	1,920	22,579	6,272	261.33	104.53
2,100	6,720	134.4	2,688	2,016	23,708	6,586	274.40	109.76
2,200	7,040	140.8	2,816	2,112	24,837	6,899	287.47	114.99
2,300	7,360	147.2	2,944	2,208	25,966	7,213	300.53	120.21
2,400	7,680	153.6	3,072	2,304	27,095	7,526	313.60	125.44
2,500	8,000	160.0	3,200	2,400	28,224	7,840	313.60	125.44

Table 5. Dairy Cow Data [6]

Dairy Cow (500 kg)			
		Units	**Approximate Ranges (if highly variable)**
Manure	35	Wet kg/animal/day	
Mass of Solids	4.5	Solid kg/animal/day	
Approximate Burner Efficiency	70%		0.5 to 0.8
Biogas Yield	0.3	Cubic meter/kg	0.2 to 0.4
Combustion Energy from Methane	28	MJ/cubic meter	
Density of Manure Solution	50	kg/cubic meter	
Retention Time	20	days	8 to 20
Percentage of Methane in Biogas	60%		50% to 70%
Approximate Generator Efficiency	40%		25% to 45%

Table 6. Steam Case with Dairy Cow Waste

Number of Dairy Cow	Mass of Solids	Volume of Digester Fluid	Approximate Digester Volume	Volume of Biogas Generated	Thermal Energy Output	Thermal Energy Output	Thermal Power	Electrical Power
	kg/day	m^3/day	m^3	m^3/day	MJ/day	kWh/day	kW	kW
100	450	9	180	135	1,588	441	18.38	7.35
200	900	18	360	270	3,175	882	36.75	14.70
300	1,350	27	540	405	4,763	1,323	55.13	22.05
400	1,800	36	720	540	6,350	1,764	73.50	29.40
500	2,250	45	900	675	7,938	2,205	91.88	36.75
600	2,700	54	1,080	810	9,526	2,646	110.25	44.10
700	3,150	63	1,260	945	11,113	3,087	128.63	51.45
800	3,600	72	1,440	1,080	12,701	3,528	147.00	58.80
900	4,050	81	1,620	1,215	14,288	3,969	165.38	66.15
1,000	4,500	90	1,800	1,350	15,876	4,410	183.75	73.50
1,100	4,950	99	1,980	1,485	17,464	4,851	202.13	80.85
1,200	5,400	108	2,160	1,620	19,051	5,292	220.50	88.20
1,300	5,850	117	2,340	1,755	20,639	5,733	238.88	95.55
1,400	6,300	126	2,520	1,890	22,226	6,174	257.25	102.90
1,500	6,750	135	2,700	2,025	23,814	6,615	275.63	110.25
1,600	7,200	144	2,880	2,160	25,402	7,056	294.00	117.60
1,700	7,650	153	3,060	2,295	26,989	7,497	312.38	124.95
1,800	8,100	162	3,240	2,430	28,577	7,938	330.75	132.30
1,900	8,550	171	3,420	2,565	30,164	8,379	349.13	139.65
2,000	9,000	180	3,600	2,700	31,752	8,820	367.50	147.00
2,100	6,450	189	3,780	2,835	33,340	9,261	385.88	154.35
2,200	9,900	198	3,960	2,970	34,927	9,702	404.25	161.70
2,300	10,350	207	4,140	3,105	36,515	10,143	422.63	196.05
2,400	10,800	216	4,320	3,240	38,102	10,584	441.00	176.40
2,500	11,250	225	4,500	3,375	39,690	11,025	459.38	183.75

Table 7. Dairy Cow Data for the Reciprocating Generator Case [6, 22]

Dairy Cow			
		Units	**Approximate Ranges (if highly variable)**
Manure	35	Wet kg/animal/day	
Mass of Solids	4.5	Solid kg/animal/day	
Biogas Yield	0.3	Cubic meter/kg	0.2 to 0.4
Combustion Energy from Methane	28	MJ/cubic meter	
Density of Manure Solution	50	kg/cubic meter	
Retention Time	20	days	8 to 20
Percentage of Methane in Biogas	60%		50% to 70%
Approximate Generator Efficiency	40%		25% to 45%

Table 8. Reciprocating Generator Case with Dairy Cow Waste

Number of Dairy Cow	**Mass of Solids**	**Volume of Digester Fluid**	**Approximate Digester Volume**	**Volume of Biogas Generated**	**Thermal Power**	**Electrical Power**
	kg/day	**m^3/day**	**m^3**	**m^3/day**	**kW**	**kW**
100	450	9	180	135	26.25	9.19
200	900	18	360	270	52.50	18.38
300	1,350	27	540	405	78.75	27.56
400	1,800	36	720	540	105.00	36.75
500	2,250	45	900	675	131.25	45.94
600	2,700	54	1,080	810	157.50	55.13
700	3,150	63	1,260	945	183.75	64.31
800	3,600	72	1,440	1,080	210.00	73.50
900	4,050	81	1,620	1,215	236.25	82.69
1,000	4,500	90	1,800	1,350	262.50	91.88
1,100	4,950	99	1,980	1,485	288.75	101.06
1,200	5,400	108	2,160	1,620	315.00	110.25
1,300	5,850	117	2,340	1,755	341.25	119.44
1,400	6,300	126	2,520	1,890	367.50	128.63
1,500	6,750	135	2,700	2,025	393.75	137.81
1,600	7,200	144	2,880	2,160	420.00	147.00
1,700	7,650	153	3,060	2,295	446.25	156.19
1,800	8,100	162	3,240	2,430	472.50	165.38
1,900	8,550	171	3,420	2,565	498.75	174.56
2,000	9,000	180	3,600	2,700	525.00	183.75
2,100	9,450	189	3,780	2,835	551.25	192.94
2,200	9,900	198	3,960	2,970	577.50	202.13
2,300	10,350	207	4,140	3,105	603.75	211.31
2,400	10,800	216	4,320	3,240	630.00	220.50
2,500	11,250	225	4,500	3,375	656.25	229.69

Figure 4 displays different values of electrical power generated (kW) as a function of the number of animals:

WASTE TIRE FUEL

Scrap tires are old tires that are no longer fit for their original use. Historically, scrap tires have been disposed of and placed into landfills or put into an immense pile (Figure 5). Unfortunately, scrap tires occupy a great deal of space in landfills because they cannot be compressed and do not biodegrade. Because of this, in the mid-1980s many states began to create scrap tires management programs. A large number of states do not allow whole tires to be placed in landfills and often require that the tires be shredded to decrease the volume of space they occupy. Fortunately, tires have a very high energy content, which is typically around 15,000 Btu per pound.[1] This energy density value is even higher than the energy density of coal, which is usually about 2,500 Btu per pound lower. As a result of the high energy content, scrap tires can provide an abundant source of energy. The usage of shredded scrap tire material as fuel is commonly referred to as tire derived fuel, or TDF.[4]

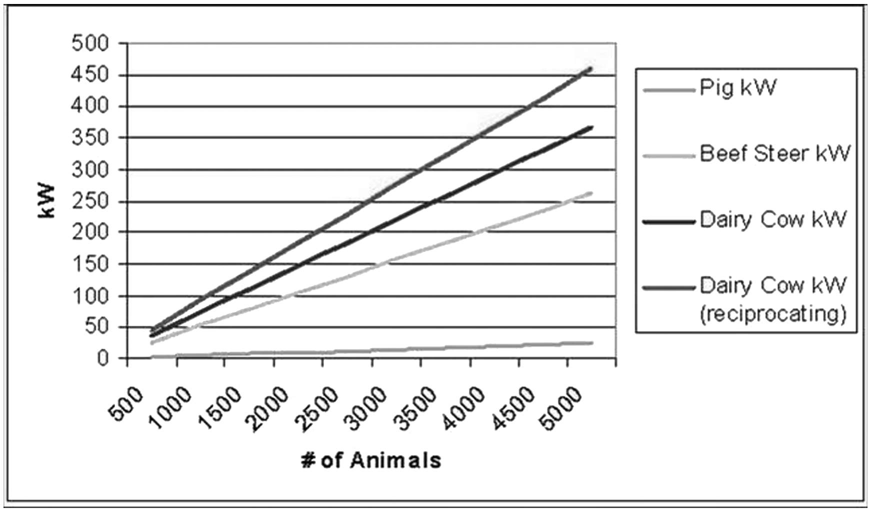

Figure 4. Power from Different Animals

Figure 5. Tire Stock Pile

As stated by the Scrap Tire Management Council, a good rule of thumb is that one scrap tire is generated for every person each year in the United States.[3] With the current U.S. population over 300 million people, this yields about 300 million scrap tires per year. According to the Rubber Manufacturers of America, this number is actually marginally higher, but this article will assume a value of 1 tire per person per year in the United States.

Although this number is changing over time, only about 80% of the 300 million scrap tires are used in a productive fashion. Some of these expedient uses include fuel, asphalt material, or civil engineering functions.[2] Despite the fact that many waste tires are being used in a beneficial manner, the country can still use around 60 million scrap tires constructively. Assuming an average scrap tire weighs around 18 pounds, this means that about 1.08 billion pounds of tires go to waste. Using the values of 15,000 Btu per pound of tire and conservatively approximating that 1 MMBtu of tire fuel saves $10, this equals a potential 16,200,000 MMBtu (4,747,751,550 kWh) of energy and $162,000,000 of dollar savings. Lastly, while combusting tire derived fuel or scrap tires in their whole form is not necessarily the most optimal use, it is vastly superior to placing old tires into landfills.

GENERAL USES OF TIRES AS A FUEL SOURCE

Tire-based fuel is often burned alongside another fuel such as coal. Before combustion, tires are often shredded but occasionally they are burned as whole units. The primary industries that use tire derived fuel are cement industries, the pulp and paper industries, and power generation industries. In addition, some boilers use tire derived fuel.[5]

The cement industry is one of the largest consumers of scrap tires. Unlike many industries, they often burn whole tires instead of shredded tires (Figure 6). As of 2003, the industry burned around 53 million tires. The pulp and paper industry is also a large consumer of tire derived fuel.[2]

Figure 6.
Whole Tires Being Burned.

SOURCES OF TIRES

The most abundant source of tires is waste streams from the general population. Yielding about one tire per person per year, the general population provides a total of approximately 300 million tires per year. In the early 1980s and before, most all tires were disposed of into landfills or tire piles. Over time, many scrap tire stockpiles became very prodigious. As a result, many companies have taken advantage of these large caches of scrap tires. The process of using up stockpiles of scrap tires is generally referred to as abatement and the goal of abatement projects is typically to productively dispose of stockpiled scrap tires. These projects have been in place for many years and as a result, the amount of scrap tires in stockpiles has diminished significantly.[2] Nevertheless, there still exists a myriad of stockpiled scrap tires that can be consumed. Unfortunately, portions of these stockpiles are not always the easiest to access.

USAGE CONSTRAINTS

For many combustion applications, tires must be reduced in size before burning because of space constraints. Many boilers cannot handle full size tires and require them to be shredded. The shredding requirement adds on additional processing costs. Because tires are tough and durable, the expense and energy needed for shredding is large. In addition, because the tire derived fuel is acquired in shredded form the end user cannot capitalize on the tipping fees associated with picking up whole tires. Despite these processing and acquisition drawbacks, tire derived fuel is still less expensive than more well known fuel sources such as natural gas and coal.[5,11,13]

For some boilers and kilns, few or no modifications to the equipment have to be made to co-fire tires with other fuel sources such as coal. However, special feeding devices and conveyors are necessary to provide the equipment with a steady stream of scrap tires or shredded tire derived fuel. These specialized loading mechanisms can often cost a great deal of money and increase maintenance requirements.[5]

Another processing constraint is that for certain applications, the user of tire derived fuel must remove the steel wires in the tires before combustion. This is because the wires may impede the feeding process or leave unwanted residue in the combustion ash. This costly step of tire de-wiring is in addition to shredding and is very common in the pulp and paper industry.[2]

In certain areas, transportation costs between the primary supply point of scrap tires and the end user can impose a serious constraint on the usage of tired based fuel. Because of these shipping costs and lack of local availability, certain regions of the country do not effectively support a meaningful scrap tire market. As a result, in these regions one must landfill scrap tires.[2]

POTENTIAL APPLICATIONS

The one tire per person per year rule of thumb is a United States based figure. Many nations in this world do not produce scrap tires at this rate. Developing nations clearly have a lower rate of creating scrap tires per person per year. As these nations become more affluent and larger percentages of their populations can afford automobiles, then it logically follows that the rate of scrap tire generation per person per year will increase. Although unexpected changes in technology, lifestyle, political systems, or stagnant economic growth could profoundly change the future availability scrap tires in such cases, there exists a reasonable likelihood that these waste streams will burgeon. When one combines this productivity per person rate increase with a growing population, there is much potential for new scrap tire waste streams.

According to the Rubber Manufacturers Association, tire derived fuel may benefit from utility deregulation. One logical result of utility deregulation is an elevated level of competition between power generation companies. Price reductions are a likely eventuality resulting from deregulation and increased competition. This may force generation utilities to more aggressively seek out methods for reducing the cost of generating electricity. Because tire derived fuel has excellent heating values and low costs, it can provide a substitute for fuels such as coal.[2]

ADVANTAGES OF TIRE DERIVED FUEL

One of the greatest traits of scrap tire fuel is their unit cost. Tire fuel costs are significantly lower than natural gas costs and the overall unit costs of tire fuel are even less expensive than coal. Even if the scrap tire fuel requires processing, such as shredding and de-wiring, their costs still remain low. In addition, if a company uses whole tires instead of shredded tire derived fuel, they will receive a tipping fee for collecting the whole scrap tires. These fees are usually very small, but they will help offset transportation costs. Furthermore, as traditional fuel prices rise even higher, the cost advantages inherent to tire-based fuel will only increase.[2]

One other advantage of tire fuel is that it has lower levels of NO_x emissions compared to many common fossil fuels. This property of lower NO_x emissions from tire-based fuel is particularly useful if industries are required to lower their NO_x emissions. In practice, co-firing tire derived fuel with coal has reduced NO_x emissions.[1,2]

Lastly, scrap tire fuel represents the largest use of waste tires in the United States.[2] A great advantage of using scrap tires as fuel is that this process prevents massive stockpiles of waste tires from accumulating. Waste tires historically were placed into landfills or into stockpiles. Unfortunately, tires occupy hefty amounts of space in landfills and cannot be reduced in size by means of compression. Furthermore, stockpiles are unsightly and present a potential health hazard. Large stockpiles provide an excellent habitat for rodents and irksome mosquitoes. The process of burning scrap tires for fuel helps combat the buildup of tire garbage.

DISADVANTAGES OF TIRE DERIVE FUELS

One intrinsic disadvantage of burning tire derived fuel is that the combustion process can give off harmful emissions. However, the negative aspects of these emissions are not excessively horrible because tire derived fuel often replaces coal, and coal combustion has many emissions problems. The process of burning tires has a poor reputation because of peoples' observations and perceptions of tire yard fires. Tire fires can last for great durations, emit a gigantic quantity of smoke, and generate inordinate amounts of pollution such as harmful oils and vapors (Figure 7). However, these tire stockpile fires are profoundly different from tire-based fuel combustion. Tire yard fires occur in open air, burn at relatively low temperatures, and do not have complete combustion. Scrap tire fuel combustion occurs in a much more controlled environment and at significantly higher temperatures. This results in complete combustion, much less toxic pollution, and no large plumes of black smoke.[2,5,12,14]

Another disadvantage of using tire derived fuel is that when one burns the tires, they can no longer be used for other applications. There are many potential uses of scrap tires in addition to fuel, some of which include rubber modified asphalt, crumb rubber, playground surfaces, running track surfaces, molded products, animal bedding, and many

Figure 7. Tire Fire

civil engineering applications. Sending scrap tires away for usage as fuel is not always the most optimal method of consumption and using tires in this capacity can limit other opportunities. [2, 13]

WASTE TIRE FUEL CASE: CEMENT KILNS

The purpose of this next section is to do a theoretical analysis of the costs and benefits associated with establishing a tire-based fuel program. This example will study the cost and benefits associated with scrap tire fuel in the cement industry, the largest industrial consumer of fuel-destined waste tires. An important fact to note is that the cement industry often burns whole tires in its kilns as opposed to shredded tires. As a result, some of the costs, fuel transportation issues, aspects of the combustion process, and loading mechanism will differ greatly from other industrial applications.

The primary raw materials involved in the process of making Portland cement include limestone, gypsum, clay, sand, and iron. The limestone, gypsum, clay, and sand are crushed and blended. These raw materials are heating in a rotary kiln along with iron to temperatures around 2700°F. Most of the processing energy needed for manufacturing the cement is used during the heating process in the rotary kiln. The rotary kilns that heat the mixtures are often fired by coal, but some kilns co-fire coal with tire-based fuel.[11]

Tires contain steel wires and when a cement company co-fires whole scrap tires with coal, they no longer need to supplement their process with any iron. However, tires have an elevated zinc content, which changes the quality of the cement. For example, if the zinc content is too high, one effect is that the set time typically increases.[11] Clearly, there are some minor additional benefits and drawbacks associated with using tire derived fuel as a supplemental fuel. Because these benefits and drawbacks are fairly negligible and can be difficult to quantify, they will not be considered for savings calculations.

ANTICIPATED SAVINGS

The primary cost savings that will result from using scrap tire fuel are energy savings from reduced coal usage. Tire-based fuel is less expensive to procure than coal, and by burning some tire fuel in place of coal, significant savings will ensue. In addition to tire-based fuel being less costly than coal, if one uses whole tires as their fuel source, they can obtain a tipping fee for disposing of the whole scrap tires.

The actual values of savings vary greatly depending on the various costs associated with tire-based fuel, cost of coal, size of rotary kiln, equipment utilization factors, and percent of tire-based fuel used in place of coal. Many of these factors, such as fuel costs, vary with time and location. As a result, this article will use reasonable ranges to determine potential savings.

The actual percent of coal replaced by scrap tire fuel varies significantly. According to most publications, tire fuel usually replaces between 10% and 20% of the coal used in cement rotary kilns.[10, 12]

FUEL SHIPPING COSTS

According to the California Integrated Waste Management Board, shipping a truck load of tires in a tractor trailer requires 24,700 Btu of diesel fuel for every mile traveled. A conservative approximation of the fuel economy for a semi-trailer truck with a 15-ton load is 5 miles per gallon of diesel fuel and 6 miles per gallon without a load. Consequently, the shipping costs vary greatly depending on the amount of distance one must travel.[10, 13]

Over time, the shipping costs associated with transporting coal have fluctuated wildly. According to the United States Department of Energy's Energy Information Administration, recent average transportation costs per ton of coal were $9.78. This value represents the average costs across all of the United States and considers all modes of transportations and for the purposes of this article will provide a rough estimate of shipping costs.

FUEL AND ENERGY SAVINGS—EXAMPLE

The savings calculations for this example will be based on a small kiln used in a Portland cement manufacturing facility in central Florida. This kiln only uses coal, and this example will explore some possible values of savings if it were to co-fire scrap tires with the coal. To simplify this initial case, the example will assume that the source of scrap tires is close enough so that the tipping fees breakeven against the total shipping costs. All fuel usage values and costs for this example will be derived from actual historical data from this plant.[15] The fuel usage and costs are shown in Table 9.

Table 9. Coal Consumption
January 2004 through September 2004

Date	Cost	Tons
Jan-04	88,379	1,163
Feb-04	71,613	942
Mar-04	53,679	706
Apr-04	71,088	935
May-04	111,216	1,463
Jun-04	72,083	948
Jul-04	70,737	931
Aug-04	62,820	827
Sep-04	22,947	302
Total	624,562	8,217
Average	69,396	913
Yearly Totals (approx.)	832,749	10,956

Conservatively, this example will assume scrap tire fuel replaces 15% of the yearly coal used. The fuel savings (FS) are as follows:

$$\text{FS} = \text{FR} \times \text{TC}$$

Where,

FR = Fuel savings rate, 15%
TC = Total yearly coal usage

Therefore,

$$\begin{aligned}\text{FS} &= (15\%) \times (10{,}956 \text{ tons of coal}) \\ &= 1{,}643.4 \text{ tons of coal/yr}\end{aligned}$$

The energy savings (ES) are as follows:

$$\text{ES} = \text{Fuel Savings} \times \text{C}$$

Where,

C = Conversion constant, 25,000,000 Btu/ton of coal

Therefore,
ES = (1,643.4 tons of coal/yr) × (25,000,000 Btu/ton of coal)
= 41,085 MMBtu/yr

COST SAVINGS

Calculated from Table 9, the average overall cost per ton of coal is $76. Therefore, the yearly cost savings (CS) is as follows:

CS = Fuel Savings × J
Where,
J = Cost per ton of coal, $76/ton
Therefore,
CS = (1,643.4 tons of coal/yr) × ($76/ton)
= $124,898/yr

It is important to note that the fuel usage of this kiln is small and at many other facilities, actual fuel and cost savings will be much higher.

IMPLEMENTATION & IMPLEMENTATION COST

For the implementation of a scrap tire fuel system, the primary on-site improvements include a tire feeding system and space for the storage of materials (Figure 8). It is extremely difficult to provide an exact cost of implementation for this project because every time a company creates one of these systems, it must be custom built. The costs of this project depend on a wide variety of factors, such as the design and complexity of the feeding system and kiln. According to the Scrap Tire Management Council, the implementation costs of a project such as this are typically between $200,000 and $500,000 (as of today). Furthermore, the California Integrated Waste Management Board also states that the costs of these projects typically do not exceed $500,000.[10, 11]. This example will conservatively approximate an implementation of cost $350,000.

Figure 8. TDF Feeding System

SIMPLE PAYBACK PERIOD (SPP) and RETURN ON INVESTMENT (ROI)

The calculations for simple payback period used extremely conservative approximations for implementation costs. According to the Scrap Tire Management Council, payback periods for these types of projects are typically no longer than 18 months.[11] As a result, in practice these numbers should be much more favorable. Below are our estimations for the SPP and ROI according to our assumptions.

SPP = Implementation Cost (\$)/Cost Savings (\$/yr)
= (\$350,000)/(\$124,898/yr)
= 2.8 years

ROI = Cost Savings (\$/yr) × 100/Implementation Cost (\$)
= (\$124,898/yr) × (100)/(\$350,000)
= 35.69 %/yr

EXTENSIONS AND EXPANSIONS

The above example is simplified and does not effectively describe the large range of values many of the project parameters can take. As a result, this section will expand on the above case and display more ranges of values. The calculations in Table 10 vary the percent tire-based fuel from 10% to 20% with 1% increments and compare it with implementation costs ranging from $200,000 to $500,000 with $50,000 intervals. The calculations used in this section are identical to the methods used above.

Figure 9 illustrates the payback period as a function of the percentage of tire fuel used with a fixed implementation cost of $350,000. Similar to the original example, this example and plot uses the assumption that tipping fees breakeven against overall shipping costs.

Table 10. Variable Percent Tire-fuel and Variable Implementation Cost

Fuel Consumption (tons of coal)	Percent Tires	Fuel Savings (tons of coal)	Energy Savings (MMBtu)	Cost Savings	Implementation Cost	SPP	ROI
10,956	10%	1,095.60	27,390	83,266	200,000	2.40	41.6%
	11%	1,205.16	30,129	91,592		2.18	45.8%
	12%	1,314.72	32,868	99,919		2.00	50.0%
	13%	1,424.28	35,607	108,245		1.85	54.1%
	14%	1,533.84	38,346	116,572		1.72	58.3%
	15%	1,643.40	41,085	124,898		1.60	62.4%
	16%	1,752.96	43,824	133,225		1.50	66.6%
	17%	1,862.52	46,563	141,552		1.41	70.8%
	18%	1,972.08	49,302	149,878		1.33	74.9%
	19%	2,081.64	52,041	158,205		1.26	79.1%
	20%	2,191.20	54,780	166,531		1.20	83.3%
10,956	10%	1,095.60	27,390	83,266	250,000	3.00	33.3%
	11%	1,205.16	30,129	91,592		2.73	36.6%
	12%	1,314.72	32,868	99,919		2.50	40.0%
	13%	1,424.28	35,607	108,245		2.31	43.3%
	14%	1,533.84	38,346	116,572		2.14	46.6%
	15%	1,643.40	41,085	124,898		2.00	50.0%
	16%	1,752.96	43,824	133,225		1.88	53.3%
	17%	1,862.52	46,563	141,552		1.77	56.6%
	18%	1,972.08	49,302	149,878		1.67	60.0%
	19%	2,081.64	52,041	158,205		1.58	63.3%
	20%	2,191.20	54,780	166,531		1.50	66.6%
10,956	10%	1,095.60	27,390	83,266	300,000	3.60	27.8%
	11%	1,205.16	30,129	91,592		3.28	30.5%
	12%	1,314.72	32,868	99,919		3.00	33.3%
	13%	1,424.28	35,607	108,245		2.77	36.1%
	14%	1,533.84	38,346	116,572		2.57	38.9%
	15%	1,643.40	41,085	124,898		2.40	41.6%
	16%	1,752.96	43,824	133,225		2.25	44.4%
	17%	1,862.52	46,563	141,552		2.12	47.2%
	18%	1,972.08	49,302	149,878		2.00	50.0%
	19%	2,081.64	52,041	158,205		1.90	52.7%
	20%	2,191.20	54,780	166,531		1.80	55.5%
10,956	10%	1,095.60	27,390	83,266	350,000	4.20	23.8%
	11%	1,205.16	30,129	91,592		3.82	26.2%
	12%	1,314.72	32,868	99,919		3.50	28.5%
	13%	1,424.28	35,607	108,245		3.23	30.9%
	14%	1,533.84	38,346	116,572		3.00	33.3%

(*Continued*)

Table 10. Variable Percent Tire-fuel and Variable Implementation Cost (*Continued*)

	15%	1,643.40	41,085	124,898		2.80	35.7%
	16%	1,752.96	43,824	133,225		2.63	38.1%
	17%	1,862.52	46,563	141,552		2.47	40.4%
	18%	1,972.08	49,302	149,878		2.34	42.8%
	19%	2,081.64	52,041	158,205		2.21	45.2%
	20%	2,191.20	54,780	166,531		2.10	47.6%
10,956	10%	1,095.60	27,390	83,266	400,000	4.80	20.8%
	11%	1,205.16	30,129	91,592		4.37	22.9%
	12%	1,314.72	32,868	99,919		4.00	25.0%
	13%	1,424.28	35,607	108,245		3.70	27.1%
	14%	1,533.84	38,346	116,572		3.43	29.1%
	15%	1,643.40	41,085	124,898		3.20	31.2%
	16%	1,752.96	43,824	133,225		3.00	33.3%
	17%	1,862.52	46,563	141,552		2.83	35.4%
	18%	1,972.08	49,302	149,878		2.67	37.5%
	19%	2,081.64	52,041	158,205		2.53	39.6%
	20%	2,191.20	54,780	166,531		2.40	41.6%
10,956	10%	1,095.60	27,390	83,266	450,000	5.40	18.5%
	11%	1,205.16	30,129	91,592		4.91	20.4%
	12%	1,314.72	32,868	99,919		4.50	22.2%
	13%	1,424.28	35,607	108,245		4.16	24.1%
	14%	1,533.84	38,346	116,572		3.86	25.9%
	15%	1,643.40	41,085	124,898		3.60	27.8%
	16%	1,752.96	43,824	133,225		3.38	29.6%
	17%	1,862.52	46,563	141,552		3.18	31.5%
	18%	1,972.08	49,302	149,878		3.00	33.3%
	19%	2,081.64	52,041	158,205		2.84	35.2%
	20%	2,191.20	54,780	166,531		2.70	37.0%
10,956	10%	1,095.60	27,390	83,266	500,000	6.00	16.7%
	11%	1,205.16	30,129	91,592		5.46	18.3%
	12%	1,314.72	32,868	99,919		5.00	20.0%
	13%	1,424.28	35,607	108,245		4.62	21.6%
	14%	1,533.84	38,346	116,572		4.29	23.3%
	15%	1,643.40	41,085	124,898		4.00	25.0%
	16%	1,752.96	43,824	133,225		3.75	26.6%
	17%	1,862.52	46,563	141,552		3.53	28.3%
	18%	1,972.08	49,302	149,878		3.34	30.0%
	19%	2,081.64	52,041	158,205		3.16	31.6%
	20%	2,191.20	54,780	166,531		3.00	33.3%

The calculations in Table 11 explore various levels of shipping costs based on the yearly fuel usage in the prior example and the distance traveled. In addition, this table displays values of yearly tipping fees. One very important fact to take note of is that the costs only include fuel charges for each year. In practice, the total expenses for shipping would be larger because this example neither accounts for nor quantifies costs such as truck rental or maintenance fees, labor charges, insurance costs, and other related costs. In addition, this example assumes whole tires are being shipped via truck in 15-ton loads, and the truck must make a roundtrip each time. Also note that the 15-ton value of scrap tires

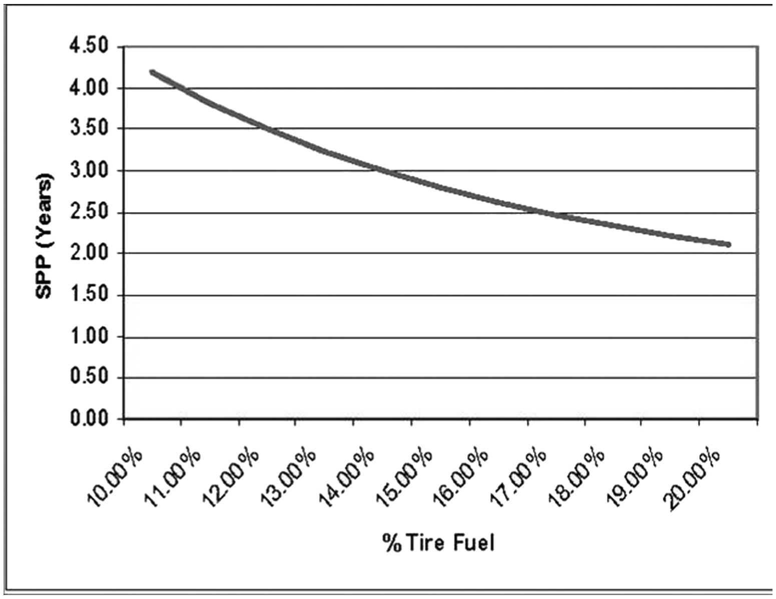

Figure 9. Payback Period

is approximately what a semi-trailer truck can hold in a full load.[10] Lastly, for calculation purposes, this example uses fractional truck loads to display long run costs. The fixed values used in Table 11 are as follows:

Tons of coal per year = 10,956 tons
Energy of Coal = 25 MMBtu/ton of coal
Energy of TDF = 15,000 Btu/lb of tire derived fuel
Cost of Diesel Fuel = $2.50/gal
Full truck load weight = 30,000 pounds
Tipping Fee = $40 per ton (very conservative approximation) [20]

A sample calculation for the shipping costs using 10% tire fuel at a distance of 100 miles is as follows:

Fuel Costs = Distance × [(Fuel cost × Number of truck loads/M1) + (Fuel cost × Number of truck loads/M2)]

Table 11. Shipping and Tipping Fees

Fuel Consumption (tons of coal)	Percent Tires	Fuel Savings (tons of coal)	Energy Savings (MMBtu)	Energy per pound of TDF (MMBtu/lb)	Pounds of TDF	Tons per truckload	Number of Truckloads	Total Per-mile fuel costs (loaded)	Total Per-mile fuel costs (empty)	Total Miles Traveled	Total Tipping Fees	Total Fuel Costs (roundtrip)
10,956	10.0%	1,095.6	27,390	0.015	1,826,000	15	60.87	30.43	25.36	20	36,520	1,115.89
										40		2,231.78
										60		3,347.67
										80		4,463.56
										100		5,579.44
										200		11,158.89
										300		16,738.33
										400		22,317.78
10,956	12.5%	1,369.5	34237.5	0.015	2,282,500	15	76.08	38.04	31.70	20	45,650	1,394.86
										40		2,789.72
										60		4,184.58
										80		5,579.44
										100		6,974.31
										200		13,948.61
										300		20,922.92
										400		27,897.22
10,956	15.0%	1,643.4	41,085	0.015	2,739,000	15	91.30	45.65	38.04	20	54,780	1,673.83
										40		3,347.67
										60		5,021.50
										80		6,695.33
										100		8,369.17
										200		16,738.33
										300		25,107.50
										400		33,476.67
10,956	17.5%	1,917.3	47,932.5	0.015	3,195,500	15	106.52	53.26	44.38	20	63,910	1,952.81
										40		3,905.61
										60		5,858.42
										80		7,811.22
										100		9,764.03
										200		19,528.06
										300		29,292.08
										400		39,056.11
10,956	20.0%	2,191.2	54,780	0.015	3,652,000	15	121.73	60.87	50.72	20	73,040	2,231.78
										40		4,463.56
										60		6,695.33
										80		8,927.11
										100		11,158.89
										200		22,317.78
										300		33,476.67
										400		44,635.56

Where,

Number of truck loads
= Number of trips per year, 60.87
M1 = Loaded fuel efficiency, 5 miles/gal
M2 = Unloaded fuel efficiency, 6 miles/gal

Therefore,

Fuel Costs = 100 miles × [($2.5/gal × 60.87 trips/year × (5miles/gal)–1)
+ ($2.5/gal × 60.87 trips/year × (6miles/gal)–1)]
= $5,579.75/year

Figure 10 charts the distance at which tipping fees breakeven against fuel shipping costs. For these calculations, the example uses moderate approximations for all numbers. Fuel costs are $2.5 per gallon, tipping fees are $40 per ton, scrap tire fuel percentage is 15%, and the fuels values are derived from the above case. The breakeven point occurs at approximately 690 miles.

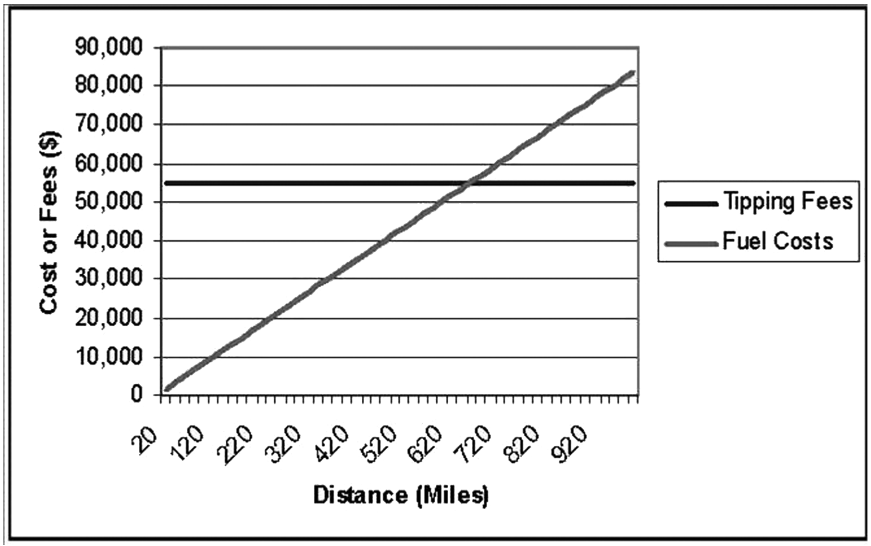

Figure 10. Breakeven Between Tipping and Fuel Cost

ALTERNATE CASE—OTHER SCRAP TIRE USES

This section will analyze fuel savings in three other cement facilities that actually used tire fuel to supplement their coal usage. The values are shown in Tables 12 through 14. These three facilities total fuel savings from using tires in place of coal during 2003 was significantly higher than the potential savings in the previous example.[21] The appendix tables examine the gross energy and cost savings resulting from offset coal usage during that year for varying coal prices. These tables do not factor in additional costs or savings, such as maintenance fees, shipping costs, tipping revenues, or additional labor expenditures. The calculations for the energy savings (ES) and fuel savings (FS) are as follows:

$$\begin{aligned} ES &= (\text{Tons of tires/yr}) \times (2000\ \text{lb/ton}) \times (15{,}000\ \text{Btu/lb tire}) \\ &\quad \times (10^{-6}\ \text{MMBtu/Btu}) \end{aligned}$$

And,

$$FS = ES \times T \times C$$

Where,

$$T = 1/25\ \text{tons of coal/MMBtu}$$

$$C = \text{Cost of coal, units of \$/ton}$$

Using the California Portland Cement Company as an example, if the cost of coal, C, is $20 per ton and 20,452 tons of tires are used in a given year, the savings are as follows:

$$\begin{aligned} ES &= (20{,}452\ \text{tons/yr}) \times (2000\ \text{lb/ton}) \times (15{,}000\ \text{Btu/lb}) \\ &\quad \times (10^{-6}\ \text{MMBtu/Btu}) \\ &= 613{,}560\ \text{MMBtu/yr} \end{aligned}$$

and

$$\begin{aligned} FS &= (613{,}560\ \text{MMBtu/yr}) \times (1/25\ \text{tons of coal/MMBtu}) \times \\ &\quad (\$20/\text{ton of coal}) \end{aligned}$$

Therefore,

$$FS = \$490{,}848/\text{yr}$$

Table 12. Savings at Additional Facilities, Case 1 [21] California Portland Cement Company, 2003

Tires Burned	Tons of Tires Burned	Pounds of Tires Burned	Average Weight per Tire	Energy from Tires (MMBtu)	Tons of Coal offset	Cost of Coal ($/ton)	Fuel Savings
2,200,000	20,452	40,904,000	18.59	613,560	24,542	$10	$245,424
						$12	$294,509
						$14	$343,594
						$16	$392,678
						$18	$441,763
						$20	$490,848
						$22	$539,933
						$24	$589,018
						$26	$638,102
						$28	$687,187
						$30	$736,272
						$32	$785,357
						$34	$834,442
						$36	$883,526
						$38	$932,611
						$40	$981,696
						$42	$1,030,781
						$44	$1,079,866
						$46	$1,128,950
						$48	$1,178,035
						$50	$1,227,120
						$52	$1,276,205
						$54	$1,325,290
						$56	$1,374,374
						$58	$1,423,459
						$60	$1,472,544
						$62	$1,521,629
						$64	$1,570,714
						$66	$1,619,798
						$68	$1,668,883
						$70	$1,717,968
						$72	$1,767,053
						$74	$1,816,138
						$76	$1,865,222
						$78	$1,914,307
						$80	$1,963,392
						$82	$2,012,477
						$84	$2,061,562
						$86	$2,110,646
						$88	$2,159,731
						$90	$2,208,816

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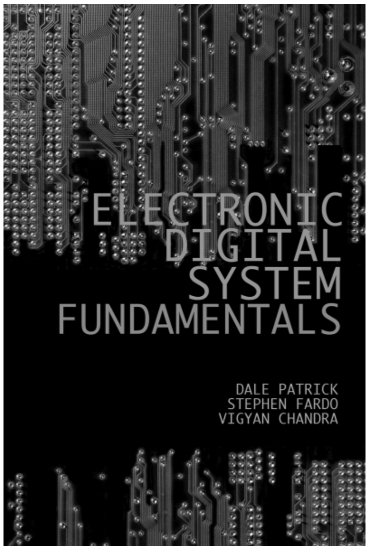

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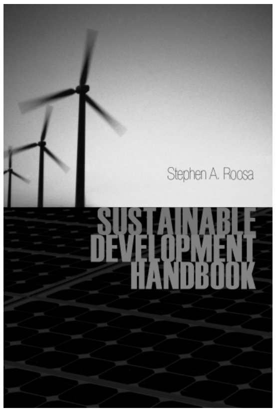

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Table 13. Savings at Additional Facilities, Case 2 [21] Mitsubishi Cement Company, 2003

Tires Burned	Tons of Tires Burned	Pounds of Tires Burned	Average Weight per Tire	Energy from Tires (MMBtu)	Tons of Coal offset	Cost of Coal ($/ton)	Fuel Savings
2,100,000	19,415	38,830,000	18.49	582,450	23,298	$10	$232,980
						$12	$279,576
						$14	$326,172
						$16	$372,768
						$18	$419,364
						$20	$465,960
						$22	$512,556
						$24	$559,152
						$26	$605,748
						$28	$652,344
						$30	$698,940
						$32	$745,536
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						$40	$931,920
						$42	$978,516
						$44	$1,025,112
						$46	$1,071,708
						$48	$1,118,304
						$50	$1,164,900
						$52	$1,211,496
						$54	$1,258,092
						$56	$1,304,688
						$58	$1,351,284
						$60	$1,397,880
						$62	$1,444,476
						$64	$1,491,072
						$66	$1,537,668
						$68	$1,584,264
						$70	$1,630,860
						$72	$1,677,456
						$74	$1,724,052
						$76	$1,770,648
						$78	$1,817,244
						$80	$1,863,840
						$82	$1,910,436
						$84	$1,957,032
						$86	$2,003,628
						$88	$2,050,224
						$90	$2,096,820

Table 14. Savings at Additional Facilities, Case 3 [21] Lehigh Southwest, 2003

Tires Burned	Tons of Tires Burned	Pounds of Tires Burned	Average Weight per Tire	Energy from Tires (MMBtu)	Tons of Coal offset	Cost of Coal ($/ton)	Fuel Savings
1,600,000	14,987	29,974,000	18.73	449,610	17,984	$10	$179,844
						$12	$215,813
						$14	$251,782
						$16	$287,750
						$18	$323,719
						$20	$359,688
						$22	$395,657
						$24	$431,626
						$26	$467,594
						$28	$503,563
						$30	$539,532
						$32	$575,501
						$34	$611,470
						$36	$647,438
						$38	$683,407
						$40	$719,376
						$42	$755,345
						$44	$791,314
						$46	$827,282
						$48	$863,251
						$50	$899,220
						$52	$935,189
						$54	$971,158
						$56	$1,007,126
						$58	$1,043,095
						$60	$1,079,064
						$62	$1,115,033
						$64	$1,151,002
						$66	$1,186,970
						$68	$1,222,939
						$70	$1,258,908
						$72	$1,294,877
						$74	$1,330,846
						$76	$1,366,814
						$78	$1,402,783
						$80	$1,438,752
						$82	$1,474,721
						$84	$1,510,690
						$86	$1,546,658
						$88	$1,582,627
						$90	$1,618,596

CONCLUSIONS

This article concludes that both biogas and scrap tired based fuel are excellent sources of alternative energy for certain businesses to use. Using digesters to produce biogas has many great benefits. Not only does a farm that implements a biogas digester and generator system gain an abundant supply of electricity and heat, but also numerous other benefits such as sources of fertilizer, bedding, and odor control. The total value of these energy and non-energy related benefits make biogas projects highly worthwhile. Using waste tires as a supplement to coal is also a profitable practice. This study concludes that there exists a tremendous potential for cement manufacturers to obtain large amounts of fuel savings in their kilns. If the source of tires is reasonably close, then the overall value of these projects is augmented even more from tipping fees. Despite high initial costs, paybacks for these ventures are quickly making them valuable.

FUTURE WORK

Because of time constraints and limitations on expertise, there are several areas of this project that would heavily benefit from future research. For biogas and biogas production, more detailed research about inhibitors, the effects of temperatures on digestion, the effects of digester pH level, and a comprehensive case study of an actual biogas facility would be invaluable. In addition, more research on emissions issues with tire combustions and a thorough study of facilities that use shredded tire derived fuel in boilers would be extremely beneficial.

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