ENVIRO-ECONOMIC COMPARISON OF DISTRIC ENERGY SYSTEMS USING NATURAL GAS AND WASTE ENERGY RESOURCES: CASE STUDY

Behnaz Rezaie[1], Bale V. Reddy[2], Marc A. Rosen[2]
[1]University of Idaho, Moscow, Idaho, USA
[2]University of Ontario Institute of Technology, Oshawa, Ontario, Canada
rezaie@uidaho.edu, bale.reddy@uoit.ca, marc.rosen@uoit.ca

ABSTRACT

District energy systems provide an important means of mitigating greenhouse gas emissions and the significant related concerns associated with global climate change. In this study, natural gas and waste to energy are compared as energy sources for a district energy system which serves a community including commercial and educational buildings. The district energy system is assessed preliminarily for the considered energy resources in two main ways, by considering CO_2 emissions and economic aspects. The results indicate that waste to energy is the better option from economic and environmental points of view for the studied case. The results are expected to allow energy technology suppliers to work advantageously with communities while accounting appropriately for economic issues and CO_2 emissions associated with these energy technologies.

INTRODUCTION

One means of mitigating energy and environmental concerns is through the use of district energy (DE) systems, since they can integrate renewable energy and other complementary systems like thermal energy storage [1-3]. Since economics and environmental impact are major factors in decision making and design, many assessments accounting for these factors have been performed of DE systems. District energy can provide efficiency, environmental and economic benefits to communities and energy consumers [4]. Difs et al. state that DE systems usually exhibit lower environmental impacts compared to conventional systems [5], and analyze heating loads to demonstrate that expanding DE applications in industrial processes leads to increased resource energy efficiency.

The energy source for district heating systems can be fossil fuels or other energy sources, and hybrid systems combining two or more energy sources, such as natural gas (NG), wood waste, municipal solid waste and industrial waste heat, can be economically feasible [6]. Persson and Werner consider heat supplies for DE to include heat from combined heat and power (CHP), waste-to-energy (WTE), biomass and geothermal energy plants, as well as industrial excess heat [7]. Ostergaard et al. investigated a DE system that integrates geothermal heat, wind power, and biomass [8]. This flexibility is one advantage of district energy systems. The thermal energy needed by the district grid is often supplied by a dedicated plant, but industrial waste energy can be an attractive alternative because it permits depreciation and maintenance costs for the power plant to be reduced [9]. Although fossil fuels are commonly the primary sources of the thermal energy supply [10], hybrid systems combining renewable or alternative energy technologies such as solar collectors, heat pumps, polygeneration, seasonal heat storage and biomass systems, have begun to be used as the energy sources [11]. The objective of this study is to improve understanding of district energy systems and their energy sources, by comparing two sources of energy, natural gas and WTE, for a particular DE system in terms of technology, environment, and economics.

METHODOLOGY

I. Energy Analysis

An energy balance for a general DE system, with a variable source of energy and various consumers, can be written as follows:

$$\sum E_{sup} = \sum E_{dem} + \sum E_{loss} \quad (1)$$

Here, E_{sup}, E_{dem}, and E_{loss} denote energy supply, energy demand, and energy loss, respectively; $\sum E_{sup}$ is the summation of all energy resources in the DE system; $\sum E_{dem}$ is total energy demand of the DE system, and $\sum E_{loss}$ is the sum of all heat losses including thermal network and consumer losses. Thus we can write:

$$\sum E_{sup} = E_{sup1} + E_{sup2} + \ldots + E_{sup\,n} \quad (2)$$

Here, indices 1 to n represent the particular energy supply to the DE system. Also,

$$\sum E_{dem} = E_{dem.cons1} + E_{dem.cons2} + \ldots + E_{dem.cons\,n} \quad (3)$$

where $E_{dem.cons}$ denotes energy demand of the consumer. Here, indices 1 to n represent the consumers in the DE system. Furthermore,

$\sum E_{loss} = E_{loss.TN} + E_{loss.cons1} + E_{loss.cons2} + \ldots E_{loss.cons\ n}$ (4)

Here, $E_{loss.TN}$ is energy loss by the thermal network and $E_{loss.cons}$ represents the energy loss by a particular consumer which is noted by the indices. Controlling the losses is an extensive topic which has direct impact on efficiency. Consumer losses can be improved by better building insulation. Also, energy losses in thermal networks and energy plants can be reduced by insulation and high efficiency equipment, which help to improve the efficiency of the DE system.

The energy efficiency of the DE system η_{DE} expresses the energy demand divided by the total energy input for the DE system:

$$\eta_{DE} = \frac{\sum E_{dem}}{\sum E_{sup}} \quad (5)$$

where E_{sup} and E_{dem} are as defined previously.

II. Environmental Impact

Examining the environment impact of a product or process can be complex, because the ecosystem includes all animals and plants living on the earth (land, water and atmosphere) and it needs to be examined at present and in the future. Environmental and ecosystem specialists have modeled ecosystem reactions to changes, covering multiple interactions of environmental factors. Some indicators have been introduced to reduce the complexity of comprehensive environmental impact assessments. CO_2 emission can be treated as an indicator for environmental impact of a product or process, because increasing the atmospheric CO_2 concentration results in an increase in the average global temperature.

In this research, the CO_2 emitted from various energy suppliers is initially determined in similar conditions. Consistency of evaluation is important for permitting fair judgements and comparisons of energy options. In the next step, the CO_2 emitted for various energy technologies is evaluated over their lifetimes to compare their environmental impacts. A more comprehensive evaluation of environmental impact can be performed by expanding to a life cycle analysis of each energy technology.

III. Cost Analysis

Cost estimation is important for assessing each option considered. This is often done by comparing new proposals with existing or past projects in the field. The time and cost for every energy option are important factors in project management. Initial costs as well as operating costs over the life of every energy option are determined in this study, considering the terms described in this section.

The future monetary value is calculated by considering compound interest as follows:

$$Y_n = Y_0\,(1+IR)^n \quad (6)$$

where Y_n denotes the future monetary value in year n, Y_0 the present monetary value, n the number of years, and IR the inflation rate. The future value formula normalizes the monetary value at different time periods. When the inflation rate is a positive number, money is devalued with the passing of time. To evaluate the cost of a project, the future value formula has to be applied to estimate the correct monetary value in each time period.

The loan for a product is calculated via the capital recovery factor, which results in monthly payments for the loan:

$$M = \mathrm{P}\left(\frac{[\mathrm{i}\,(1+\mathrm{i})^{\mathrm{N}}]}{[(1+\mathrm{i})^{\mathrm{N}}-1]}\right) \quad (7)$$

when M denotes the monthly payment (capital recovery) in \$, P the principal in \$, i the monthly interest rate, and N the number of monthly payments. This equation can be applied to compute the payments for any loan, mortgage, or investment.

Since the value of money generally changes notably over long time frames, Equation (6) is used in this research several times to determine financial values at different times, and Equation (7) is applied to determine the capital recovery for each energy technology. The cost of future repayments, if the entire cost is borrowed from a financial institution, is determined. The payments of the original investment significantly affect the financial characteristics of each energy supplier.

IV. Enviro-Economic Function

Rezaie et al. [12] introduced a function to determine the economic equivalent of the environmental impact and other financial factors of a DE system. This function assesses the energy technology of a DE system with multiple interacting characteristics in an economic manner that accounts for financial, technological and environment factors, and takes the following form:

$$OC = \sum_{g=1}^{n}(FC + I\&M)(1+IR)^g + \sum_{a=1}^{q}(12M)(1+IR)^a + \sum_{g=1}^{n} CT\,(1+IR)^g - \sum_{g=1}^{n} TB(1+IR)^g \quad (8)$$

Here, CT denotes the annual carbon tax; TB the tax benefit; a the number of amortization years, which is from 1 to *q*; *FC* the annual fuel cost, *I&M* the insurance and maintenance annual costs, and *g* the operating life of the DE system, which is from 1 to *n*. The annual payment on the initial loan can be written as 12*M*. Both *CT* and *TB* depend greatly on the type of energy supply and its conversion technology, and vary by jurisdiction and region, and with time, since policies governing them vary, particularly when political directions change. Equation (8) characterises the environmental impact of an energy technology in economic terms. For non-fossil fuels, *CT* = 0 during operation of the technology. The enviro-economic function assesses the energy technology of a DE system with multiple interacting characteristics in an economic manner that accounts for financial, technological and environment factors.

MODELING DISTRICT ENERGY SYSTEM ENERGY SUPPLIER

One method of modeling a DE system is with demand profiles of building heating loads. Initially, occupant behaviour in every building needs to be considered, and then the heat loads of all consumers have to be added together. The DE plant needs to be able to satisfy the total heat load of consumers as well as heat losses in the thermal network and consumers. Thus, the total energy of a DE plant can be quantified by adding total heat loss to total heat load.

Sizing a DE system starts with knowing the consumers' heat demand characteristics. A heat plant has to be able to satisfy the consumers' heat demand after deducting all losses between the heat plant and the consumers. For the heat plant in a DE system often two heating systems are considered [13]. One is the primary system, which provides the major energy and operates on a regular basis. The second is the back up and it operates only when the heating load exceeds the capacity of the primary system. This secondary or auxiliary system typically has a smaller capacity and it operates occasionally during a year. Since the majority of the energy demand is covered by the primary system, it draws more attention and there are various methods to size the primary system. The ASHRAE handbook [13] suggests using average monthly energy demand (annual demand/12) for sizing the primary system, while [4, 14] suggests that 60% to 70% of the peak is adequate for sizing; these recommendations are for the Canadian environment. Another study [4] suggests using 60% of the peak demand for sizing the primary system, and states that in this instance the primary system usually can satisfy 90% of the demands of the DE system. Just 10% of heat demand is covered by the secondary system in this case.

To illustrate, the heat load of a typical DE system and the two sizing methods of the primary system are shown on the characteristic curve of the DE system in Figure 1. It is seen that the 60%-of-peak method suggests a primary system with a larger capacity compared with the average-load method. Thus, the auxiliary system would be larger based on the average-load method while the 60%-of-peak method offers a smaller system. The auxiliary system operates for less time with the 60%-of-peak than with the average-load method. A DE system can use various types of energy supply and, generally, the primary system is modeled for that type of energy.

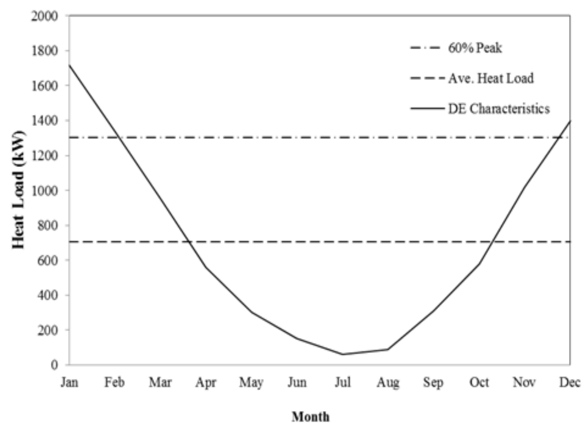

Figure 1: Comparison of two sizing methods for the DE system. Data are for a typical DE system operating in the Canadian climate

There are various energy resources for the DE system as explained earlier. In this study, the sizing of the primary system of the DE system for natural gas and waste-to-energy (WTE) is examined in a consistent manner. To achieve consistency, the auxiliary system remains the same for all energy options, but the primary system is modeled for the various technologies relevant to the energy options. The performance of the DE system in similar circumstances with the various energy technologies can be then compared. Note that comparing outcomes of each energy option for the primary system, which covers the heat demands of the most consumers, provides more reliable results and conclusions.

Figure 2 illustrates two energy technologies that are used in this research for the primary system in the DE system. Note that the configuration of the primary technology with the auxiliary in Figure 2 is only one connection option and is shown in a simplified form without considering valves and other minor devices.

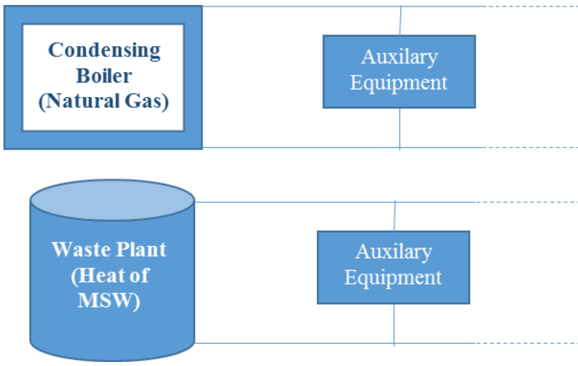

Figure 2: Simplified models of various energy option technologies and auxiliary system in the DE system

I. Natural Gas

Canada has vast natural gas resources, representing the third largest in the world [15]. Pollutants generated by natural gas are the lowest among fossil fuels; therefore, it is used commonly for heating and other processes. For this reason, natural gas is often considered a base energy option for DE systems. Furnaces, water heaters, and boilers can be considered as the primary systems. The application of condensing boilers in DE systems is growing because these have the highest efficiencies, and losses of energy on this scale are notable. Condensing technologies have higher fuel efficiencies because they capture the energy in flue gases through condensing the water vapor (steam) that usually exits up the flue. The efficiency of major condensing boilers, based on manufacturers' catalogues, is reported to be in the range of 88% to 95% [16, 17]. Using condensing boilers in a DE system is common in industry, the Friedrichshafen DE system in Germany being an example [18]. Figure 2 illustrates a DE system with natural gas as a source of energy.

II. Waste Energy

Community solid waste is at present an important issue of urban life, with energy demand increasing due to growth in population and expanding demands for better living standards. A system that reduces waste and simultaneously increases energy supply would be dually beneficial. Modern waste-to-energy (WTE) technology converts municipal solid waste (MSW) to energy. Connecting a WTE plant to a DE system is one method of shifting towards sustainable communities. Figure 2 shows a simplified model of a DE system connected to a WTE plant.

Prior to planning and designing a waste-to-energy technology, waste availability must be known and waste characteristics must be understood in terms of quantity and quality. The quantity of waste is one the parameters used to size a WTE plant. In addition, the quality of the waste is used to determine the energy recoverable from the waste. Note that sometimes different energy bases are used; waste energy is often quoted on a higher heating value (HHV) in the US basis and on a lower heating value (LHV) in Europe [19]. Canadian energy consumption characteristics are closer to American than European, in large part because of the similarity between Canadian and American lifestyles. In this study, US waste characteristics are considered. Various methods and databases can be used to determine the heating value of waste. Here, Dulong's formula [20] is used to determine the HHV (in Btu/lb):

$$HHV = 14{,}544\,C + 62{,}028\,(H_2 - O_2/8) + 4050\,S \quad (9)$$

where C, H, O_2 and S denote carbon, hydrogen and oxygen and sulphur contents of the waste, respectively. Equation (9) can be applied to most wastes. For a typical American waste, for example, $C = 0.257$, $H_2 = 0.047$, $O_2 = 0.21$, and $S = 0.001$ [19], so $HHV = 5{,}040$ Btu/lb (or 29,936 kJ/kg).

ANALYSIS AND CASE STUDY

To demonstrate the application of two energy resources (natural gas and WTE) in a DE system and permit comparisons, a DE system is designed for Ontario/Canada. The DE system is designed based on building heat load data for the Ontario climate [20]. Financial aspects of the case study like inflation rate (IR) and interest rate are assumed according to present financial and industrial markets. Illustrative example can be any DE system with different properties. The modeling approach is described in this section, set up to allow consistent comparisons of different energy resources. A case study is considered and associated HVAC calculations are simplified.

A DE system is considered covering 25,000 m^2 of urban area including multi-floor buildings. Building one is a four-floor office building containing government offices, used mainly from 8 am to 4:30 pm (business hours). By adding commuting times of personnel to/from the building, the usage time of the building is taken to be 7:30 am to 5 pm on weekdays. Building two is a six-floor office building, in which all offices are used by law firms. The working time of this building is from 7:30 to 6 pm. Building three is a three story educational building, used by instructors and students from 8 am to 7:30 pm. The proposed DE system can operate with different energy resources, which are examined in this section. For the economic modeling, IR is assumed to be 2%, based on Central Bank of Canada rate, and the interest rate is considered 5%, a typical present market value. Insurance and maintenance of equipment costs are assumed to be 3%

of the initial investment, while project management costs are assumed to be 10%. These percentages are typical of industry.

Figure 3 presents a simplified illustration of the DE system including consumers, the thermal network, and the heat plant. Analysing consumer heat demand in a DE system is an initial step because the DE plant is typically designed according to consumer heat demand. To customise the heat plant of the DE system, the consumer heat load is determined by assessing all buildings in the system. Each building has a specific heating load and the summation determines the total heat load for the DE system. In the case study, the institutional building exhibits the main heat load during business hours, off and off peak loads in the late afternoon, evening, and night.

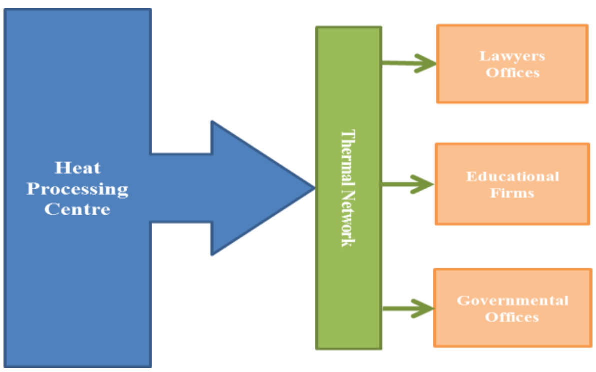

Figure 3: Simplified layout of illustrative DE system

Table 1: Monthly heat and electrical power consumption of the DE system

Month	Peak electrical power use (kW)	Energy usage/month (MWh)
Jan	1,720	1,280
Feb	1,340	997
Mar	950	707
Apr	560	417
May	300	223
Jun	150	112
Jul	60	45
Aug	90	67
Sep	310	231
Oct	580	432
Nov	1,020	759
Dec	1,400	1,042
Annual	**-**	**6,309**

The DE system energy consumption is equal to the energy consumptions of the three buildings plus the heat loss of the DE system (see Table 1). The average monthly energy consumption of the proposed DE system is considered for an Ontario climate by using data for buildings in Ontario [20]. It is seen that the energy consumption is higher in late fall, winter, and early spring than in late spring, early fall and summer, due to ambient temperature variations.

With Table 1, a characteristic curve of the proposed DE system is constructed (Figure 4). The grey area represents the energy demand over a typical year that is to be covered by the primary and secondary systems. The times of the peak loads of the buildings are similar because all buildings are used during weekday working hours. Thus, the peak load of the DE system is almost the summation of peak the loads of each building. The peak load of the DE system is seen to be 1,720 kW which is higher than the energy usage depicted in Table 1. This should provide adequate capability to cover the peak load by the DE plant.

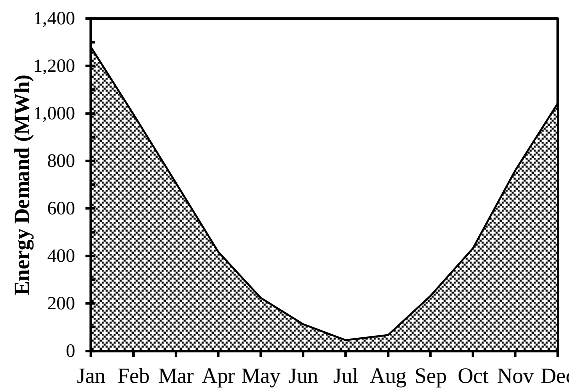

Figure 4: Annual heat load characteristics of the proposed DE system

As mentioned previously, there are two methods for sizing the primary system in the DE system: average-load and 60%-of-peak. Both are applied for sizing the primary energy supply of the proposed DE system, as tabulated in Table 2. With the average-load method, the outcome of the annual consumption divided by 12 months from Table 1 (8,480/12 = 707 kW or 6,309/12 = 526 MWh) gives the size of the primary system while with the 60%-of-peak approach 60% of the peak load (1,720 × 60% = 1,032 kW or 1,280 × 60% = 768 MWh) determines the size. For the proposed DE system the capacity of the primary system should then be about 1,032 kW. Hence, the auxiliary system size is the difference between peak (1,720 kW) and capacity of primary system (1,032 kW), which is about 688 kW. Since 1302 kW and 688 kW are not systems that can be found in the market, the size should be rounded. That is, 1,032 kW can be rounded up to 1,100 kW or rounded down to 1,000 kW, while the auxiliary system size can be rounded up to 700 kW or rounded down to 650 kW. To cover the 60% of load, the primary is round up to 1100 kW and auxiliary system is round down to 650 kW. At peak times both systems (1,100 + 650 = 1,750 kW) can cover the peak (1,720 kW).

Table 2: Sizing options for primary system

Parameter	Electrical power use (kW)	Electrical energy use (MWh)
Annual sum	-	6,309
Monthly average-load	707	526
60%-of-peak	1,302	969

Project management is also part of the cost for operating the project. For this case, the project management is assumed 10% of the equipment cost.

I. Natural Gas

Due to the high efficiency, it is assumed, when the DE system uses natural gas as the energy source, a condensing boiler is used in the system. The efficiency of such a boiler is considered 90%, which is the middle point of reported efficiency [16,17] for condensing boilers. The capacity of the boiler is 1,100 kW as was calculated in previous sections for the primary system for the DE system.

A. Economic Aspects

To analyse the economics of using natural gas, the initial cost of natural gas technology and operating costs during operation of the system are evaluated. As mentioned earlier, the energy conversion technology for natural gas in this case is a condensing boiler with a capacity of 1,100 kW. Its initial cost, including installation, is $37,000 [16]. Also, there are operating costs (fuel, insurance, maintenance) incurred as l the boiler operates. Insurance and maintenance costs are assumed to be 3% of the initial cost, based on actual percentages in industry, while fuel costs are calculated. First, the energy that the boiler uses to satisfy consumer demand is determined. The energy content of the natural gas (based on HHV) is 38 MJ/m^3 [21,22]. For an energy efficiency of 90% for the condensing boiler, the monthly consumption of the natural gas in the DE system is then calculated (see Figure 5). Note that in January, February, and December, the boiler is working at its maximum capacity of 1,100 kW and the remaining heat demand is satisfied by the auxiliary system. The greatest monthly fuel consumptions occur in January, February, and December.

The monthly fuel cost can be calculated as the cost of natural gas. The cost of natural gas on a 5-year contract in Ontario is 0.155 \$/m^3 [21, 23]. This price includes 0.076 \$/m^3 for transportation to the DE system plant. The monthly cost of energy consumption is now computed. The total operating and fixed cost includes 3% of the initial cost for insurance and maintenance as well as the fuel cost of the condensing boiler. The results of summing the costs are depicted in Figure 6, where each column represents the monthly cost of the boiler. In cold months (December and January), due to increased fuel costs, the monthly cost is higher than in summer months. The maximum monthly cost occurs in January, February, and December.

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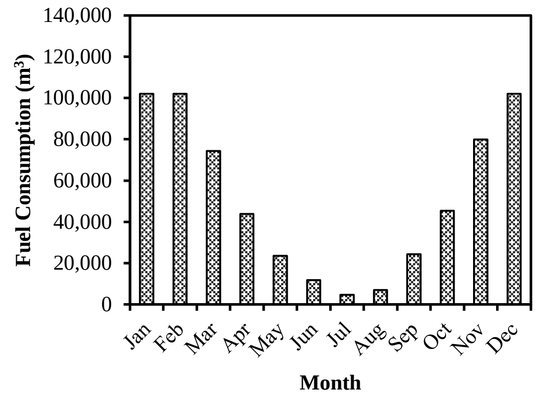

Figure 5: Monthly natural gas consumption of the DE system

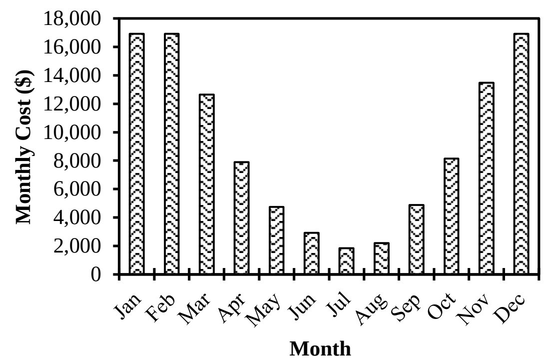

Figure 6: Natural gas technology monthly cost (fixed and operating costs)

Using Equation (6) for the DE system when the lifetime *n* of the DE system is assumed to be 25 years, and IR is assumed to be 2%, annual operating cost of the natural gas consumption for the condensing boiler Y_0 is evaluated as follows:

$$664{,}118 \text{ m}^3 \times 0.155 \text{ \$/m}^3 = \$\ 102{,}939$$

where 0.155 \$/m^3 is cost of the natural gas as explained earlier and 664,118 m^3 is the annual natural gas consumption of the boiler. It is calculated by adding all the bars in Figure 6, which represents the annual natural gas consumption.

In the next step, Equation (7) is applied to the DE system to find the capital recovery payments for the condensing boiler. Here, P = 37,000, $I = \frac{5\%}{12}$ (when the interest rate of the loan is assumed 5%), and N=10×12=120 (when the amortization is 10 years). Figure 6 illustrates the sum of the loan payment and the fuel cost, plus the insurance and maintenance costs. On the 10th year, the trend of the graph in Figure 7 changes because of completing the loan payment. From the 10th year onward, therefore, the annual cost curve shifts down. The total initial, fixed and operating costs, for the lifetime of the condensing boiler (25 years), is $4,200,000. The grand cost is in $4,600,000, when the 10% project management cost is included.

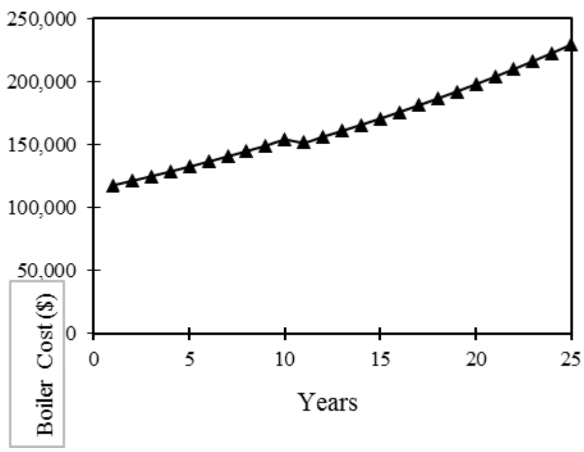

Figure 7: Annual cost of natural gas technology over its lifetime

To provide further insight into the boiler's total cost, Figure 8 shows the breakdown of the total cost. When natural gas used as the energy resource for the DE system, fuel plus insurance and maintenance are the major costs. For a condensing boiler, the operation cost is greater than capital recovery.

B. Environmental Aspects

Although natural gas is one of the cleanest fossil fuels because it has the lowest CO_2 emission of the fossil fuels [15], the CO_2 emission impacts the environment. Here, CO_2 emission is estimated as an indicator of the environmental impact of using a natural gas boiler. Natural Resources Canada specifies that burning Canadian natural gas emits 56 kg CO_2/GJ [24]. With data on fuel consumption of the condensing boiler, the monthly CO_2 emission of the boiler is calculated (see Figure 9). The, annual CO_2 emission by the boiler can be determined with Figure 9. Also, provided the performance and efficiency of the boiler stay the same over time, the total CO_2 emission over the 25-year life of the boiler is 29,474 t.

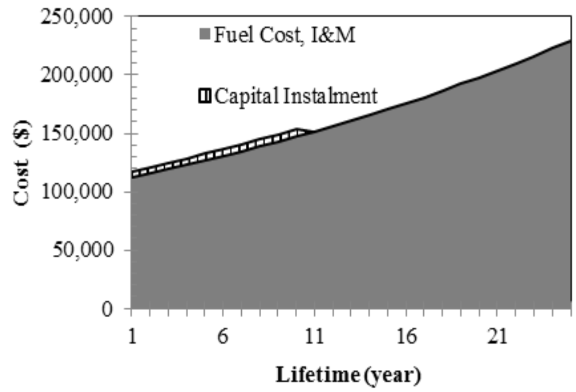

Figure 8: Cost breakdown of natural gas

In January, February, and December, as explained in previous section, the boiler is operating at its maximum capacity of 1300 kW and the remainder of the heat load is covered by the auxiliary system. Consequently, the greatest monthly CO_2 emission by the boiler occurs in January, February, and December.

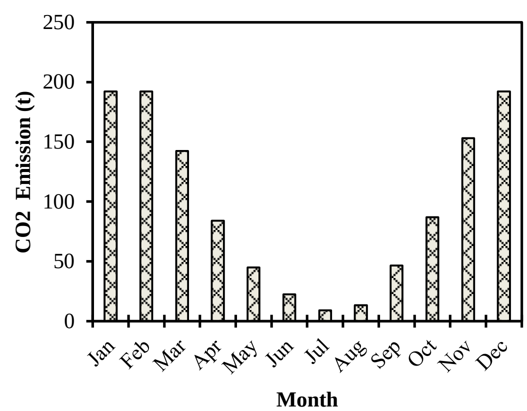

Figure 9: Breakdown by month of annual CO_2 emission of the natural gas boiler

II. Waste Energy

Based on previous sizing of the primary system, the waste-to-energy plant needs to provide 768 MWh of heat. This number is rounded up to 1,000 MWh, because systems in the market are available with round capacities. By assuming an efficiency of 80% for the waste-to-energy plant, the amount of needed waste to operate the proposed DE system can be evaluated. Figure 10 illustrates the monthly waste consumption for the waste-to-energy plant with a capacity of 1,000 MWh, which is 150 t/month. The greatest monthly waste consumptions, and apparent waste costs, occur in January, February, and December.

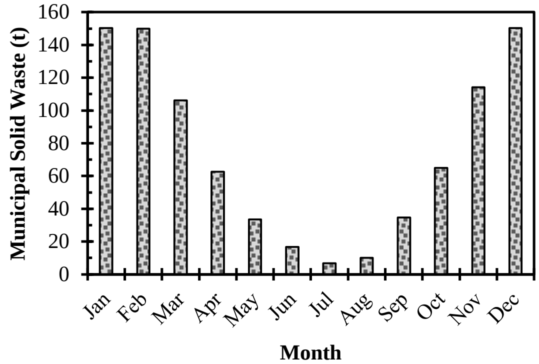

Figure 10: Monthly waste needed by WTE plant to satisfy DE system heat demand

A. Economic Aspects

WTE plants costs have been reported in many countries with different capacities and waste characteristics. Durkin reports various sizes and costs including construction, and equipment and interconnection expenses [19]. Note that land acquisition and development are project oriented and thus not included in the reported cost. The relation between cost and size for the reported WTE plant are illustrated in Figure 11. The thick dashed grey curve represents the data curve (three data points are shown). To provide an accurate estimation, the equation of the curve is determined via curve fitting. The thin black curve is a close fit and its equation is written in Figure 11, as y=23,563$x^{0.2081}$, where x is capacity of the WTE plant in tons per day (TPD) and y is the cost. Accordingly, the cost of the WTE plant with a capacity between 350 TPD to 2,500 TPD can be calculated.

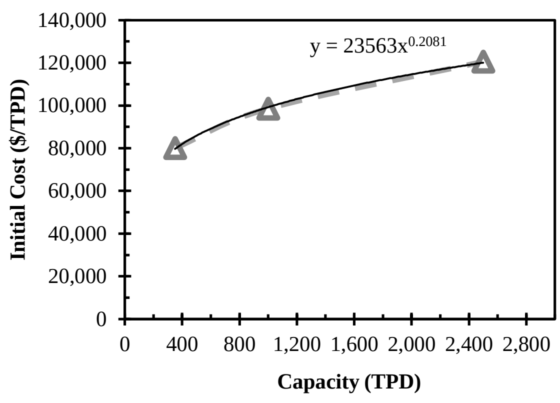

Figure 11: Cost curve for WTE plants with plant capacity, and curve fitting equation

Therefore, a WTE plant with a capacity of 150 t/month (Figure 11) with a maximum performance of 5 TPD (150/30) can satisfy the daily demand of the DE system. From the cost curve equation in Figure 11 with x=5, the WTE plant unit cost is calculated as:

y = 23,563 $(5)^{0.2081}$= 32,937 \$/TPD

Finally, the WTE plant cost with a 5 TPD capacity is:

Cost = 5 (TPD) × 32,937 (\$/TPD) = \$164,685

To obtain a more accurate cost estimation, 30% of the government rebate that applies to other cases is not applied to the WTE to cover the land cost. This is an estimation and, depending on location, can be higher or lower. Such as with other technologies, 3% of initial the cost is considered for maintenance and insurance costs. Further, the cost of waste as the fuel for the WTE is considered. The tipping fee for garbage depends on the labour rate, transportation, and characteristics of the waste. The tipping fee in this study is assumed to be 80 \$/t of garbage [19, 25]. The monthly cost of the WTE in a typical year is shown in Figure 12.

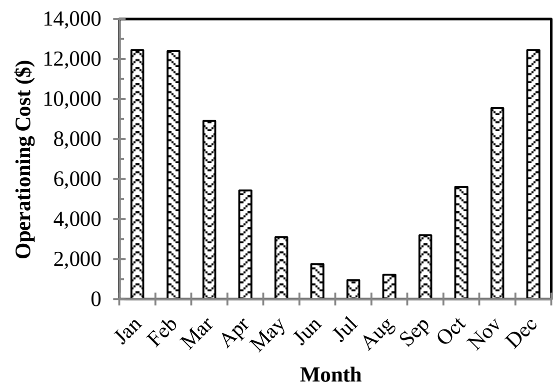

Figure 12: Monthly cost of WTE plant to cover the DE system

The initial and operating costs are substituted into Equations (6) and (7) considering the 25-year lifetime of the WTE plant. The economic assumptions are the same as other options $n=25$, IR =2%, $I = \frac{5\%}{12}$ for the interest rate of the loan of 5%, and N=10×12=120 for a 10 year amortization. The annual costs are illustrated in Figure 13 where it can be observed that after 10 years there is a reduction in the annual cost due to paying off of the loan. From year 11 onward, the annual cost shifts down and includes only operating costs. The total cost over the lifetime of the WTE without considering project management cost is \$3,100,000. The overall results with the 10% project management cost is \$3,400,000.

Figure 14 shows the elements of the total cost, and provides additional insights for economic decisions.

Figure 14 illustrates that the main cost of the WTE plant is assigned to tipping waste and I&M, while paying the loan instalments plays a minor role.

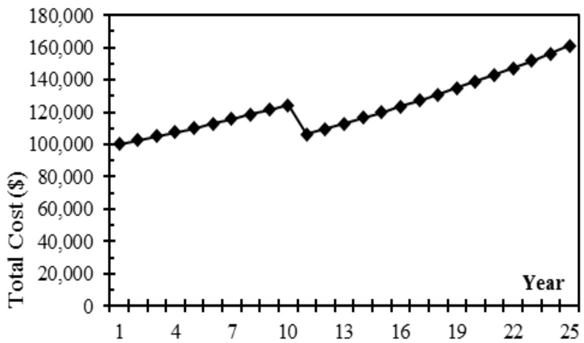

Figure 13: Annual costs of WTE plant over its lifetime

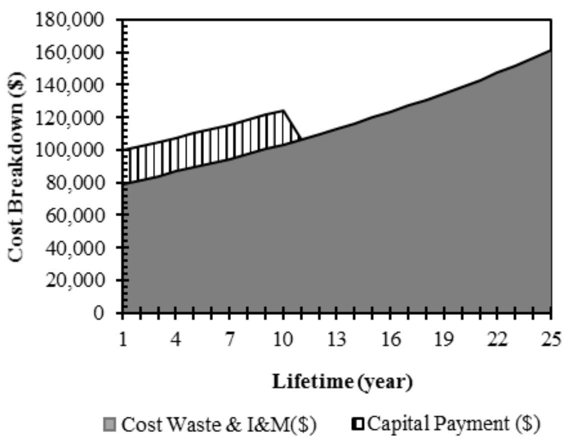

Figure 14: WTE plant cost breakdown

B. Environmental Aspects

An analysis of the environmental aspects of the WTE plant is potentially vast, because the garbage composition is not constant and materials in the garbage are both synthetic and organic. Consequently, the result of burning such materials varies. The various data are reported for CO_2 emissions, but depending on the percentage of moisture in the garbage, the socioeconomics of the community and the season of the year, the CO_2 emissions of WTE plants vary. For similar DE systems that operate using municipal solid waste incineration, unit emissions are reported as 43 kg CO_2/GJ to 48 kg CO_2/GJ [29]. Here, an average value 45.5 kg CO_2/GJ is used as an estimate the DE system emission. In the next step, based on energy generated by the WTE plant, the CO_2 emission is calculated. The results of the monthly CO_2 emissions for the DE system, when the WTE plant is the main source of energy, are shown in Figure 15.

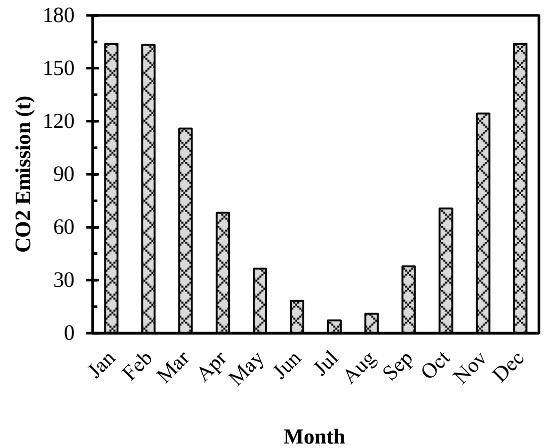

Figure 15: Monthly breakdown of typical annual CO_2 emission for the WTE plant

Note that a WTE plant differs from most other types of energy resources in one particular aspect: municipal garbage constantly produced by residents. In some months, there is little or no demand by the DE system for the full capacity of the WTE plant. Thus, there are various operation options for these months:

1. Burn the garbage and store the heat in a thermal energy storage;
2. Burn the garbage and use the thermal energy for other applications; and
3. Store the garbage and burn it if there is demand for heat.

Depending on the management, location, municipality, budget, and garbage type, one of the above options can be selected. Each scenario is a project by itself and needs detailed design.

RESULTS AND DISCUSSION

Two energy resources DE systems are assessed and compared technically, economically and environmentally: natural gas, and waste energy. The technologies are sized for a common DE system to permit consistent comparisons.

I. Economic Appraisal

The economic comparison of energy resource technologies assume a 25-year lifetime for each technology. Annual costs are evaluated over the lifespan of each energy technology. The revenue of the DE system from selling heat is considered to be the same for all technologies. But, this amount is not considered in the economic assessments, since it is a constant in all comparisons. The annual costs of the two technologies for the proposed DE system are contrasted in Figure 16. The costs of both technologies decreases after 10 years, when the loan on the initial investment is paid off. The initial investment is lower for the incineration-based WTE system than the natural gas system. Figure 17 compares the overall cost of the energy options for the proposed DE system. It can be observed that the WTE plant is less expensive for the proposed DE system than the natural gas condensing boiler. The cost breakdowns of each energy supply for the DE system in Figures 8 and 14 show that NG technology has the highest fuel cost and I&M cost, while WTE technology has the lowest cost.

Note that to make economic decisions, other financial factors, such as project circumstances, must be considered.

II. Environmental Appraisal

The environmental performance of the DE system is an important factor in decision making, including choosing an energy supply. Figure 18 compares the CO_2 emissions during a typical year for both energy supply technologies. The natural gas is seen to exhibit higher CO_2 emissions than the WTE system.

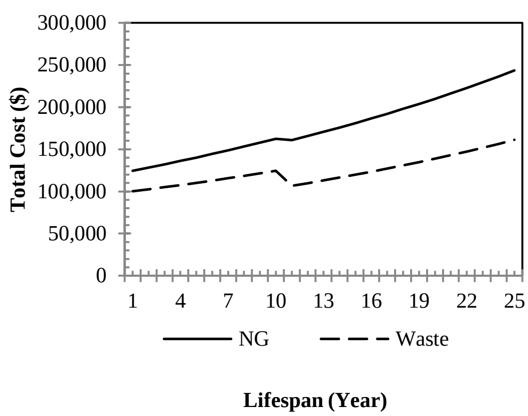

Figure 16: Comparison of annual costs for two types of energy supply to DE system

Environmental aspects of industrial projects are attracting increasing attention in recent years for various reasons:

1. Protecting the environment;
2. Receiving government tax incentives for good environmental stewardship;
3. Reducing carbon taxes and/or mitigating limitations associated with carbon caps; and
4. Satisfying industry standards and governmental regulations.

III. Comprehensive Appraisal

To provide a comprehensive approach, the CO_2 emissions of each energy option for the proposed DE system are evaluated economically. As the DE systems provide heat for the community they are usually considered businesses and pay tax. The various levels of the government sometimes offer tax benefits for businesses that do not use fossil fuels. This tax benefit is assumed here (based on the average for some available programs) to be 10% of the revenue of the DE system. The average cost of heat for DE system consumers is considered to be 0.20 $/kWh [16]. The tax benefit is assumed to be 1% of the DE system revenue when WTE technology is employed. The financial value of the tax benefit for each technology for an annual energy demand 6,309 MWh, over 25 years, is estimated to be:

(6,309 MWh/yr)(1%)(0.20 $/kWh)(25 yr) = $314,450

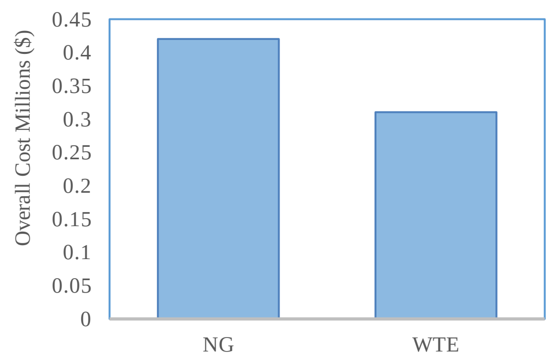

Figure 17: Comparison of overall cost (including initial investment, operational, and management costs) for two types of energy supply to DE system

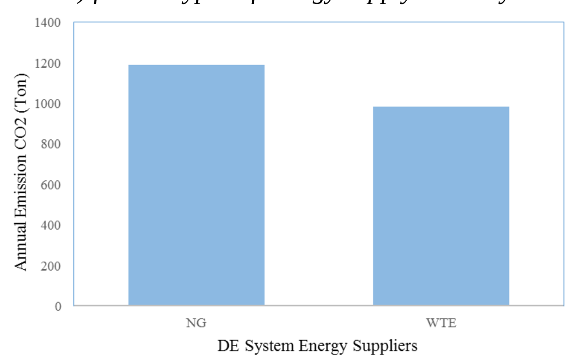

Figure 18: Comparison of annual CO_2 emissions for two types of energy supply to DE system

In Figure 19, the estimated carbon tax for natural gas and the tax benefit for WTE technology are shown. Since the tax benefit reduces both the tax and the overall cost, it has a negative value in Figure 19. But, there is an extra tax for fossil fuel technologies in some jurisdictions, e.g., a carbon tax is imposed in many parts of Canada (Quebec, British Columbia, and Alberta). A carbon tax is set based on such factors as type of fuel and industry. For the DE system operating on natural gas, the carbon tax is considered here to be 12 \$/tCO_2. The DE system using natural gas as the source of energy can be shown with Figure 19 to pay a carbon tax of \$354,000 (i.e., 1,180 tCO_2/yr× 12 \$/tCO_2 × 25 yr) over 25 years.

The tax benefits and carbon tax for energy suppliers is added to more accurately reflect the overall cost of each technology. The modified results are shown in Figure 20. The procedure used to develop Figure 20 is based on Equation (8), where economic aspects (including FC, I&M, M, and CT) as well as the environmental aspects in the form of a tax benefit, are captured. It can be observed that the WTE plant is less expensive, based on the grand total cost (including initial, operational, and management as well as tax benefits and carbon tax) for the proposed DE system than the natural gas condensing boiler.

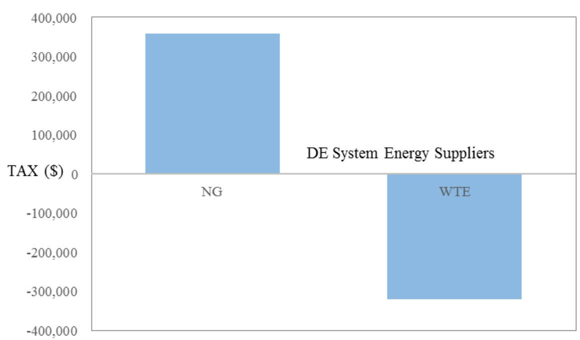

Figure 19: Estimated carbon tax for natural gas and tax benefit for WTE technology

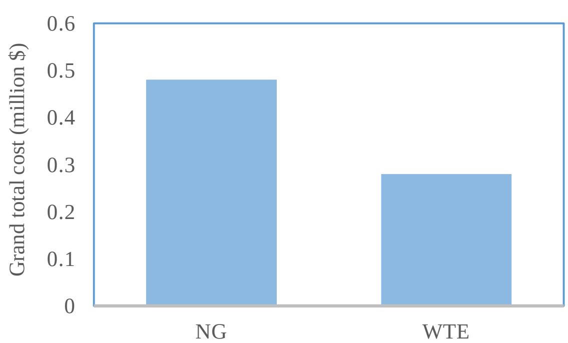

Figure 20: Comparison of grand total cost including initial, operational, and management costs plus the carbon tax and tax benefit over 25 years, for two types of energy supply to DE system

CONCLUSIONS

A methodology for analysing various energy options for DE systems from the perspectives of energy, economics, and CO_2 emissions is developed. An enviro-economic function is used to capture the carbon dioxide emission and economic characteristics of the energy supply technology. For illustration, a case study involving a community-based DE system is considered. A characteristic heat load of the proposed DE system is developed, and energy options (natural gas and waste) for the DE system are compared in a consistent manner. The systems are sized for each energy option, to permit the CO_2 emissions and economic characteristics of each technology to be analyzed. The results for this case study indicate that waste-to-energy technology is more advantageous than natural gas for the DE system from a financial point. Further, an overall appraisal, which captures the CO_2 emission and financial characteristics in the form of cost, demonstrates that the option using waste-to-energy is superior to that using natural gas.

ACKNOWLEDGEMENT

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