

# **Analysis of Green Energy Options for The Phipps Conservatory**

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**Executive summary:**

This report presents the analysis of six scenarios for providing the Phipps Conservatory and Botanical Gardens (Phipps) with electrical power and thermal energy via on-site generation or purchases of renewable energy credits:

- 1) A 5kW solid oxide fuel cell (SOFC) fuelled with natural gas
- 2) Digester 1: A small anaerobic digester (AD) providing methane for a 5 kW SOFC (living machine: a digester + fuel cell)
- 3) Digester 2: A large AD using outside waste sources fuelling a 125kW SOFC (living machine: a digester + fuel cell)
- 4) Digester 3: A small AD and natural gas fuelling a 125kW SOFC
- 5) Purchasing wind power equivalent to 5kW of generation
- 6) Purchasing wind power equivalent to 125kW of generation

The private, social and total net present values (NPVs) over a 25-year lifespan of these six options were estimated, and both financial and non-monetized costs and benefits analyzed. Under our assumptions, all options were found to have negative private (i.e. only considering Phipps’ finances) NPVs on this timeframe. Only the wind power options had positive NPVs when social benefits were considered. The value of the ‘living machine’ options as technology demonstration or educational projects may make them worth the additional expense.

Qualitative relative rankings of the project options and benefits are summarized here:

<b>Options</b>	NPV	Environmental	Education	Demonstration	Facility (Space)	Uncertainty
100% Wind	●	●	●	○	●	●
Digester 1	●	●	●	●	●	●
Digester 2	○	●	●	●	○	○
Digester 3	●	●	●	●	●	●
Fuel cell alone	●	○	●	●	●	●
<b>Legend</b>	● Best (5)	● (4)	● (3)	● (2)	○ Worst (1)	

The results of this analysis did not identify one definitive course of action; rather the analysis identifies the relative costs and benefits of each technology option. This analysis allows Phipps to evaluate this multi-criteria investment decision by assigning relative weights as deemed appropriate to Phipps’ mission to the benefits provided by each option, and proceed with the most appropriate investment decision. For example, if Phipps weighs demonstration, education and environmental aspects as most important and space required and certainty of the costs and NPV as less important in their decision criteria they would choose Digester 2.

## 1. Motivation and overview

Located in Pittsburgh, Pennsylvania, the Phipps Conservatory and Botanical Gardens was first opened in 1893<sup>1</sup>. It is one of the oldest and largest conservatories in the United States, housing a range of tropical plants, palms, orchids, ferns and succulent plants. Presently, the conservatory is undergoing a major renovation and expansion. An explicit goal of this expansion is to incorporate a range of projects to reduce the environmental footprint associated with the facility as well as promote and educate the community about environmentally friendly technologies and practices.

One proposal currently under consideration is to use fuel cells for on-site production of electricity and heat. Fuel cells directly convert the chemical energy of gaseous and liquid fuels into electrical energy by a highly efficient and clean electrochemical oxidation process<sup>2</sup>. Relative to conventional forms of electrical generation, fuel cells emit minimal levels of criteria air pollutants<sup>3</sup> and are associated with significant reductions in greenhouse gas (GHG) emissions - specifically carbon dioxide (CO<sub>2</sub>). Air pollution is one of the main negative side-effects (or negative environmental externalities) associated with electricity generation; fuel cells have the potential to substantially reduce these impacts. To this end, two fuel cell-based schemes are proposed to provide electricity and heat for the Phipps Conservatory:

1. A natural gas-fuelled 5 kW solid oxide fuel cell (SOFC) for the main building (the welcome center and offices) which will meet a portion of the electricity and heat load demand. (Scenario 1)
2. A digester and fuel cell (also SOFC) arrangement which uses organic waste from Phipps' greenhouses and café to generate electricity and heat. (Scenarios 2 and 3)

The objective of this work is to provide a basic evaluation of the technical and economic feasibility of using fuel cells and/or digesters to meet the electricity and heat load for Phipps. These options are compared to other energy sources including grid electricity, electricity from wind (in the form of renewable energy certificates) and steam provided by the neighboring Bellefield Boiler.

## 2. Baseline energy characteristics of Phipps Conservatory

A full knowledge of the current energy demand and sources at Phipps Conservatory is essential for effectively assessing the suitability of alternative power and heat generation schemes. Estimates were developed based on usage data provided by Phipps staff and details of regional energy supply in the Pittsburgh area.

### 2.1. Electricity: annual usage and summary of loads

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<sup>1</sup> <http://www.phipps.conservatory.org/facilities/history/index.html>

<sup>2</sup> Singh, P. & Minh, N.Q. (2004). "Solid oxide fuel cells: technology status" *Applied Ceramic Technology* 1(1): 5 – 15

<sup>3</sup> Criteria air pollutants refer to six airborne species that the USEPA has classified as injurious to human health and harmful to the environment. The list is comprised of carbon monoxide (CO), lead (Pb), nitrogen dioxide (NO<sub>2</sub>), ozone (O<sub>3</sub>), particulate matter (PM), and sulfur dioxide (SO<sub>2</sub>).

Due to the construction activity and temporary space closures resulting from the renovations, 2004-05 electricity data provided only rough estimate of actual consumption. The addition of the proposed expanded facilities will increase the Phipps base and peak electricity loads and were not estimated for this analysis. Data used for this analysis was compiled from utility bills<sup>4</sup> provided by Phipps and employ a range of assumptions. This analysis will only examine the current Schenley Park conservancy site and omit any other Phipps facilities. Since access to reliable electricity data was only available from January 2005 to June 2005, we simulated an annual load profile by mirroring this six-month load over a one-year period. While not ideal, this method yields a reasonable representation of annual electricity load given the data available. Using this method, the average annual electricity usage by Phipps is estimated to be 745,000 kilowatt-hours (kWhr). However, as Phipps is currently in the midst of a significant expansion with the addition of new production and tropical greenhouses, the electrical usage can be expected to increase significantly in coming years.

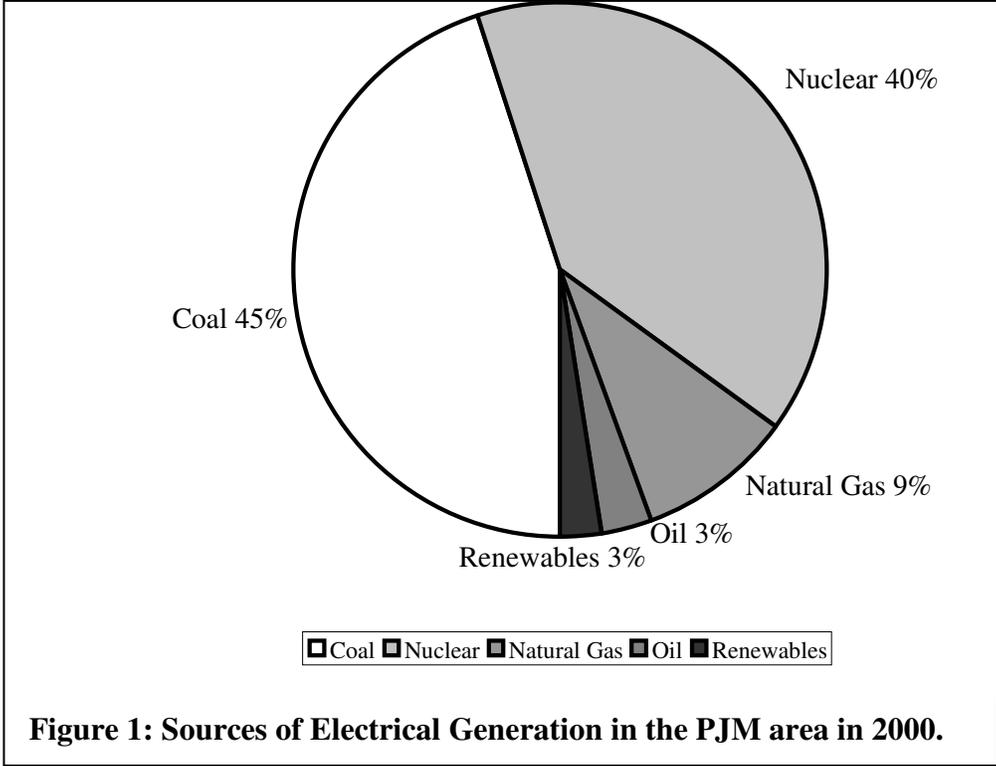
## **2.2. Environmental characteristics of baseline energy**

To evaluate whether proposed alternative power sources will have net environmental benefits, the baseline environmental characteristics of the electricity and heat used at Phipps are needed. In Pittsburgh, electricity from the grid is served by the Pennsylvania – New Jersey – Maryland (PJM) interconnect area. The majority of the capacity is coal and nuclear generation, supplemented by small quantities of natural gas and oil. Approximately, 3% of the demand is met by renewable sources comprised mainly of hydropower and biomass-firing with a small quantity of wind energy. The composition of the generation capacity in the PJM area as of 2000 is shown in Figure 1<sup>5</sup>.

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<sup>4</sup> Utility bill information included both actual and estimated figures and provides only an approximation of Phipps' electricity load.

<sup>5</sup> Environmental Protection Agency (2000). EGrid at <http://www.epa.gov/cleanenergy/egrid/index.htm>



The average emissions associated with a kilowatt of electricity from the PJM power mix are summarized in Table I<sup>6</sup>. Presently, other criteria pollutants are not included in the database. To estimate the PM emissions, a PM emission factor for coal fired power plants was found in literature. Since coal dominates the PM emissions, it was divided by 2 to roughly correspond to the percentage of coal in the generation mix<sup>7</sup>.

Phipps meets the majority of its heating load using steam from the Bellefield Boiler plant. This plant operates on a varying combination of coal, natural gas and no.2 fuel oil; the current mix is approximately 30% coal and 70% natural gas<sup>8</sup>. Emission factors for the Bellefield Boiler are presented in Table II<sup>9</sup>.

**Table I. Emission factors from PJM generation mix in g/kWh**

Pollutant	Emission factor
Nitrogen oxides	1.1
Sulfur dioxide	3.5
Particulate matter	0.075
Carbon dioxide	500

<sup>6</sup> Environmental Protection Agency (2000). EGrid at <http://www.epa.gov/cleanenergy/egrid/index.htm>

<sup>7</sup> An emission factor of 0.15 g/kWh was used for PM<sub>10</sub>. Albina, D.O. & Themelis, N.J. (2003). "Emissions for waste-to-energy: a comparison with coal-fired power plants". ASME International Mechanical Engineering Congress & Exhibition, Washington, DC, November 16 – 21

<sup>8</sup> Personal communication with Brad Hochburg, December 6<sup>th</sup> 2005

<sup>9</sup> Emissions for boilers are normally presented in terms of mmBtu of input fuel. We assume 60% boiler efficiency and 1,176 Btu/lb of steam. The CO<sub>2</sub> was estimated assuming 4,810 lb of CO<sub>2</sub> per ton of coal and 120,000 lbs of CO<sub>2</sub>/mmcf of natural gas.

**Table II. Bellefield boiler emission factors in g/MMBtu and g/kg of steam**

<b>Pollutant</b>	<b>g/MMBtu</b>	<b>g/kg</b>
Nitrogen oxides	496	1.20
Sulfur dioxide	457	1.10
Particulate matter	132	0.32
Carbon Dioxide	123,000	300

Please see appendix A for further discussion of baseline energy sources

### **3. Green Power Scenarios**

Six scenarios for providing efficient and green electric power and heating for Phipps Conservatory were considered in our analysis:

- 1) Fuel cell: a 5kW SOFC fuel by natural gas
- 2) Digester 1: using digester + 5kW fuel cell
- 3) Digester 2: using large digester + 125kW SOFC with make-up organic waste
- 4) Digester 3: using smaller digester + 125kW SOFC with make-up natural gas
- 5) Purchasing 5kW of wind power
- 6) Purchasing 125kW of wind power

#### **3.1. Fuel Cells**

A fuel cell is an electrochemical device similar to a battery, but differing from the latter in that it is designed for continuous replenishment of the reactants consumed; i.e. it produces electricity from an external fuel supply of biogas or hydrogen as opposed to the limited internal energy storage capacity of a battery (see appendix B).

Some benefits of fuel cell technology are<sup>10</sup>:

- More efficient than combustion technologies that produce cost savings for power generation
- Reduces or eliminates air emissions contributing to greenhouse gases
- Modular construction can be easily scaled up or down in size
- Distributed power generation reduces transmission losses
- Can be used for cogeneration of heat and power (see appendix B)
- Can use a variety of fuels
- Reduces hazardous and controlled wastes generated by traditional combustion generators
- Lower maintenance costs

##### **3.1.1. Electrical characteristics of fuel cells**

Solid oxide fuel cell systems (SOFC) used with and without digester systems will be based on technology produced by Siemens Power Generation Inc.. The larger unit under consideration has a nominal electrical output of 125kW and is currently in a pre-production stage of development. The smaller 5kW fuel cell will nominally generate five kilowatts of electricity and deliver approximately four kilowatts of thermal energy (kWt) with electrical and overall efficiencies of 45% and 80%, respectively. This five kilowatt fuel cell will be purchased from a

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<sup>10</sup> Joint service pollution prevention technical library <http://p2library.nfesc.navy.mil/>

Canadian company called Fuel Cell Technologies (FTC), which has developed a small scale fuel cell unit based on technology licensed from Siemens Power Generation.

### 3.1.2. Environmental characteristics of fuel cells

As mentioned previously, one of the main benefits of fuel cell technology is that as an electrochemical energy conversion device, it has low emissions of both criteria air pollutants and greenhouse gases. Table III shows the emission factors for the SOFC<sup>11</sup> (see appendix B for comparisons with other technologies). In principle, a fuel cell will only produce water. However, when a hydrocarbon is used (instead of pure H<sub>2</sub> fuel), there are other emissions as well. Since the hydrocarbon is completely oxidized, the amount of CO<sub>2</sub> produced is in proportion to the amount of carbon in the fuel. The CO<sub>2</sub> produced is less than other energy conversion technologies because of the higher efficiency of a fuel cell<sup>12</sup>. The CO<sub>2</sub> emissions were calculated assuming a 45 % electrical efficiency.

Use of the fuel cell's waste heat to meet the heating load at Phipps results in additional CO<sub>2</sub> savings. Lacking detailed information about the total heat load and profile, it is difficult to estimate the potential for heat usage. As an estimate, it is assumed that 50% of the heat produced on an annual basis is utilized by Phipps. The emissions displaced by use of the 5 kW natural-gas-fuelled SOFC are presented in Table III; these values were calculated by assuming that 100% of the electricity and 50% of the heat output from the fuel cell are used by Phipps and offset emissions from Phipps' existing electricity and heat sources (PJM and the Bellefield Boiler).

**Table III. Emission factors and displaced emissions for the SOFC (in g/kWh and kg/year)**

Pollutant	Emission factor (g/kWh)	Emissions (kg/year)
Nitrogen oxides	0.01	77
Sulfur dioxide	0.0001	158
Particulate matter	~ 0	7
Carbon dioxide	422	10,470

### 3.1.3. Fuel cell capital and operating expenses

Stationary fuel cell generation units are a developing technology and thus capital costs are still significantly higher than other competing generation technologies (e.g. internal combustion engines and turbines). Capital costs for these more mature technologies are typically on the order of one to several thousand dollars per installed kW. The price quoted for the installation of a 5 kW fuel cell in the Phipps Welcome center is \$300,000<sup>13</sup>, making it (at ~ \$60,000/ kW) many times more expensive than conventional technologies. However, fuel cell technologies are projected to mature over the course of the next decade to the point where equipment cost approaches \$400/kW<sup>14</sup>. Annual operating and maintenance (O&M) expenses were assumed to

<sup>11</sup> NOx and SO2 emission factors are from

<http://www.powergeneration.siemens.com/en/fuelcells/benefits/index.cfm?session=1717390x49386849>

<sup>12</sup> M.W.Ellis, M.R.von Spakovsky, D.J.Nelson. Fuel cell systems: Efficient, flexible energy conversion for the 21st century, Proceedings of the IEEE 89 (2001) 1808-1818.

<sup>13</sup> Personal communication with Richard Piacentini, November 21, 2005

<sup>14</sup> Voigt, T.C., *SECA - The Challenge for Small-Scale, Ultra-Low Cost SOFC Power System*, Presented at: 3rd Annual SECA Workshop, March, 2002, Washington, D.C.

be 3% of the initial equipment capital cost; this value represents a conservative estimate. Current SOFC technology requires little regular maintenance but does require that the fuel cell stack be replaced every five years. The cost of stack replacement was assumed to be 25% of the total system capital cost every five years of operation; this estimate is based on in-use data from installed fuel cells<sup>15</sup>.

### **3.2. Fuel Cell with Digester Scenarios**

An anaerobic digester is a potential source for gas to power the fuel cell; the union of a digester and fuel cell fits especially well with the ‘greening’ of Phipps and demonstrating the concept of a ‘living machine’. Anaerobic digestion (AD) is a process in which organic waste is decomposed by bacteria in a sealed container (called the digester) to create a mixture of gases commonly called biogas. Biogas is mostly composed of methane (CH<sub>4</sub>: 50 - 70%) and carbon dioxide (CO<sub>2</sub>: most of the remainder); depending on the sulfur content of the waste stream, it may also contain troublesome amounts of corrosive and poisonous hydrogen sulfide (H<sub>2</sub>S). The high methane content of biogas allows it to be used as a fuel in combustion engines and boilers; it can also be reformed to provide the hydrogen required to operate fuel cells. Biogas is well-suited to use in reformer-driven fuel cell (i.e. not one that relies on an external pure hydrogen source) as the CO<sub>2</sub> in the biogas acts as a reforming agent, which aids in the conversion of the biogas into a gas suitable to fuel a fuel cell<sup>16</sup>. Biogas is thus a reasonable fuel choice for use in the high-temperature reforming SOFC under consideration by Phipps.

Anaerobic digesters are currently in wide use for processing waste from a variety of sources. They are often installed both as a means to process a particular concentrated waste stream (thus avoiding other treatment and potential odor issues) and also to harvest the energy contained in the waste to create electric power or process heat. Waste streams commonly used are: animal waste (manure/bedding), municipal waste (sewage sludge and the organic fraction of solid waste), and crop residues and industrial waste water (with high organic loading)<sup>17</sup>. A wide variety of digester types and technologies are currently in use and under development; a full review of these types and their suitability to potential feedstock sources at Phipps would be the next step if a digester is determined to be a viable option for on-site power and heat generation. Key variables in digester design are digester temperature and phase (wet or dry), the number of stages in the digestion process and the extent and type of mixing that occur in the digester.

#### **3.2.1. Digester specification for Phipps installation**

As was detailed in an earlier report by Kyle Meisterling<sup>18</sup>, the main waste streams being considered for use in a digester for use on-site at Phipps Conservatory are the compostable waste from plant cultivation/production (clippings, etc.) and the organic food waste from the Phipps Garden Café. Meisterling estimated a total annual waste flow of approximately 170 tons/year from these two sources. A relatively convenient source of additional organic matter (akin to the

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<sup>15</sup> Colella, W.G., et al., *Evaluation of the financial and environmental feasibility of a network of distributed 200 kW(e) combined heat and power fuel cell systems on the Stanford University campus*. Fuel Cells, 2005. 5(1): p. 148-166.

<sup>16</sup> Van herle, J., Y. Membrez, and O. Bucheli, *Biogas as a fuel source for SOFC co-generators*. Journal of Power Sources, 2004. 127(1-2): p. 300-312.

<sup>17</sup> OTA, *Energy from Biological Processes: Volume II-Technical and Environmental Analyses*. 1980, Office of Technology Assessment: Washington, D.C.

<sup>18</sup> Meisterling, K., *Methane production from waste*, Memo to R. Piacentini. August, 2005: Pittsburgh, PA.

café waste from Phipps) would be the food waste from the University Center (UC) at neighboring Carnegie Mellon University (CMU). An analysis of a composting program for the UC estimated (based on a conservative estimate of 15% organic waste fraction) a total organic waste production of approximately 50 tons/year from the UC eating facilities<sup>19</sup>. The waste streams under consideration are described as the organic fraction of municipal solid wastes (OFMSW); digesters for processing this feedstock are not in wide use in the U.S., though they are fairly common in parts of Europe (see Appendix C for further description).

Based on analysis of potential waste-sources within and around Phipps and the fuel cell equipment under consideration (5kWe and 125 kWe systems from Siemens), three potential digester designs were considered and are summarized below in Table IV. *Digester 1* is the smallest and simplest scenario and consists of a digester system to process organic waste generated on-site at Phipps feeding biogas to a 5kW fuel cell system for creating power and heat. *Digester 2* is a scenario in which a 125 kWe fuel cell is fed entirely by a large digester on-site at Phipps which would require organic waste from Phipps, the UC and a large additional quantity of waste from other sources. The *Digester 3* scenario assumes the use of waste from Phipps and the UC in a small digester to run a 125 kWe fuel cell, with additional fuel provided by natural gas.

**Table IV – Digester configurations considered for installation at Phipps**

<b>Scenario</b>	<b>Fuel Cell</b>	<b>Waste sources</b>	<b>Additional NG?</b>	<b>Digester Size</b>
Digester 1	5 kWe	Phipps (170 tons/yr)	No	Smallest
Digester 2	125 kWe	Phipps + UC + <i>much more</i> (4400 tons/yr)	No	Largest
Digester 3	125 kWe	Phipps + UC (220 tons/yr)	Yes	Medium

Data from a survey conducted by R.W. Beck of OFMSW digester facilities in Europe<sup>20</sup> was used to estimate gas production and size and cost data for the three digester systems. The size of the digester was estimated based on the total volume of waste expected on a daily basis (assuming densities of 900 and 700 kg/m<sup>3</sup> for Phipps garden and café waste, respectively) and a typical digester retention time of 20 days<sup>21</sup>. A second estimate for digester volume was based on a heuristic suggested by an EPA contractor<sup>22</sup>, that a cubic meter of digester volume is required for each 1.2 kg of volatile solids (VS – the fraction of solids that is convertible to gas, typically 15% for OFMSW) added to the digester per day. Estimates of gas production are based on the average gas production per ton of waste in the systems surveyed by R.W. Beck.

Facility capital costs were estimated based on surveyed data of capital costs per-ton-waste-throughput vs. annual waste throughput from Beck report, shown in Figure D1 in Appendix D. High- and low-range estimates for Phipps facility cost were made based on a power-law linear

<sup>19</sup> Carling, J., Jaramillo, P., Luscher, A., *Economic and Environmental Cost-Benefit Examination of Carnegie Mellon University Center Collection of Pre-consumer Food Waste for Composting*, Report for 12-704 - Civil Systems Investment Planning and Pricing, December, 2003

<sup>20</sup> Beck, R.W., *Anaerobic Digestion Feasibility Study for the Bluestem Solid Waste Agency and Iowa Department of Natural Resources*. 2004, R.W. Beck.

<sup>21</sup> Meisterling, K., *Methane production from waste*, Memo to R. Piacentini. August, 2005: Pittsburgh, PA.

<sup>22</sup> Moser, M., *Anaerobic Digesters Control Odors, Reduce Pathogens, Improve Nutrient Manageability, Can be Cost Competitive with Lagoons, and Provide Energy Too!* 2004, EPA Agstar Program.

regression fit and a facility average, respectively. It must be noted that the systems surveyed by Beck process between 4,500 and 160,000 tons of waste per year, while the waste flow from Phipps is on the order of 200 tons per year. Cost estimation for AD facilities sized for Phipps is thus complicated by the fact that there are few existing precedents (see Appendix C for a discussion of AD installation details), and the estimated and actual project costs may differ significantly. In particular, costs and feasibility of Digester 2, which uses a ‘large’ digester, are particularly uncertain because of: 1) the large volume of outside waste required (~4000 tons/year); 2) the large digester volume required (a cylinder approximately 4 meters tall x 15 meters in diameter); 3) the siting and permitting issues involved with both placing the digester and handling the large volume of waste required to operate it. Appendix D contains a table of the important parameters used in the financial modeling and sizing of these digester systems, along with the assumptions used in determining these parameters.

### 3.2.2. Environmental costs and benefits

The major environmental benefits of the use of a digester-fuel cell system are the air emissions avoided relative to the baseline; power and heat from baseline generation facilities emit relatively more pollutants. The use of methane produced from biomass (as is the case in the digester systems) results in no net emissions of CO<sub>2</sub>, as carbon from the atmosphere is captured during the growth of the biomass. Further, as discussed above, the emissions of criteria air pollutants from the operation of the SOFC are far below other power generation technologies. Using the same approach as outlined in section 3.1.2, the displaced emissions for the three fuel cell configurations are calculated and are tabulated in Table VII. Beyond those shown, there are various other environmental benefits associated with the use of a digester to create biogas that were not accounted for in this analysis. For example, through use of an AD to create biogas, upstream pollutant emissions from the production and transport of natural gas and emissions of methane (CH<sub>4</sub>) produced during the decaying of biomass are avoided. The latter effect is significant as CH<sub>4</sub> is 23 times more potent as a GHG than CO<sub>2</sub><sup>23</sup>. These displaced emissions assume that all of the electricity and 50% of the usable heat produced (that which is not used to keep the digester at proper operation temperature) is consumed either on-site or nearby. See Appendix D for further details on these assumptions and the resulting heat and electricity output values for the three digester arrangements.

**Table VII. Displaced emission (kg/yr) from digester-fuel cell arrangements relative to electricity from PJM and heat from Bellefield Boiler**

<b>Pollutant</b>	<b>Digester 1</b>	<b>Digester 2</b>	<b>Digester 3</b>
Nitrogen oxides	58	1300	1700
Sulfur dioxide	150	3700	3800
Particulate matter	5	100	150
Carbon dioxide	24,000	550,000	220,000

### 3.3. Increasing share of wind-power

If the goal of a green energy program at Phipps is simply to reduce the environmental impacts of the energy use, another potential solution is to increase the purchases of wind power certificates.

#### 3.3.1. Cost of increasing to varying shares of wind power

<sup>23</sup> It is estimated that 153 g of CH<sub>4</sub> is avoided per kWh.

This strategy was compared on a cost-benefit basis with the purchase of either the 5 kW SOFC for the Welcome Center or any of the fuel cell-digester arrangements for onsite generation. This amounts to 41.6 MWh and 1,040 MWh of electrical load for the 5 kW and 125 kW SOFC, respectively (assuming 95% availability). For each kilowatt-hour of wind power purchased, Phipps currently pays an additional \$0.01018/kWh premium over current utility rates.

### 3.3.2. Environmental benefits of wind power

Table VIII shows the emissions displaced -relative to PJM - for a purchase of wind-power equivalent to that generated by 5 kW and a 125 kW on-site generation systems.

**Table VIII. Displaced emission (kg/yr) from wind power relative to power from PJM generation**

<b>Pollutant</b>	<b>5 kW</b>	<b>125 kW</b>
Nitrogen oxides	47	1,170
Sulfur dioxide	144	3,600
Particulate matter	20,690	517,200
Carbon dioxide (equivalent)	3	78

## 4. Cost-Benefit Analysis

To evaluate the most financially effective manner for the ‘greening’ of Phipps’ energy supply, a traditional cost benefit analysis was performed. The primary analysis was conducted using only private costs incurred by Phipps and then the analysis was expanded to include consideration of social costs such as the costs associated with pollutant emissions. The private cost-benefit analysis included only variables that pertained to the capital purchase and operation of the fuel cell and living machine, and the expense of increasing the share of wind power purchased by Phipps. Private costs included capital and operations and maintenance (O&M) expenses, including interest accrued on capital debt. Private benefits included avoided expense of electricity purchases. Since Phipps is a nonprofit 501-c(3) mission-driven organization, we conducted the analysis under the assumption that Phipps has no federal, state, or local income tax liability. Benefits such as interest payments on capital debt, depreciation charges, and renewable energy production tax credits (PTC) do not act as a shield against tax liabilities. As an organization with no tax liability, Phipps may be eligible for a federal Renewable Energy Production Incentive (REPI) payment, and was assumed to be eligible as a baseline assumption in this analysis. The REPI is a payment of \$0.019/kWh (adjusted for inflation), and was reauthorized in the Energy Policy Act of 2005 for systems installed until the end of 2006. The delivered price of electricity which Phipps currently pays was assumed to be \$0.10/kWh; expanded analysis examined the private cost-benefit analysis considering electricity prices of \$0.06-0.014/kWh.

### 4.1. Determining private NPV

The annual stream of costs and benefits generates a series of net cash flows for Phipps. Using the financial assumptions outlined in Table IX and the project assumptions outlined in the following section, the Net Present Value (NPV) of each option over the project lifetime was computed. From the perspective of the Phipps, the option with the highest NPV value would be the most efficient green power option, all other considerations being equal.

**Table IX: Project Financial Assumptions**

Project Life (yr)	25
Project Start Year	2005
Down Payment (% equity)	20%
Loan Rate	7%
Loan Period (years)	15
Depreciation Method	Double Declining Balance
Renewable Production Incentive (\$/kWh)	\$0.015
Social Discount Rate <sup>24</sup>	3.5%
Internal Discount Rate	10%
Electricity Price (\$/kWh)	\$0.06 - \$0.14

#### 4.2. Determining social NPV – including environmental costs and benefits

As outlined in the above sections, energy use results in emissions that impose social costs (e.g. health and property value impacts of air pollution). Therefore, the real project NPV from the perspective of society or a firm facing an emission trading scheme or Pigovian taxes<sup>25</sup> to offset the social cost of emissions must include the social costs in the NPV analysis. We calculated the social cost of avoided emissions by electricity generation versus the do-nothing option, which resulted in an annual stream of social costs for each generation option. This cost stream was included in the private NPV analysis resulting in a total NPV analysis.

One method of evaluating the benefit of displacing these emissions is to monetize the pollutants' impacts. If the 'correct' value is applied, the monetary value associated with these emissions should represent the externality or social cost associated by these emissions. In this work, we use the social costs as tabulated by Matthews and Lave<sup>26</sup>. These values in 2005 dollars are tabulated in Table X.

**Table X. Externality costs associated with pollutants (in 2005 \$/metric ton)**

Species	Min	Median	Mean	Max
NO <sub>x</sub>	344	1,660	4,384	14,873
SO <sub>2</sub>	1,206	2,818	3,131	7,358
CO <sub>2</sub>	3	22	20	36
PM <sub>10</sub>	1,487	4,384	6,732	25,363

The benefit derived from the use of a fuel cell is a function of the electricity usage displaced by its use. Since the fuel cells considered for the Phipps facility are expected to provide constant electrical power (or provide base-load), it is assumed that the average grid emission factors for the PJM generation area (in Table I) adequately represent the displaced emissions. In addition, there is a temporal element to this analysis as our project is being evaluated over 20 years. The Energy Information Administration (EIA) forecasts that most new capacity will be added after

<sup>24</sup> This is the 30-year constant-dollar social discount rate dictated by the Office of Management and Budget for evaluating federal projects. *Discount Rates for Cost-Effectiveness Analysis of Federal Programs*. Federal Register. Volume 69, Number 38, February 26, 2004, Notices. Available URL: [http://www.whitehouse.gov/omb/fedreg/2004/040226-a94\\_appx-c.pdf](http://www.whitehouse.gov/omb/fedreg/2004/040226-a94_appx-c.pdf).

<sup>25</sup> A Pigovian tax is a tax levied to correct the negative social side-effects of an activity.

<sup>26</sup> Matthews, H.S. & Lave, L.B. (2000) "Applications of environmental valuation for determining externality costs" *Environmental Science & Technology* 34: 1390 - 1395

2010 with the majority of the growth in natural gas and coal<sup>27</sup>. If new capacity favors natural gas and old coal plants are retired, then the CO<sub>2</sub> intensity of the electricity in the PJM mix will be reduced in future years from the year 2000 baseline. To maximize the social benefits, we assume that the fuel cell will displace the emissions as presented in Table I. The annual social benefits (reduction in costs associated with replacement of PJM/Bellefield generation) for the six scenarios considered are shown below in Tables XI and XII.

**Table XI. Comparison of annual social benefits from use of four fuel cell based options (in 2005\$/year)**

<b>Species</b>	<b>Fuel cell 5kW</b>	<b>Digester 1 – 5 kW</b>	<b>Digester 2 – 125 kW (no NG)</b>	<b>Digester 3– 125 kW (with NG)</b>
Nitrogen oxide	\$117	\$97	\$2,167	\$2,820
Sulfur dioxide	\$437	\$421	\$10,343	\$10,840
Particulate matter	\$28	\$21	\$433	\$668
Carbon dioxide	\$194	\$516	\$12,119	\$4,917
<b>Total</b>	<b>\$775</b>	<b>\$1,055</b>	<b>\$25,062</b>	<b>\$19,246</b>

**Table XII. Annual social benefits for purchase of wind power (in 2005 \$/year)**

<b>Species</b>	<b>Wind power for 5 kW</b>	<b>Wind power for 125 kW</b>
Nitrogen oxide	\$77	\$1,930
Sulfur dioxide	\$406	\$10,150
Particulate matter	\$14	\$340
Carbon dioxide	\$453	\$11,340
<b>Total</b>	<b>\$950</b>	<b>\$23,760</b>

According to the assumed valuations, the social benefits associated with the use of a 5 kW fuel cell and 5 kW worth of wind power are nearly equivalent. The Digester 1 scenario (5 kW fuel cell with digester) looks significantly more favorable; these additional benefits stem largely from avoided CO<sub>2</sub> emissions, the valuation of which is highly uncertain. For similar reasons, Digester 2 (125 kW fuel cell running entirely on biomass) has the highest social benefit, followed by the larger purchase of wind power and finally the Digester 3 scenario (a 125 kW fuel cell mostly fueled with natural gas). These benefits again assume that all the electricity generated and 50% of the useful heat can be used on site or nearby. It is unclear whether demand for the 125 kW generation scenarios will be easily accessible; the social benefits for these scenarios are therefore possibly overstated.

#### **4.3. Total cost-benefit analysis – private and social**

Table XIII depicts the initial private, social and total (private + social) NPV results calculated using \$0.10/kWh as the electricity price. All options considered here have negative private net present values over the assumed 25-year project lifetime, indicating that none of these projects make sense from Phipps' private financial standpoint. On the other hand, the emissions reductions associated with all of these projects provide social benefits which result in positive (and reasonably large in the case of the 125kW-sized projects) social NPVs. The total NPVs for all of the fuel cell-based projects are negative, indicating that the substantial costs associated

<sup>27</sup> <http://www.eia.doe.gov/oiaf/aeo/electricity.html>

with the implementation these new technologies overwhelm the private and public financial benefits they offer. Only the two wind-power options provide positive total NPVs; this is a result of their total elimination of air pollutant emissions associated with electricity use at Phipps and the fact that wind-power technology is a more mature (and thus less expensive) technology than the other options considered.

**Table XIII: Lifetime (25 yr.) Private, Social and Total NPVs for green power options (\$2005)**

<b>Option</b>	<b>Private NPV</b>	<b>Social NPV</b>	<b>Total NPV</b>
<b>Natural Gas Fuel Cell (5 kW)</b>	(\$153,970)	\$12,781	(\$141,189)
<b>Digester/Fuel Cell 1 (5kW)</b>	(\$405,203)	\$17,390	(\$387,813)
<b>Digester/Fuel Cell 2 (125kW + waste)</b>	(\$2,084,234)	\$413,065	(\$1,671,169)
<b>Digester/Fuel Cell 3 (125 kW + NG)</b>	(\$476,279)	\$317,195	(\$159,083)
<b>Wind Purchase (5 kW)</b>	(\$3,794)	\$15,237	\$11,443
<b>Wind purchase (125 kW)</b>	(\$96,124)	\$386,027	\$289,904

### Sensitivity Analysis

An analysis was performed to determine the sensitivity of the project private net present value to changing or uncertain model parameters. The actual NPV of a project over its lifetime will differ from our modeled value; a good way to determine the robustness of the private NPV forecasts is to model the effects of changes in those input parameters considered important and variable in the model. The impact of uncertainties/fluctuations in parameters including capital and O&M expenses, internal discount rate, renewable energy tax credit and market prices for electricity, natural gas, steam and organic waste (purchased for the Digester 2 scenario) were modeled. The sensitivity analysis compared NPV from baseline parameter assumptions to a range of alternative parameter values. Fluctuations in electricity price, internal discount rate, and capital and O&M expenses had significant impacts on NPV, as is shown in Figures 1A-D in Appendix E. This plot indicates that within the foreseeable range of electricity prices, only Digester 3 has a positive NPV and this only with electricity prices above \$0.16/kWh (or roughly two times the current price paid by Phipps for electricity). As would be expected, the NPV of the Digester 3 scenario (which depends largely on natural gas for operation) is very sensitive to changes in natural gas prices. For example, for a gas price of less than \$7/MCF, this project has a positive 25-year NPV, while the negative NPV of the baseline scenario doubles to a net loss of more than \$1 million if natural gas is priced at \$22/MCF. Analogously, the Digester 2 scenario, which relies on a large supply of sorted, delivered organic waste, here nominally assumed to be priced at \$60/ton, is very sensitive to the price.

The baseline assumptions in the NPV analysis are a loan (note) rate of 7% and an internal discount rate of 10%. We assumed a note rate of 7% due to the assumption that Phipps has a favorable credit rating and access to at or below commercial lending rates because of its institutional status. We assumed a 10% internal discount rate as a reasonable baseline rate for a restricted (or dedicated) loan or donation to a nonprofit and the loan amount's time value in creating or fulfilling mission objectives with acquired capital. Both of these parameters are varied in the sensitivity analyses. However, under these baseline assumptions, Phipps would value capital at a higher rate than its loan rate, which would lead to a strategy of consistent borrowing. These assumptions also result in a more favorable NPV to projects with a higher capital cost, such as the large digester, and result in a less favorable NPV when the capital cost is adjusted lower. While the consequences of these assumptions may produce unfavorable analysis

results in certain situations, we feel they are reasonable baseline parameters for these scenarios and constitute only one factor in the decision-making process.

#### **4.4. Limitations, Assumptions and Further Work**

The cost benefit analysis includes simplifying assumptions and omissions that have the potential to change the outcomes. We assumed a single price of electricity under any scenario. This price would be independent of market prices in a deregulated electricity market such as Pennsylvania, or subject to Public Utility Commission regulations in a traditional market. These market scenarios require different strategies to operate efficiently and maximize revenue. We assumed that the all projects would commence with capital financing and construction in the beginning of year 0 and the constructed generation plant would begin revenue operations at the beginning of year 1 for a period of 25 years, using 2005 dollars. As stated above, we assumed Phipps has no taxable income to offset and the organization is eligible for the renewable energy production incentive instead of the renewable energy tax credit. If we instead assumed that taxable income existed for the Phipps, the NPVs of the projects would be significantly increased. This is a result of the significant amount of interest on accrued debt on the large capital purchases, the annual operating expenses of the equipment, and the renewable production tax credit, which would all act as a shield against any income taxes. This work also assumed that the capital purchases by Phipps would be financed with a 20 percent equity payment and 80 percent debt. As a mission-driven nonprofit, Phipps may be able to investigate alternative financing methods for large renewable energy capital equipment such as external capital leases, the issuance of tax-free debt, federal and state loan guarantee programs, and other methods utilized by nonprofits to reduce the cost of capital investments. A sample NPV calculation is presented in Appendix F.

Other expenses that Phipps would incur include additional labor required, net increases in property taxes, applicable state and local income taxes and/or power generator operating license fees. Although these were not included in the analysis, their overall impact is expected to be minimal and should be captured within the sensitivity analysis. While the changes in major financial assumptions would change project outcomes, for the purpose of a project level technology screening, changes in financial assumptions should not drastically change the results.

##### **4.4.2. Discussion of non-monetized benefits**

Education: The conservatory has drawn more than 1.8 million visitors since 1993<sup>28</sup>. Among these visitors are also regular groups of school children from the region who visit the conservatory. Phipps is an educational institution and a location for people to ponder their connection with the living world, making Phipps an ideal launch pad for environmental consciousness and sustainable practices. The adoption of fuel cell and digester technology provides an ideal opportunity to educate school children and others in the community about alternatives to centralized generation of electricity and low emission systems.

Demonstration: The early adoption of advanced green-power technology such as on-site power generation from a digester and fuel cell would highlight Phipps' efforts to be an institution on the cutting edge of green technology. The integration of such (locally-developed, in the case of Siemens fuel cells) technology will surely attract attention from those with interests in the

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<sup>28</sup> Phipps Conservatory and Botanical gardens Visitors guide

development of advanced technology. Such a project distinguishes Phipps as a pioneer in adopting sustainable strategies. Phipps vision of tomorrow is reflected in a variety of current practices: from their waterless urinals to the biodegradable cutlery in their café; using advanced green power technologies would only add the ability to demonstrate this vision.

### 5. Recommendations and Conclusions

Our cost-benefit analysis of these six potential scenarios suggests there is no distinct ‘best’ solution to provide green power for Phipps Conservatory with current technology. Based purely on private financial metrics, all options have negative NPVs over a 25 year life-span. However the options involving additional purchase of wind-power have slight positive NPVs when the social costs associated with the region’s current electricity and heat-generating facilities are considered. The high capital costs (and large technical and financial uncertainties) associated with the installation of fuel cells and solid-waste digesters make these systems financially untenable on the basis of private NPV. However, based on non-monetized benefits related to Phipps’ status as an mission-driven institution and as a leader in adopting sustainable practices, these options should still be considered. In the end, the value-added by having these technologies on-site at the conservatory must be a multi criteria decision analysis by the board and management of Phipps, weighing the benefits of each option as it pertains to Phipps’s mission, vision, and values.

Table XIV shows our relative ranking of the six options based on subjective and objective measures that may influence this decision. The ‘NPV’ and ‘Environmental’ criteria are based on the private and social NPVs calculated in this analysis, respectively. The ‘Education’ and ‘Demonstration’ criteria subjectively rank the considered power options based on our perception of the educational and technology demonstration value of the different options. Options were ranked in the ‘Facility’ column based on our judgment of the difficulty and space requirements associated with their installation on the Phipps Conservatory campus. The column labeled ‘Uncertainty’ ranks our confidence in the values (e.g. capital and O&M costs, digester parameters, etc.) used in the analyses - and thus impacts valuations.

**Table XIV: Ranking of options based on potential decision-making criteria**

<b>Options</b>	NPV	Environmental	Education	Demonstration	Facility (Space)	Uncertainty
100% Wind	●	●	●	○	●	●
Digester 1	●	●	●	●	●	●
Digester 2	○	●	●	●	○	○
Digester 3	●	●	●	●	●	●
Fuel cell alone	●	○	●	●	●	●
<b>Legend</b>	● Best (5)	● (4)	● (3)	● (2)	○ Worst (1)	

The following summary statements can be made about each option analyzed:

- **Wind-power:** Most cost effective and least uncertain option reviewed, but lacks the on-site demonstration and education value of fuel-cell systems.
- **Fuel cell:** Best financial performance of the fuel-cell options and a good option for demonstration of emerging-technology energy systems; good educational value because of placement in Visitor Center. However, does not fit into the idea of the 'living machine' and still runs on fossil fuel; there is the potential to add a digester after initial installation.
- **Digester 1:** Small digester and fuel cell could run entirely/mostly off waste from Phipps, good demonstration/educational value (closed loop/living machine), significant financial liability and uncertainty related to design/citing/operation of digester.
- **Digester 2:** Large fuel cell/large digester has worst financial outlook because of large capital and operating costs. Siting and operation of digester are a *serious* concern (50' diameter x 20' high digester and > 4200 tons/year waste required) and risk due to developmental technology is significant. Good potential for technology demonstration.
- **Digester 3:** Large fuel cell with small digester runs mostly on natural gas, less educational/demonstration value than Digester 2, but also less financial risk (due to smaller capital investment). Waste source and handling are less of an issue, but the feasibility depends heavily on having a demand for all electricity and heat and on the stability of natural gas prices.

### **Appendix A:**

There are two sources of uncertainty that need additional clarification. The first is the local versus regional generation mix emission factors. The second is the amount of waste heat that can be used on site in the cogeneration application. In this addendum, we discuss these issues and comment on their effect on the results.

### **Part I. Comparison of the Duquesne Light Company Power Control Area to the Pennsylvania – New Jersey – Maryland (PJM) Interconnect Average**

The PJM Interconnect is the largest centrally dispatched control area in North America, coordinating the movement of electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia<sup>29</sup>. Except in periods of shortage of generation in these areas, all the electricity consumed in these states is generated within the PJM generation pool. The average PJM values are, therefore, broadly indicative of the displaced emissions from the installation of an onsite fuel cell. However, the composition of the generation pool that serves most of the Pittsburgh load (Duquesne Light) is different than the average as shown in Figure 1. The main difference is that the immediate generation is over 90% coal compared to the PJM average of 45%. In Table 1, the effect of the generation mix on the emission factors for the system is presented. In general, the coal fired generation increases the emission factors by about a factor of two. This makes intuitive sense as the nuclear plants which have almost zero air emissions comprise 40% of the PJM generation pool, but are not present in the Duquesne Light mix.

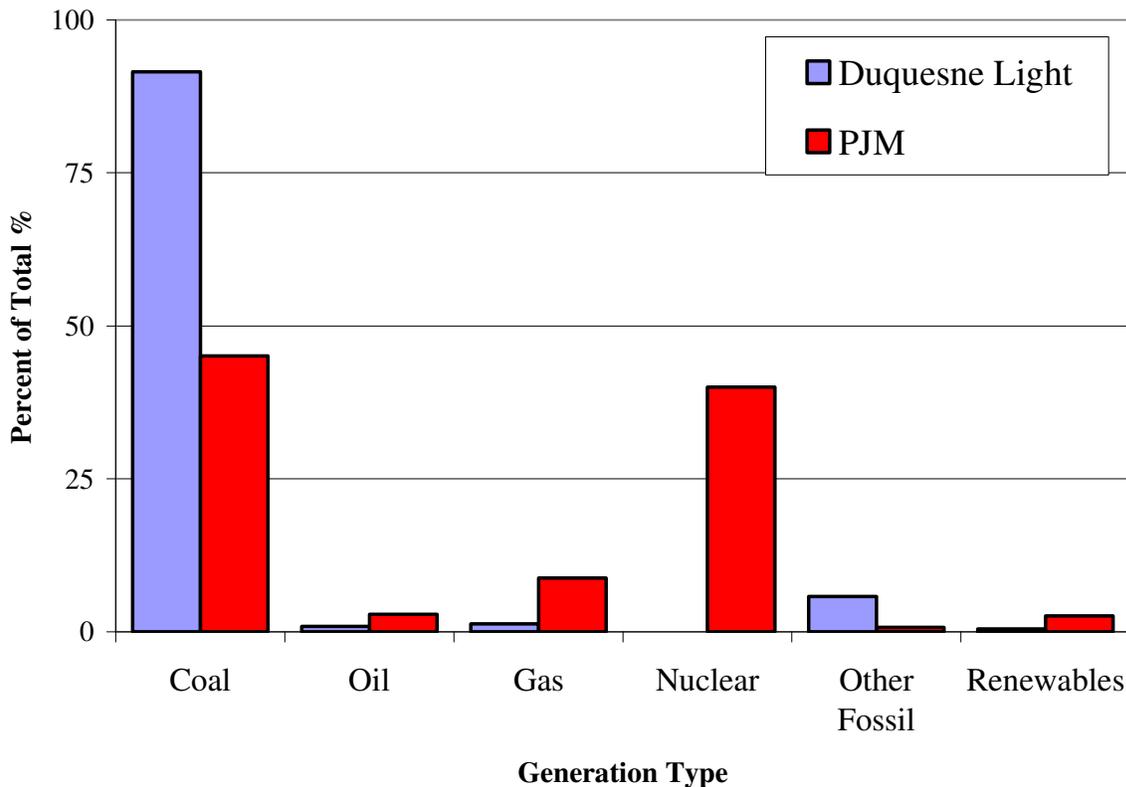
**Table 1. Emission factors for Duquesne Light and PJM Interconnect in g/kWh<sup>2</sup>**

<b>Pollutant</b>	<b>Duquesne Light</b>	<b>PJM</b>
Nitrogen oxides	2.8	1.1
Sulfur dioxide	1.7	3.5
Particulate matter	0.15	0.075
Carbon dioxide	1160	500

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<sup>29</sup> <http://www.pjm.com/index.jsp>

**Figure 1. Generation mix for the Duquesne Light and the PJM Interconnect<sup>30</sup>**



Having identified this difference, the next step is to evaluate what the changes are to the social costs and the net present value (NPV) of the fuel cell, fuel cell – digester options, and wind purchases. Following the same process as in the main text, the NPV for the four options with the basecase assumptions are shown in Table 2.

**Table 2. Net present value (in thousands of dollars) of the social and total costs for the Duquesne Light emission factors**

Options	Social NPV	Total NPV
Fuel Cell	\$21	-\$130
Digester/Fuel Cell 1	\$26	-\$380
Digester/Fuel Cell 2	\$630	-\$1,450
Digester/Fuel Cell 3	\$530	\$58
Wind Purchase (5 kW)	\$24	\$20
Wind purchase (125 kW)	\$600	\$500

Overall, the results remain the same. There is one notable difference. With the PJM emission factors, the NPV for the digester/Fuel Cell 3 option is negative (-\$160 thousand). With the Duquesne Light emission factors, the NPV for this option is positive and outranks the 5 kW wind purchase.

<sup>30</sup> <http://www.epa.gov/cleanenergy/egrid/index.htm>

## Part II. Combined heat and power (CHP) – Displaced emissions as a function of useful heat captured

Along with producing electricity, fuel cells also produce heat. When the heat can be used in addition to the electricity, overall system efficiencies can exceed 80%. This is known as combined heat and power (CHP). The usefulness of a CHP is a function of the coincidence between the waste heat from the generation and the actual heat load of the facility. One way of analyzing CHP is by comparing the heat to power ratio (HPR) for a technology to the heat to electrical power requirements for the facility: the better the match, the more effective the CHP application.

$$HPR = \frac{\text{energy produced (or consumed) as heat}}{\text{energy produced (or consumed) as electricity}}$$

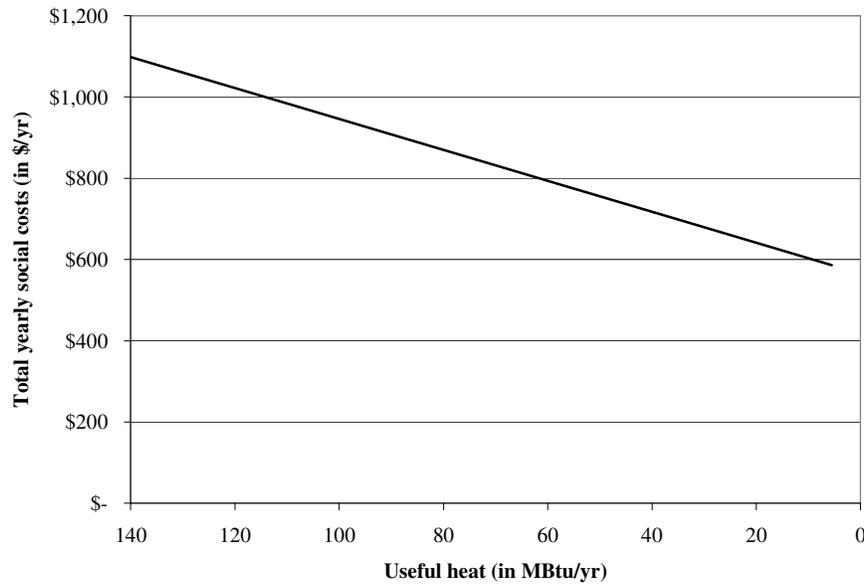
Normally, a CHP system is sized to optimize the combined usage of electricity and heat over the course of the year either in terms of private savings or efficiency. In this study, the size of the fuel cell is fixed. The potential private savings and environmental benefits for the heat are evaluated in terms of how much of the heat from the fuel cell can be used on site. A fuel cell has a HPR of 1 - 1.4 (i.e., more heat is produced per unit of electrical power). For example, Carnegie Mellon University (CMU)'s HPR ranges from 0.3 in the summer to 2.2 in January<sup>31</sup>. Since we do not have seasonal data for the Phipps conservatory, we assume that 50% of the useful heat produced by the fuel cell can be used by the facility.

In Figure 2, we show the effect on the yearly social cost of the displaced emissions (both the grid and the Bellefield boiler) for the 5 kW fuel cell as a function of useful heat captured. For the 5 kW fuel cell, the total NPV is still negative even if all the heat produced can be used. The NPV remains negative for the Digester/Fuel Cell 1 and Digester/Fuel Cell 2 configurations. As the amount of heat used increases for the Digester/Fuel Cell 3, the NPV changes from negative to positive.

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<sup>31</sup> Strachan, N. & Farrell, A. (2002). "Emissions from Distributed Generation" *CEIC Working Paper*

**Figure 2. Yearly social cost (in \$) from total displaced emissions for the 5 kW fuel cell as a function of useful heat captured**



## **Appendix B** **How a fuel cell works**

Essentially, a fuel cell works by passing streams of fuel (usually hydrogen) and oxidants over electrodes that are separated by an electrolyte. This produces a chemical reaction that generates electricity without requiring the combustion of fuel, or the addition of heat as is common in the traditional generation of electricity<sup>32</sup>

A fuel cell power system is comprised of a number of components:

- 1) Unit cells in which the electrochemical reactions take place
- 2) Stacks, in which the individual cells are modularly combined by electrically connecting the cells to form units with the desired output capacity
- 3) The rest of the equipment

For Phipps we can use two varieties (as these are the two types that allow methane as the anode gas, and do not require an additional reformer)<sup>33</sup>

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<sup>32</sup> Naturalgas.org: <http://www.naturalgas.org/environment/technology.asp#fuelcells>

<sup>33</sup> Rocky Mountain Institute: <http://www.rmi.org/sitepages/pid556.php>

Fuel Cell Type	Electrolyte	Anode Gas	Cathode Gas	Temperature	Efficiency
<b>Molten Carbonate (MCFC)</b>	Alkali-Carbonates	hydrogen, methane	atmospheric oxygen	650°C (1200°F)	40–55%
<b>Solid Oxide (SOFC)</b>	Ceramic Oxide	hydrogen, methane	atmospheric oxygen	800–1000°C (1500–1800°F)	45–60%

**Solid Oxide Fuel Cell (SOFC):**

These fuel cells are best suited for large-scale stationary power generators that could provide electricity for factories or towns. SOFCs use a prefabricated ceramic sandwich between electrodes. SOFCs make excellent co-generation devices for industrial applications where high temperature steam is required.

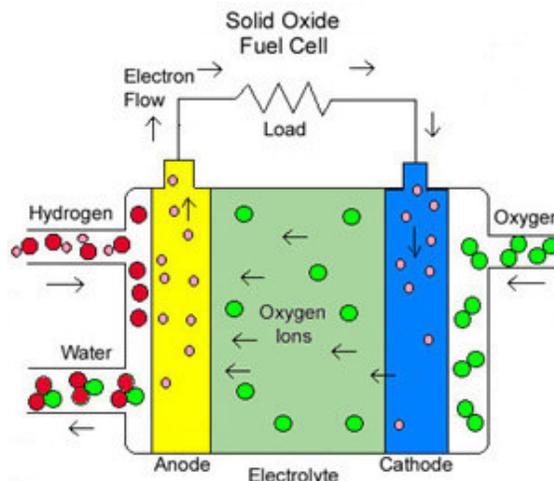


Figure A1. Workings of the solid oxide cell<sup>34</sup>

Environmental Benefits:

- 1) High efficiencies for converting methane to electricity. Therefore CO<sub>2</sub> lower than conventional technologies (50% less)
- 2) NO<sub>x</sub> production is less than 0.5ppm
- 3) SO<sub>x</sub>, CO, VOCs are not measurable
- 4) Waste digester is used to produce the biogas needed to power 5kW of the fuel cell.
- 5) Solid state cells means no corrosion or leaks
- 6) Water is not used in the SOFC (unlike the MCFC system)

Table A1. Comparison on three different electricity generating technologies<sup>35</sup>

<sup>34</sup> American History of the fuel cell <http://americanhistory.si.edu/fuelcells/basics.htm#q3>

	MCFC	SOFC	Diesel Engine
Electrical efficiency using natural gas (net AC/LHV), %	45-50	<b>45-50*</b>	35
Performance degradation, %/1000 hrs	0.6	<b>&lt;0.10</b>	0.2
Emissions using natural gas: NO <sub>x</sub> , g/MWh	<10	<b>&lt;10</b>	700
SO <sub>x</sub> , g/MWh	<0.1	<b>&lt;0.1</b>	1
Noise, dBA @ 10 m	65	<b>65</b>	80-90
Water consumption, gal/MWh	88	<b>0</b>	0
Total fuel efficiency using natural gas (net AC/LHV), %	70	<b>80-85</b>	~78

#### Costs:

- 1) The solid state cells can crack- they will need to be replaced, which means more materials will be needed for regular replacement
- 2) Operating at high temperatures means that the SOFC will need enough chemical and structural stability to endure the strain-tougher materials come with a higher environmental cost

#### **Appendix C:**

##### **Technology description for digester**

An OFMSW digester system includes 4 necessary sub-systems independent of the electrical generation equipment (the SOFC in this case):

- **Waste handling** includes the equipment and facilities required to receive and process – generally through wet or dry grinding/shredding, or conversion to high-liquid slurry through addition of water- the incoming waste. Waste handling facilities must be designed with citing and the flow of waste in mind. This would be a particular challenge for Phipps, especially for an installation such as ‘Digester 2’, as any installation will face serious space and citing constraints due to Phipps’ location and proximity to Schenley Park and the CMU campus.
- The **digester** is the vessel (including associated hardware) in which the waste is processed anaerobically (with little oxygen) to produce biogas. The digester must be sized for waste to

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<sup>35</sup> Siemens Westinghouse <http://www.powergeneration.siemens.com/en/fuelcells/benefits/index.cfm>

have adequate residence time (typically 15 -25 days) for full digestion. There are various digester designs available for processing OFMSW<sup>36, 37</sup> in wet and dry forms.

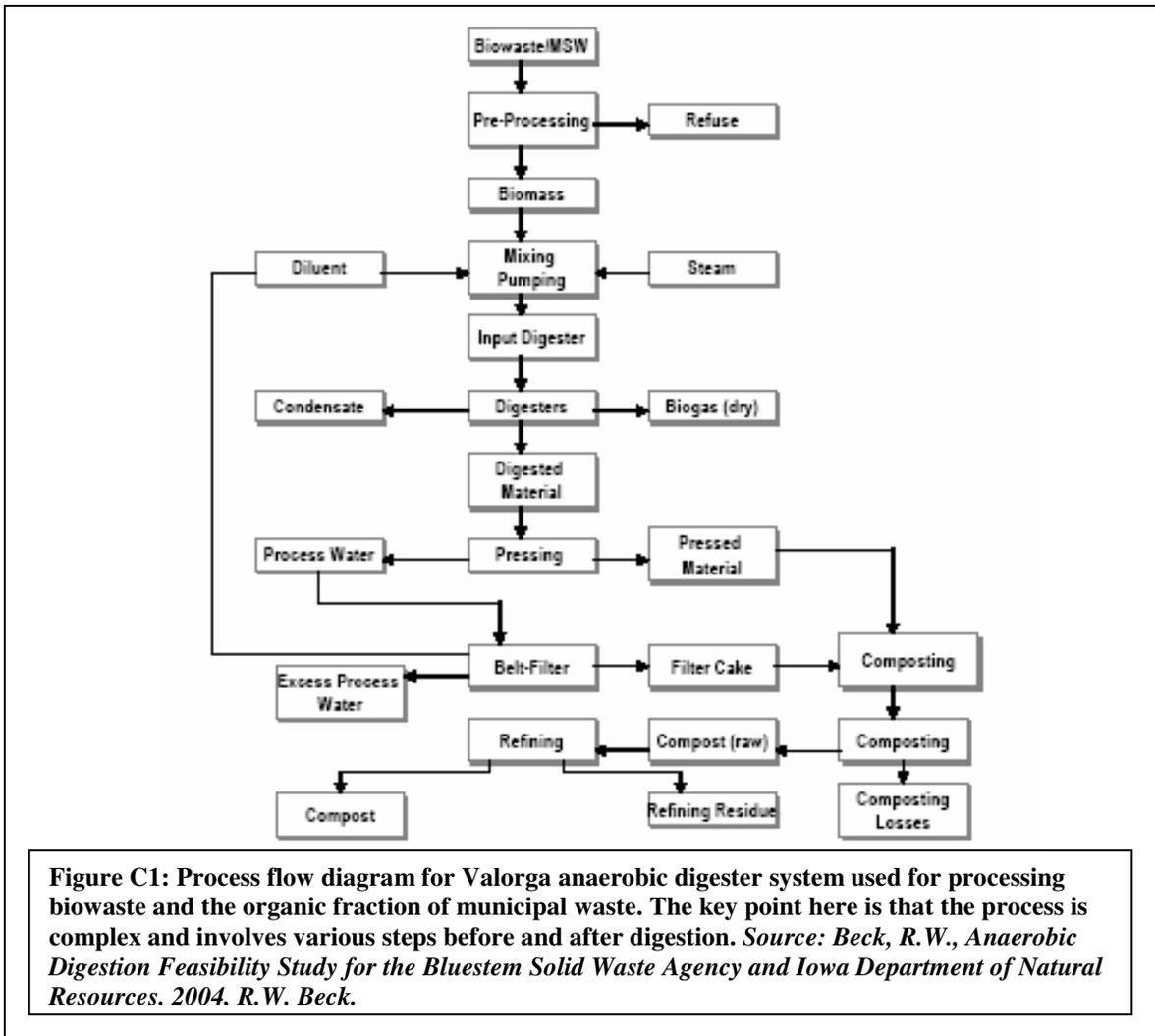
- The **gas handling** subsystem is made up of components used to clean the biogas for use in the fuel cell. This generally consists of scrubbers and condensers to remove sulfur and excess water from the biogas stream.
- **Effluent separation** equipment handles the waste after it has been processed in the digester. Generally, liquid is extracted from the digestate (which is by now well-processed, odor-free, nitrogen-rich matter); solids can be used as soil amendment (compost) after some final conditioning, liquids can be recycled to the AD process or used as fertilizer.

Clearly, anaerobic digestion is a relatively simple concept which requires significant complexity in implementation; this can be seen in the process diagram of a solid-waste AD facility shown in Figure C1. The fauna necessary for effective digestion of waste– the array of bacterial species that actually do all the work – exist in a relatively fragile balance inside the digester. This means that the waste used as feedstock needs to be sorted and properly processed before use and that the digester system needs some level of monitoring and maintenance. Further, as these systems (especially of the size and type that would be appropriate for application at Phipps) are not in wide-spread use, this project should be considered a developmental project (as opposed to a turn-key installation) and the associated uncertainties in cost, complexity and down-time taken into account.

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<sup>36</sup> Beck, R.W., *Anaerobic Digestion Feasibility Study for the Bluestem Solid Waste Agency and Iowa Department of Natural Resources*. 2004, R.W. Beck.

<sup>37</sup> Ostrem, K., *Greening Waste: Anaerobic Digestion for Treating the Organic Fraction of Municipal Solid Wastes*, Department of Earth and Environmental Engineering. 2004, Columbia University.



<b>APPENDIX D: Digester Systems: Parameters and Assumptions</b>				
<b>Parameter</b>	<b>Calculation Method /Assumptions</b>	<b>Parameter Value</b>		
		<b>Digester 1</b>	<b>Digester 2</b>	<b>Digester 3</b>
Total Capital Cost (\$)	(High/Low value for OFMSW facilities <sup>38</sup> )*(tons waste/year) + (\$10,000/kWe for fuel cell). See figure D1 below.	\$1,900,000 ± \$1,600,000	\$5,100,000 ± \$2,800,000	\$3,400,000 ± \$3,000,000
Annual O&M (\$/yr)	3% of total capital cost	\$56000 ± \$62000	\$150,000± \$120,000	\$102,284 ± \$106,585
Digester methane production (m <sup>3</sup> /yr)	(Average of per-ton biogas production of OFMSW facilities – 82 ± 14 m <sup>3</sup> /ton waste/year <sup>39</sup> )*(Annual waste tonnage in digester)/(biomass 65% methane)	9200 ± 4600	230,000 ± 115,000	12,000 ± 6,000
Digester Volume (cubic meters)	Method 1: (Tons waste/day)*(m <sup>3</sup> /ton waste)*(20 day residence time)*(3 dilution factor)	51 ± 23	500 ± 100	76 ± 12
	Method 2: Tons waste/year * 15% Volatile Solids (VS) / 1.2 kg.VS/cubic meter digester <sup>40</sup>			
Digester footprint (diameter – meters)	Assumed: digester is a 4 meter tall cylinder.	4 ± 2	13 ± 3	5 ± 1
Cogen thermal output (MBtu/year)	Digester 1&3: Assume 25% of thermal energy from co-gen unit is used for heating load; remaining 75% goes to provide heat for digester or is not used due to lack of demand	28 ± 4	691 ± 104	1243 ± 186
	Digester 2: Assume 45% of thermal energy from co-gen unit is used for heating load; 10% goes to provide heat for digester, half of remaining is used.			
Electrical output (kWhr/yr)	Assume 95% availability and nominal output of Siemens SOFC systems (5 and 125 kWe)	41610 ± 4161	1040250 ± 104025	1040250 ± 104025
Outside waste usage (tons/yr)	Annual imported tonnage required to run fuel cell at 95% availability with FC gas-to-electricity efficiency of 45% and digester gas production of 82 m <sup>3</sup> /ton waste/year. Priced at \$60/ton (Phipps pays ~\$10/ton for removal of green waste <sup>41</sup> )	0 ± 70	4000 ± 500	0 ± 100
NG usage (MCF/yr)	Natural gas required above biogas methane content to run fuel cell at 95% availability with FC gas-to-electricity efficiency of 45%	0 ± 150	0 ± 3,000	7500 ± 800

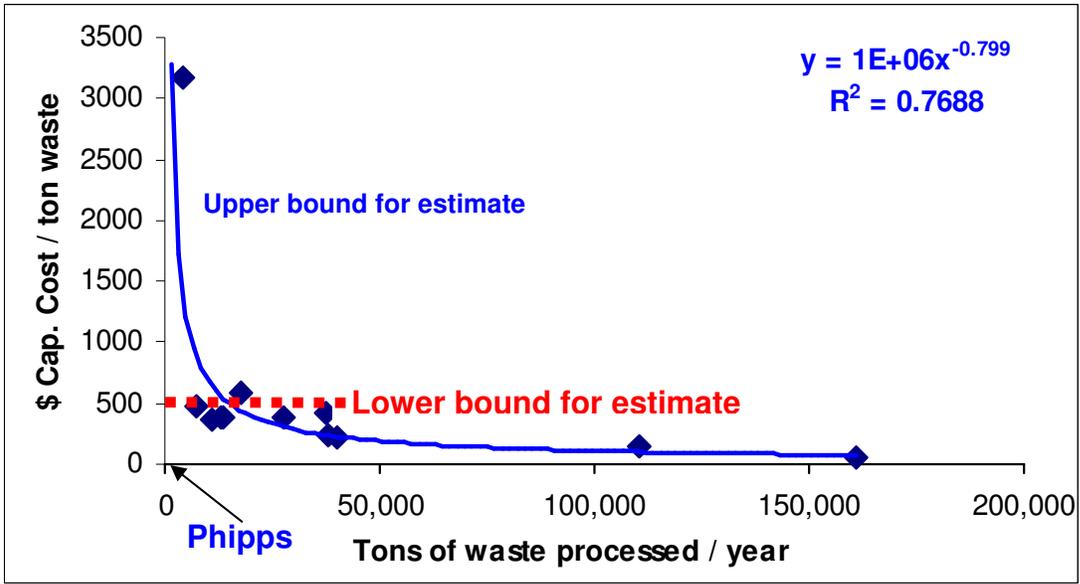
<sup>38</sup> Beck, R.W., Anaerobic Digestion Feasibility Study for the Bluestem Solid Waste Agency and Iowa Department of Natural Resources. 2004, R.W. Beck.

<sup>39</sup> Ibid.

<sup>40</sup> Moser, M., Anaerobic Digesters Control Odors, Reduce Pathogens, Improve Nutrient Manageability, Can be Cost Competitive with Lagoons, and Provide Energy Too! 2004, EPA Agstar Program.

<sup>41</sup> Meisterling, K., *Methane production from waste*, Memo to R. Piacentini. August, 2005: Pittsburgh, PA. and Personal Communication from R.Piacentini

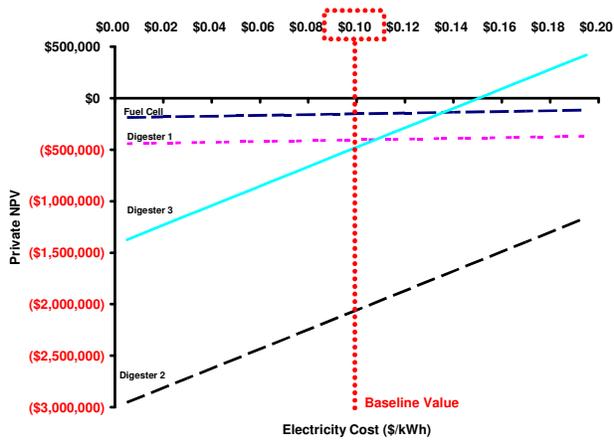
Appendix D cont.



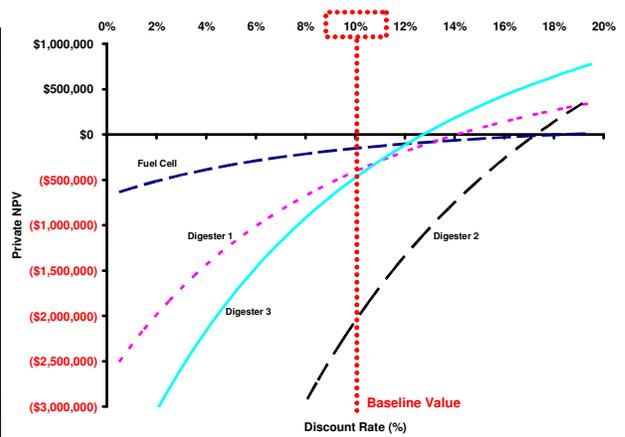
Appendix D Figure D1: Capital costs for OFMSW digester installations surveyed by R.W. Beck (ref). Power-law curve-fit is upper bound for estimate of cost, lower bound provided by average of sub-20,000 ton/year facilities (~\$500/ton)

Appendix E

Appendix E

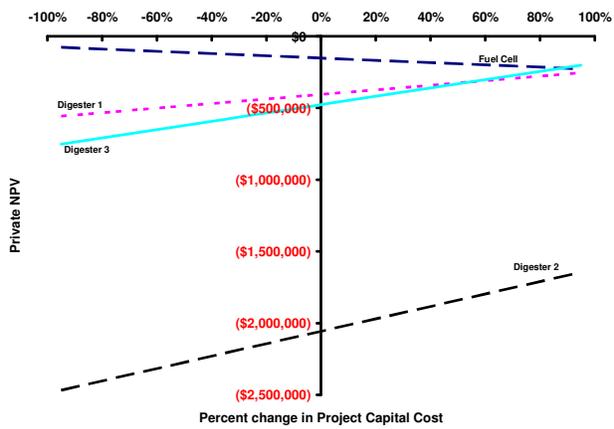


A- Assumed Electricity Price

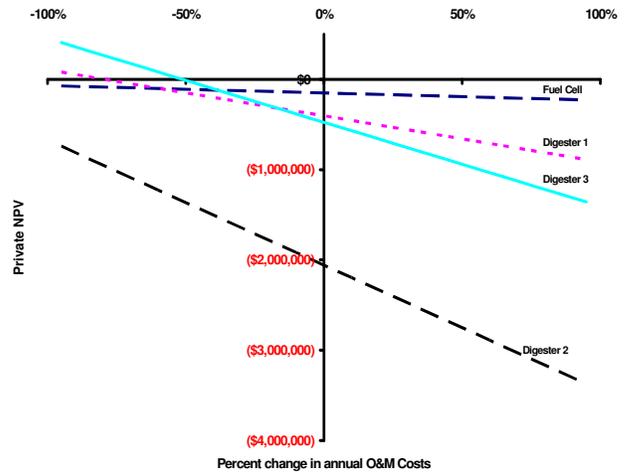


B - Assumed Discount Rate

C- Project Capital Cost



D - Project Annual O&M



**Appendix E** - Figures 1A-D: Sensitivity of fuel-cell based projects' NPVs to uncertainties and fluctuations in model parameters. In each plot, all model parameters are constant except the one indicated; fluctuations in the values of those shown here have significant effects on project outcome.