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Center for Sustainable Systems
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## Document Description

# LIFE CYCLE ENERGY AND ENVIRONMENTAL ANALYSIS OF THE NEXTENERGY MICROGRID POWER PAVILION

Scott G. Baron, Gregory A. Keoleian, and David V. Spitzley
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## Executive Summary

This study develops a framework and analytical model based on life-cycle assessment (LCA) for NextEnergy to evaluate the environmental and energy life cycle performance of its Microgrid Pavilion (hereafter "the microgrid"). Life cycle assessment is an analytical tool based on ISO 14040 standards that characterize the full energy and environmental consequences of a product or service system. A key aspect of the LCA for this study is the inclusion of upstream or pre-combustion processes in energy modeling. The energy and emissions resulting from all processes before a fuel is combusted or converted to electricity or heat energy (e.g. extraction, reformation, delivery) are modeled in the report.

The microgrid analyzed is comprised of nine distributed generation technologies designed to provide combined heat and power to NextEnergy facilities. The baseline for the analysis is a conventional system comprised of the Detroit electric power grid and an industrial boiler (with 75% efficiency). Table ES-1 lists the distributed generation units that are included in the proposed microgrid. Table ES-2 shows the fuel mix modeled in the report for the Detroit regional power grid.

**Table ES-1: Microgrid Distributed Generation Technologies**

| DG Unit | Fuel Source | Size | Description |
|---|---|---|---|
| ENF-7 (4) | Hydrogen | 5 kW (each) | Proton Exchange Membrane (PEM) fuel cells |
| ENX-55 | Natural Gas | 52 kW | External combustion (Stirling Cycle), induction genset |
| ENX-55 | Hydrogen | 52 kW | External combustion (Stirling Cycle), induction genset |
| ENI-85 | Natural Gas | 85 kW | Automotive derivative internal combustion, synchronous genset |
| ENI-150 | Natural Gas | 150 kW | Automotive derivative internal combustion, synchronous genset |
| ENE-210 | Natural Gas | 202 kW | Exhaust gas recirculation internal combustion, synchronous genset |
| ENT-400 | Natural Gas | 396 kW | Miniturbine, permanent magnet genset |
| Stuart IC | Hydrogen | 120 kW | Automotive derivative internal combustion, synchronous genset |
| Unisolar | Sunlight | 30 kW | Thin-film, photovoltaic system |

**Table ES-2: Detroit Grid Fuel Mix Characteristics 2001**

| Fuel Type | DTE Fuel Mix (used in model) | Regional Fuel Mix (MI, IL, IN, OH, and WI) |
|---|---|---|
| Coal | 76.7% | 71.3% |
| Nuclear | 18.1% | 22.7% |
| Gas | 3.2% | 3.8% |
| Oil | 0.6% | 0.8% |
| Hydroelectric | 0.1% | 0.5% |
| Renewables | 1.3% | 0.9% |

Source: DTE Energy

The life cycle model created for NextEnergy is designed to be flexible and easily used for assessing the relative life cycle performance of the microgrid compared to the conventional system. The model calculates the total life cycle energy use and emissions for both systems to produce the same level of electrical and thermal output based on the specified operating parameters for the microgrid to meet a certain electrical load.

The model results indicate how different specified operating configurations of the microgrid affect its relative life cycle performance compared to the conventional system. System efficiencies are presented to compare the complete life cycle performance between the two systems. Thermal energy and electrical energy are combined in order to provide a normalized basis for comparison. The efficiency of each system is measured as the total energy output of the system (Btu) divided by the life cycle input into the system (Btu). Although heat and electricity have different thermodynamic qualities, this technique is useful for comparing the relative performance of the two systems.

In this report the model results are analyzed for both the microgrid as a system and also for each individual distributed generation unit. Seven operating configurations are analyzed in order to demonstrate the relative performance of the microgrid system based on different combinations and output levels of distributed generation units of the microgrid (Table ES-3). The unit-by-unit analysis compares the performance of each unit running at 100% capacity to the conventional system (Table ES-4). In addition to system efficiencies, the life cycle energy consumption and life cycle $CO_2$ and $NO_x$ emissions are compared.

**Table ES-3: Summary System Efficiencies and Life Cycle Performance**

| Scenario | Microgrid System Efficiency | Conventional System Efficiency | Life Cycle Energy Savings* | Life Cycle Emissions Reduction |
|---|---|---|---|---|
| 1(a). All units run at 100% capacity | 37.2% | 39.0% | -4.8% | $NO_x$: 64%<br>$CO_2$: 34% |
| 1(b). Meet expected building load | 41.1% | 37.7% | 8.3% | $NO_x$: 65%<br>$CO_2$: 42% |
| 1(c). Meet double expected building load | 38.8% | 38.4% | 1.0% | $NO_x$: 66%<br>$CO_2$: 37% |
| 2(a). Only NG units | 37.4% | 39.5% | -5.6% | $NO_x$: 59%<br>$CO_2$: 22% |
| 2(b). Only H2 units | 35.8% | 36.6% | -2.2% | $NO_x$: 93%<br>$CO_2$: 96% |
| 3. No CHP | 20.5% | 29.0% | -41.5% | $NO_x$: 47%<br>$CO_2$: 4% |
| 4. W/out ENT 400 unit | 61.6% | 42.7% | 30.7% | $NO_x$: 76%<br>$CO_2$: 71% |

*Life cycle energy use for conventional system– life cycle energy use for microgrid system divided by life cycle energy use for conventional system

**Table ES-4: Summary Unit Efficiencies and Life Cycle Performance**

| DG Unit | DG Unit Efficiency | Conventional System Efficiency | Life Cycle Energy Savings | Life Cycle Emissions Reduction |
|---|---|---|---|---|
| ENE-210 | 77.8% | 44.8% | 42.4% | $NO_x$: 87%<br>$CO_2$: 67% |
| ENF-7 (4) | 29.7% | 29.0% | 2.4% | $NO_x$: 100%<br>$CO_2$: 100% |
| ENI-85 | 75.0% | 45.5% | 39.3% | $NO_x$: 86%<br>$CO_2$: 53% |
| Stuart IC | 23.4% | 29.0% | -23.9% | $NO_x$: 91%<br>$CO_2$: 94% |
| ENI-150 | 69.2% | 43.3% | 37.4% | $NO_x$: 32%<br>$CO_2$: 56% |
| ENT-400 | 14.4% | 29.0% | -101.4% | $NO_x$: 28%<br>$CO_2$: -74% |
| ENX-55 (NG) | 73.5% | 45.5% | 38.1% | $NO_x$: 84%<br>$CO_2$: 89% |
| ENX-55 (H2) | 60.9% | 46.9% | 23.0% | $NO_x$: 95%<br>$CO_2$: 97% |
| Unisolar | 360.2% | 29.0% | 91.9% | $NO_x$: 100%<br>$CO_2$: 89% |

The following key findings can be reached from the above results:

- The microgrid system consumes slightly more life cycle energy (4.8%) than the conventional system when all units are run at 100% capacity. However, the microgrid outperforms the conventional system with respect to life cycle energy use by the largest margin (30.7%) when the inefficient ENT 400 is turned off. The ENT 400 unit skews the overall microgrid results in all scenarios because of its large capacity (400 kW) and low efficiency (16%).
- The microgrid system provides a life cycle emissions reduction compared to the conventional system under all scenarios (47% to 93% reductions of $NO_x$ emissions and 4% to 96% reduction of $CO_2$ emissions for all scenarios analyzed). The microgrid system operates based on cleaner technologies and fuels than the conventional system.
- The microgrid performs the worst compared to the conventional system with respect to life cycle energy use when the combined heat and power capabilities for distributed generation units that have CHP options are turned off in the model (the microgrid consumes 41.5% more life cycle energy than the conventional system).
- Recovery of thermal energy for other productive uses significantly benefits the life cycle performance of the microgrid (the system efficiency is 37.2% with CHP compared to 20.5% when the CHP is turned off).
- The life cycle energy of the microgrid system is reduced with the avoidance of line losses from long distance transmission of power. Line losses for a conventional system typically account for 8% of the life cycle energy.
- On a unit-by-unit basis, all of the microgrid units outperform the conventional system with respect to life cycle energy use except the ENT 400 and the Stuart IC. The most efficient units from a life cycle perspective are the Unisolar PV array (360%) and the ENE-210 unit (77.8%).
- On a unit-by-unit basis all of the units outperform the conventional system with regard to $CO_2$ emissions except the ENT 400 unit and all of the units outperform the conventional system with regard to $NO_x$ emissions.
- In general, the microgrid system has a higher upstream energy use than the conventional system. The microgrid is fueled mainly by natural gas and hydrogen, which both require proportionately more upstream energy (e.g. extraction and reformation) than the main fuel that power the Detroit grid (e.g. coal and nuclear).
- The Unisolar PV array greatly outperforms the conventional system with respect to both life cycle energy use and environmental emissions, even when the energy required to build the solar array is factored into the calculations. This result suggests that based on LCA criteria, renewable energy sources should be encouraged to minimize energy and environmental impacts.

The life cycle microgrid model is the first step for evaluating the performance of the NextEnergy Microgrid Pavilion. Future research efforts should build on the model by adding a life cycle economic analysis to assess the relative economic performance of the microgrid and the conventional system. An additional analysis should incorporate all of the life cycle frameworks (energy, emissions, economics) to optimize system performance to determine what operating conditions result in the lowest possible life cycle impact.

## Acknowledgements

This project was supplied by a grant (Agreement—EEF Grant PSC-03 from NextEnergy to the University of Michigan) for the project period September 1, 2003 to June 30, 2004. The study was part of Task 3 of the overall project entitled: Technology Assessment and Evaluation for the NextEnergy Zone Microgrid System. Principal investigators for the project included: Johannes Schwank, Gregory Keoleian, Arvind Atreya, and Jerry Mader from the University of Michigan.

The authors of this report wish to thank Michael Saldana from DTE Energy Technologies, Jim Croce from NextEnergy, and Ed Danieli from Praxair, Inc. for their assistance in providing data and technical advice for the study. We also thank Helaine Hunscher for her editorial assistance.

# I. Goal of Study

Distributed generation (DG) has received considerable attention as an alternative to grid-based power for its environmental, security, reliability, and efficiency benefits. However, these factors are generally assumed to be positive without complete analytical rigor. This analysis builds a framework based on life-cycle assessment (LCA) for NextEnergy to evaluate the magnitude of the environmental and total fuel cycle benefits from its Microgrid Power Pavilion (hereafter the “microgrid”) compared to a conventional system (Detroit electric grid and a conventional thermal system). A functional and adaptable model is provided for NextEnergy (in Microsoft Excel®) to evaluate the microgrid under a range of operating conditions and input assumptions (the software should be used in conjunction with this report).

LCA is an analytical tool based on ISO 14040 standards in the field of Industrial Ecology that characterizes the full energy and environmental consequences of a system. This analysis uses the foundation of LCA to focus on two impacts relevant to the NextEnergy microgrid: environmental (emissions) and total fuel cycle energy use. Environmental impacts examined include emissions of $NO_x$ and $CO_2$. These emissions have been linked to environment and human health impacts such as climate change, asthma, and acidification. Total fuel cycle energy from a process includes extraction of energy resources from the Earth, refining, transportation, combustion (or conversion), transmission losses, and delivery to the end customer (final energy). This complete energy and environmental accounting gives useful metrics for determining the larger picture comparative efficiency and performance between systems.

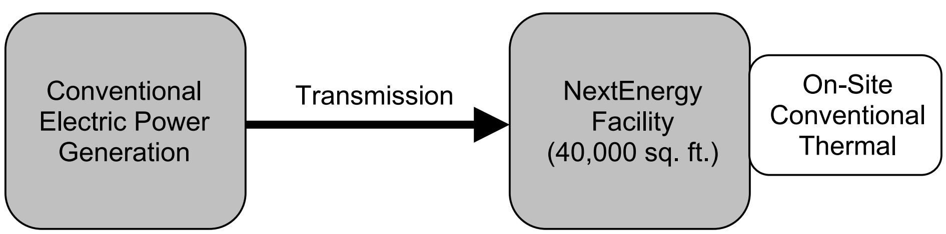
# II. Framework of Study

### 1. Systems Studied
### 1.1 Conventional System

The conventional system is composed of two subsystems:

- Detroit electric power grid (hereafter the “grid”)
- Conventional industrial thermal system (producing the same heat output as the microgrid)

**Figure 2.1 Conventional Heat and Power System**



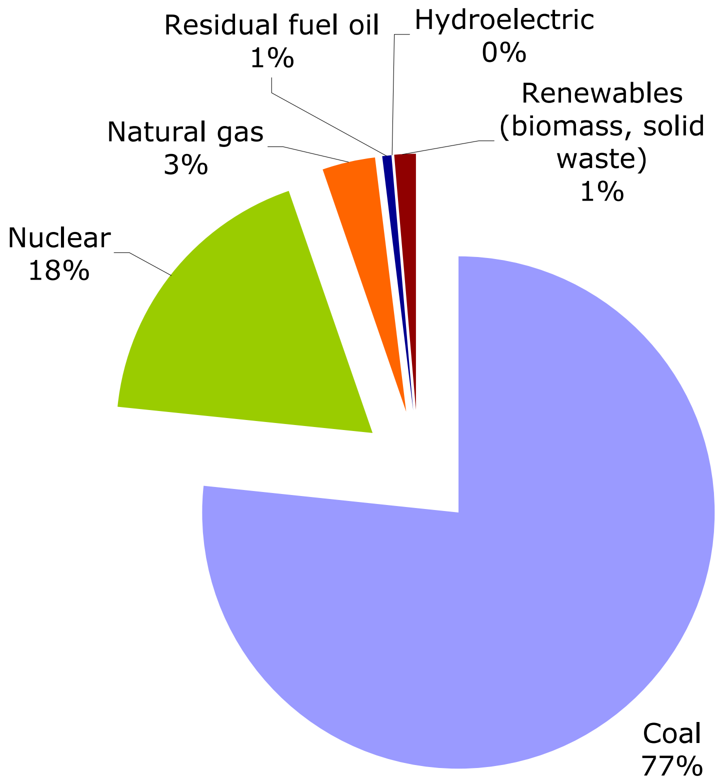

Electric power generation in the model represents the DTE Energy generation mix as represented in Table 2.1 and Figure 2.2:

**Table 2.1 Detroit Grid Fuel Mix Characteristics 2001**

| Source | DTE Fuel Mix (used in model) | Regional Fuel Mix (MI, IL, IN, OH, and WI) |
|---|---|---|
| Coal | 76.7% | 71.3% |
| Nuclear | 18.1% | 22.7% |
| Gas | 3.2% | 3.8% |
| Oil | 0.6% | 0.8% |
| Hydroelectric | 0.1% | 0.5% |
| Renewables | 1.3% | 0.9% |

Source: DTE energy

**Figure 2.2 Detroit Grid Fuel Mix**

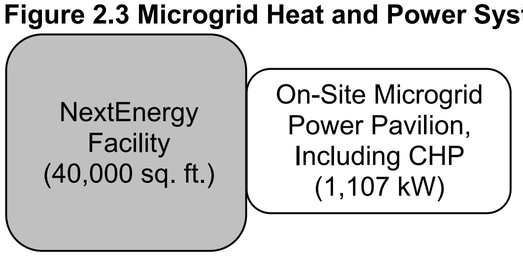



**1.2 NextEnergy Microgrid ("microgrid")**
The proposed system is composed of the generation technologies in Table 2.2—total capacity 1,107 kW:

**Table 2.2: Microgrid Distributed Generation Technologies**

| DG Unit | Fuel Source | Size | Description |
|---|---|---|---|
| ENF-7 (4) | Hydrogen | 5 kW (each) | Proton Exchange Membrane (PEM) fuel cells |
| ENX-55 | Natural Gas | 52 kW | External combustion (Stirling Cycle), induction genset |
| ENX-55 | Hydrogen | 52 kW | External combustion (Stirling Cycle), induction genset |
| ENI-85 | Natural Gas | 85 kW | Automotive derivative internal combustion, synchronous genset |
| ENI-150 | Natural Gas | 150 kW | Automotive derivative internal combustion, synchronous genset |
| ENE-210 | Natural Gas | 202 kW | Exhaust gas recirculation internal combustion, synchronous genset |
| ENT-400 | Natural Gas | 396 kW | Miniturbine, permanent magnet genset |
| Stuart IC | Hydrogen | 120 kW | Automotive derivative internal combustion, synchronous genset |
| Unisolar | Sunlight | 30 kW | Thin-film, photovoltaic system |

**Figure 2.3 Microgrid Heat and Power System**



## 2. Baseline

The NextEnergy microgrid is intended to replace both electricity from the Detroit grid and also the thermal needs for the associated facilities, using waste heat from the on-site generation (combined heat and power). Therefore, the baseline for this analysis is the DTE Energy electric power grid and a conventional thermal system that would be needed to provide the same level of electricity and thermal energy as the microgrid system. NextEnergy may also have an additional thermal system installed as backup for when the microgrid is not producing thermal energy. This is outside of the boundaries of the LCA calculations because in the comparative analysis the additional system would net out with additional capacity from the conventional system.

## 3. Functional Unit

The functional unit, or basis for comparison, in this study is based on the total electricity produced by the microgrid. Once the total electricity output of the microgrid is determined, the model calculates the total usable heat generated by the microgrid and the needed total fuel cycle energy (electricity and thermal) for the conventional system to produce the same electricity and thermal output as the microgrid system. The functional unit for the analysis is measured by the time frame input that the user selects for the model (hour, day, month, or year). This flexibility is built into the model in order to allow the user to examine the performance of the microgrid over timeframes where data is available. For example, by selecting the "hour" timeframe, the user could enter input data based on real-time operation. By selecting the "year" timeframe, the user could enter average annual load factors for each unit to measure an average performance. In all cases the model calculates outputs based on annual average operating performance; the average generally does not reflect specific time-of-day or seasonal variation (e.g. Detroit grid peak output or peak solar irradiation).

**Table 2.3 Normalized Model Outputs**

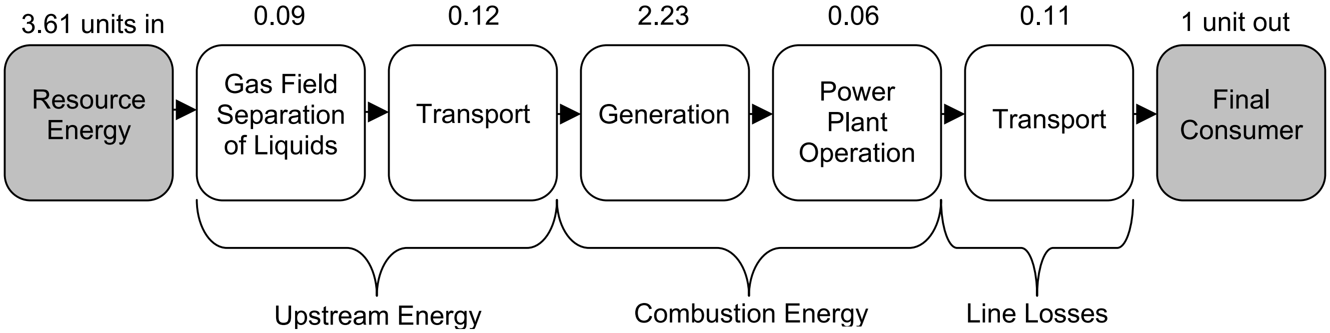
| Metric | Unit of Measurement | Description |
|---|---|---|
| Environmental emissions ($NO_x$, $CO_2$) | lb/time frame (e.g. lb/hour) | Indicates the total pounds of pollutants for both the microgrid and conventional system over chosen period of time |
| Life cycle energy | Btu/time frame (e.g. Btu/hour) | Indicates the total energy in Btu (including upstream, combustion, line losses, inverter losses) for both the microgrid and conventional system over chosen period of time |

## 4. System Boundaries

LCA is a comprehensive tool that measures the complete energy and environmental impacts associated with a system or product. A key aspect of LCA is the inclusion of upstream or pre-combustion accounting, which accounts for the energy and emissions resulting from any processes before a fuel is combusted (e.g. extraction, reformation, delivery). Accounting for upstream energy is apparent in the debate concerning hydrogen for example. Because hydrogen must be reformed or extracted from other energy carriers (e.g. natural gas, methane), the energy required to extract the hydrogen must be considered to measure the complete efficiency of the fuel cell device.

Fuel cycle accounting for electricity generally considers three main areas identified in Figure 2.4, upstream energy, combustion energy, and line losses (transmission losses). The figure shows that accounting for the upstream energy and line loss stages in the total fuel cycle for a natural gas-fired power plant represents 9% of the total fuel cycle. This type of accounting is generally missing from most comparative assessments, but is critical for accurately assessing the relative performance of the microgrid and the conventional system.

**Figure 2.4 Example of a Total Fuel Cycle for Providing 1 Unit of Electrical Energy from a Gas-Fired Power Plant**




Source: Keoleian and Ross, 2001

The energy and emissions from the production of the capital equipment for the microgrid and the conventional system are excluded from this analysis. Because this energy use is expected to be small compared to the total fuel cycle energy, this assumption is unlikely to change the results of the analysis significantly. In the case of large-scale power plants, the construction energy has been found to be less than 1% of the energy embodied in the fuels feeding the plant over its service life (Keoleian, 2003). However, for the photovoltaic system, the upstream manufacturing energy is included because it represents a larger proportion of the total energy burden for the device given that the fuel is “free”.

**5. Data Requirements**

The data required to complete the analysis came from the following sources:

**Table 2.4: Primary Data Sources**

| Data | Source | Description |
|---|---|---|
| DG unit specifications | Spec sheets provided by DTE and NextEnergy | Includes net electrical output, efficiency, heat rate, fuel, emissions, etc. for each DG unit |
| Life-cycle energy and emissions | “Energy Requirements and Environmental Emissions for Fuel Consumption”, Franklin Associates 2000 | Includes fuel and emissions impacts at upstream and combustion stages for multiple fuel types. Data also used for upstream stages of DG units |
| DTE fuel mix | http://www.dteenergy.com/community/environmental/fuelMix.html | Used to calculate the relative energy and emissions impact from the Detroit grid |
| Upstream hydropower energy and emissions | “Life Cycle Environmental and Economic Assessment of Willow Biomass Electricity.” Spitzley, D. V. and G. A. Keoleian. 2004 | Data used to calculate the upstream impact from the hydropower used to make hydrogen |
| Hydrogen delivery | Praxair, Inc., email communication | Includes H2 processing energy, H2 transportation and delivery |
| Hydrogen liquefaction energy | "Costs of Storing and Transporting Hydrogen" by Wade Amos, NREL. 1998 | Energy required to liquefy H2 gas for delivery |
| Hydrogen production efficiencies | "The Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems"- Argonne National Laboratory, for GM June 2001 | Used to calculate the upstream energy to make hydrogen from alternative production methods |
| Predicted NextEnergy electricity demand | DTE and NextEnergy Analysis | Approximate microgrid output levels to match expected building loads |

# III. Description of Life Cycle Analysis Model

**1. Summary of Model**
The Life Cycle Analysis Model created for NextEnergy (hereafter "microgrid model") is designed to be flexible and easily used for assessing the relative impact of the microgrid compared to the conventional system. The model has two main outputs:

- Total Life Cycle Energy Use for the microgrid and conventional system (Btu/time period)
- Total Life Cycle Emissions for the microgrid and conventional system (lb/ time period)

Based on these two outputs it is possible to determine the relative performance of each system under a chosen set of operating conditions. The model first determines the microgrid energy use and impact based on individual generating unit operating input assumptions and then determines the grid impact based on meeting the same electricity and thermal needs as produced by the microgrid. Therefore, the model is able to evaluate the performance of two different systems with the exact same outputs (electricity and thermal).

The model is created in Microsoft Excel and contains 7 worksheets. Cells with blue font are user definable while all cells with black font color are formulas. Red font color indicates an important message or instructions to be followed by the user. Many cells include comments with data sources, assumptions, or calculations.

**2. Description of Model Worksheets**

**2.1 Main Module**
This worksheet contains the final calculations for the Total Life Cycle Energy Use and Total Life Cycle Emissions for both the microgrid and the conventional system. These outputs are used to create graphs for a visual comparison.

**Table 3.1: User Input Parameters for Main Module**

| User Definable Cells | Description and Instructions |
|---|---|
| Measurement period | The user can specify what period of time to analyze the systems: year, month, day, hour |
| Percentage of total expected load met | This variable represents the percentage of the expected NextEnergy electricity load that will be met with the microgrid (36% of the total load is expected to be peak load--Jim Croce, 2004).<br>This percentage is used to calculate the "Average energy (kWh) required to meet building load", which is specified in red font under the "Total Electricity Production." This value is merely a reference for the user to see how the chosen microgrid electricity production compares with the actual expected needs of the building. |
| Electricity: On or Off | Chose either "on" or "off" to specify whether each unit should be included in the analysis. |
| Load Factor | The load factor is the main control variable in the model. It is used to specify the output level of each DG unit. Load factor represents the percentage of time the unit is running (or ran) compared to the maximum capable output (for example, the maximum yearly output (8760 hours) for a 50 kW unit is 50*8760 = 438,000 kWh. If the unit produced 43,800 kWh, then the load factor would be 10%). The load factor can also be used to match output of the DG units to meet the expected building load. |
| CHP used | This variable allows the user to specify if combined heat and power is being used by units where it is possible. |

## 2.2 Life Cycle Parameters

This worksheet contains all of the input data used to calculate the life cycle energy and emissions impact based on the fuels used in both the microgrid and conventional systems. There are four sections in this worksheet:

**Table 3.2: Life Cycle Model Parameters**

| Section | Description and Instructions |
|---|---|
| Grid life cycle energy | This section contains the upstream and combustion energy for the grid based on fuel type. |
| Grid emissions profile | This section contains the upstream and combustion emission factors for the grid based on fuel type. |
| Industrial boiler emissions profile | This section includes the upstream and combustion emissions for a conventional boiler system for meeting the thermal needs of the NextEnergy facility. |
| Life cycle energy hydrogen production for NextEnergy | This section includes all of the input data required to determine the upstream energy and emissions from hydrogen production. Input assumptions are based largely on data from Praxair, Inc. and the total amount of hydrogen used is calculated based on generation of each H2 unit. The final calculation involves three life-cycle stages: energy required to generate the hydrogen (a byproduct from another process—% is assigned), the energy required to liquefy the hydrogen, and the energy required to transport the hydrogen to Detroit. Emissions are calculated at each of those stages for both NOx and $CO_2$. |

## 2.3 Microgrid Assumptions

This worksheet contains the input data for all of the microgrid DG units. Most of this data came from spec sheets provided by DTE energy and NextEnergy (see Appendix 5) and is used to calculate the combustion energy and emissions for the microgrid.

**Table 3.3: User Input Parameters for Microgrid Operation**

| User Definable Cells | Description and Instructions |
|---|---|
| # of generating units | Specifies the number of units for each technology: currently, only the fuel cells have more than one generating unit. |
| Net electrical output (kW) | The maximum generating capacity of the unit. |
| Shaft power (kW) | The total power delivered from the conversion device to the associated generator before it is converted to electricity. Where shaft power was not specified in the spec sheets, it is assumed that there is a 10% loss from shaft power to electrical power (based on observed relationship from other DG units where data were available). |
| Net electrical efficiency | The inverse of the heat rate; measure of electrical output per energy input into the generating unit. For the PV device, the net electrical efficiency represents the net energy ratio—the amount of energy produced by the device divided by the total production energy required to make the device, assuming average solar irradiation in Detroit for a 20 year service life (Source: Keoleian 2003). |
| CHP option | Indicates if combined heat and power is possible with each DG unit. |
| Efficiency w/CHP | The total efficiency including electrical and captured waste heat for CHP. |
| Total recovery heat (MMBtu/hr) | The amount of heat recovered per hour of operation at full capacity. |
| Heat rate (Btu/kWh) | Measure of the efficiency of the device. The amount of Btus required to generate 1 kWh by definition; maximum efficiency is 3,412 Btu/kWh (although the thermodynamic limit is much less). The solar heat rate is based on the energy required to build the device. |

| | |
|---|---|
| Fuel (LHV) (MMBtu/hr) | The amount of fuel consumed at full capacity. Hydrogen fuel input based on 270 Btu/cuft (LHV). |
| Fuel (cuft/hr) | The amount of fuel consumed at full capacity. |
| Inverter loss (%) | Represents the loss in converting DC electricity to AC. Only a consideration for the DC units. |
| Combustion $NO_x$ (g/bhp-hr) | $NO_x$ emission rate during combustion. Zero for the PV array and fuel cell. |
| Combustion $CO_2$ (g/bhp-hr) | $CO_2$ emission rate during combustion. Zero for hydrogen units and PV. |

**2.4 Output Graphs**
This worksheet contains graphs that visually illustrate the performance of the microgrid in comparison to the conventional system. The five main graphs are: Detroit Grid Energy Mix, Total Life Cycle Energy (Btu/time period), Total Life Cycle Energy Use Breakdown (%), Total $CO_2$ Emissions (lbs/time period), and Total NOx Emissions (lbs/time period).

**2.5 Monthly Load NextEnergy**
This worksheet contains the expected demand load based on DTE and NextEnergy projections. The total electricity, peak demand, and natural gas consumption is broken out by month and is a function of the total square feet. If NextEnergy were to expand to provide power to other buildings in the area, the user could change the "total building square footage" to project a new expected load profile for a building of comparable design and usage patterns.

**2.6 Detroit Grid**
This worksheet contains input data on the fuel mix of the Detroit electrical grid and reference calculations based on meeting NextEnergy's expected load. There are five sections of the worksheet as described below:

**Table 3.4: Detroit Grid Model Parameters**

| Section | Description and Instructions |
|---|---|
| Detroit grid fuel mix | The user specifies the specific fuel mix of the grid, which is used for all grid calculations. The default numbers are based on the grid profile as of 2001. |
| Life cycle energy consumption | This section shows the energy use calculations (Btu/kWh) for the different grid technologies by upstream, combustion, and line loss stages of the life cycle. |
| Life cycle energy consumption of Detroit grid to meet needs of NextEnergy facility | This section shows the calculations for the amount of primary energy (Btu) needed for the upstream, combustion and line loss stages of the Detroit grid to meet the same energy needs of the NextEnergy facility. |
| Life cycle emissions profile Detroit grid | This section shows the calculations for the amount of emissions resulting from each of the Detroit grid generation technologies by life cycle stage (lbs/kWh). |
| Life cycle emissions of Detroit grid to meet needs of NextEnergy facility | This section shows the total pollution (lbs) of emissions resulting from the Detroit grid for meeting the expected electricity and heating needs of the NextEnergy facility. |

**2.7 Building Assumptions**
This worksheet contains input assumptions created by DTE and NextEnergy used to determine the expected energy, peak power, and natural gas needs of the NextEnergy facility.

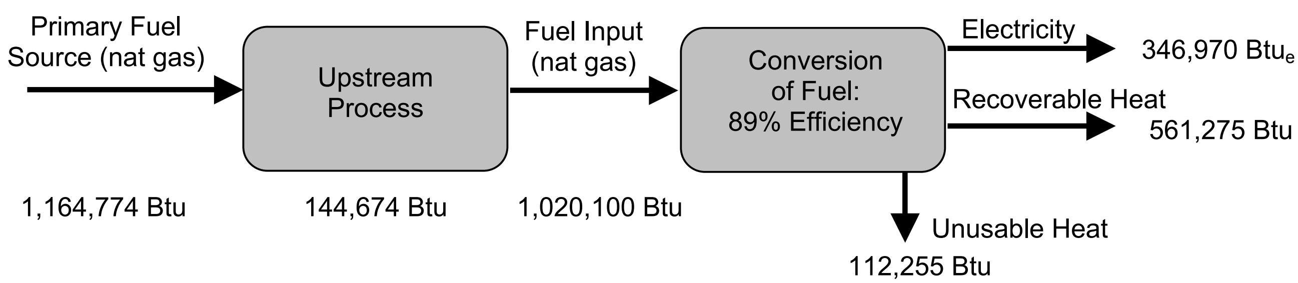
**3. Sample Life Cycle Energy Flow Charts and Calculations**
Sample life cycle energy flow charts and calculations are presented for example units to demonstrate the functionality of the model. A natural gas unit (ENE 210 EGR), hydrogen unit (ENF fuel cells), and the photovoltaic array (Unisolar) provide a comprehensive sample of the computations in the model. The calculations for the conventional system are also shown to demonstrate how the baseline scenario is generated. Emissions calculations are described in Section 4 of this chapter.

**3.1 Natural Gas Unit: ENE 210 EGR**
A typical natural gas unit with combined heat and power uses natural gas as a fuel input, producing electricity, usable heat, and unusable heat as outputs. LCA measures the upstream energy required to process and deliver the natural gas to the conversion device ("Upstream Process"). In the case of this unit, with combined heat and power, the device is 89% efficient (efficiency is defined as energy generated by unit divided by direct energy input into unit)—compared to only 34% efficient when only producing electricity.

**Table 3.5: ENE 210 EGR Model Parameters**

| | |
|---|---|
| Measurement period | Hour |
| Heat rate (Btu/kWh) | 10,100 |
| Electrical efficiency | 34% |
| Package efficiency | 89% |
| Load factor (could be any value) | 50% |
| Fuel input at full capacity (MMBtu/hr) | 2.041 |
| Fuel input (cuft/hr) | 2,243 |
| Upstream natural gas energy use (Btu/cuft) | 129 |

**Energy Flow Chart**




**Life Cycle Energy Calculations**

***Fuel input: method #1***

$$F_{in} = E_{gen} H_{in} \quad (1)$$

$F_{in}$ = Total fuel input (Btu)
$E_{gen}$ = Total electricity generation (kWh)
$H_{in}$ = Heat input rate (Btu/kWh)

*Numeric Example:*
1,020,100 Btu =101 kWh * 10,100 Btu/kWh

***Fuel input: method #2***

$$F_{in} = f_{cap} \alpha t \quad (2)$$

$F_{in}$ = Total fuel input (Btu)
$f_{cap}$ = Total input flow rate at full capacity (MMBtu/hr)
$\alpha$ = Load factor (%)
$t$ = Time (hr)

*Numeric Example:*
1,020,500 Btu (rounding explains difference from above calculation) = 2.041 MMBtu/hr *1,000,000 Btu/MMBtu * 50% * 1 hr

***Upstream process: Natural Gas***

$$E_{up,NG} = \hat{E}_{up,NG} V_{NG} \alpha t \quad (3)$$

$E_{up,NG}$ = Total upstream energy use for natural gas (Btu)

$\hat{E}_{up,NG}$ = Specific upstream energy use for natural gas (Btu/cuft)

$V_{NG}$ = Natural gas input volumetric flow rate (cuft/hr)

$\alpha$ = Load factor (%)

$t$ = Time (hr)

*Numeric Example:*
144,674 Btu = 129 Btu/cuft * 2,243 cuft/hr * 50% * 1 hr

***Conversion of Fuel: Electricity***

$$E_{gen} = F_{in} \eta \quad (4)$$

$E_{gen}$ = Total electricity generation ($Btu_e$)

$F_{in}$ = Total fuel input (Btu)

$\eta$ = Electrical conversion efficiency (%)

*Numeric Example:*
346,970 Btu = 1,020,500 Btu * 0.34

***Conversion of Fuel: Heat***

$$H_{out} = F_{in}(\lambda - \eta) \quad (5)$$

$H_{out}$ = Total heat output (Btu)

$F_{in}$ = Total fuel input (Btu)

$\lambda$ = Overall package energy conversion efficiency (%, with CHP)

$\eta$ = Electrical conversion efficiency (%)

*Numeric Example:*
561,275 Btu = 1,020,500 Btu * (0.89-0.34)

***Conversion of Fuel: Unusable Heat***

$$H_{un} = F_{in}(1 - \lambda) \quad (6)$$

$H_{un}$ = Total unusable heat output (Btu)

$F_{in}$ = Total fuel input (Btu)

$\lambda$ = Overall package energy conversion efficiency (%, with CHP)

*Numeric Example:*
112,255 Btu = 1,020,500 Btu * (1 – 0.89)

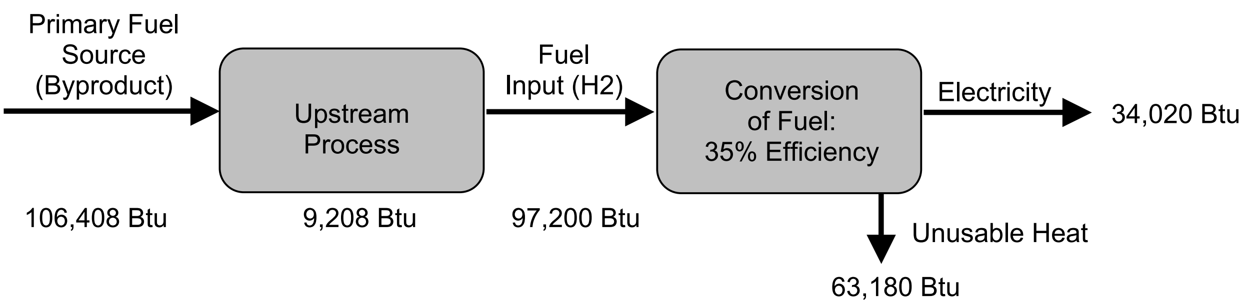
### 3.2 Fuel Cells (ENF Units)

Hydrogen fuel cells convert hydrogen (H2) to electricity through an electrochemical process. The source of hydrogen used for fuel is critical for understanding the overall efficiency of the fuel cell device from a life cycle perspective. Available hydrogen acquisition techniques include natural gas reformation, steam reformation, and electrolysis. However, the system modeled for NextEnergy is unique because the hydrogen is a byproduct from another process (chlorine manufacturing), where it is recovered, liquefied, and shipped to NextEnergy via diesel trucks. A hydropower dam generates the electricity supplied to this process. The utilization of renewable hydropower allows this system to minimize the use of fossil fuels relative to other hydrogen production routes.

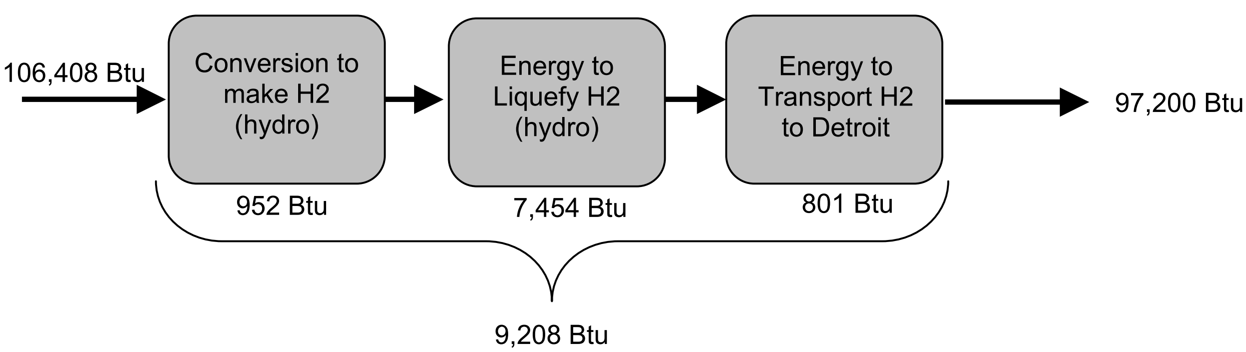
**Table 3.6: ENF Units Model Parameters**

| | |
|---|---|
| Measurement period | Hour |
| Heat rate (Btu/kWh) | 9,720 |
| Electrical efficiency | 35% |
| Load factor (could be any value) | 50% |
| Fuel input at full capacity (MMBtu/hr) | 0.049 |
| Fuel input (cuft/hr) | 180 |
| Conversion burden (see below) | 1.44% |
| Hydropower heat rate (Btu/kWh) | 3,414 |
| Hydropower upstream energy use (Btu/kWh) | 109 |
| Conversion energy to make H2 (lbs/kWh) | 0.025 |
| Total hydrogen needed at 50% load factor (lb, kg) | 0.47 (0.2126) |
| Liquefaction energy (kWh/kg) | 10.275 |
| Hydrogen storage capacity per truck (kg) | 3,500 |
| NextEnergy utilization per truckload | 20% |
| Distance from Praxair, Inc. to NextEnergy (miles) | 250 |
| Truck gas mileage (mpg) | 6 |
| Upstream diesel energy factor (MMBtu/1000 gallons) | 19 |
| Combustion diesel energy factor (MMBtu/1000 gallons) | 139 |

**Energy Flow Chart**




**Hydrogen Upstream Flow Chart**



## Life Cycle Energy Calculations

***Fuel input: method #1***

$$F_{in} = E_{gen} H_{in} \quad (7)$$

$F_{in}$ = Total fuel input (Btu)
$E_{gen}$ = Total electricity generation (kWh)
$H_{in}$ = Heat input rate (Btu/kWh)

*Numeric Example:*
97,200 Btu = 10 kWh * 9,720 Btu/kWh

***Fuel input: method #2***

$$F_{in} = f_{cap} \alpha t \quad (8)$$

$F_{in}$ = Total fuel input (Btu)
$f_{cap}$ = Total input flow rate at full capacity (MMBtu/hr)
$\alpha$ = Load factor (%)
$t$ = Time (hr)

*Numeric Example:* (rounding explains difference from method #1)
98,000 Btu = (0.049 MMBtu/hr * 4 units) * 1,000,000 Btu/MMBtu * 50% * 1 hr

***Conversion of Fuel: Electricity***

$$E_{gen} = F_{in} \eta \quad (9)$$

$E_{gen}$ = Total electricity generation ($Btu_e$)
$F_{in}$ = Total fuel input (Btu)
$\eta$ = Electrical conversion efficiency (%)

*Numeric Example:*
34,020 Btu = 97,200 Btu * 35%

***Conversion of Fuel: Energy Loss***

$$E_{loss} = F_{in}(1 - \eta) \quad (10)$$

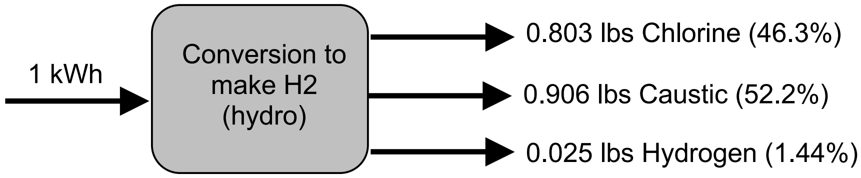
$E_{loss}$ = Total energy loss during conversion (Btu)
$F_{in}$ = Total fuel input (Btu)
$\eta$ = Electrical conversion efficiency (%)

*Numeric Example:*
63,180 Btu = 97,200 Btu * (1 – 0.35)

***Upstream Process: Hydrogen***

Hydrogen byproduct burden

The hydrogen supplied to NextEnergy is a byproduct of another process and the total process burden is allocated to all products using a mass-based approach. The resulting allocation for hydrogen in the production process is 1.44%. The calculation and flow chart are shown below:




Conversion to make H2

$$E_{acq,H_2} = (E_{pot,hydro} + E_{up,hydro}) m_{H_2} \hat{E}_{acq,H_2} M_{H_2} \qquad (11)$$

$E_{acq,H_2}$ = Total acquisition energy for hydrogen gas production (Btu)

$E_{pot,hydro}$ = Implied potential energy equivalent of hydropower (defined as 3,414 Btu/kWh)

$E_{up,hydro}$ = Life cycle energy associated with operation of a large hydroelectric facility (Btu/kWh)

$\hat{E}_{acq,H_2}$ = Specific energy required for hydrogen gas production (Btu/lb)

$m_{H_2}$ = Energy allocation of hydrogen in product stream (%)

$M_{H_2}$ = Total mass of hydrogen consumed by system (lb)

*Numeric Example:*

952 Btu = [(3,414 Btu/kWh + 109 Btu/kWh) * (1 kWh/0.025 lb H2) * 1.44%] * 0.47 lb

Energy to Liquefy H2

Praxair, Inc. receives the H2 gas from the byproduct processes by pipeline, which it then converts to liquid hydrogen for transport. The model uses published estimates for the energy required to liquefy hydrogen but does not account for the energy required to pump the hydrogen to Praxair, Inc (due to lack of data).

$$E_{liq,H_2} = M_{H_2} \hat{E}_{liq,H_2} \qquad (12)$$

$E_{liq,H_2}$ = Total energy required to liquefy hydrogen gas (Btu)

$M_{H_2}$ = Total mass of hydrogen consumed by system (kg)

$\hat{E}_{liq,H_2}$ = Specific energy required to liquefy hydrogen gas (kWh/kg)

*Numeric Example:*

7,454 Btu = 0.2126 kg * 10.275 kWh/kg * 3,412 Btu/kWh

Energy to Transport Liquid Hydrogen to NextEnergy

The liquid hydrogen is put on diesel trucks and shipped to NextEnergy (250 miles one way). According to Ed Danieli at Praxair, Inc., each truck carries 3,500 kg of hydrogen, where 20% is expected to go to NextEnergy per truckload (the rest going to other places in the Detroit area). The following formulas show how the transportation/distribution energy use is calculated:

$$N = \frac{M_{H_2}}{M_{truckload}} \qquad (13)$$

$$V_{diesel} = N \times D \div FE \qquad (14)$$

$$E_{trans,H_2} = V_{diesel}\left(\hat{E}_{up,diesel} + \hat{E}_{comb,diesel}\right) \qquad (15)$$

$N$ = Total number of full truckload hydrogen shipments required to meet NextEnergy demand
$M_{H_2}$ = Total mass of hydrogen consumed by system (lb)
$M_{truckload}$ = Total mass of hydrogen in a fully loaded truck (lb)
$V_{diesel}$ = Total volume of diesel fuel required to deliver hydrogen (gal)
$D$ = Total distance from Praxair (supplier) to NextEnergy, round trip (miles)
$FE$ = Fuel economy of diesel trucks used for delivery (miles/gal)
$E_{trans,H_2}$ = Total energy required to transport hydrogen (Btu)
$\hat{E}_{up,diesel}$ = Specific upstream energy required for production and delivery of diesel fuel (MMBtu/1000 gal)
$\hat{E}_{comb,diesel}$ = Specific combustion energy associated with use of diesel fuel (MMBtu/1000 gal)

*Numeric Example: Equation (13)*
0.00006 trips to NextEnergy = 0.2126 kg / 3500 kg

Note: Partial trip in this case because measurement period is short (hour), therefore very little hydrogen is required.

*Numeric Example: Equation (14)*
0.005 gallons = 0.00006 * 500 / 6 miles/gallon

Note: Answer is small because measurement period is short (hour); therefore very little hydrogen is required.

*Numeric Example: Equation (15)*
802 Btu = 0.005 gallons * [(19 MMBtu/ 1000 gallons) + (139 MMBtu/ 1000 gallons)] * 1,000,000 Btu/MMBtu

### 3.3 Unisolar PV Array

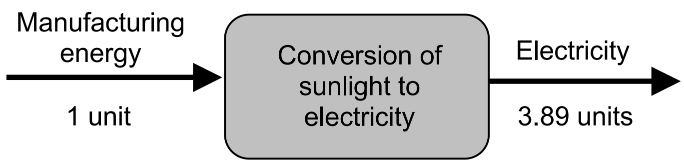
The energy and emissions required in the production of the photovoltaic array at the NextEnergy site are evaluated following guidelines for LCA. Energy and emissions are modeled based on previously published studies of Unisolar amorphous silicon photovoltaic arrays. This evaluation considers the acquisition of materials, and the production of the array. The materials of construction and manufacturing of other microgrid units has not been considered due to a lack of data or limited potential for effect on the overall results. However, published data are available for the PV array and the impacts of production and manufacturing are critical determinants of overall system life cycle performance.

**Table 3.7: Unisolar PV Array Model Parameters**

| Measurement period | Hour |
|---|---|
| Heat rate (Btu/kWh) | 877 |
| Electrical production efficiency* | 389% |
| Load factor (not user definable) | 16% |
| Reference solar irradiation for power rating ($W/m^2$) | 1,000 |
| Average daily solar irradiation for Detroit ($Wh/m^2/day$) | 3,779 |

* Net electrical efficiency represents the net energy ratio—the amount of energy produced by the device divided by the total production energy required to make the device, assuming average solar irradiation in Detroit for a 20 year service life (Source: Keoleian 2003).

**Energy Flow Chart**




**Life Cycle Energy Calculations**

***<u>Conversion of sunlight to electricity</u>***

The relationship between rated power and efficiency of a system is based on equation 16 (Source: Keoleian and Lewis 2003).

$$W_p = \theta I_r A \qquad (16)$$

$W_p$ = Rated peak power output for PV (kW)
$\theta$ = Conversion efficiency (electricity generation divided by solar input)
$I_r$ = Reference solar irradiance for PV peak power rating (defined as 1,000 $W/m^2$)
$A$ = Area of PV array ($m^2$)

*Numeric Example (after rearranging terms):*

$$\theta A = \frac{30 \text{ kW} \times 1000 \text{ W/kW}}{1000 \text{ W/m}^2} = 30 \text{ m}^2$$

$$E_{gen} = \theta A I_{detroit} t \qquad (17)$$

$E_{gen}$ = Total electricity generation (kWh)
$\theta$ = Conversion efficiency (electricity generation divided by solar input)
$I_{detroit}$ = Average daily solar irradiance in Detroit, MI ($W/m^2$)
$A$ = Area of PV array ($m^2$)
$t$ = Operating time for PV array (h)

*Numeric Example:*
4.72 kWh = 30 $m^2$ * 3,779 $Wh/m^2/day$ * (1 day/24 h) * 1 h

***PV efficiency***

$$\kappa = \frac{I_{\det roit}}{I_r} \tag{18}$$

$\kappa$ = Apparent load factor (average annual power output relative to peak power output)

$I_{\det roit}$ = Average daily solar irradiance in Detroit, MI (W/m$^2$)

$I_r$ = Reference solar irradiance for PV peak power rating (defined as 1,000 W/m$^2$)

*Numeric Example:*
15.7% = 157 W/m$^2$ / 1000 W/m$^2$

***Net electrical efficiency***

An alternative way to measure the efficiency of the solar device is to measure the amount of energy required to build the device compared to the amount of energy produced. It has been previously measured that over the 20-year life of a solar system with continuous operation in Detroit, it produces 3.89 times the amount of energy that was needed to build it (Keoleian and Lewis, 2002). This translates into an implied heat rate of 877 Btu/kWh (3,412/3.89). This heat rate is used as a way to account for the energy impact due to the creation of the solar device and is accounted for in the "Microgrid Combustion Energy Use" variable in the model.

### 3.4 Conventional System

The conventional system impact is comprised of combustion energy, upstream energy, line losses, and thermal system requirements. The model first determines the microgrid energy use and impact based on the operating input assumptions of each unit and then determines the conventional system impact based on meeting the same electricity and thermal needs.

To demonstrate how the grid impacts are calculated, consider the output from Example #1 (Section 3.1): Natural gas unit ENE 210 EGR. With a 50% load factor, the unit generates 101 kWh per hour. The model uses this electricity output to calculate the amount of energy (Btu) that is needed to deliver 101 kWh to NextEnergy using grid power.

**Table 3.8: Model Parameters for Conventional System**

| Measurement period | Hour |
|---|---|
| Upstream energy use (Btu/kWh) | 356 |
| Combustion energy use (Btu/kWh) | 10,541 |
| Line loss energy use (Btu/kWh) | 872 |
| Boiler efficiency | 75% |
| Energy content of natural gas (MMBtu/1000 cuft) | 1,600,000 |
| Lower heating value of natural gas (Btu/cuft) | 1,160 |
| Upstream energy use natural gas (Btu/cuft) | 129 |

Equation 19 applies for calculating the energy impact at each of the life cycle stages:

$$E_i = E_{grid}\bar{E}_i \tag{19}$$

$E_i$ = Primary energy requirements for life cycle stage *i* (Btu)

$E_{grid}$ = Total electricity generated by the grid (kWh)

$\bar{E}_i$ = Primary energy requirements for life cycle stage *i* per unit electricity generated (Btu/kWh)

*Numeric Examples:*

***Upstream energy use***
35,956 Btu = 101 kWh * 356 Btu/kWh

***Combustion energy use***
1,064,641 Btu = 101 kWh * 10,541 Btu/kWh

***Line loss energy use***
88,072 Btu = 101 kWh * 872 Btu/kWh

Total energy use = $\sum_i E_i$ = 1,188,669 Btu

Because the natural gas unit ENE 210 EGR is a combined heat and power unit, the conventional system must deliver the same thermal output as the unit to compare systems equitably. The necessary thermal from a conventional system would be from a natural gas boiler installed in the building operating at approximately 75% efficiency. Running at a 50% load factor, the natural gas ENE DG unit produces 561,275 Btu of recoverable heat. The following equations show the calculations to account for the life cycle energy for an equivalent amount of heat from a conventional thermal system. Equations 20 and 21 show the calculation for determining the amount of energy required to deliver the same thermal output.

***Boiler heating energy***

$$F_{in} = \frac{H_{out}}{\phi} \tag{20}$$

$F_{in}$ = Total fuel energy input for boiler (Btu)
$H_{out}$ = Total heat output produced by the microgrid (Btu)
$\phi$ = Boiler thermal efficiency (%)

*Numeric example:*
748,367 Btu = 561,275 Btu / 0.75 efficiency

***Upstream energy from production of natural gas fuel***

$$E_{up,NG} = \frac{F_{in}}{LHV_{NG}} \hat{E}_{up,NG} \tag{21}$$

$E_{up,NG}$ = Upstream energy use in natural gas production (Btu)
$F_{in}$ = Total fuel energy input for boiler (Btu)
$LHV_{NG}$ = Lower heating value of natural gas (Btu/$ft^3$)
$\hat{E}_{up,NG}$ = Upstream energy use in natural gas production (Btu/ $ft^3$)

*Numeric example:*
83,224 Btu = (748,367 Btu / 1,160 Btu/cuft) * 129 Btu/cuft

Total energy use for equivalent thermal system = $F_{in} + E_{up,NG}$ = 748,367 + 83,224 = 831,590 Btu

**4. Sample Life Cycle Emissions Flow Charts and Calculations**
The second component of the life cycle analysis in addition to the life cycle energy is the life cycle environmental emissions. The model accounts for two main types of environmental effects, emissions of

$NO_x$ and $CO_2$. $NO_x$ is a principal component to the formation of smog and contributes to acidification of lakes and streams and to human health problems. $CO_2$ does not have direct human health consequences, but contributes to the greenhouse effect and global warming. $NO_x$ emissions are regulated, as $NO_2$, under the Clean Air Act while $CO_2$ emissions are not regulated.

This section includes the calculations performed for each of the four examples above. Emissions calculations are demonstrated for only NOx emissions in these examples but the calculations are the same for $CO_2$ emissions. For the microgrid technologies, the emissions rates are calculated first based on maximum output and then scaled based on the load factor. The grid emissions rates are based on average emission rates as a function of electricity generation.

### 4.1 Natural Gas Unit: ENE 210 EGR

***Upstream emissions***

$$\dot{M}_{NO_x,up} = V_{NG}\bar{M}_{NO_x up,NG} \tag{22}$$

$\dot{M}_{NO_x,up}$ = Total upstream $NO_x$ pollution (lb/hr)

$V_{NG}$ = Volumetric flow rate of natural gas (cuft/hr)

$\bar{M}_{NO_x up,NG}$ = Upstream $NO_x$ pollution from natural gas production (lb/cuft)

*Numeric Example:*
0.269 lb/hr = (0.12 lb / 1000 cuft) * 2,243 cuft/hr

***Combustion emissions***

$$\dot{M}_{NO_x,comb,NG} = W_p\bar{M}_{NO_x comb,NG} \tag{23}$$

$\dot{M}_{NO_x,comb,NG}$ = Total combustion $NO_x$ pollution (lb/hr)

$W_p$ = Peak power capacity (kW)

$\bar{M}_{NO_x comb,NG}$ = $NO_x$ pollution from natural gas combustion (lb/kWh)

*Numeric Example:*
0.097 lb/hr = 202 kW * 0.00048 lb/kWh

### 4.2 Fuel Cells (ENF Units)

***Upstream emissions***

The upstream emissions values for the hydrogen units are entered in the model as fixed parameters based on running the units at full capacity. The final emissions calculations are based on scaling the total emissions by the load factor of the unit.

The upstream emissions from the production of hydrogen are from two sources. First, there are emissions associated with the electricity use required to make and liquefy the hydrogen gas. Although this electricity is expected to come from hydropower, there is a small emissions factor resulting from the construction of the hydropower facility. Second, there are emissions from the transportation of liquid hydrogen to NextEnergy via diesel trucks. Equations 24 and 25 show the calculations for the upstream hydrogen emissions for the fuel cell unit.

$$\dot{M}_{NO_x prod,H_2} = \frac{(\hat{E}_{acq,H_2} + \hat{E}_{liq,H_2})M_{H_2}}{3{,}412\ \text{Btu/kWh}}\bar{M}_{NO_x,hydro} \tag{24}$$

$\dot{M}_{NO_x,prod,H_2}$ = Total $NO_x$ emissions associated with production of hydrogen (lbs)

$\hat{E}_{acq,H_2}$ = Electricity required for hydrogen gas production (Btu of electricity/lb)

$\hat{E}_{liq,H_2}$ = Electricity required to liquefy hydrogen gas (Btu of electricity /lb)

$M_{H_2}$ = Total mass of hydrogen consumed by system (lb)

$\bar{M}_{NO_x,hydro}$ = Life cycle $NO_x$ emissions associated with operation of a large hydroelectric facility (lbs/kWh)

*Numeric Example:*
0.000652 lb = [(2,032 Btu/lb + 15,902 Btu/lb) * 0.94 lb / 3,412 Btu/kWh] * 0.000132 lb/kWh

Note: Fuel cell unit is running at 100% capacity

$$\dot{M}_{NO_x,trans,H_2} = V_{diesel}\bar{M}_{NO_x,diesel} \quad (25)$$

$\dot{M}_{NO_x,trans,H_2}$ = Total $NO_x$ emissions associated with transportation of hydrogen to NextEnergy (lbs)

$V_{diesel}$ = Total volume of diesel fuel required to deliver hydrogen (gal)

$\bar{M}_{NO_x,diesel}$ = Life cycle $NO_x$ emissions associated with production and combustion of diesel fuel (lbs/gal)

*Numeric Example:*
0.0022 lb = 0.01012 gallons * 218 lb / 1000 gallons

Note: Fuel cell unit is running at 100% capacity

Total $NO_x$ emissions = Conversion + Transportation = 0.000652 + 0.0022 = 0.00285 lb

***<u>"Combustion" (fuel cell operation) emissions</u>***

While the combustion of hydrogen does not produce $CO_2$ emissions, low-level emissions of $NO_x$ are expected from all of the hydrogen units due to the presence of nitrogen in the air.

### 4.3 Unisolar PV Array

As with the fuel cell device, the solar array does not result in combustion emissions. However, for this analysis, the emissions from the manufacture of the solar array are included. Equation 26 shows the calculation used in the model.

***<u>Upstream emissions</u>***

$$\dot{M}_{NO_x solar} = \bar{M}_{NO_x,solar}W_p \quad (26)$$

$\dot{M}_{solar}$ = Total NOx emissions from the production of the solar array (lb/hr)

$W_p$ = Peak power capacity (kW)

$\bar{M}_{NO_x,solar}$ = $NO_x$ pollution from production of the solar array allocated over 20 years of continuous operation (lb/kWh)

*Numeric Example:*
0.017 lb/hr = 0.00057 lb/kWh * 30 kW

***Combustion (conversion) emissions***
There are no conversion emissions from the use of the solar array.

**4.4 Conventional System**
The emissions from the conventional electric grid are calculated in the same fashion as the life cycle energy use, where the emissions are a function of the total electricity and thermal production from the microgrid.

To demonstrate how the grid impacts are calculated, consider the output from Example #1 (Section 4.1): Natural gas unit ENE 210 EGR. With a 50% load factor, the unit generates 101 kWh per hour and 748,367 Btu of thermal energy. The model uses this electricity and thermal output to calculate the amount of emissions resulting from the delivery of 101 kWh to NextEnergy using grid power and a conventional thermal system.

***Emissions from grid electricity***

$$\dot{M}_{NO_x,grid} = \bar{M}_{NO_x,grid} E_{grid} \quad (27)$$

$\dot{M}_{NO_x,grid}$ = Total $NO_x$ pollution from grid electricity generation (lb)

$E_{grid}$ = Total electricity generated by the grid (kWh)

$\bar{M}_{NO_x,grid}$ = $NO_x$ pollution with the grid fuel cycle (lb/kWh)

*Numeric Example:*
0.72 lb = 0.0071 lbs/kWh * 101 kWh

***Emissions from thermal system***

$$\dot{M}_{NO_x,boiler} = \frac{F_{in}}{LHV_{NG}} \bar{M}_{NO_x,NG} \quad (28)$$

$\dot{M}_{NO_x,boiler}$ = Total $NO_x$ pollution associated with boiler operation (lb)

$F_{in}$ = Total fuel energy input for boiler (Btu)

$LHV_{NG}$ = Lower heating value of natural gas (Btu/$ft^3$)

$\bar{M}_{NO_x,NG}$ = Total $NO_x$ pollution associated with production and combustion of natural gas (lb/cuft)

*Numeric Example:*
0.35 lb = 748,367 Btu * 1 cuft / 910 Btu * 0.43 lb $NO_x$ / 1000 cuft

## 5. Model Assumptions

This section lists the assumptions made in the microgrid model. In general, most assumptions in the model are referenced as a comment in the cell where the assumption is relevant. Each of the assumptions made in the model are broken out by worksheet with further justification in the following table.

**Table 3.9: Model Assumptions**

| Worksheet | Assumption | Explanation |
|---|---|---|
| Main module | The default "percentage of total expected load met" should be set to 36% if NextEnergy seeks only to meet peak loads. | Estimate according to Michael Saldana and Jim Croce at NextEnergy. |
| Main module | The thermal requirements for the conventional system are supplied by a conventional boiler with 75% efficiency. | "Conventional boiler efficiency is 70 to 75 percent, and some older boilers operate as low as 60 percent before retrofitting." (Source: Honeywell) |
| Main module | The model does not account for unit inefficiencies due to partial loads. For example, if a unit is set to run at a 2% load factor, the model does not account for the potential inefficiencies due to very low production. | There is no available data for how units would run at extremely low output levels. |
| Main module | There are no line losses for the microgrid system. | Line losses between the microgrid and the NextEnergy facility are expected to be negligible due to the immediate proximity |
| Life Cycle Parameters | Franklin Associates life cycle energy and emissions data can be applied to the Detroit grid. | The generation assets in the Franklin Associates data are representative of the national average. The model accounted for the relative percentage of each of these units for the Detroit grid and the expected variance from the Franklin data is small. |
| Life Cycle Parameters | The total hydrogen needed in the system is a function of the fuel consumption of the hydrogen units running, not what is actually delivered to the site. | The model does not account for stored hydrogen or any losses resulting from storage or delivery of hydrogen to NextEnergy. |
| Life Cycle Parameters | Because the hydrogen is created as a byproduct from another system (chlorine production), the impact is calculated as a percentage on a mass-basis. | This is an accepted convention in LCA. Alternative approaches could have accounted for the hydrogen burden by economic value (weighting the economic value of hydrogen to the other byproducts). |
| Life Cycle Parameters | Hydrogen is created as a byproduct from a chlorine plant using hydroelectric power; all conversion power estimates are based on actual data. | Source: Praxair, Inc. |
| Life Cycle Parameters | The mass-basis calculation for hydrogen is based on only one of two processes (diaphragm cell and membrane cell) that are used to create the hydrogen byproduct. 1.44% is used in the model. | The relative percentages of the two systems are unknown. However, each system results in approximately the same mass fractions of hydrogen relative to other products.<br>Diaphragm burden = 1.44%<br>Membrane burden = 1.39% |
| Life Cycle | The energy to liquefy hydrogen is based | Data not available |

| | | |
|---|---|---|
| Parameters | on published studies and does not include the energy required to pump the hydrogen from supplier facilities to Praxair, Inc. | |
| Life Cycle Parameters | The default percentage of the truck carrying hydrogen that goes to NextEnergy is set at 20%. | Estimate according to Ed Danieli at Praxair, Inc. |
| Life Cycle Parameters | Truck gas mileage is 6 mpg | Assuming the same mpg for backhauls 6 mpg estimate for carrying liquid hydrogen: "Costs of Storing and Transporting Hydrogen" by Wade Amos, NREL. 1998 |
| Life Cycle Parameters | The hydrogen used at NextEnergy is only being supplied by Praxair, Inc. based on their system of production. | If NextEnergy switched hydrogen suppliers, the model would have to be adapted to reflect different hydrogen generation assumptions. |
| Microgrid Assumptions | When the shaft power is not available, it is assumed that net electrical output is 90% of shaft power. | Based on observed shaft efficiencies for other devices where data is available. |
| Microgrid Assumptions | The PV array has a 20-year life. | Based on average continual use (consistent estimate in published sources of data). |
| Microgrid Assumptions | The ENI 85 unit input is based on spec sheets for the ENI 75. | Not all ENI 85 data was available at the time of building the model. |
| Detroit Grid | The Detroit grid generation mix is based on data from 2001. | The most recent available data is from 2001, but this information should be updated when possible. |

**6. Model Limitations**

The model is designed to be as flexible as possible so the user can easily change input assumptions. All user-definable cells are in blue font. However, limitations of the analysis may include:

- The model only accounts for $NO_x$ and $CO_2$ emissions. Other emissions that could have been tracked are CO, particulates, and $SO_2$ for example, but the data were not available for most DG units.
- The modeled hydrogen system is a unique system with high efficiencies. If NextEnergy switched its hydrogen supplier, and the new system would need to be modeled to reflect different life cycle energy and emissions profiles.
- The model is not designed to optimize life cycle energy use or emissions; it only calculates the impacts based on user defined specifications.
- In all cases the model calculates outputs based on annual average operating performance; the average generally does not reflect specific time-of-day or seasonal variation (e.g. Detroit grid peak output or peak solar irradiation).

# IV. Model Results

The model results are indicated by two main outputs. The first output is the life cycle energy use of the microgrid system and the conventional system, which represents the total energy (upstream, combustion, line losses, thermal, inverter losses) required to produce the same electricity and thermal needs for the NextEnergy facility under both systems. The second output is the environmental impact ($NO_x$ and $CO_2$ emissions) based on the complete life cycle of each system.

The model results are presented at a system level and by individual DG units. The system level results show how the microgrid performs for four input scenarios. The unit-by-unit analysis shows how each unit operates when run at full capacity compared to the grid. All of the results presented are based on a measurement period of one hour (for simplicity).

**1. Microgrid System Scenario Analysis**
The microgrid can operate under a wide range of conditions that result in different life cycle impacts depending on which units are chosen to operate for what length of time. This section explores possible scenarios of microgrid operation and compares the energy and environmental performance against the conventional system in each scenario. While a multitude of different microgrid arrangements is possible, the following four categories and scenarios are presented to illustrate how the microgrid performs against the conventional system given realistic assumptions. All outputs are displayed on an hourly level in the analysis in order to keep the number of digits small in the output results. The results represent an *average* hour of operation for the microgrid (e.g. PV performance is based on annual average solar irradiation) and conventional systems (e.g. not displacing peak power).

System efficiencies are calculated based on the total energy output of the system divided by the life cycle input into the system. In order to calculate these efficiencies thermal energy and heat energy are combined in order to compare complete systems. Although heat and electricity have different thermodynamic qualities, this technique is useful for measuring overall performance.

**Scenarios Analyzed**

1. Generation
   a. All units run at 100% capacity
   b. All units run at equal load factors to approximately meet expected building load
   c. All units run at equal load factors to approximately meet double the expected building load
2. Fuel mix
   a. Run only the natural gas powered units
   b. Run only the hydrogen powered units
3. Turn off combined heat and power option for all units
4. Turn off inefficient ENT 400 (at 16% efficiency) unit

***<u>Scenario 1(a): All units run at 100% capacity</u>***

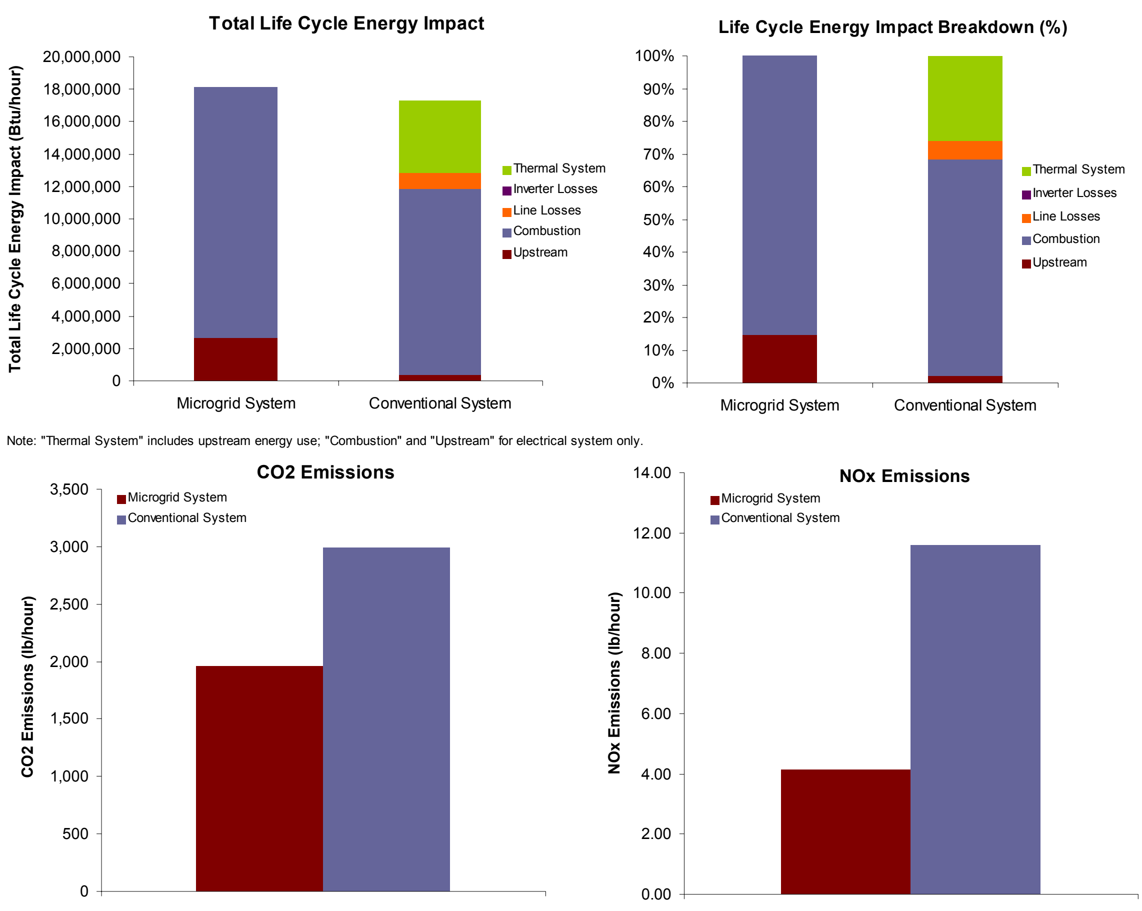
This scenario shows how the microgrid performs against the grid when all DG units are run at 100% capacity. While it is unlikely that this scenario will ever materialize because prototype units may need to be shut down for repair, it provides an upper bound scenario. (Note that the solar array can only be run at 16% load factor based on sunlight distribution in the Detroit area).

## Table 4.1: Scenario 1(a)—All Units Run at 100% Capacity

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 387,062 | 451,203 | 838,265 | 2,647,483 |
| Total Combustion Energy Use | Btu/Hour | 11,466,107 | 4,057,327 | 15,523,434 | 15,464,933 |
| Total Line Losses Energy Use | Btu/Hour | 948,254 | 0 | 948,254 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 22,080 |
| Total Life Cycle Energy Use | Btu/Hour | 12,801,423 | 4,508,529 | **17,309,952** | **18,134,496** |
| Total NOx Emissions | lb/Hour | 9.67 | 1.92 | **11.59** | **4.14** |
| Total CO2 Emissions | lb/Hour | 2,519 | 468 | **2,987** | **1,960** |
| Total Electrical Energy Produced | kWh | | | | 1,088 |
| Total Heat Energy Produced | Btu | | | | 3,042,995 |
| Microgrid System Efficiency | % | | | | 37.2% |
| Conventional System Efficiency | % | | | | 39.0% |

When run at full capacity, the conventional grid slightly outperforms the conventional system with respect to life cycle energy but not environmental emissions. The larger upstream energy component for the microgrid system is a result of greater use of natural gas and hydrogen, both of which require more upstream energy than coal, the dominant fuel for the conventional system. The combustion energy for the microgrid is dominated by the inefficient ENT 400 unit, with 16% efficiency. The main advantage of the microgrid is that it avoids the need for a thermal system and transmission losses.

## Figure 4.1: Scenario 1(a)—All Units Run at 100% Capacity



***Scenario 1(b): All units run at equal load factors to approximately meet expected building load***

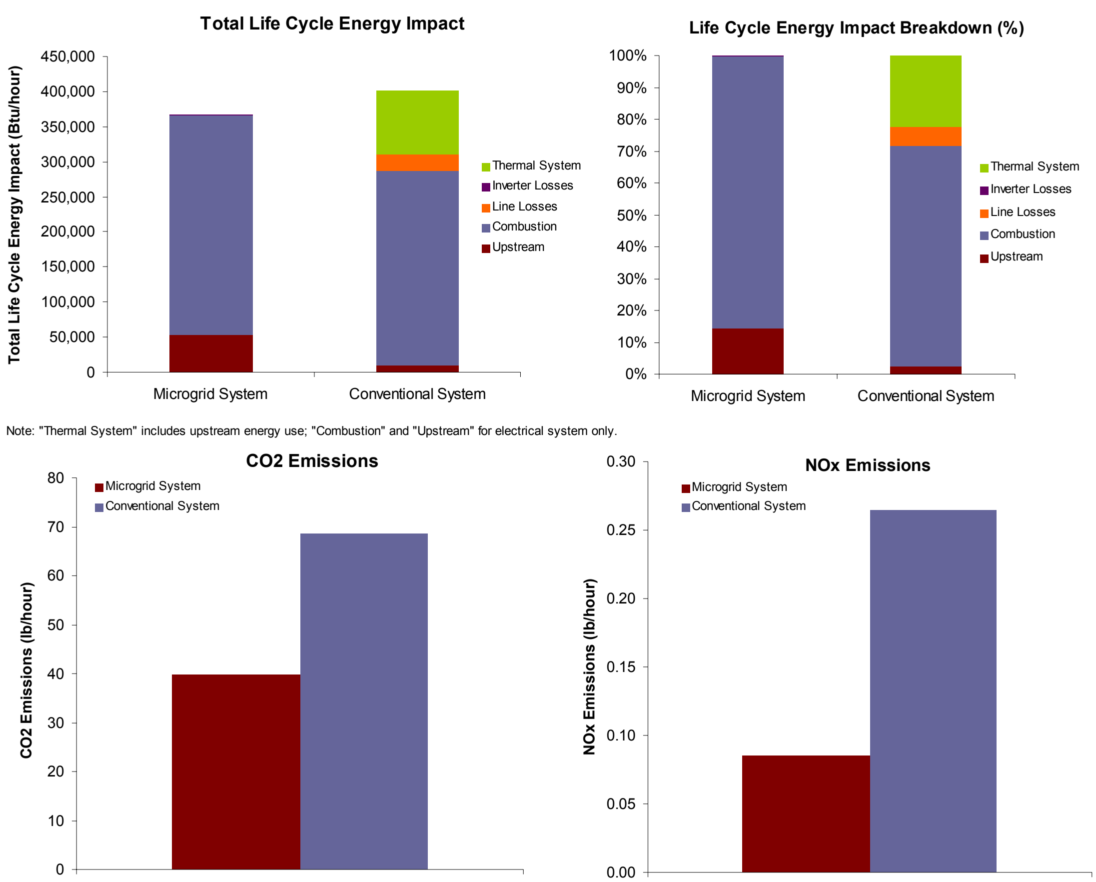
This scenario shows how the microgrid performs when all units are scaled back equally to meet the expected NextEnergy building load. The output is based on the assumption that the microgrid will only operate during peak hours of the day (36% of the time). Based on this level of operation, the microgrid would need to generate 27 kWh of electricity to meet building needs. To adjust the microgrid output to produce 27 kWh, the load factor for each unit is manually adjusted until a total of about 27 kWh of electricity is being produced. In this case, each unit is run at a 2% load factor (which is unlikely, but possible over a course of a year).

**Table 4.2: Scenario 1(b)—All Units Run to Meet Building Load**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 9,394 | 9,024 | 18,418 | 52,950 |
| Total Combustion Energy Use | Btu/Hour | 278,288 | 81,147 | 359,435 | 313,373 |
| Total Line Losses Energy Use | Btu/Hour | 23,015 | 0 | 23,015 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 768 |
| Total Life Cycle Energy Use | Btu/Hour | 310,697 | 90,171 | **400,868** | **367,090** |
| Total NOx Emissions | lb/Hour | 0.23 | 0.04 | **0.26** | **0.09** |
| Total CO2 Emissions | lb/Hour | 59 | 9 | **69** | **40** |
| Total Electrical Energy Produced | kWh | | | | 26 |
| Total Heat Energy Produced | Btu | | | | 60,860 |
| Microgrid System Efficiency | % | | | | 41.1% |
| Conventional System Efficiency | % | | | | 37.7% |

In Scenario 1(b) the microgrid outperforms the conventional system with regard to life cycle energy and environmental emissions. The result is expected with a scaling back of the inefficient ENT 400 unit.

**Figure 4.2: Scenario 1(b)—All Units Run to Meet Building Load**



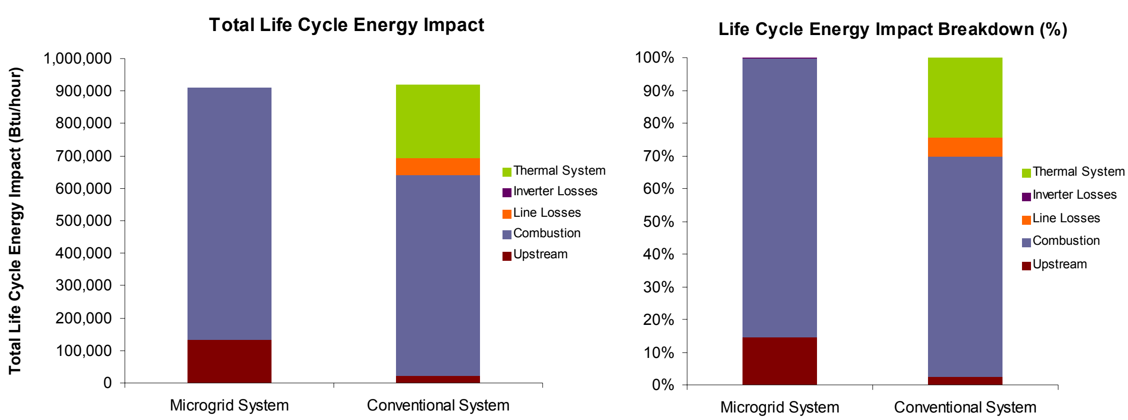
**_Scenario 1(c): All units run at equal load factors to approximately meet double the expected building load_**

This scenario shows how the microgrid performs when the expected building load is doubled. In this case, each unit is run at a 5% load factor to produce 59 kWh of electricity. The relative efficiencies are not the same as in scenario 1(b) because the PV unit is set to operate at 16% efficiency all of the time. The analysis assumes that the PV unit cannot be turned off and that the solar irradiation is based on an average hour.

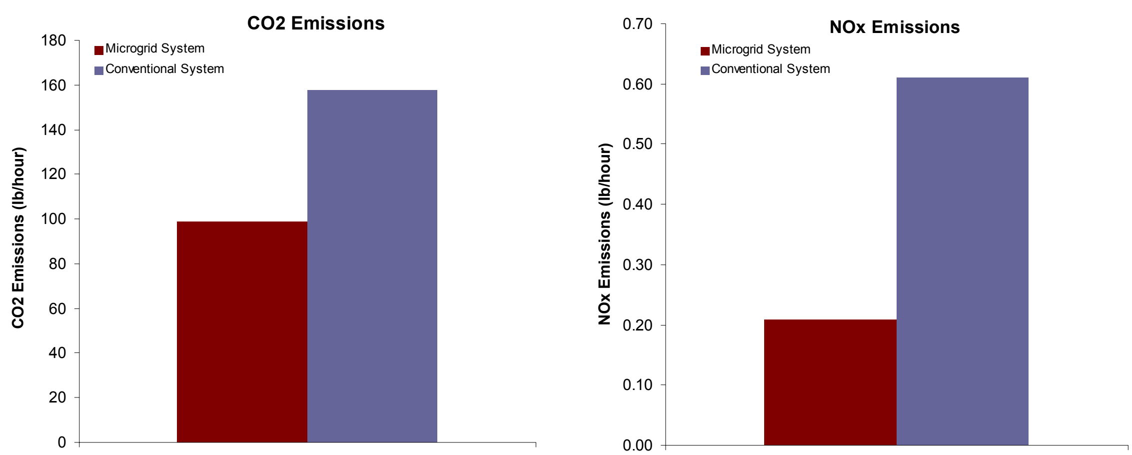
### Table 4.3: Scenario 1(c)—All Units Run to Meet Double Building Load

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 20,955 | 22,560 | 43,516 | 132,374 |
| Total Combustion Energy Use | Btu/Hour | 620,772 | 202,866 | 823,639 | 777,196 |
| Total Line Losses Energy Use | Btu/Hour | 51,338 | 0 | 51,338 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 1,420 |
| Total Life Cycle Energy Use | Btu/Hour | 693,066 | 225,426 | **918,493** | **910,990** |
| Total NOx Emissions | lb/Hour | 0.52 | 0.10 | **0.61** | **0.21** |
| Total CO2 Emissions | lb/Hour | 134 | 23 | **158** | **99** |
| Total Electrical Energy Produced | kWh | | | | 59 |
| Total Heat Energy Produced | Btu | | | | 152,150 |
| Microgrid System Efficiency | % | | | | 38.8% |
| Conventional System Efficiency | % | | | | 38.4% |

### Figure 4.3: Scenario 1(c)—All Units Run to Meet Double Building Load




Note: "Thermal System" includes upstream energy use; "Combustion" and "Upstream" for electrical system only.



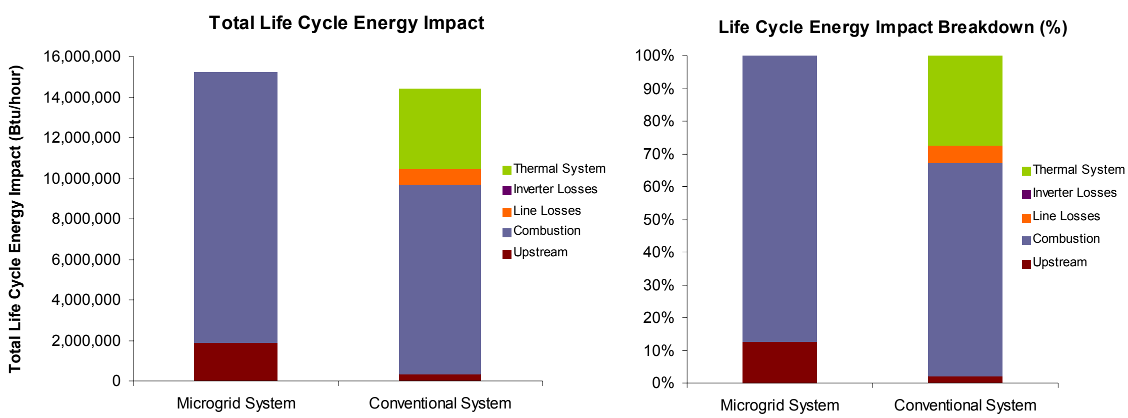
***Scenario 2(a): Only the natural gas powered units operating***

This scenario shows how the microgrid performs when only the units that operate on natural gas are operated. All of the units that run on hydrogen are turned off. All of the natural gas units are also set to 100% load factor.

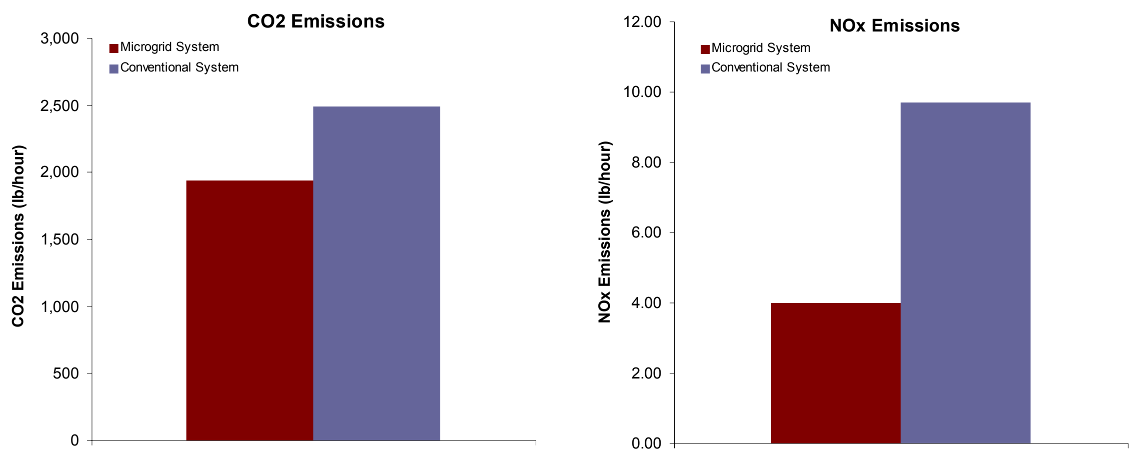
**Table 4.4: Scenario 2(a)—Natural Gas Units Only**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 315,987 | 394,956 | 710,942 | 1,892,430 |
| Total Combustion Energy Use | Btu/Hour | 9,360,604 | 3,551,540 | 12,912,144 | 13,322,375 |
| Total Line Losses Energy Use | Btu/Hour | 774,127 | 0 | 774,127 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 0 |
| Total Life Cycle Energy Use | Btu/Hour | 10,450,718 | 3,946,496 | **14,397,213** | **15,214,805** |
| Total NOx Emissions | lb/Hour | 8.01 | 1.68 | **9.69** | **4.01** |
| Total CO2 Emissions | lb/Hour | 2,084 | 409 | **2,494** | **1,939** |
| Total Electrical Energy Produced | kWh | | | | 888 |
| Total Heat Energy Produced | Btu | | | | 2,663,655 |
| Microgrid System Efficiency | % | | | | 37.4% |
| Conventional System Efficiency | % | | | | 39.5% |

**Figure 4.4: Scenario 2(a)—Natural Gas Units Only**




Note: "Thermal System" includes upstream energy use; "Combustion" and "Upstream" for electrical system only.



In Scenario 2(a), the conventional system outperforms the microgrid with respect to life cycle energy but the microgrid outperforms the conventional system with regard to environmental emissions. Again, the results are likely skewed by the operation of the inefficient ENT 400 unit.

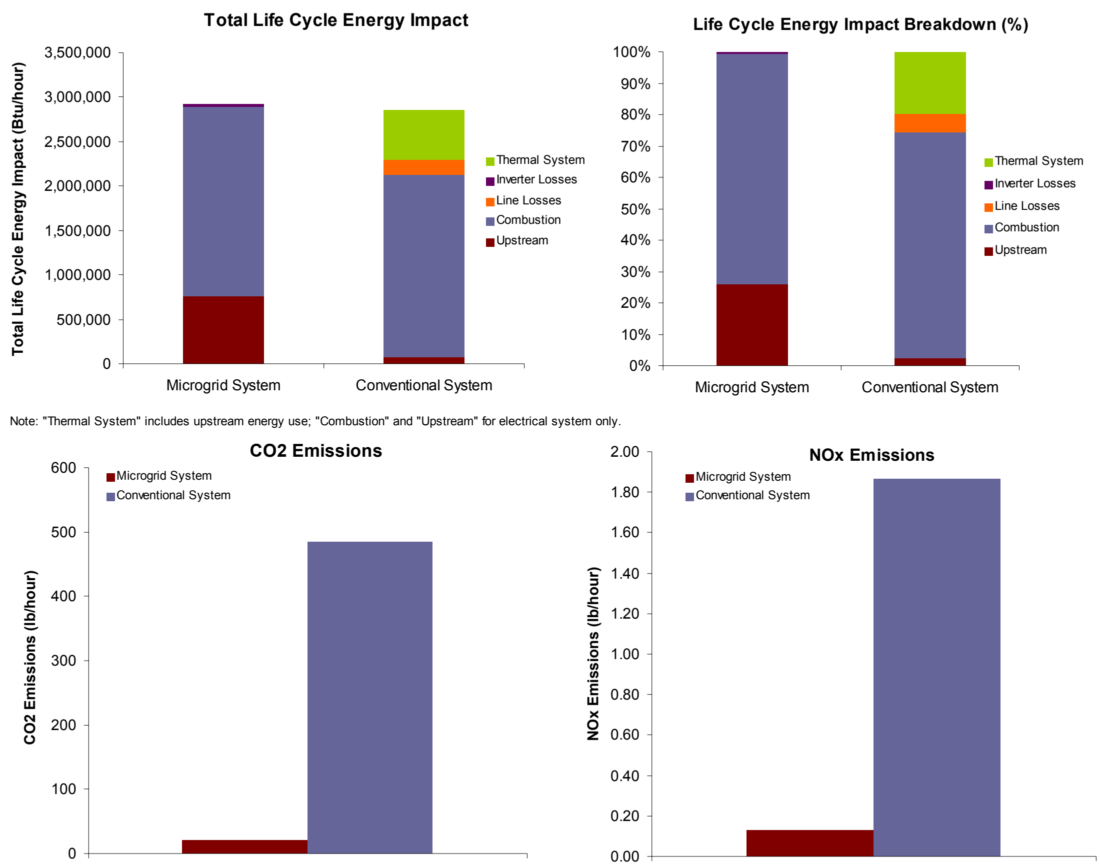
***<u>Scenario 2(b): Only the hydrogen powered units operating</u>***

This scenario shows how the microgrid performs when only the units that are fueled by hydrogen are operational. All of the hydrogen units are also set to 100% load factor.

**Table 4.5: Scenario 2(b)—Hydrogen Units Only**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 69,389 | 56,247 | 125,636 | 755,053 |
| Total Combustion Energy Use | Btu/Hour | 2,055,538 | 505,787 | 2,561,325 | 2,138,400 |
| Total Line Losses Energy Use | Btu/Hour | 169,994 | 0 | 169,994 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 21,747 |
| Total Life Cycle Energy Use | Btu/Hour | 2,294,921 | 562,034 | **2,856,955** | **2,915,201** |
| Total NOx Emissions | lb/Hour | 1.63 | 0.24 | **1.87** | **0.13** |
| Total CO2 Emissions | lb/Hour | 426 | 58 | **484** | **20** |
| Total Electrical Energy Produced | kWh | | | | 195 |
| Total Heat Energy Produced | Btu | | | | 379,340 |
| Microgrid System Efficiency | % | | | | 35.8% |
| Conventional System Efficiency | % | | | | 36.6% |

**Figure 4.5: Scenario 2(b)—Hydrogen Units Only**




In Scenario 2(b) the microgrid and conventional system have approximately the same life cycle energy impact but the microgrid greatly outperforms the conventional system with respect to environmental emissions.  This result is expected given that hydrogen units emit very little pollutants and the production of hydrogen was mainly from hydropower in this case.  The upstream energy impact for the microgrid system is large, however, because the creation of hydrogen is energy-intensive.

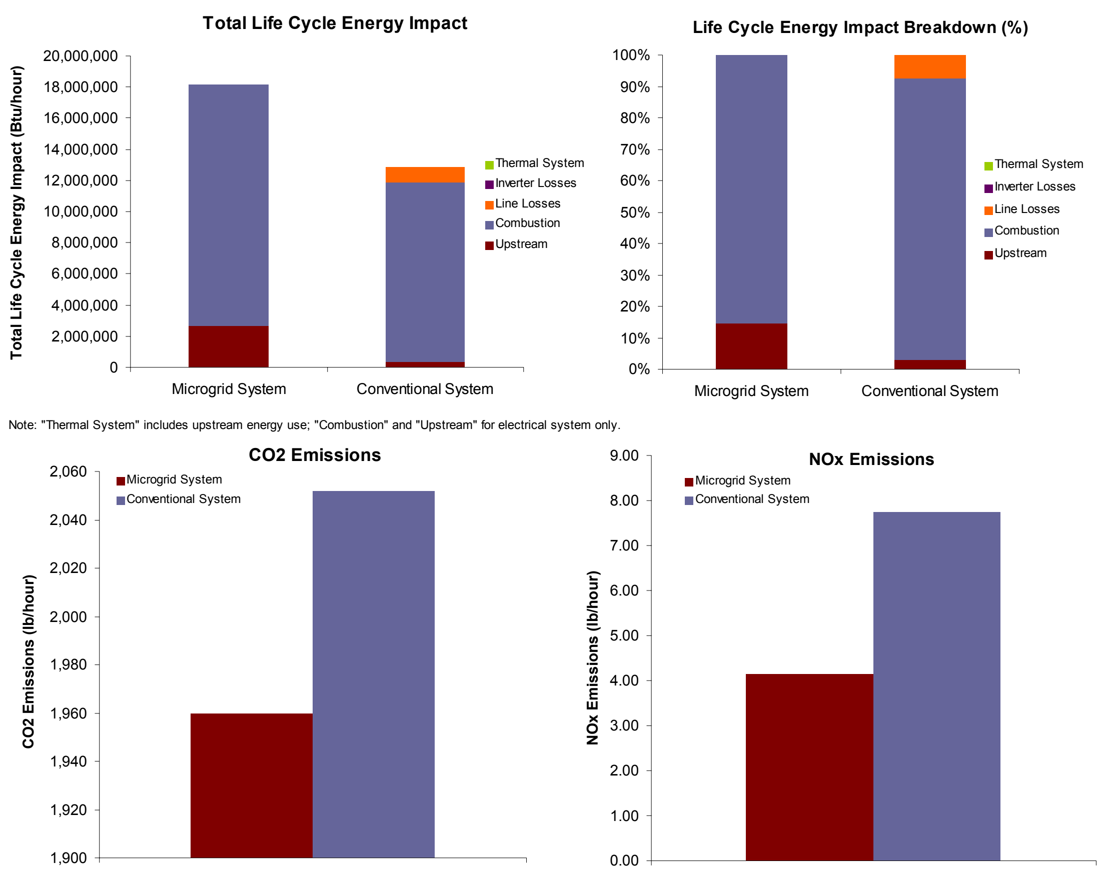
***Scenario 3: Turn off combined heat and power in all units where possible***

This scenario shows how the microgrid performs when all DG units that have combined heat and power applications turn off the thermal component.  This scenario is designed to test how the microgrid efficiency is enhanced by the ability to generate and utilize waste heat.  For this analysis all units have a load factor of 100%.

**Table 4.6: Scenario 3—No Combined Heat and Power**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 387,062 | 0 | 387,062 | 2,647,483 |
| Total Combustion Energy Use | Btu/Hour | 11,466,107 | 0 | 11,466,107 | 15,464,933 |
| Total Line Losses Energy Use | Btu/Hour | 948,254 | 0 | 948,254 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 22,080 |
| Total Life Cycle Energy Use | Btu/Hour | 12,801,423 | 0 | **12,801,423** | **18,134,496** |
| Total NOx Emissions | lb/Hour | 7.75 | 0.00 | **7.75** | **4.14** |
| Total CO2 Emissions | lb/Hour | 2,052 | 0 | **2,052** | **1,960** |
| Total Electrical Energy Produced | kWh | | | | 1,088 |
| Total Heat Energy Produced | Btu | | | | 0 |
| Microgrid System Efficiency | % | | | | 20.5% |
| Conventional System Efficiency | % | | | | 29.0% |

**Figure 4.6: Scenario 3–No Combined Heat and Power**



In Scenario 3 the conventional system greatly outperforms the microgrid system with respect to life cycle energy use but the microgrid outperforms the conventional system with respect to environmental emissions. This result is expected given that the efficiency of the microgrid is much lower without utilizing the package efficiencies from combined heat and power.

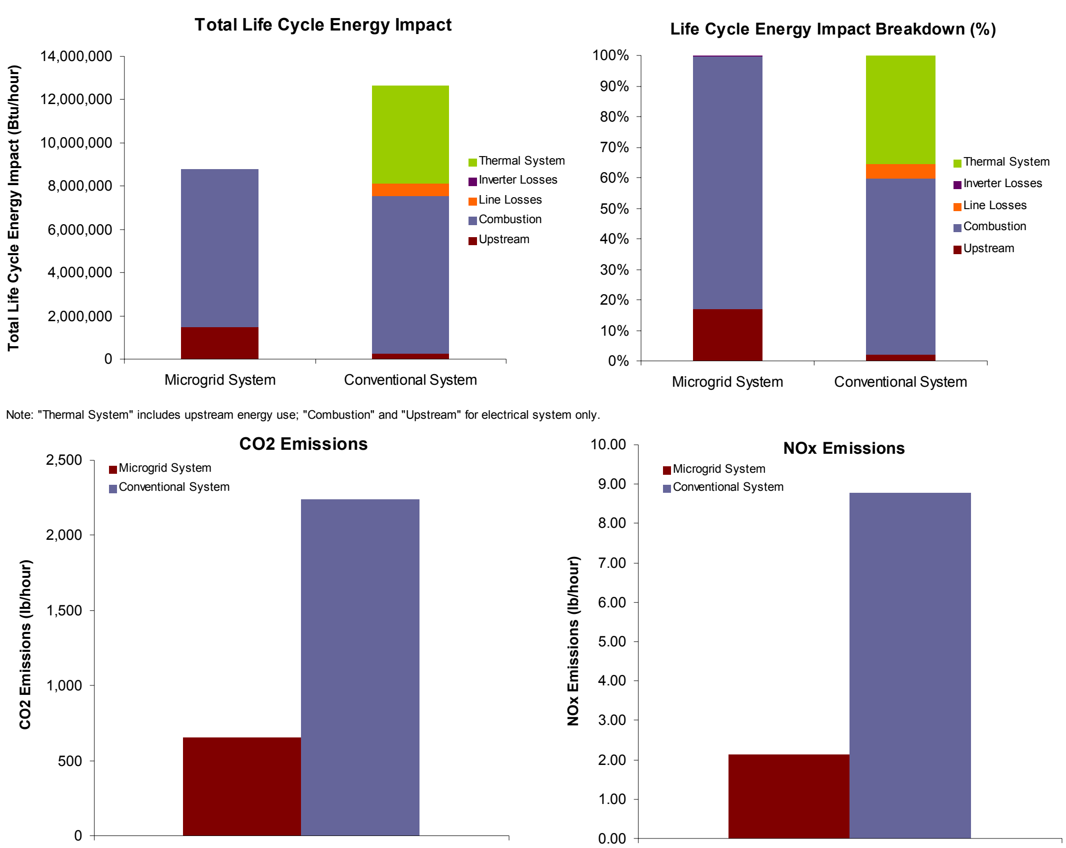
## ***Scenario 4: Turn off inefficient ENT 400 unit***

This scenario does not include the inefficient ENT 400 unit. Because the ENT 400 has an extremely low efficiency and a large capacity, it has a large negative influence on the life cycle energy use for the microgrid (compared to scenario 1(a)). This is a more likely operating scenario given that the ENT 400 will likely not be in operation very often due to its low efficiency (Michael Saldana, DTE, 2003).

**Table 4.7: Scenario 4—No ENT 400 Unit (Only Efficient Units)**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 246,149 | 451,203 | 697,352 | 1,483,387 |
| Total Combustion Energy Use | Btu/Hour | 7,291,784 | 4,057,327 | 11,349,110 | 7,267,733 |
| Total Line Losses Energy Use | Btu/Hour | 603,035 | 0 | 603,035 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 22,080 |
| Total Life Cycle Energy Use | Btu/Hour | 8,140,968 | 4,508,529 | **12,649,497** | **8,773,200** |
| Total NOx Emissions | lb/Hour | 6.85 | 1.92 | **8.77** | **2.12** |
| Total CO2 Emissions | lb/Hour | 1,772 | 468 | **2,240** | **653** |
| Total Electrical Energy Produced | kWh | | | | 692 |
| Total Heat Energy Produced | Btu | | | | 3,042,995 |
| Microgrid System Efficiency | % | | | | 61.6% |
| Conventional System Efficiency | % | | | | 42.7% |

**Figure 4.7: Scenario 4—No ENT 400 Unit (Only Efficient Units)**



As expected, the microgrid significantly outperforms the conventional system with respect to life cycle energy and environmental emissions when the ENT 400 unit is not operational. In all other scenarios except for scenario 3 and 2(b), without the ENT 400 unit running, the microgrid outperforms the conventional system for both sets of metrics.

**2. Distributed Generation Unit Analysis**

This section compares each individual distributed generation unit's performance to the conventional system when operating at 100% capacity for one hour (100% load factor). The results are useful for showing the relative performance of each unit separate from the entire microgrid system. In addition, the heat rate and emissions rates for $CO_2$ and $NO_x$ are compared to published data on similar units where available.

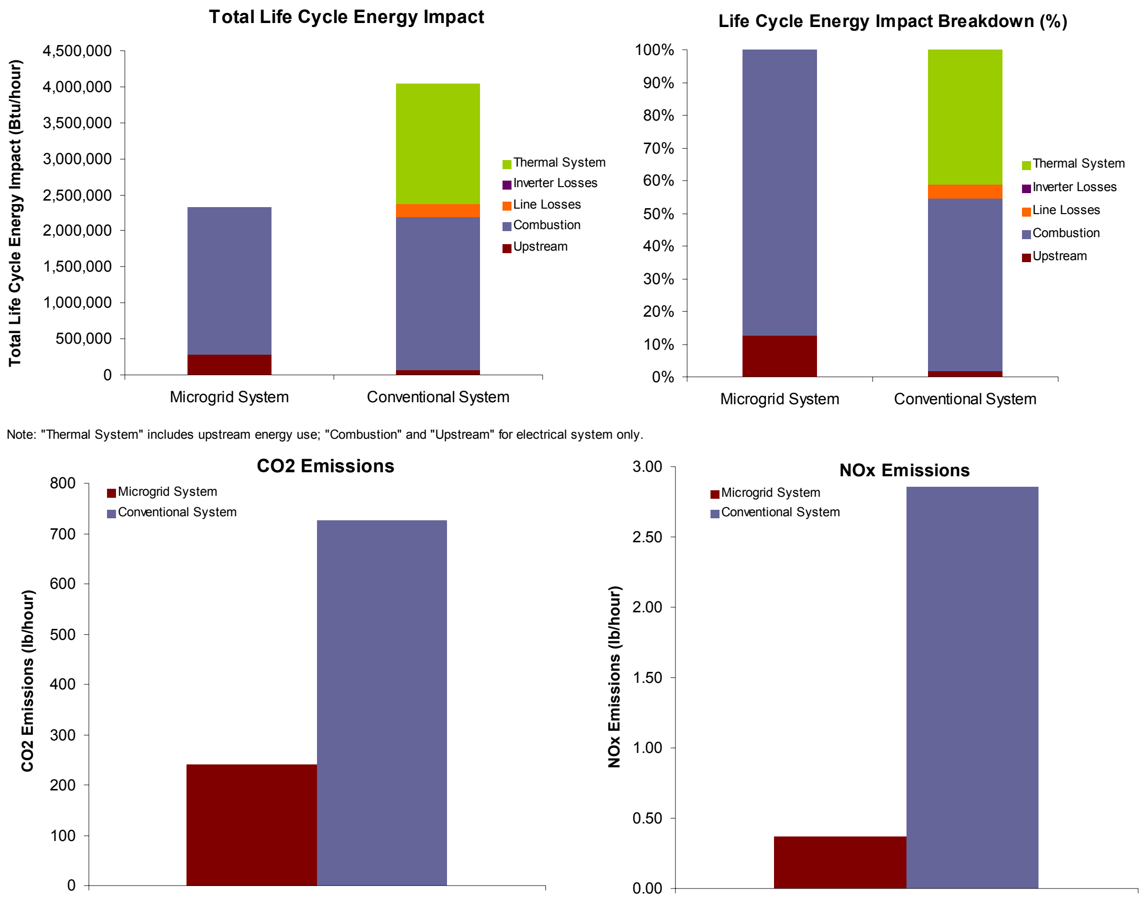
***ENE 210 EGR, NG***

The ENE 210 unit is an exhaust gas recirculation internal combustion running on natural gas. The results for the ENE 210 EGR unit are based on a 100% load factor with CHP turned on. At full capacity, the ENE 210 is 33% more efficient than the conventional system on a life cycle basis.

**Table 4.8: Life Cycle Performance of ENE 210 Unit**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 71,880 | 166,447 | 238,327 | 289,347 |
| Total Combustion Energy Use | Btu/Hour | 2,129,327 | 1,496,733 | 3,626,060 | 2,040,200 |
| Total Line Losses Energy Use | Btu/Hour | 176,097 | 0 | 176,097 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 0 |
| Total Life Cycle Energy Use | Btu/Hour | 2,377,303 | 1,663,180 | **4,040,483** | **2,329,547** |
| Total NOx Emissions | lb/Hour | 2.15 | 0.71 | **2.85** | **0.37** |
| Total CO2 Emissions | lb/Hour | 554 | 173 | **726** | **242** |
| Total Electrical Energy Produced | kWh | | | | 202 |
| Total Heat Energy Produced | Btu | | | | 1,122,550 |
| Microgrid System Efficiency | % | | | | 77.8% |
| Conventional System Efficiency | % | | | | 44.8% |

**Figure 4.8: Life Cycle Performance of ENE 210 Unit**




The ENE 210 EGR input parameters are comparable with other published examples of natural gas IC engine technologies (note: none of these technologies specified the use of EGR).

**Table 4.9: ENE 210 Compared with Other Published Sources**

| | **Microgrid Model** | **Pepermans, Driesen et al.** | **Greene and Hammerschlag (2000)** |
|---|---|---|---|
| $CO_2$ (lb/kWh) | 1.2 | 1.1 – 1.4 | 0.95 – 1.2 |
| $NO_x$ (lb/kWh) | 0.0018 | 0.00044 – 0.0022 | 0.018 – 0.053 |
| Energy (comb.) (Btu/kWh) | 10,100 | 8,130 – 12,195 | 8,130 – 10,350 |

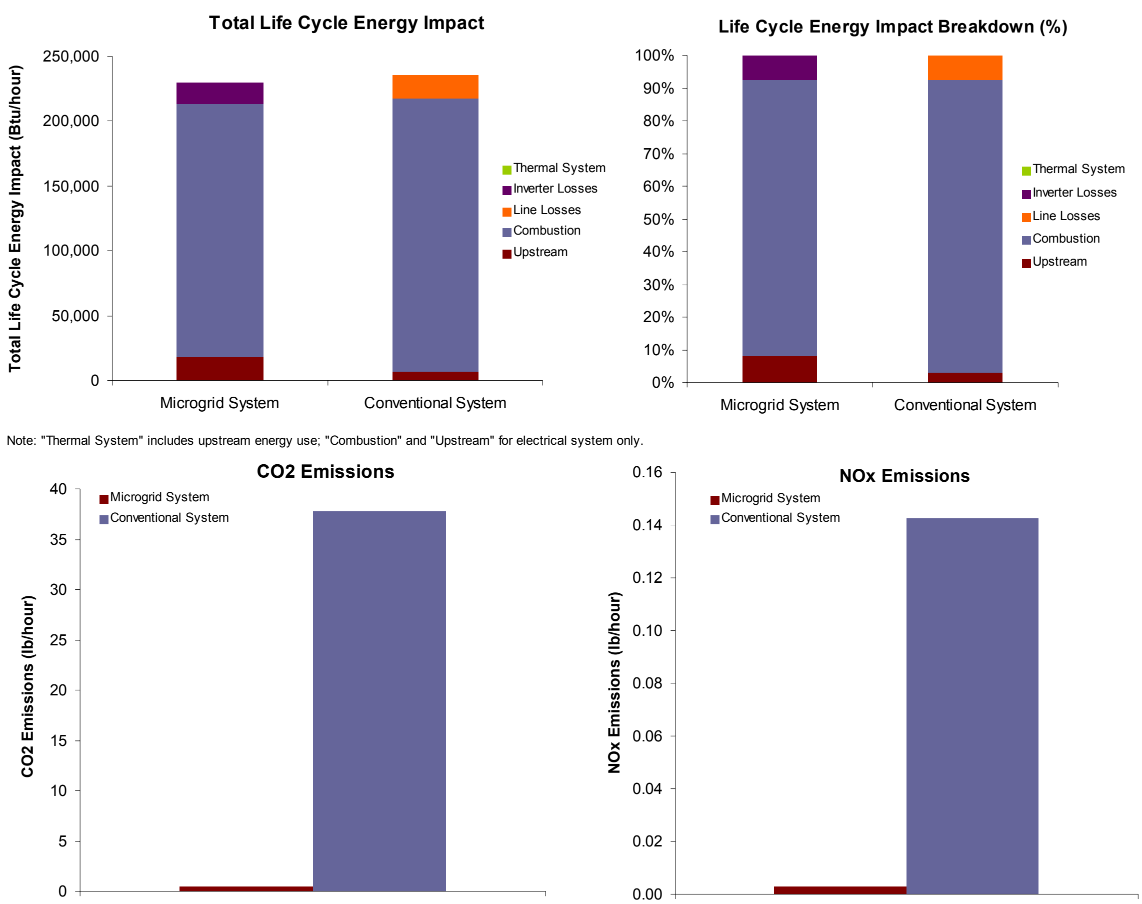
***ENF 7, H2***

The ENF 7 is a Proton Exchange Membrane (PEM) fuel cell running directly on hydrogen. The results are for four ENF 7 units based on a 100% load factor. At full capacity, the ENF 7 is slightly more efficient than the conventional system on a life cycle basis. The systems have comparable combustion energy uses, and the line loss energy use for the conventional system is approximately the same as the inverter loss energy use for the fuel cells.

**Table 4.10: Life Cycle Performance of ENF 7 Unit**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 7,117 | 0 | 7,117 | 18,416 |
| Total Combustion Energy Use | Btu/Hour | 210,824 | 0 | 210,824 | 194,400 |
| Total Line Losses Energy Use | Btu/Hour | 17,435 | 0 | 17,435 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 17,025 |
| Total Life Cycle Energy Use | Btu/Hour | 235,377 | 0 | **235,377** | **229,841** |
| Total NOx Emissions | lb/Hour | 0.14 | 0.00 | **0.14** | **0.00** |
| Total CO2 Emissions | lb/Hour | 38 | 0 | **38** | **0** |
| | | | | | |
| Total Electrical Energy Produced | kWh | | | | 20 |
| Total Heat Energy Produced | Btu | | | | 0 |
| Microgrid System Efficiency | % | | | | 29.7% |
| Conventional System Efficiency | % | | | | 29.0% |

**Figure 4.9: Life Cycle Performance of ENF 7 Unit**



The ENF 7 input parameters are comparable with other published examples of hydrogen fuel cell technologies.

**Table 4.11: ENF 7 Compared with Other Published Sources**

| | Microgrid Model | Pepermans, Driesen et al.* | Greene and Hammerschlag(Hammerschlag (2000)* |
|---|---|---|---|
| $CO_2$ (lb/kWh) | 0.10 | n/a | 0.8 – 1.4 |
| $NO_x$ (lb/kWh) | 0.0006 | $1.1x10^{-5} – 2.2x10^{-5}$ | $<5x10^{-5}$ |
| Energy (fuel) (Btu/kWh) | 9,720 | 9,756 | 6,829 – 11,775 |

* $H_2$ is from natural gas

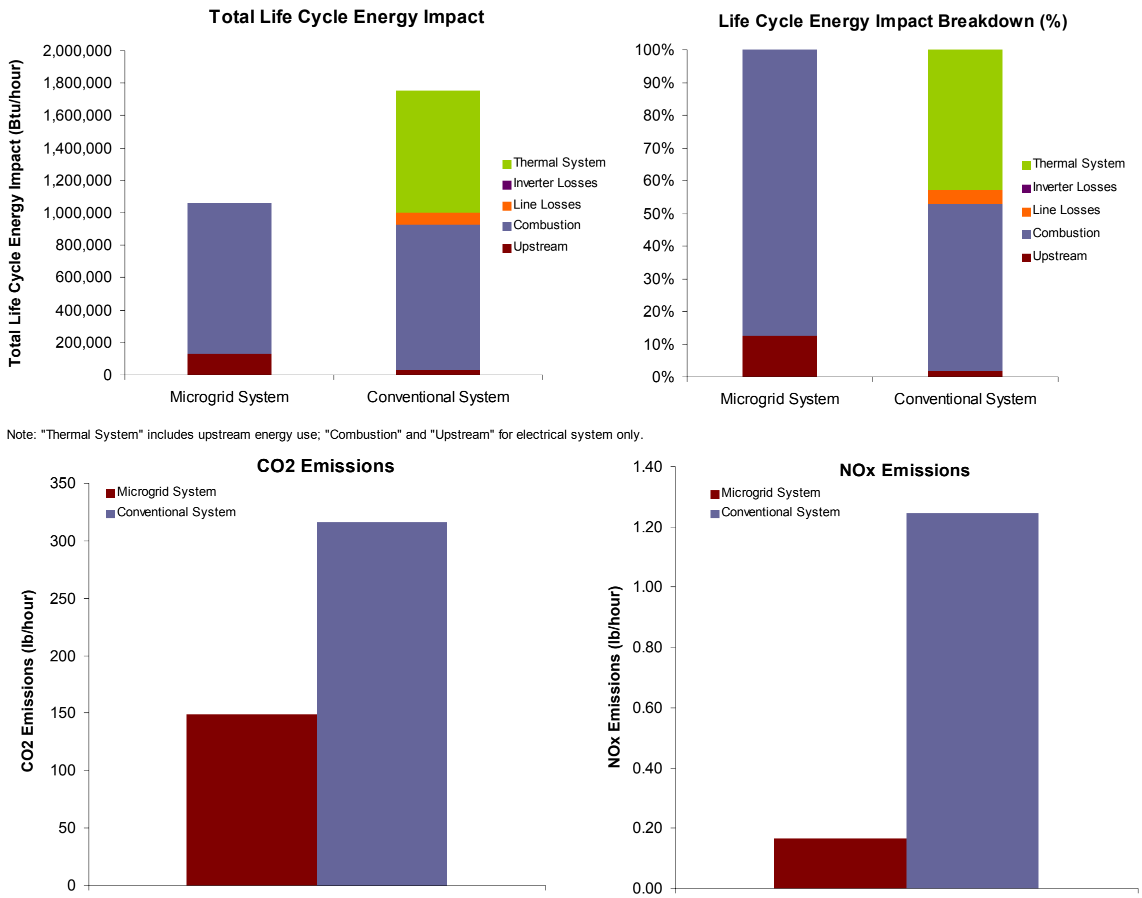
***ENI 85, NG***

The ENI 85 is an automotive derivative internal combustion running on natural gas. The results for the ENI 85 unit are based on a 100% load factor with CHP turned on. At full capacity, the ENI 85 is 29.5% more efficient than the conventional system on a life cycle basis.

**Table 4.12: Life Cycle Performance of ENI 85 Unit**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 30,246 | 75,185 | 105,431 | 133,128 |
| Total Combustion Energy Use | Btu/Hour | 896,004 | 676,080 | 1,572,084 | 929,475 |
| Total Line Losses Energy Use | Btu/Hour | 74,100 | 0 | 74,100 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 0 |
| Total Life Cycle Energy Use | Btu/Hour | 1,000,350 | 751,265 | **1,751,615** | **1,062,603** |
| Total NOx Emissions | lb/Hour | 0.93 | 0.32 | **1.24** | **0.17** |
| Total CO2 Emissions | lb/Hour | 238 | 78 | **316** | **148** |
| Total Electrical Energy Produced | kWh | | | | 85 |
| Total Heat Energy Produced | Btu | | | | 507,060 |
| Microgrid System Efficiency | % | | | | 75.0% |
| Conventional System Efficiency | % | | | | 45.5% |

## Figure 4.10: Life Cycle Performance of ENI 85 Unit




The ENI 85 input parameters are comparable with other published examples of automotive derivative engines. However, the $CO_2$ emission rate is slightly higher than other sources.

**Table 4.13: ENI 85 Compared with Other Published Sources**

| | Microgrid Model | Pepermans, Driesen et al. | Greene and Hammerschlag (2000) |
|---|---|---|---|
| $CO_2$ (lb/kWh) | 1.75 | 1.1 – 1.4 | 0.95 – 1.2 |
| $NO_x$ (lb/kWh) | 0.0019 | 0.00044 – 0.0022 | 0.018 – 0.053 |
| Energy (comb.) (Btu/kWh) | 10,935 | 8,130 – 12,195 | 8,130 – 10,350 |

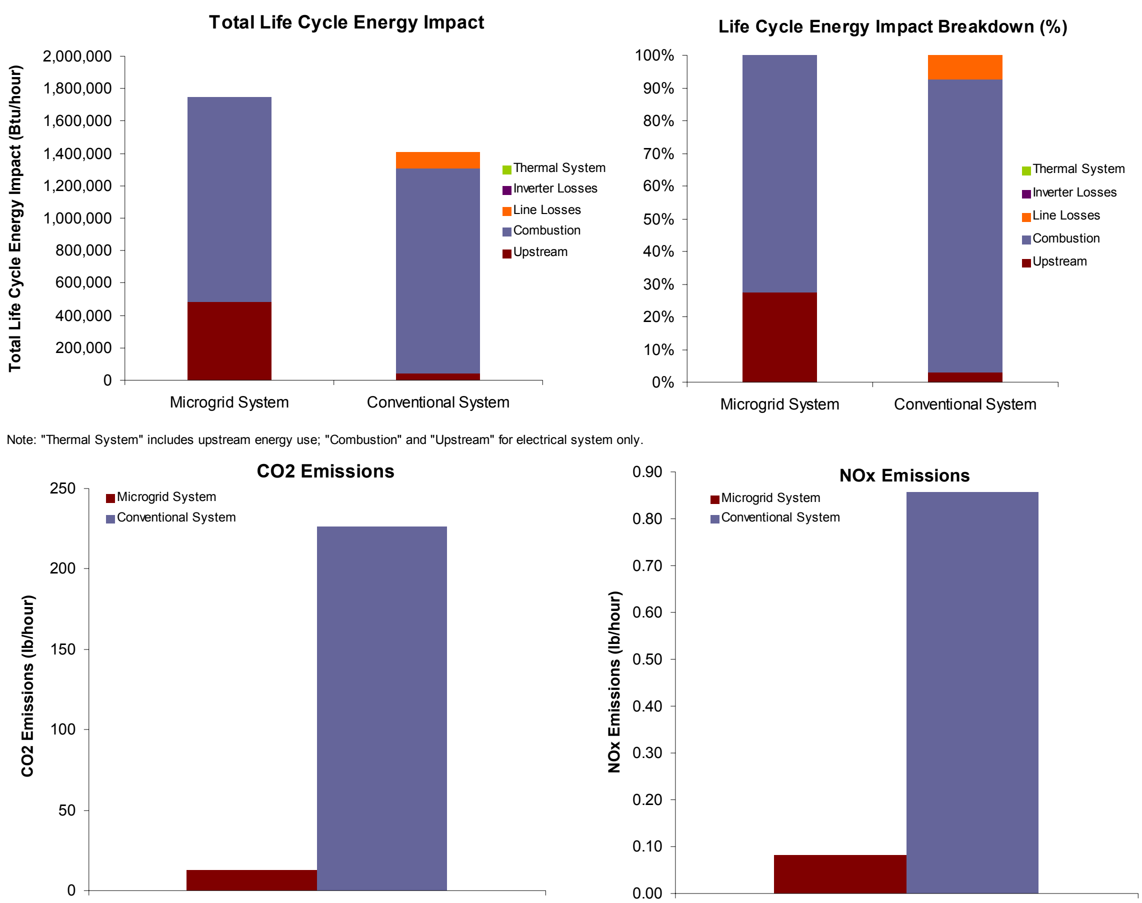
***Stuart IC, H2***

The Stuart IC is an automotive derivative internal combustion running on hydrogen. The results for the Stuart IC unit are based on a 100% load factor. At full capacity, the conventional system is 5.6% more efficient than the Stuart IC on a life cycle basis. Most of the impact from the Stuart IC is due to the large upstream energy use from hydrogen reformation.

**Table 4.14: Life Cycle Performance of Stuart IC Unit**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 42,701 | 0 | 42,701 | 480,860 |
| Total Combustion Energy Use | Btu/Hour | 1,264,946 | 0 | 1,264,946 | 1,269,000 |
| Total Line Losses Energy Use | Btu/Hour | 104,612 | 0 | 104,612 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 0 |
| Total Life Cycle Energy Use | Btu/Hour | 1,412,259 | 0 | **1,412,259** | **1,749,860** |
| Total NOx Emissions | lb/Hour | 0.86 | 0.00 | **0.86** | **0.08** |
| Total CO2 Emissions | lb/Hour | 226 | 0 | **226** | **13** |
| Total Electrical Energy Produced | kWh | | | | 120 |
| Total Heat Energy Produced | Btu | | | | 0 |
| Microgrid System Efficiency | % | | | | 23.4% |
| Conventional System Efficiency | % | | | | 29.0% |

**Figure 4.11: Life Cycle Performance of Stuart IC Unit**




Due to a lack of available data, microgrid model results for this technology were not compared to other published examples IC engines run on hydrogen for the generation of electricity

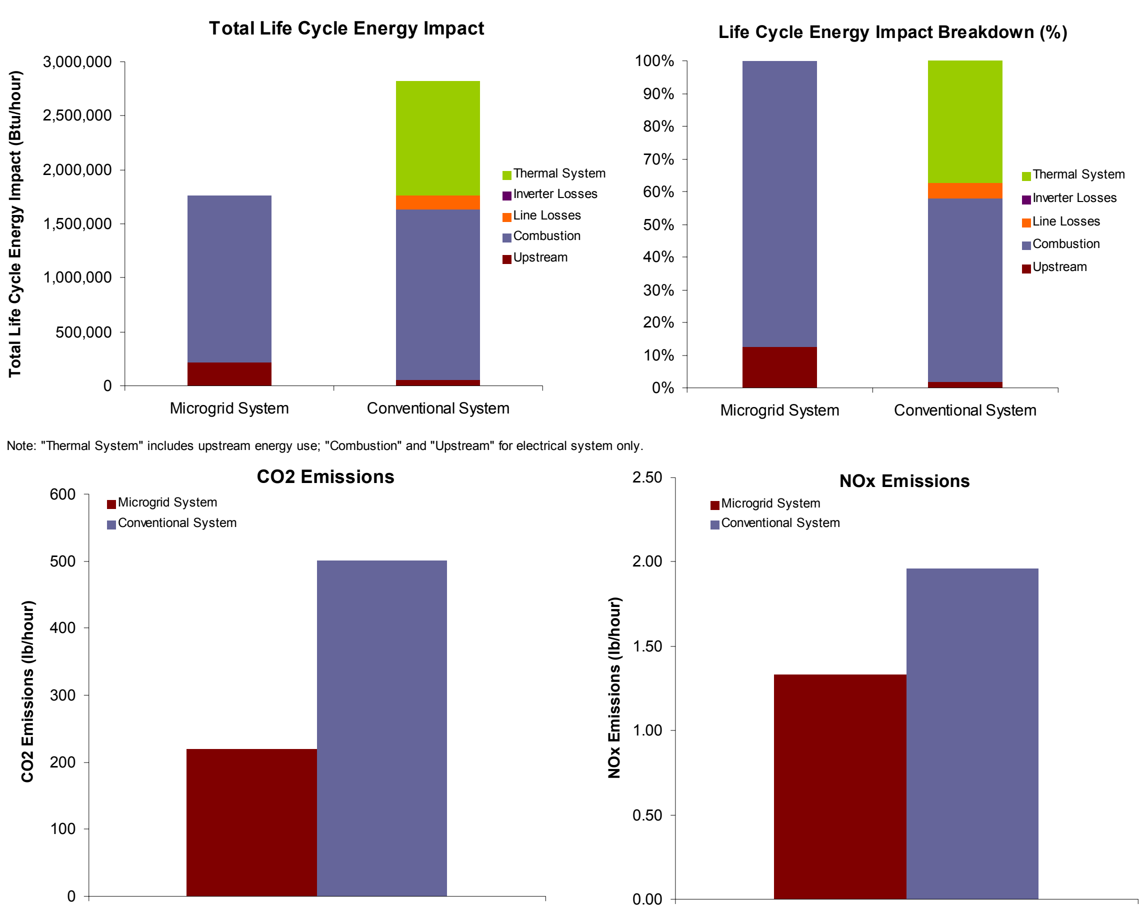
## *ENI 150, NG*

The ENI 150 is an automotive derivative internal combustion running on natural gas. The results for the ENI 150 unit are based on a 100% load factor with CHP turned on. At full capacity, the ENI 150 is 25.8% more efficient than the conventional system on a life cycle basis.

### Table 4.15: Life Cycle Performance of ENI 150 Unit

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 53,376 | 105,151 | 158,527 | 219,042 |
| Total Combustion Energy Use | Btu/Hour | 1,581,183 | 945,540 | 2,526,723 | 1,545,000 |
| Total Line Losses Energy Use | Btu/Hour | 130,765 | 0 | 130,765 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 0 |
| Total Life Cycle Energy Use | Btu/Hour | 1,765,324 | 1,050,691 | **2,816,014** | **1,764,042** |
| Total NOx Emissions | lb/Hour | 1.52 | 0.45 | **1.96** | **1.33** |
| Total CO2 Emissions | lb/Hour | 392 | 109 | **501** | **220** |
| Total Electrical Energy Produced | kWh | | | | 150 |
| Total Heat Energy Produced | Btu | | | | 709,155 |
| Microgrid System Efficiency | % | | | | 69.2% |
| Conventional System Efficiency | % | | | | 43.4% |

### Figure 4.12: Life Cycle Performance of ENI 150 Unit



The ENI 150 input parameters are comparable with other published examples of automotive derivative engines (note: published sources exclude upstream data and are expected to slightly underestimate emissions):

**Table 4.16: ENI 150 Compared with Other Published Sources**

| | Microgrid Model | Pepermans, Driesen et al. | Greene and Hammerschlag (2000) |
|---|---|---|---|
| $CO_2$ (lb/kWh) | 1.47 | 1.1 – 1.4 | 0.95 – 1.2 |
| $NO_x$ (lb/kWh) | 0.0089 | 0.00044 – 0.0022 | 0.018 – 0.053 |
| Energy (comb.) (Btu/kWh) | 10,300 | 8,130 – 12,195 | 8,130 – 10,350 |

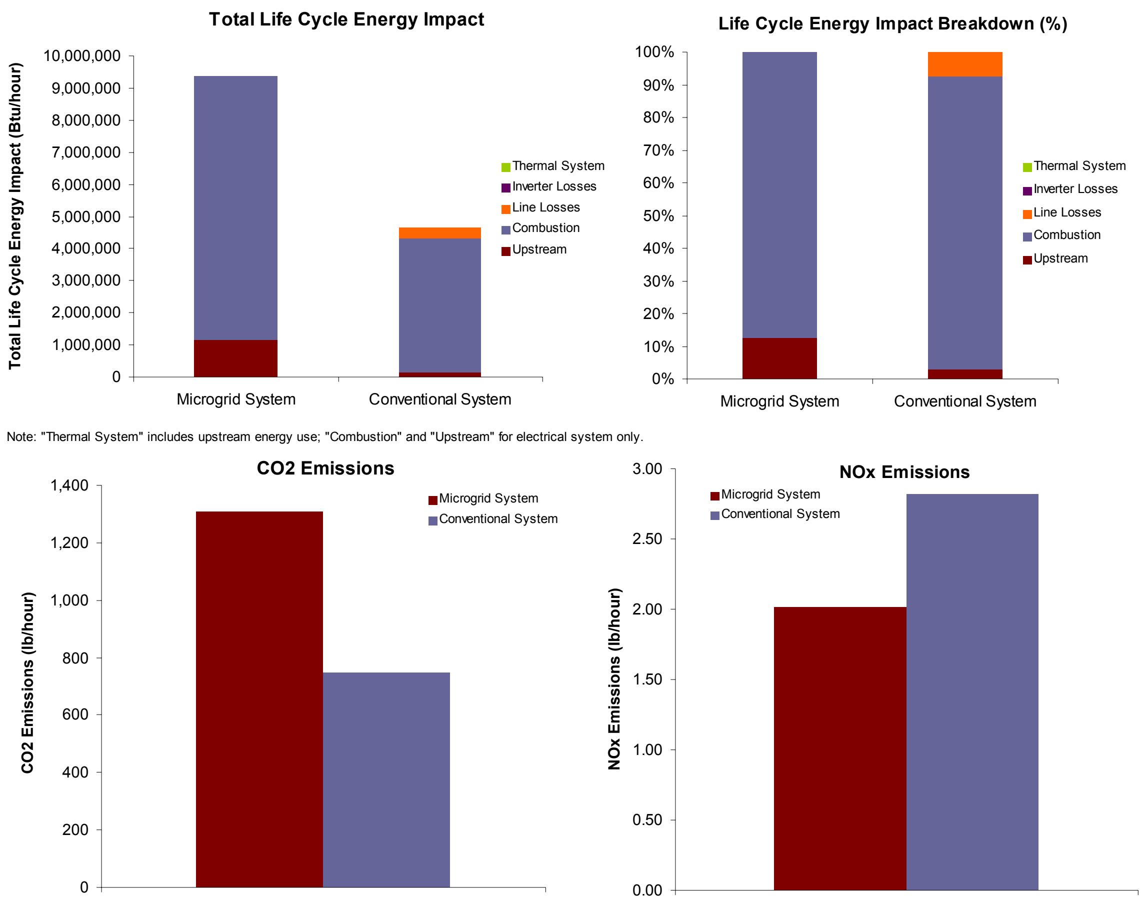
***ENT 400, NG***

The ENT 400 is a miniturbine running on natural gas. The results for the ENT 400 unit are based on a 100% load factor. At full capacity, the conventional system is 14.6% more efficient than the ENT 400 on a life cycle basis. This poor life cycle performance severely affects the performance of the entire microgrid when this unit is running because of the low efficiency and large capacity of the unit.

**Table 4.17: Life Cycle Performance of ENT 400 Unit**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 140,913 | 0 | 140,913 | 1,164,096 |
| Total Combustion Energy Use | Btu/Hour | 4,174,323 | 0 | 4,174,323 | 8,197,200 |
| Total Line Losses Energy Use | Btu/Hour | 345,219 | 0 | 345,219 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 0 |
| Total Life Cycle Energy Use | Btu/Hour | 4,660,455 | 0 | **4,660,455** | **9,361,296** |
| Total NOx Emissions | lb/Hour | 2.82 | 0.00 | **2.82** | **2.02** |
| Total CO2 Emissions | lb/Hour | 747 | 0 | **747** | **1,307** |
| Total Electrical Energy Produced | kWh | | | | 396 |
| Total Heat Energy Produced | Btu | | | | 0 |
| Microgrid System Efficiency | % | | | | 14.4% |
| Conventional System Efficiency | % | | | | 29.0% |

**Figure 4.13: Life Cycle Performance of the ENT 400 Unit**




The ENT 400 input parameters are comparable with other published examples of natural gas microturbine technologies. This may not be an error given that the ENT unit is a prototype, resulting in greater inefficiencies.

**Table 4.18: ENT 400 Compared with Other Published Sources**

| | **Microgrid Model** | **Pepermans, Driesen et al.** | **Greene and Hammerschlag (2000)** |
|---|---|---|---|
| $CO_2$ (lb/kWh) | 3.3 | 1.6 | 1.3 – 1.8 |
| $NO_x$ (lb/kWh) | 0.0051 | 0.00022 | 0.0002 – 0.0014 |
| Energy (comb.) (Btu/kWh) | 20,700 | 11,382 – 13,659 | 11,382 – 15,521 |

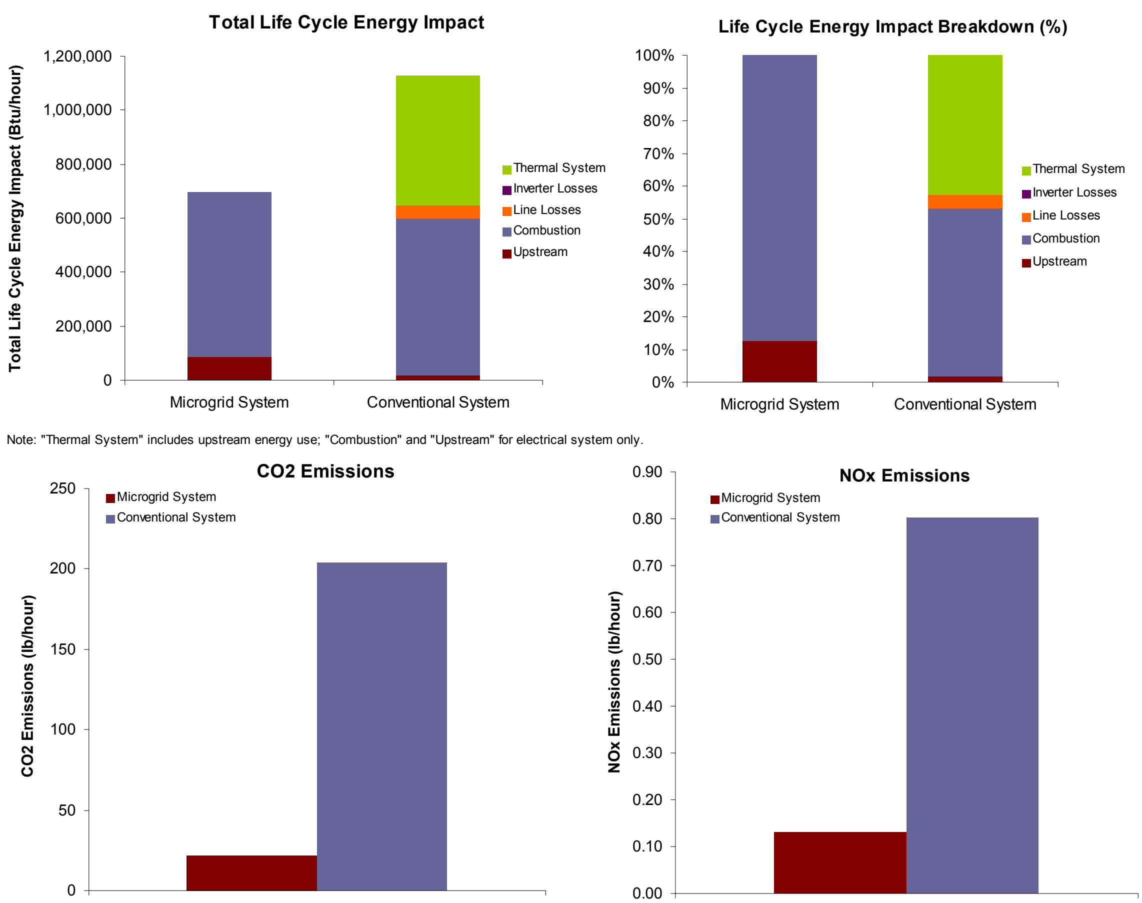
***ENX 55, NG***

The ENX 55 is an external combustion (Stirling Cycle) engine running on natural gas. The results for the ENX 55 (NG) unit are based on a 100% load factor with CHP turned on. At full capacity, the ENX 55 (NG) unit is 28.1% more efficient than the conventional system on a life cycle basis.

**Table 4.19: Life Cycle Performance of ENX 55 (NG) Unit**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 19,571 | 48,173 | 67,745 | 86,817 |
| Total Combustion Energy Use | Btu/Hour | 579,767 | 433,187 | 1,012,954 | 610,500 |
| Total Line Losses Energy Use | Btu/Hour | 47,947 | 0 | 47,947 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 0 |
| Total Life Cycle Energy Use | Btu/Hour | 647,285 | 481,360 | **1,128,645** | **697,317** |
| | | | | | |
| Total NOx Emissions | lb/Hour | 0.60 | 0.20 | **0.80** | **0.13** |
| Total CO2 Emissions | lb/Hour | 154 | 50 | **204** | **22** |
| | | | | | |
| Total Electrical Energy Produced | kWh | | | | 55 |
| Total Heat Energy Produced | Btu | | | | 324,890 |
| Microgrid System Efficiency | % | | | | 73.5% |
| Conventional System Efficiency | % | | | | 45.4% |

**Figure 4.14: Life Cycle Performance of the ENX 55 (NG) Unit**




No comparable data sources were available for external combustion engines used to generate electricity, however, several observations can be made based on model calculations. Current efficiency level (31%, 11,100 Btu/kWh) is comparable to other natural gas engine technologies. However, emission levels for $CO_2$ are noticeably lower than expected. The Microgrid model uses 0.40 lbs $CO_2$/kWh (based on data from spec sheets), but a carbon balance analysis suggests a conservative estimate for the emission rate should be approximately 1.18 lbs $CO_2$/kWh. This discrepancy needs to be investigated further.

**Table 4.20: Carbon Balance for ENX 55 Unit**

**Carbon Balance for ENX 55 Unit**

| | | |
|---|---|---|
| **Natural Gas (NG) Input** | | |
| Heat Input Rate | 11,100 | btu/kWh |
| Heating Value for NG | 23,032 | btu/lb |
| Mass Input Rate for NG | 0.482 | lb NG/kWh |
| | | |
| **Carbon (C) Input** | | |
| Weight Percentage C in NG | 74% | |
| Mass Input Rate for C | 0.357 | lb C/kWh |
| | | |
| **Carbon Output** | | |
| Carbon Monoxide (CO) Emission Rate | 0.0010 | lb CO/kWh |
| Weight Percentage C Emitted as Hydrocarbon | 10% | Weight % C emitted as HC |
| | | |
| Carbon Output as CO | 0.0004 | lb C in CO/kWh |
| Carbon Output as HC | 0.0357 | lb C in HC/kWh |
| | | |
| Carbon Remainder | 0.321 | lb C availble for CO2/kWh |
| | | |
| ***Expected CO2 Emissions*** | ***1.18*** | ***lb CO2/kWh*** |

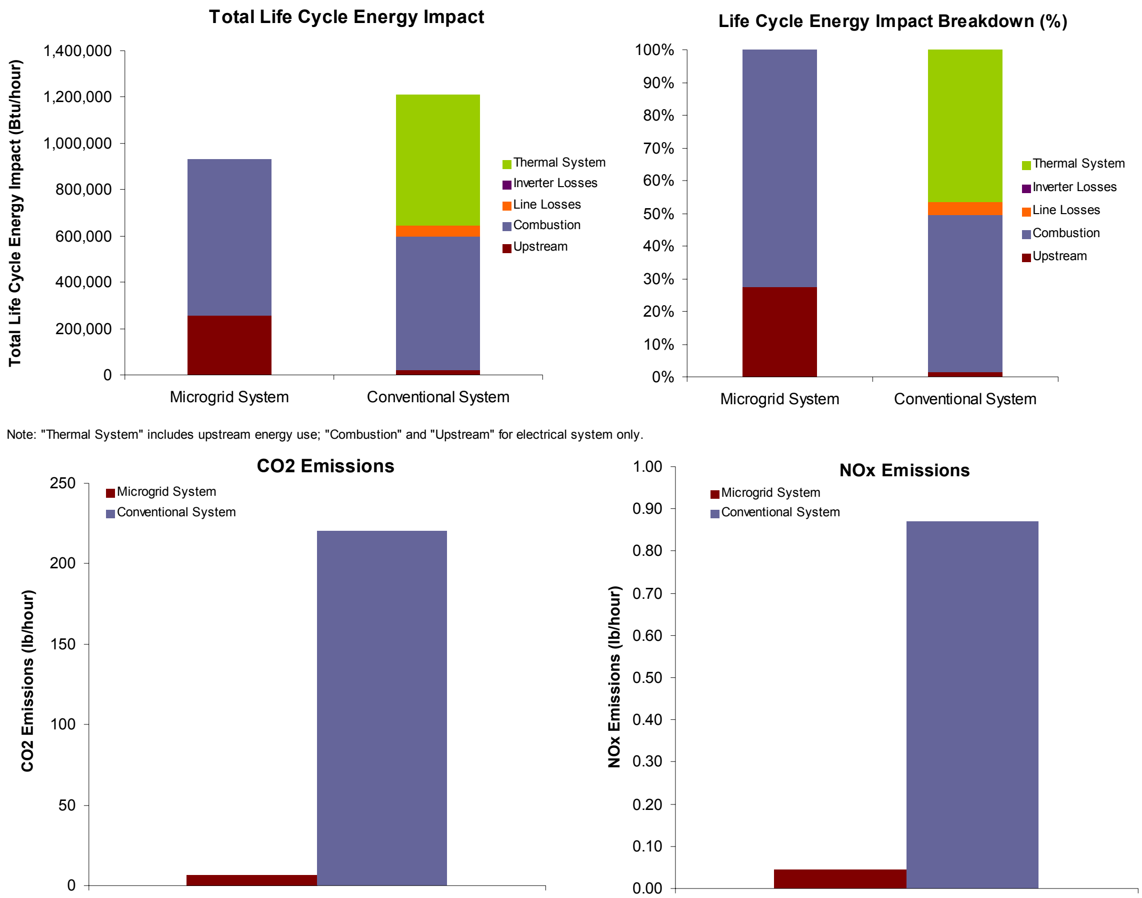
***<u>ENX 55, H2</u>***

The ENX 55 is an external combustion (Stirling Cycle) engine running on hydrogen. The results for the ENX 55 (H2) unit are based on a 100% load factor with CHP turned on. At full capacity, the ENX 55 (H2) unit is 14% more efficient than the conventional system on a life cycle basis.

**Table 4.21: Life Cycle Performance of the ENX 55 (H2) Unit**

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 19,571 | 56,247 | 75,818 | 255,777 |
| Total Combustion Energy Use | Btu/Hour | 579,767 | 505,787 | 1,085,554 | 675,000 |
| Total Line Losses Energy Use | Btu/Hour | 47,947 | 0 | 47,947 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 0 |
| Total Life Cycle Energy Use | Btu/Hour | 647,285 | 562,034 | **1,209,319** | **930,777** |
| Total NOx Emissions | lb/Hour | 0.63 | 0.24 | **0.87** | **0.04** |
| Total CO2 Emissions | lb/Hour | 162 | 58 | **220** | **7** |
| Total Electrical Energy Produced | kWh | | | | 55 |
| Total Heat Energy Produced | Btu | | | | 379,340 |
| Microgrid System Efficiency | % | | | | 60.9% |
| Conventional System Efficiency | % | | | | 46.9% |

**Figure 4.15: Life Cycle Performance of the ENX 55 (H2) Unit**




No comparable data sources were available for external combustion engines used to generate electricity but the model is consistent with expected behavior.

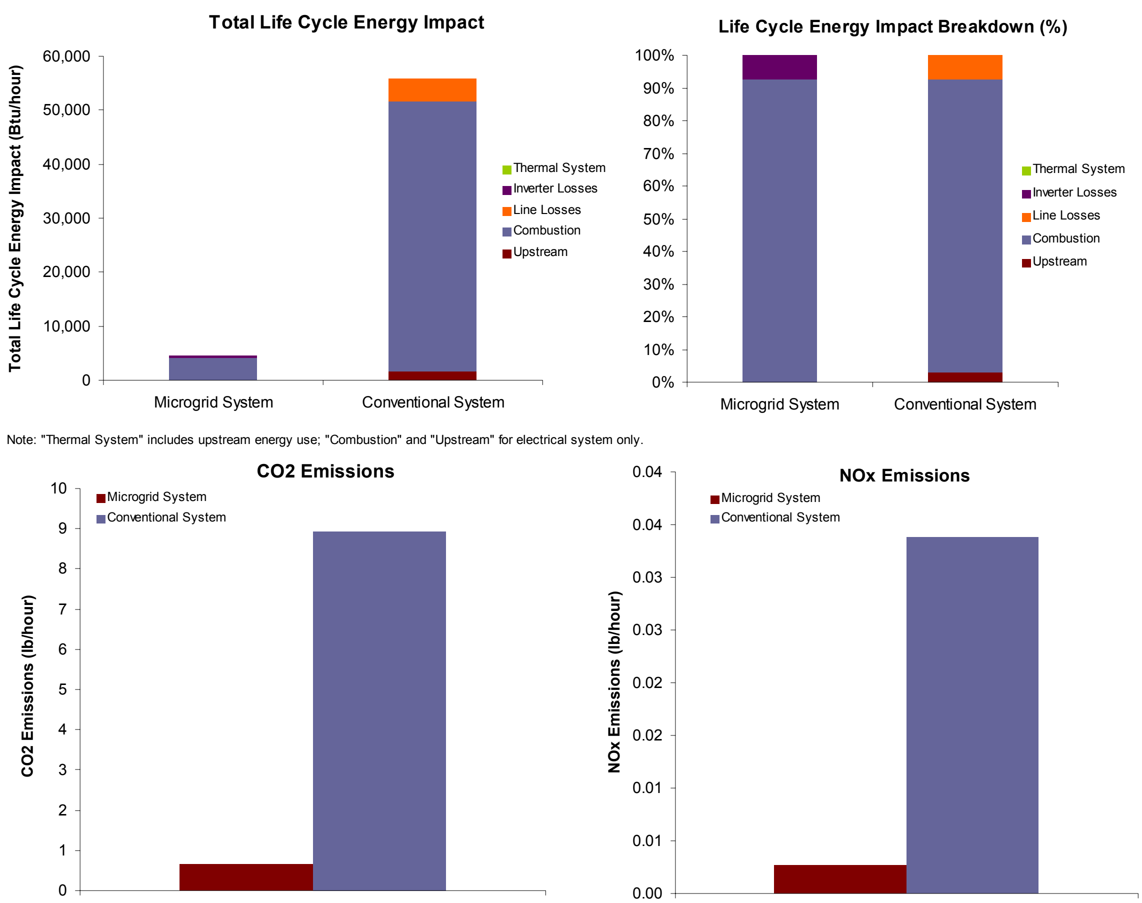
***<u>Unisolar, Sun</u>***

The results for the Unisolar PV array are based on a 16% load factor. Because the sunlight is "free" (solar energy) and the only energy accounted for in the analysis is the energy to make the device, the efficiency is over 100% (more energy output than energy input; this energy input excludes the solar energy input during operation). Therefore, the upstream, energy for the PV system is zero. The manufacturing energy is recorded as "combustion" energy in the model outputs for accounting purposes. This convention is unique to the PV system.

## Table 4.22: Life Cycle Performance of the Unisolar PV Array

| Life Cycle Metric | Unit | Conventional System | | | Microgrid System |
|---|---|---|---|---|---|
| | | Grid Electricity | Thermal | Total | |
| Total Upstream Energy Use | Btu/Hour | 1,687 | 0 | 1,687 | 0 |
| Total Combustion Energy Use | Btu/Hour | 49,965 | 0 | 49,965 | 4,158 |
| Total Line Losses Energy Use | Btu/Hour | 4,132 | 0 | 4,132 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 333 |
| Total Life Cycle Energy Use | Btu/Hour | 55,784 | 0 | **55,784** | **4,490** |
| Total NOx Emissions | lb/Hour | 0.03 | 0.00 | **0.03** | **0.00** |
| Total CO2 Emissions | lb/Hour | 9 | 0 | **9** | **1** |
| Total Electrical Energy Produced | kWh | | | | 5 |
| Total Heat Energy Produced | Btu | | | | 0 |
| Microgrid System Efficiency | % | | | | 360.2% |
| Conventional System Efficiency | % | | | | 29.0% |

## Figure 4.16: Life Cycle Performance of the Unisolar PV Array




The Microgrid model results are based on research at the Center for Sustainable Systems at the University of Michigan for PV arrays in Southeast, MI. This data has been compared to other published sources (Spitzley and Keoleian, 2004).

## V. Key Findings

The model results indicate that different specified operating conditions of the microgrid affect its relative life cycle performance compared to the conventional system. System efficiencies are presented to compare the complete life cycle performance between the two systems. Thermal energy and heat energy are combined in order to provide a normalized basis for comparison and the efficiency of each system is based on the total energy output of the system (Btu) divided by the life cycle input into the system (Btu). Although heat and electricity have different thermodynamic qualities, this technique is useful for comparing the relative performance of the two systems. Tables 5.1 through 5.4 summarize the results for both the system and unit-by-unit analyses in the report.

**Table 5.1: Summary of Total Life Cycle Energy and Emissions from Analyzed Scenarios**

| Scenario | Life Cycle Energy Use: Microgrid System (Btu/hour) | Life Cycle Energy Use: Conventional System (Btu/hour) | Life Cycle Emissions: Microgrid System (lb/hour) | Life Cycle Emissions: Conventional System (lb/hour) |
|---|---|---|---|---|
| 1(a). All units run at 100% capacity | 18,100,000 | 17,300,000 | $NO_x$: 4.14<br>$CO_2$: 1,960 | $NO_x$: 11.60<br>$CO_2$: 2,980 |
| 1(b). Meet expected building load | 367,000 | 400,000 | $NO_x$: 0.09<br>$CO_2$: 40 | $NO_x$: 0.26<br>$CO_2$: 69 |
| 1(c). Meet double expected building load | 910,000 | 918,000 | $NO_x$: 0.21<br>$CO_2$: 99 | $NO_x$: 0.61<br>$CO_2$: 158 |
| 2(a). Only NG units | 15,200,000 | 14,300,000 | $NO_x$: 4.01<br>$CO_2$: 1,930 | $NO_x$: 9.69<br>$CO_2$: 2,490 |
| 2(b). Only H2 units | 2,910,000 | 2,850,000 | $NO_x$: 0.13<br>$CO_2$: 20 | $NO_x$: 1.87<br>$CO_2$: 484 |
| 3. No CHP | 18,100,000 | 12,800,000 | $NO_x$: 4.14<br>$CO_2$: 1,960 | $NO_x$: 7.75<br>$CO_2$: 2,050 |
| 4. W/out ENT 400 unit | 8,770,000 | 12,600,000 | $NO_x$: 2.12<br>$CO_2$: 653 | $NO_x$: 8.77<br>$CO_2$: 2,240 |

**Table 5.2: Summary System Efficiencies and Life Cycle Performance**

| Scenario | Microgrid System Efficiency | Conventional System Efficiency | Life Cycle Energy Savings* | Life Cycle Emissions Reduction |
|---|---|---|---|---|
| 1(a). All units run at 100% capacity | 37.2% | 39.0% | -4.8% | $NO_x$: 64%<br>$CO_2$: 34% |
| 1(b). Meet expected building load | 41.1% | 37.7% | 8.3% | $NO_x$: 65%<br>$CO_2$: 42% |
| 1(c). Meet double expected building load | 38.8% | 38.4% | 1.0% | $NO_x$: 66%<br>$CO_2$: 37% |
| 2(a). Only NG units | 37.4% | 39.5% | -5.6% | $NO_x$: 59%<br>$CO_2$: 22% |
| 2(b). Only H2 units | 35.8% | 36.6% | -2.2% | $NO_x$: 93%<br>$CO_2$: 96% |
| 3. No CHP | 20.5% | 29.0% | -41.5% | $NO_x$: 47%<br>$CO_2$: 4% |
| 4. W/out ENT 400 unit | 61.6% | 42.7% | 30.7% | $NO_x$: 76%<br>$CO_2$: 71% |

*Life cycle energy use for conventional system– life cycle energy use for microgrid system divided by life cycle energy use for conventional system

**Table 5.3: Summary of Total Life Cycle Energy and Emissions from Unit-by-Unit Analyses**

| Unit | Life Cycle Energy Use: DG Unit (Btu/hour) | Life Cycle Energy Use: Conventional System (Btu/hour) | Life Cycle Emissions: DG Unit (lb/hour) | Life Cycle Emissions: Conventional System (lb/hour) |
|---|---|---|---|---|
| ENE-210 | 2,320,000 | 4,040,000 | $NO_x$: 0.37<br>$CO_2$: 242 | $NO_x$: 2.85<br>$CO_2$: 726 |
| ENF-7 (4) | 229,000 | 235,000 | $NO_x$: 0.0<br>$CO_2$: 0.0 | $NO_x$: 0.40<br>$CO_2$: 38 |
| ENI-85 | 1,060,000 | 1,750,000 | $NO_x$: 0.17<br>$CO_2$: 148 | $NO_x$: 1.24<br>$CO_2$: 316 |
| Stuart IC | 1,740,000 | 1,410,000 | $NO_x$: 0.08<br>$CO_2$: 13 | $NO_x$: 0.86<br>$CO_2$: 226 |
| ENI-150 | 1,760,000 | 2,810,000 | $NO_x$: 1.33<br>$CO_2$: 220 | $NO_x$: 1.96<br>$CO_2$: 501 |
| ENT-400 | 9,360,000 | 4,660,000 | $NO_x$: 2.02<br>$CO_2$: 1,300 | $NO_x$: 2.82<br>$CO_2$: 747 |
| ENX-55 (NG) | 697,000 | 1,120,000 | $NO_x$: 0.13<br>$CO_2$: 22 | $NO_x$: 0.80<br>$CO_2$: 204 |
| ENX-55 (H2) | 930,000 | 1,200,000 | $NO_x$: 0.04<br>$CO_2$: 7 | $NO_x$: 0.87<br>$CO_2$: 220 |
| Unisolar | 4,490 | 55,000 | $NO_x$: 0<br>$CO_2$: 1 | $NO_x$: 0.03<br>$CO_2$: 9 |

**Table 5.4: Summary Unit Efficiencies and Life Cycle Performance**

| DG Unit | DG Unit Efficiency | Conventional System Efficiency | Life Cycle Energy Savings | Life Cycle Emissions Reduction |
|---|---|---|---|---|
| ENE-210 | 77.8% | 44.8% | 42.4% | $NO_x$: 87%<br>$CO_2$: 67% |
| ENF-7 (4) | 29.7% | 29.0% | 2.4% | $NO_x$: 100%<br>$CO_2$: 100% |
| ENI-85 | 75.0% | 45.5% | 39.3% | $NO_x$: 86%<br>$CO_2$: 53% |
| Stuart IC | 23.4% | 29.0% | -23.9% | $NO_x$: 91%<br>$CO_2$: 94% |
| ENI-150 | 69.2% | 43.3% | 37.4% | $NO_x$: 32%<br>$CO_2$: 56% |
| ENT-400 | 14.4% | 29.0% | -101.4% | $NO_x$: 28%<br>$CO_2$: -74% |
| ENX-55 (NG) | 73.5% | 45.5% | 38.1% | $NO_x$: 84%<br>$CO_2$: 89% |
| ENX-55 (H2) | 60.9% | 46.9% | 23.0% | $NO_x$: 95%<br>$CO_2$: 97% |
| Unisolar | 360.2% | 29.0% | 91.9% | $NO_x$: 100%<br>$CO_2$: 89% |

The following key findings can be reached from the above results:

- The microgrid system consumes slightly more life cycle energy (4.8%) than the conventional system when all units are run at 100% capacity. However, the microgrid outperforms the conventional system with respect to life cycle energy use by the largest margin (30.7%) when the inefficient ENT 400 is turned off. The ENT 400 unit skews the overall microgrid results in all scenarios because of its large capacity (400 kW) and low efficiency (16%).
- The microgrid system provides a life cycle emissions reduction compared to the conventional system under all scenarios (47% to 93% reductions of $NO_x$ emissions and 4% to 96% reduction of $CO_2$ emissions for all scenarios analyzed). The microgrid system operates based on cleaner technologies and fuels than the conventional system.
- The microgrid performs the worst compared to the conventional system with respect to life cycle energy use when the combined heat and power capabilities for distributed generation units that have CHP options are turned off in the model (the microgrid consumes 41.5% more life cycle energy than the conventional system).
- Recovery of thermal energy for other productive uses significantly benefits the life cycle performance of the microgrid (the system efficiency is 37.2% with CHP compared to 20.5% when the CHP is turned off).
- The life cycle energy of the microgrid system is reduced with the avoidance of line losses from long distance transmission of power. Line losses for a conventional system typically account for 8% of the life cycle energy.
- On a unit-by-unit basis, all of the microgrid units outperform the conventional system with respect to life cycle energy use except the ENT 400 and the Stuart IC. The most efficient units from a life cycle perspective are the Unisolar PV array (360%) and the ENE-210 unit (77.8%).
- On a unit-by-unit basis all of the units outperform the conventional system with regard to $CO_2$ emissions except the ENT 400 unit and all of the units outperform the conventional system with regard to $NO_x$.
- In general, the microgrid system has a higher upstream energy use than the conventional system. The microgrid is fueled mainly by natural gas and hydrogen, which both require proportionately more upstream energy (e.g. extraction and reformation) than the main fuel that power the Detroit grid (e.g. coal and nuclear).
- The Unisolar PV array greatly outperforms the conventional system with respect to both life cycle energy use and environmental emissions, even when the energy required to build the solar array is factored into the calculations. This result suggests that based on LCA criteria, renewable energy sources should be encouraged to minimize energy and environmental impacts.

The life cycle microgrid model is the first step for evaluating the performance of the NextEnergy Microgrid Pavilion. Future research efforts should build on the model by adding a life cycle economic analysis to assess the relative economic performance of the microgrid and the conventional system. An additional analysis should incorporate all of the life cycle frameworks (energy, emissions, economics) to optimize system performance to determine what operating conditions result in the lowest possible life cycle impact.

## VI. Recommendations for Future Research

The model developed for this project is a useful tool for analyzing the energy and environmental performance of the NextEnergy microgrid but additional areas of research could enhance the model capabilities.

- Build an economic analysis into the life cycle study to better inform decisions makers about what technologies should be run to optimize performance compared to the conventional system.
- Create a GUI (graphical user interface) front to the model for display at the NextEnergy facility. An ideal GUI would include a touch-screen display where the user can specify different input options and see immediate output results.
- Build a Monte Carlo analysis into the model to run simulations on all possible combinations of scenarios where the microgrid outperforms the conventional system.
- Update the model with current input data for the microgrid and the generation mix of the Detroit grid.
- Build a new section of the model that calculates the life cycle hydrogen impact when the hydrogen is generated onsite.
- Build an optimization function into the model. A revised model should be designed to optimize on life cycle energy, economics, $NO_x$ emissions, or $CO_2$ emissions to meet at specified load.

## Appendix 1: Sources Referenced


Amos, Wade. (1998). "Costs of Storing and Transporting Hydrogen." National Renewable Energy Laboratory. TP-570-25106.

DTE Energy. http://www.dteenergy.com/community/environmental/fuelMix.html

Franklin Associates, a Service of McLaren/Hart/Jones, (2000) "Energy Requirements and Environmental Emissions for Fuel Consumption." pp.165-262

General Motors, Argonne National Lab, et al. (2001). Well-to-Wheel Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – North American Analysis.

Greene, N. and R. Hammerschlag (2000). "Small and Clean Is Beautiful: Exploring the Emissions of Distributed Generation and Pollution Prevention Policies." *The Electricity Journal* 13(5): 50-60.

Keoleian, G.A. and G. Lewis (2003). "Modeling the life cycle energy and environmental performance of amorphous silicon BIPV roofing in the US." *Renewable Energy*. Volume 28. pp. 271-293

Pepermans, G., J. Driesen, et al. "Distributed generation: definition, benefits and issues." *Energy Policy* In Press, Corrected Proof.

Perry, R. H. and D. Green, Eds. (1984). *Perry's Chemical Engineers' Handbook*. New York, McGraw-Hill.

Praxair, Inc. Personal communication.

Spitzley, D. V. and G. A. Keoleian (2004). Life Cycle Environmental and Economic Assessment of Willow Biomass Electricity: A Comparison with Other Renewable and Non-Renewable Sources. Ann Arbor, MI, Center for Sustainable Systems: 72.

## Appendix 2: Glossary

**Allocation:** partitioning the input or output flows of a unit process to the product system under study

**Biomass:** the total dry organic matter or stored energy content of living organisms that is present at a specific time in a defined unit of the Earth's surface

**Btu (British thermal unit):** a standard unit for measuring the quantity of heat energy equal to the quantity of heat required to raise the temperature of 1 pound of water by 1 degree Fahrenheit

**Cogeneration:** the process of generating electricity and using the waste low-quality heat for industrial, mechanical, cooling, or heating purposes

**Combined heat and power (CHP):** the production of electricity or mechanical power where the waste heat is recovered for process use

**Combustion energy:** the energy due to the combustion of these primary fuels by the customer, to produce electricity, to generate heat and power for industrial purposes, or to provide energy for transportation

**Combustion emissions:** the emissions due to the combustion of these primary fuels by the customer, to produce electricity, to generate heat and power for industrial purposes, or to provide energy for transportation

**Elementary flow:** 1) material or energy entering the system being studied, which has been drawn from the environment without previous human transformation, 2) material or energy leaving the system being studied, which is discarded into the environment without subsequent human transformation

**Energy carriers:** types of energy that can be transported, such as electricity, coal, and natural gas

**Fossil fuel:** any naturally occurring organic fuel, such as petroleum, natural gas, or coal

**Fossil fuel steam-electric power plant:** an electricity generation plant in which the prime mover is a turbine rotated by high-pressure steam produced in a boiler by heat from burning fossil fuels

**Fuel-related pre-combustion emissions:** the emissions associated with combustion activities to deliver the primary fuel to the main generation device (i.e. a motor that pumps natural gas through pipelines to a power plant)

**Fugitive emissions:** unintended leaks of gas from the processing, transmission, and/or transportation of fossil fuels

**Functional unit:** quantified performance of a product system for use as a reference unit in a life cycle assessment

**Heat rate:** a measure of efficiency; the ratio of fuel burned to net electricity generated

**Input:** material or energy that enters a unit process

**Life cycle:** consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to the final disposal

**Life cycle efficiency:** the ratio of total energy delivered to the total life cycle energy consumed

**Life cycle assessment (LCA):** compilation and evaluation of the inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle

**Life cycle impact assessment:** phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a system

**Life cycle interpretation:** phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistent with the defined goal and scope in order to reach conclusions and recommendations

**Life cycle inventory analysis:** phase of life cycle assessment involving the compilation and quantification of inputs and outputs, for a given product system throughout its life cycle

**Output:** material or energy that leaves a unit process

**Pre-combustion energy (upstream):** the energy requirements and environmental emissions, starting from the extraction of materials from the Earth, and ending with the delivery of the processed and refined fuels to the conversion device (i.e. power plant)

**Pre-combustion process emissions:** the process-related emissions not due to the combustion of fuel (i.e. natural gas vented at the wellhead or fugitive dusts)

**Primary resource energy:** the amount of energy embedded in a carrier when it is extracted from the Earth

**Product system:** collection of materially and energetically connected unit processes which performs one or more defined functions ("product" can also refer to service systems)

**System boundary:** interface between a product system and the environment or other product systems

**Total fuel cycle:** the total energy impact from a process including extraction of energy resources from the Earth, refining, transportation, combustion (or conversion), and delivery to the end customer (final energy)

**Unit process:** smallest portion of a product system for which data are collected when performing a life cycle assessment

# Appendix 3: E-mail Correspondence

***Correspondence with Michael Saldana from DTE Energy***

**November 26, 2003**

Scott,

I think between this response and the phone call later today, you should have everything you need to at least get started. Before I directly start answering your questions maybe an overview of the site and its operations is in order.

We are going to be installing a 1,107 kW Microgrid on the site. The Microgrid consists of generation assets located in a central Power Pavilion, the distribution backbone for power and thermal delivery to the NextEnergy facility and two future building connections (440 Burroughs, CJI) and the building interface to connect to NextEnergy. There are, of course, numerous support and ancillary systems for the Microgrid (fuel delivery, controls, grid parallel tie, etc) but I'm not sure you need all that detail quite yet.

The mix of generation assets is as follows:
- (4) ENF-7, 5kW, hydrogen, Proton Exchange Membrane (PEM) fuel cells.
- (1) ENX-55, 52kW, natural gas, external combustion (Stirling Cycle), induction genset.
- (1) ENX-55, 52kW, hydrogen, external combustion (Stirling Cycle), induction genset.
- (1) ENI-85, 85kW, natural gas, automotive derivative internal combustion, synchronous genset.
- (1) ENI-150, 150kW, natural gas, automotive derivative internal combustion, synchronous genset.
- (1) ENE-210, 202kW, natural gas, exhaust gas recirculation internal combustion, synchronous genset.
- (1) ENT-400, 396kW, natural gas, miniturbine, permanent magnet genset.
- (1) Stuart, 120kW, hydrogen, automotive derivative internal combustion, synchronous genset.
- (1) Unisolar, 30kW, thin-film, photovoltaic system.

From an operational standpoint there are several constraints that will ultimately limit the amount of runtime hours on any one unit. First, The Microgrid is designed with far more generation capability (1,107 kW) than the NextEnergy facility needs (250 kW peak demand). Second, There is also going to be a parallel, export connection made with Detroit Edison (DECo). Even though this connection will be export capable, the likelihood of DECo and NextEnergy signing a "sellback" agreement will be slim which means it will be in NextEnergy's best interest to keep this tie at net 0, no input or output. If they're not getting paid for it, there's no reason to give it to DECo for free. Conversely, since they have their own generation assets, there's no reason to buy power from DECo either. Third, the hydrogen tank storage will be limited on site to an amount roughly equal to run all of the hydrogen units listed above for approximately one day before the tank must be refueled. Fourth, most of the units we will be installing are pre-production models (betas, prototypes, etc) which means there will be some amount of misoperation to deal with as well as the simple fact that we may not want to run them for long hours or at full load to not to lighten the duty. Five, NextEnergy will be defining operational theme periods, such as "hydrogen day", "gas day", "fuel cell day", etc. All five of those constraints will result in relatively low hours for each unit, something like 1500-3000 hours per year and part load output more often than full load.

The last overview item that will effect your calculations is the use of thermal energy as well as electrical. The (2) ENXs, the ENI-85 and the ENI-150 are going to be applied in CHP (combined heat and power) mode. Each of these units are going to deliver hot water to a main header and that main header will in turn feed into a 100ton absorption chiller. From the Pavilion, the hot water and the chilled water will be fed to the facility for their use. Our thermal system is going to be supplemental only for the building which means they will only use what they need and we will only provide an amount based on which units happen to be running and at what part load.

With all the above in consideration here are the answers to your questions.

1) As stated in my unit list we are going to use three fuels, natural gas, hydrogen and solar. Find attached a zip file containing all of our unit spec sheets which will give you the amount of fuel each engine will use at full load. Don't forget to throw in some load factors for partload operation.
2) We are purchasing natural gas from MichCon. I'm not sure what rate we'll be on, but it should be one of their larger bulk transport rates, due to our potential high usage, 14,000 cfh at full load all units running. Hydrogen is going to be stored on site and trucked in for refueling. The hydrogen infrastructure is being provided by Praxair so you'll have to pursue them for more info at their end. As far as our hydrogen usage is concerned; the ENX-55 will use 2500 cfh, the Stuart will use 4700 cfh and each fuel cell will use 180 cfh. Those numbers are at full load as well.
3) Refer to spec sheets for this.
4) Refer to spec sheets for this. I will be unable to give you a full spectrum of emissions until the units are placed on test stands which won't be until May 2004.
5) No Biomass is being used.

Find attached the load profiles for the three buildings as well. Feel free to call me with any additional questions.

Sincerely,

Michael Saldana, PE
DTE Energy Technologies

Scott Baron wrote:
Great, thanks Michael.

I will mainly be looking at the life-cycle fuel impacts of the system and benchmarking it to the Detroit grid and a conventional thermal system. Some of the preliminary questions involve data on:
1) Kinds and amounts of fuel to be used at the site
2) Where the fuels come from and how produced (e.g. is hydrogen made locally or shipped in, and made from nat. gas or other fuel)
3) What are the expected conversion efficiencies of the generating devices
4) What are the expected emission rates of the generating technologies ($CO_2$, $SO_2$, $NO_x$, particulates)
5) Will biomass energy be used?

These are just some preliminary questions, but enough to show you the kinds of things that I will be modeling. Another note, this is not an engineering analysis, it is more of an environmental accounting type analysis. FYI.

**December 4, 2003**

Scott,

Here are the answers:

1) Find the estimates below for $CO_2$ for the engines that I know.
ENF 7 - You have this on the spec sheet in ppm
ENX 55(NG) - 63.94 g/bhp-hr
ENX 55(H2) - unknown (if you use the same number as the NG unit, you'll be safe.)
ENI 85 - 478.72 g/bhp-hr
ENI 150 - 420.46 g/bhp-hr
ENE 210 - 317.37 g/bhp-hr

ENT 400 - 947.61 g/bhp-hr
Stuart - unknown (use the same number as the 150 above, you'll be safe.)
PV - 0

The reason I've suggested that you use NG engine emissions for the H2 engines is that you'll introduce conservatism in your calcs. NG with the chemical composition CH4 produces excess CO and CO2 because of the prescence of the carbon atom in the fuel. H2 will produce far less than this, mainly due to combustion air going through the system then from the fuel. When I know more I'll bring you up to speed.

2) We won't be producing the CHP spec sheet for the ENI 85 for another 2 weeks. That's why I sent you the 75 spec sheet. The 75 is the predecessor of the 85 so if you use that data for now as a placeholder when you put the actual data in, it won't be far off. Of course, stupid me, that's why I should have told you when I sent it along. Sorry about that.

3) See answer above.

4) For all the hydrogen units, we unfortunately do not have efficiency data or heat rate info on them as of yet. What you can do in the meantime is use the hydrogen input data I give you below for each unit and convert that to Btu, you know the kW output and you'll be able to then calculate the heat rate, and then efficiency. Here is the flow and pressure info:

ENF 7 - 180 scfh @ 80 psi per unit
ENX 55 - 2500 scfh @ ? psi (I would use 100 psi and I will clarify when I finally find out.)
Stuart - 4700 scfh @ 150 psi

5) The natural gas usages in the spreadsheet represent full output of the unit. Whether or not the CHP system is running, this amount of NG will be burned. The electrcial efficiency then represents the percentage of this NG input that is converted into electricity and the package efficiency represents the percentage of the NG input that is converted to both electric and useful thermal energy. Let's take the ENI 150 for example. It will burn approximately 1516 scfh or 1.814 MMBtu/hr. Of this total input energy if running in CHP mode, approximately 74% will be used with the other 26% "going up the chimney". Of the useful 74%, approximately 45% (or 33.3% of the total input energy) will generate electricity and the remaining 55% (or 40.7% of the total input energy) will generate hot water. If CHP is not running then 66.7% goes up the chimney and 33.3% is used to generate electricity. I hope that didn't confuse more than it helped.

Sincerely,

Michael Saldana, PE
DTE Energy Technologies

Scott Baron wrote:

Michael,

Thanks a lot for all of the material! I have been sifting through it and trying to pull out what I need. I have some initial questions after going through it.

1) For most technologies, there are no CO2 emissions listed. Is there anyway to estimate this?

2) For the ENI 85 technology, I am missing the second page with the CHP data.

3) You didn't list a ENI 75 technology in the email, but I have the stats on it. Will that one be included?

4) Are there Net Electrical Efficiencies associated with the Stuart IC and ENF 7? What about heat rates (with H2 technologies)?

5) In the load spreadsheet, are the natural gas numbers (predicted MMBtu) for both electricity and CHP? Would there be a way to estimate which % is allocated for what (which I am sure depends on what technologies are running)?

I think that answers to these questions will keep me busy a little while longer. I REALLY appreciate your help on this.

Best,
Scott

**December 4, 2003**

Scott,

One more thing. The ENE 210 is going to be CHP capable as well. Sorry for the late development.

Mike

**January 16, 2004**

Scott,

Sorry, I guess I did miss this email. Here you go:

1) I'm not sure where you are reading on the spec sheet for the ENI 150 that the fuel usage was 0.886 MMBtu/hr. The fuel usage is in the fuel supply section and there's two numbers next to the Fuel (LHV/HHV) MMBtu/hr (GJ/hr) category 1.651 and 1.814. Now depending on what you're trying to arrive at you might use the LHV or HHV value. If trying to calculate efficiency or heat rate use the LHV value, 1.651 (which I didn't in my example.....) and if you're trying to calculate how much would be purchased from a gas company either amount or $ use HHV, 1.814. The reason for that is gas companies sell gas based on HHV so when calculating purchase criteria you must revert to this value.

2) You had it right but I forgot to give you the fuel standard for Hydrogen which you would also need. LHV is 270 Btu/cf and HHV is 300 Btu/cf. So the calc would go as follows:

For the ENX-55 the usage is 2500 scfh. To get that in MMBtu/hr you would multiply 2500 * 270 = 0.675 MMBtu/hr. The kW output of the unit is 55 kW. Therefore the heat rate is 0.675 MMBtu/hr * 1,000,000 Btu/MMBtu / 55 kW = 12,273 Btu/kWh. Efficiency would then be 3,413 Btu/kWh / 12,273 Btu/kWh = 27.8%.

3) Not sure where you got 80 kW / 75 kW in your calc. Assuming you want the final value in lbs/kWh, here's how to go.

0.76 g/bhp-hr * ( 1hp / 0.746 kW) * (0.002204 lbs / 1 g) = 0.002245 lbs/kWh. When doing the final calc for amount of emissions generated make sure you use the kW listed in the BHP (shaft) @ ISO line which for the ENT 400 is 416 not the generated output. Emissions is all about the prime mover not the electrical end.

Assume a 90% efficeincy from shaft to electrical kW so to calculate any units shaft hp or kW just divide the unit output by 0.9.

4) I'll have to follow up on this but you do see on the sheet that all emissions are < 1ppm. This is actually closer to 0 than 1 its just that the manufacturer is covering their butt. For now put 0 into your emissions values for this unit and when I give you the actual amounts you'll see that they are virtually negligible.

Sincerely,

**January 20, 2004**

Scott,

Here's the last piece on emissions I promised you. the CO, CO2 NOx and SO2 output of the fuel cells is 0.000061 lbs/hr or 0.00418 g/bhp-hr at 6.7 bhp. As I stated, this is negilible. These numbers basically represent those constituents and amounts already present in the atmosphere. The only reason the fuel cell "emits" anything is because
during the process the stack combines the hydrogen fuel with free oxygen in the air and makes water, therefore any air that passes through the stack becomes oxygen depleted not necessarily dirty.

Sincerely,

Mike

**January 20, 2004**

Scott,

Here are your answers:

1) The spec sheet you have is corrupt, unfortunately I couldn't find an electronic copy of the one I'm using. Find attached a slightly older spec sheet that is right, but has slightly different numbers than in previous emails. You can tell yours is wrong because the thermal efficiency is 143% which is impossible. Sorry about the mixup but apparently I sent you a corrupt file originally.

2) We still don't have an official spec sheet for the ENI 85, so go ahead and continue to use the ENI 75 numbers.

3) Great.

4) As you can see on the spec sheet it is approximately 16% efficient. This is a non-recuperated beta test module and therefore pretty bad. What that means is that it will probably only be run sparingly. I think I told you 1500-3000 hours of runtime for each asset. The turbine will definitely be at the low end of this range, if not lower. Also, I hope when you say skews the model you mean when running. When the turbine is running there will probably be no other asset running and since it can put out 400kW the excess power above what the site peak demand is (200kW or so) will be exported. Further, we are going to try to negotiate a "sellback" agreement with DECo for an power exported. This contract will be limited in hours to something like 400-1000 per year but that might be perfect for the times we run the turbine. In that event we will get paid 2-3 cents per kWh for the exported power and we'll probably limit the turbine runtime to less than 1000 hours.

5) scfh is Standard Cubic Feet per Hour. The "standard" just tells you what temperature and pressure the flow was measured at. Think of it as a normalized measurement. For your purposes it is the same as simple cu ft / hr.

I will try to look over your model (I am keenly interested....) but I have to find the time.
Thank you for forwarding it to me.

Sincerely,

Michael Saldana

Scott Baron wrote:

Michael,

Once again, thanks so much for all of your help. I think I am very close to being done. I have a couple of more questions, I hope you can help again. Also, I am sending you my model, if you have time to look at it.

1) Regarding #1 below, I am not sure if we have the same data. In the "CHP Capability" page 2 of the specs, I see the 1.651 MMBtu/hr entering the system; however, in the "fuel supply" section, I have different numbers. I am sending you the pdfs of the spec sheet you sent me to show you what I mean.

2) Did you mention that the ENI 85 was going to replace the ENI 75? I think I am still using ENI 75 numbers.

3) You're right about the emission calculation below, I used the wrong shaft power numbers (for another machine); but we are doing it the same way.

4) Is the ENT 400 unit really as inefficient as the numbers say? It skews the microgrid data a bit.

5) Just to double-check, does scfh=cuft/hr?

That is pretty much it, unless you can see any glaring errors in my model (which is always possible). Or unless you have any comments or ideas?

Some interesting conclusions:
It appears that when looking just at the conversion efficiencies of the microgrid and the conventional grid, they are pretty similar, not many benefits with going with the microgrid. However, when you include the life-cycle impacts, such as grid line losses and CHP, the microgrid does better. According to the data on converting hydrogen, that has not boded well for the microgrid given the energy intensity associated with doing that. I still need to run sensitivities, etc., but it appears that under some conditions the microgrid is a better choice, and under others, the conventional grid wins. However, in all cases, there are lower emissions with the microgrid.

Best,
Scott

***<u>Correspondence with Ed Danieli from Praxair, Inc.</u>***

**March 15, 2004**

Dear Scott;

Please consider this a first cut at answering the questions you posed to Jim:

1. Hydrogen Generation @ Niagara Falls:

The hydrogen is generated via electrolysis of brine. It is a BYPRODUCT of the manufacture of chlorine and sodium hydroxide. (It is generally not economic to produce hydrogen via electrolyis). We purchase the byproduct hydrogen from two different suppliers - who use two different technologies for the manufacture of chlorine/caustic soda. One supplier uses a diaphragm cell, another uses a membrane cell.

The diaphragm cell uses electricity at 3.32 volts and produces 0.803 lbs of chlorine, 0.906 lbs of caustic and 0.025 lbs of hydrogen for every KWH of electricity used.

The newer technology membrane cell uses electricity at 3.2 volts and produces 0.833 lbs of chlorine, 0.940 lbs of caustic and 0.025 lbs of hydrogen for every KWH of electricity used.

Given the fact that the hydrogen is a byproduct of another chemical process, I'm not sure how to calculate an overall efficiency for the supply system.

The hydrogen is supplied to Praxair via pipeline, it is then purified, compressed and liquefied. The exact power required is confidential, but many published studies show that liquid hydrogen can be made by using approximately 11 to 14 KWH per KG.

Both the production and liquefaction of hydrogen is done using hydropower from the Niagara Falls plant of the New York State Power Authority (which makes this renewable hydrogen).

2. Distribution Impact:

We will not be making trips to NextEnergy specifically for NextEnergy. We will be supplying NextEnergy as part of our overall supply of hydrogen to the lower Michigan penninsula. When we come across Canada, we will drive approximately 250 miles to Detroit. While we're in the vicintiy, we should deliver 80% or more of a full trailer load. A typical trailer holds between 3500 to 4500 KG of hydrogen (the bulk of the fleet is 3500 KG trailers).

3. On-site Generation Efficiency

Each supplier of on-site generators makes design decisions between capital cost and efficiency. A table showing some options is below:

| Manufacturer | Capacity (SCFH) | Efficiency (LHV %) | Power (kW) |
|---|---|---|---|
| Praxair DFMA | 2000 | 70 | 12 |
| HydrogenSource | 2000 | 59 | 45 |
| H2Gen | 2000 | 72 | 8 |
| Harvest | 2000 | 72 | 50 |
| Ztek | 2000 | 90.3 | 33 |
| Hyradix | 3531 | 59 | 15 |

The first two units are those that were proposed for NextEnergy as part of the GM/Shell DOE solicitiation. The other four are units that are currently being developed by other manufacturers. I have efficiency and power values for HydrogenSource, H2Gen and Hyradix, but am not sure if they are confidential. We are trying to find the numbers in a public forum or have the vendors tell us that we can share them.

Please be cautious with the efficiency numbers. Different companies define the number differently.

I will update the efficiency and power columns when I get public information.

In the mean time, please feel free to call me if you need anything else.

Best Regards,

Ed Danieli
Praxair, Inc

Director - Clean Fuels
Phone: 203-837-2112
FAX: 203-837-2540
EMAIL: Ed_Danieli@Praxair.com

**June 9, 2004**

Dear Scott;

A couple of quick answers:

1. The 80% reference is the portion of the truck we would deliver into southern Michigan (it's the low end of expectations). We would only plan on delivering approximately 800 KG (approximately 20% of a truck) to NextEnergy.

2. I can't forecast a number of deliveries to NextEnergy since the volume requirement is in flux. I believe that at full power load, NextEnergy will consume around 18 KG of hydrogen per hour. At that rate, we would have to make a delivery for every 44 hours of operation. One initial scenario had hydrogen use running at around 120 hours per month. At that use rate we would make a bit over 30 deliveries per year.

Best Regards,

Ed Danieli

# Appendix 4: Complete Model

## Worksheet 1: Main Module

**Dynamic LCA Model**

| | |
|---|---|
| **Measurement period** | Hour |
| **Percentage of total expected load met** | 36% |

**Electricity**

| Technology | Fuel | On or Off | Load Factor % | CHP Used | Output Level kW | Total Electricity Production kWh | Microgrid Upstream Energy Use Btu | Microgrid Combustion Energy Use Btu | Microgrid Inverter Loss Btu | Microgrid Total Life Cycle Energy Use Btu | Grid Baseline Upstream Energy Use Btu | Grid Baseline Combustion Energy Use Btu | Grid Baseline Line Losses Energy Use Btu | Grid Baseline Total Life Cycle Energy Use Btu | Microgrid Total Life Cycle NOx Emissions lb | Microgrid Total Life Cycle CO2 Emissions lb | Grid Baseline Total Life Cycle NOx Emissions lb | Grid Baseline Total Life Cycle CO2 Emissions lb | Grid Baseline Total Life Cycle SO2 Emissions lb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ENE 210 EGR | NG | On | 100% | Yes | 202 | 202.0 | 289,347 | 2,040,200 | 0 | 2,329,547 | 71,880 | 2,129,327 | 176,097 | 2,377,303 | 0.37 | 241.56 | 1.44 | 381.01 | 0.00 |
| ENF 7 | H2 | On | 100% | No | 20 | 20.0 | 77,441 | 194,400 | 21,747 | 293,589 | 7,117 | 210,824 | 17,435 | 235,377 | 0.00 | 0.49 | 0.14 | 37.72 | 0.00 |
| ENI 85 | NG | On | 100% | Yes | 85 | 85.0 | 133,128 | 929,475 | 0 | 1,062,603 | 30,246 | 896,004 | 74,100 | 1,000,350 | 0.17 | 148.47 | 0.61 | 160.32 | 0.00 |
| Stuart IC | H2 | On | 100% | No | 120 | 120.0 | 464,648 | 1,269,000 | 0 | 1,733,648 | 42,701 | 1,264,946 | 104,612 | 1,412,259 | 0.08 | 12.85 | 0.86 | 226.34 | 0.00 |
| ENI 150 | NG | On | 100% | Yes | 150 | 150.0 | 219,042 | 1,545,000 | 0 | 1,764,042 | 53,376 | 1,581,183 | 130,765 | 1,765,324 | 1.33 | 220.49 | 1.07 | 282.93 | 0.00 |
| ENT 400 | NG | On | 100% | No | 396 | 396.0 | 1,164,096 | 8,197,200 | 0 | 9,361,296 | 140,913 | 4,174,323 | 345,219 | 4,660,455 | 2.02 | 1,306.58 | 2.82 | 746.92 | 0.00 |
| ENX 55 | NG | On | 100% | Yes | 55 | 55.0 | 86,817 | 610,500 | 0 | 697,317 | 19,571 | 579,767 | 47,947 | 647,285 | 0.13 | 22.01 | 0.39 | 103.74 | 0.00 |
| ENX 55 | H2 | On | 100% | Yes | 55 | 55.0 | 212,964 | 675,000 | 0 | 887,964 | 19,571 | 579,767 | 47,947 | 647,285 | 0.04 | 6.83 | 0.39 | 103.74 | 0.00 |
| Unisolar | Sun | On | 16% | No | 4.74 | 4.7 | 0 | 4,158 | 333 | 4,490 | 1,687 | 49,965 | 4,132 | 55,784 | 0.00 | 0.66 | 0.03 | 8.94 | 0.00 |
| **Total** | | | | | **1,088** | **1,088** | **2,647,483** | **15,464,933** | **22,080** | **18,134,496** | **387,062** | **11,466,107** | **948,254** | **12,801,423** | **4.14** | **1,959.95** | **7.75** | **2051.66** | **0.00** |

Average energy (kWh) required to meet building load **27**

**Thermal System**

| Technology | Fuel | Package Efficiency | Electrical Efficiency | Total Useful Energy MMBtu/hr | Useful Heat MMBtu/hr | Total Heat Energy Recovered at Microgrid Btu | Equivalent Heat System Required (75% Efficiency) Btu | Upstream Energy for Equivalent Heat System Btu | Total Life Cycle Energy for Equivalent Heat System Btu | Total NOx Emissions lb | Total CO2 Emissions lb |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ENE 210 EGR | NG | 0.89 | 0.34 | 1.82 | 1.12 | 1,122,550 | 1,496,733 | 166,447 | 1,663,180 | 0.79 | 172.51 |
| ENF 7 | H2 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 | 0 | 0.00 | 0.00 |
| ENI 85 | NG | 0.85 | 0.31 | 0.80 | 0.51 | 507,060 | 676,080 | 75,185 | 751,265 | 0.00 | 77.92 |
| Stuart IC | H2 | 0 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 | 0 | 0.00 | 0.00 |
| ENI 150 | NG | 0.79 | 0.33 | 1.22 | 0.71 | 709,155 | 945,540 | 105,151 | 1,050,691 | 0.00 | 108.98 |
| ENT 400 | NG | 0 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 | 0 | 0.00 | 0.00 |
| ENX 55 | NG | 0.84 | 0.31 | 0.51 | 0.32 | 324,890 | 433,187 | 48,173 | 481,360 | 0.01 | 49.93 |
| ENX 55 | H2 | 0.84 | 0.28 | 0.57 | 0.38 | 379,340 | 505,787 | 56,247 | 562,034 | 0.02 | 58.30 |
| Unisolar | Sun | 0 | 0.00 | 0.00 | 0.00 | 0 | 0 | 0 | 0 | 0.00 | 0.00 |
| **Total** | | | | | | **3,042,995** | **4,057,327** | **451,203** | **4,508,529** | **0.81** | **467.64** |

**Total Results**

| Life Cycle Metric | Unit | Conventional System: Grid Electricity | Conventional System: Thermal | Conventional System: Total | Microgrid System |
|---|---|---|---|---|---|
| Total Upstream Energy Use | Btu/Hour | 387,062 | 451,203 | 387,062 | 2,647,483 |
| Total Combustion Energy Use | Btu/Hour | 11,466,107 | 4,057,327 | 11,466,107 | 15,464,933 |
| Total Line Losses Energy Use | Btu/Hour | 948,254 | 0 | 948,254 | 0 |
| Total Inverter Energy Use | Btu/Hour | 0 | 0 | 0 | 22,080 |
| Total Life Cycle Energy Use | Btu/Hour | 12,801,423 | 4,508,529 | **17,309,952** | **18,134,496** |
| Total NOx Emissions | lb/Hour | 8.56 | 0.81 | **9.37** | **4.14** |
| Total CO2 Emissions | lb/Hour | 2,519 | 468 | **2,987** | **1,960** |
| Total Electrical Energy Produced | kWh | | | | 1,088 |
| Total Heat Energy Produced | Btu | | | | 3,042,995 |
| Microgrid System Efficiency | % | | | | 37.2% |
| Conventional System Efficiency | % | | | | 39.0% |

# Worksheet 2: Life Cycle Parameters

**Grid Life Cycle Energy**

| Energy Source | Upstream<br>Coal: Btu/lb<br>Uranium: Btu/lb<br>Natural gas: Btu/cuft<br>Fuel oil: Btu/gallon | Combustion<br>Coal: Btu/lb<br>Uranium: Btu/lb<br>Natural gas: Btu/cuft<br>Fuel oil: Btu/gallon | Upstream and combustion<br>Coal: Btu/lb<br>Uranium: Btu/lb<br>Natural gas: Btu/cuft<br>Fuel oil: Btu/gallon | Quantity for 1 kWh<br>Coal:lb/kWh<br>Uranium:lb/kWh<br>Natural gas: cuft/kWh<br>Fuel oil: gallon/kWh | Total Btu for 1 kWh<br>Btu/kWh | Line loss adjustment (assume 8%)<br>Coal: Btu/kWh<br>Uranium: Btu/kWh<br>Natural gas: Btu/kWh<br>Fuel oil: Btu/kWh | Total Btu to generate 1 kWh<br>Btu/kWh | Percent upstream | Percent combustion | Percent Line-loss | Sum |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 264 | 10,402 | 10,666 | 1.01 | 10,773 | 862 | 11,634 | 2.29% | 90.30% | 7.41% | 100.00% |
| Uranium | 50,600,000 | 985,321,000 | 1,035,921,000 | 0.0000109 | 11,292 | 903 | 12,195 | 4.52% | 88.07% | 7.41% | 100.00% |
| Natural gas | 129 | 1,022 | 1,151 | 10.40 | 11,970 | 958 | 12,928 | 10.38% | 82.22% | 7.41% | 100.00% |
| Residual fuel oil | 21,000 | 149,700 | 170,700 | 0.07 | 11,608 | 929 | 12,536 | 11.39% | 81.20% | 7.41% | 100.00% |
| Hydropower | | | | | 3,414 | 273 | 3,687 | 0.00% | 92.59% | 7.41% | 100.00% |
| Renewable average | | | | | 10,350 | 828 | 11,178 | 0.00% | 92.59% | 7.41% | 100.00% |
| Hydrogen (see bottom section) | | | | | | | | | | | |

**Grid Emissions Profile**

| Energy Source | LCA energy to generate one kWh<br>Coal=lb/kWh<br>Uranium=lb/kWh<br>Natural gas=cuft/kWh<br>Fuel oil=gal/kWh | Upstream NOx<br>Coal=lbs/1000 lbs coal<br>Uranium=lbs/1000 lbs uranium<br>Natural gas=lbs/1000 cuft gas<br>Fuel oil=lbs/1000 gal fuel oil | Combustion NOx<br>Coal=lbs/1000 lbs coal<br>Uranium=lbs/1000 lbs uranium<br>Natural gas=lbs/1000 cuft gas<br>Fuel oil=lbs/1000 gal fuel oil | Upstream + Combustion NOx<br>Coal=lbs/1000 lbs coal<br>Uranium=lbs/1000 lbs uranium<br>Natural gas=lbs/1000 cuft gas<br>Fuel oil=lbs/1000 gal fuel oil | Total Nox<br>lb/kWh | Upstream CO2<br>Coal=lbs/1000 lbs coal<br>Uranium=lbs/1000 lbs uranium<br>Natural gas=lbs/1000 cuft gas<br>Fuel oil=lbs/1000 gal fuel oil | Combustion CO2<br>Coal=lbs/1000 lbs coal<br>Uranium=lbs/1000 lbs uranium<br>Natural gas=lbs/1000 cuft gas<br>Fuel oil=lbs/1000 gal fuel oil | Upstream + Combustion CO2<br>Coal=lbs/1000 lbs coal<br>Uranium=lbs/1000 lbs uranium<br>Natural gas=lbs/1000 cuft gas<br>Fuel oil=lbs/1000 gal fuel oil | Total CO2<br>lb/kWh |
|---|---|---|---|---|---|---|---|---|---|
| Coal | 1.0908 | 0.2300 | 7.9000 | 8.1300 | 0.0089 | 41.0000 | 2120.0000 | 2161.0000 | 2.3572 |
| Uranium | 0.0000 | 58000 | 0 | 58000.0000 | 0.0007 | 6929000 | 0 | 6929000.0000 | 0.0816 |
| Natural gas | 11.2320 | 0.1200 | 0.3900 | 0.5100 | 0.0057 | 15.7280 | 121.0000 | 136.7280 | 1.5357 |
| Residual fuel oil | 0.0734 | 9.2000 | 35.0000 | 44.2000 | 0.0032 | 2867.6400 | 25400.0000 | 28267.6400 | 2.0760 |
| Hydropower | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Renewable average | 0.0000 | 0.0000 | 0.0000 | 0.00057 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.14000 |
| Hydrogen | | | | | | | | | |

**Industrial Boiler Emissions Profile**

| Energy Source | Upstream NOx<br>lbs/1000 cuft gas | Combustion NOx<br>lbs/1000 cuft gas | Upstream + Combustion NOx<br>lbs/1000 cuft gas | Upstream CO2<br>lbs/1000 cuft gas | Combustion CO2<br>lbs/1000 cuft gas | Upstream + Combustion CO2<br>lbs/1000 cuft gas |
|---|---|---|---|---|---|---|
| Natural gas | 0.12 | 0.31 | 0.43 | 15.7 | 118 | 133.7 |

**Life Cycle Energy Hydrogen Production for NextEnergy**

| | |
|---|---|
| **Assumptions** | |
| Energy burden for hydrogen as byproduct from cholrine manufacture | 1.44% |
| Conversion to make H2 (lbs of H2 gas per 1 kWh input) | 0.025 |
| Conversion to liquify H2 gas (kWh/kg) | 10.275 |
| One-way milage to NextEnergy | 250 |
| Energy burden from NextEnergy portion of hydrogen in truck | 20% |
| Truck gas milage (mpg) | 6 |
| Weight of hydrogen in one truck, fully loaded (kg) | 3,500 |
| Weight of hydrogen in one truck, fully loaded (lb) | 7,716 |
| Diesel trasportation upstream energy (MMBtu/1000 gallons) | 19 |
| Diesel transportation combustion energy (MMBtu/1000 gallons) | 139 |
| Upstream CO2 emissions from hydrogen production (lb/kWh) | 0.047606 |
| Upstream NOx emissions from hydrogen production (lb/kWh) | 0.000132 |
| Distribution CO2 emissions from hydrogen transport (lb/1000 gallons diesel) | 25,427 |
| Distribution NOx emissions from hydrogen transport (lb/1000 gallons diesel) | 218 |
| **Calculations** | |
| Liquid hydrogen needed to supply H2 units (kg) | 17.43 |
| Liquid hydrogen needed to supply H2 units (lb) | 38.44 |
| Back-calculated number of hydrogen shipments to NextEnergy | 0.02491 |
| Total number of miles traveled to deliver hydrogen | 2.49069 |
| Total number of gallons used to deliver hydrogen | 0.41512 |
| Upstream distribution energy (Btu) | 8,012 |
| Combustion distribution energy (Btu) | 57,701 |
| Total distribution energy to deliver hydrogen (Btu) | 65,713 |
| Total energy to make H2 gas (Btus/lb) | 2,032 |
| Total energy to liquify H2 gas (Btus/lb) | 15,902 |
| Total energy to distribute liquid H2 to Detroit (Btus/lb) | 1,710 |
| Total upstream energy use (Btu/lb) | 19,644 |
| Total upstream energy use (Btu) | **755,053** |

| | |
|---|---|
| **Total upstream hydrogen energy use (Btu)** | **755,053** |
| Electricity CO2 emissions from upstream hydrogen production (lb) | 9.6 |
| Electricity NOx emissions from upstream hydrogen production (lb) | 0.026717 |
| Distribution CO2 emissions from upstream hydrogen production (lb) | 10.6 |
| Distribution NOx emissions from upstream hydrogen production (lb) | 0.090495 |
| **Total CO2 emissions from upstream hydrogen production (lb)** | **20** |
| **Total NOx emissions from upstream hydrogen production (lb)** | **0** |

# Worksheet 3: Microgrid Assumptions

**Input Data**

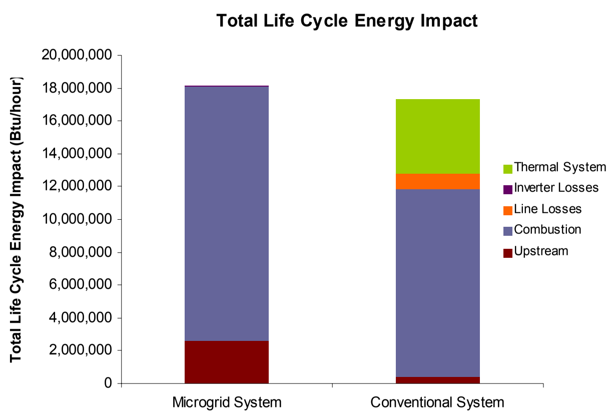
| Generating unit | Type of unit | # of generating units | Net electrical output kW | Shaft power kW | Net electrical efficiency | CHP Option | Efficiency w/CHP | Total recovery heat MMBtu/hr | Heat rate Btu/kWh | Fuel type | Fuel (LHV) MMBtu/hr | Fuel ft3/hr | Inverter Loss % | Combustion NOx g/bhp-hr | Combustion CO2 g/bhp-hr | Combustion NOx lb/kWh | Combustion CO2 lb/kWh |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ENE 210 EGR | Exhaust gas recirculation IC sync. genset | 1 | 202 | 220 | 0.34 | Yes | 0.89 | 1.123 | 10,100 | NG | 2.041 | 2243 | 0% | 0.150 | 317.37 | 0.00048 | 1.02120 |
| ENF 7 | PEM fuel cells | 4 | 5 | 5.5 | 0.35 | No | 0 | 0 | 9,720 | H2 | 0.049 | 180 | 8% | 0.000 | 0 | 0.00006 | 0.00000 |
| ENI 85 | Automotive derivative IC sync. genset | 1 | 85 | 93.5 | 0.31 | Yes | 0.85 | 0.385 | 10,935 | NG | 0.939 | 1032 | 0% | 0.150 | 478.72 | 0.00049 | 1.55578 |
| Stuart IC | Automotive derivative IC sync. genset | 1 | 120 | 132 | 0.32 | No | 0 | 0 | 10,575 | H2 | 1.269 | 4700 | 0% | 0.000 | 0 | 0.00006 | 0.00000 |
| ENI 150 | Automotive derivative IC sync. genset | 1 | 150 | 156 | 0.33 | Yes | 0.79 | 0.71 | 10,300 | NG | 1.545 | 1698 | 0% | 2.440 | 420.46 | 0.00750 | 1.29191 |
| ENT 400 | Miniturbine, permanent magnet genset | 1 | 396 | 416 | 0.16 | No | 0 | 0 | 20,700 | NG | 8.212 | 9024 | 0% | 0.760 | 947.61 | 0.00236 | 2.94104 |
| ENX 55 | External combustion, induction genset (NG) | 1 | 55 | 60.5 | 0.31 | Yes | 0.84 | 0.325 | 11,100 | NG | 0.613 | 673 | 0% | 0.288 | 63.94 | 0.00094 | 0.20780 |
| ENX 55 | External combustion, induction genset (H2) | 1 | 55 | 60.5 | 0.28 | Yes | 0.84 | 0.325 | 12,273 | H2 | 0.675 | 2500 | 0% | 0.000 | 0 | 0.00006 | 0.00000 |
| Unisolar | Thin-film photovoltaic | 1 | 30 | 30 | 3.89 | No | 0 | 0 | 877 | Sun | 0.000 | 0 | 8% | 0.000 | 0 | 0.000 | 0.000 |

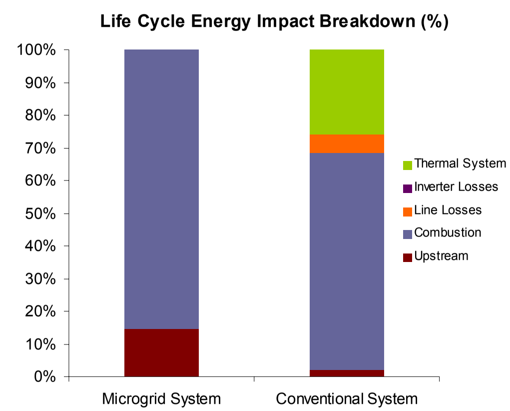
**Emissions Profile Microgrid**

**AT FULL CAPACITY**

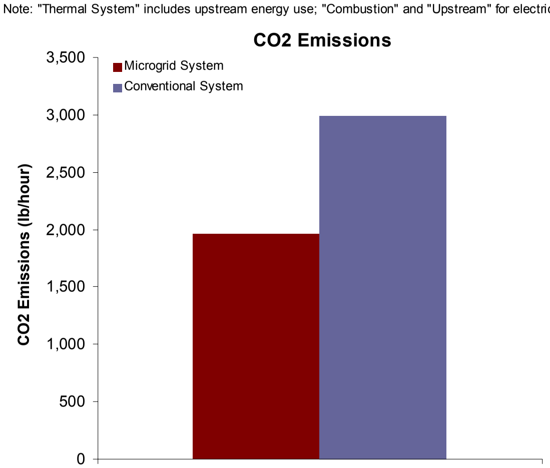
| Generating unit | Type of unit | Upstream NOx lbs/hour | Upstream CO2 lbs/hour | Combustion NOx lbs/hour | Combustion CO2 lbs/hour | Total NOx lbs/hour | Total CO2 lbs/hour |
|---|---|---|---|---|---|---|---|
| ENE 210 EGR | Exhaust gas recirculation IC sync. genset | 0.269 | 35.278 | 0.097 | 206.282 | 0.367 | 241.560 |
| ENF 7 | PEM fuel cells | 0.003 | 0.492 | 0.000 | 0.000 | 0.003 | 0.492 |
| ENI 85 | Automotive derivative IC sync. genset | 0.124 | 16.231 | 0.041 | 132.241 | 0.165 | 148.472 |
| Stuart IC | Automotive derivative IC sync. genset | 0.075 | 12.847 | 0.007 | 0.000 | 0.082 | 12.847 |
| ENI 150 | Automotive derivative IC sync. genset | 0.204 | 26.706 | 1.125 | 193.786 | 1.328 | 220.492 |
| ENT 400 | Miniturbine, permanent magnet genset | 1.083 | 141.929 | 0.934 | 1164.651 | 2.017 | 1306.580 |
| ENX 55 | External combustion, induction genset (NG) | 0.081 | 10.585 | 0.051 | 11.429 | 0.132 | 22.014 |
| ENX 55 | External combustion, induction genset (H2) | 0.040 | 6.833 | 0.003 | 0.000 | 0.043 | 6.833 |
| Unisolar | Thin-film photovoltaic | 0.017 | 4.200 | 0.000 | 0.000 | 0.017 | 4.200 |
| **Total** | | **1.89** | **255.10** | **2.26** | **1708.39** | **4.15** | **1963.49** |

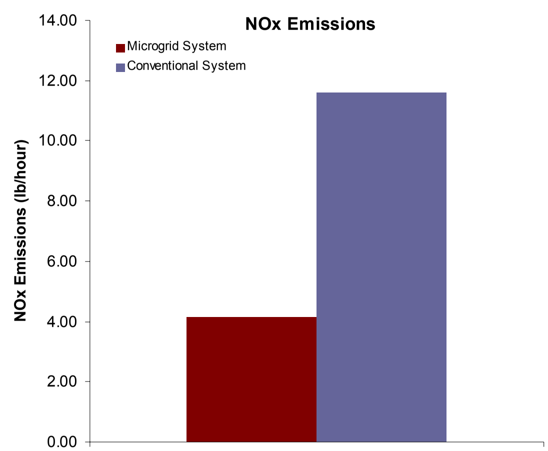
# Worksheet 4: Output Graphs (example)




Note: "Thermal System" includes upstream energy use; "Combustion" and "Upstream" for electrical system only.



## Worksheet 5: Monthly Load NextEnergy

**Expected Demand Load**

Total building square footage 40,000

| Month | Demand kWh | Peak Demand kW | Natural Gas Consumption MMBtu |
|---|---|---|---|
| Jan | 52,067 | 108 | 662 |
| Feb | 46,119 | 108 | 489 |
| Mar | 51,689 | 122 | 325 |
| Apr | 52,081 | 160 | 145 |
| May | 55,672 | 169 | 100 |
| Jun | 64,121 | 191 | 91 |
| Jul | 65,994 | 193 | 91 |
| Aug | 65,755 | 184 | 96 |
| Sep | 54,181 | 177 | 89 |
| Oct | 50,194 | 135 | 113 |
| Nov | 48,708 | 108 | 283 |
| Dec | 49,197 | 108 | 391 |
| **Total** | **655,778** | **193** | **2,874** |

# Worksheet 6: Detroit Grid

| **Detroit Grid Fuel Mix** | **Year 2001** |
|---|---|
| **Fuel Type** | **Percent** |
| Coal | 76.7% |
| Nuclear | 18.1% |
| Natural gas | 3.2% |
| Residual fuel oil | 0.6% |
| Hydroelectric | 0.1% |
| Renewables (biomass, solid waste) | 1.3% |

**Life Cycle Energy Consumption**

| **Fuel Type** | **Upstream Btu/kWh** | **Combustion Btu/kWh** | **Line-Loss Btu/kWh** | **Total Life Cycle Energy Btu/kWh** |
|---|---|---|---|---|
| Coal | 205 | 8,058 | 661 | 8,924 |
| Nuclear | 100 | 1,944 | 164 | 2,207 |
| Natural gas | 43 | 340 | 31 | 414 |
| Residual fuel oil | 9 | 61 | 6 | 75 |
| Hydroelectric | 0 | 3 | 0 | 4 |
| Renewables (biomass, solid waste) | 0 | 135 | 11 | 145 |
| **Total** | 356 | 10,541 | 872 | 11,769 |

**Life Cycle Energy Consumption of Detroit Grid to Meet Needs of NextEnergy Facility**

| **Month** | **Upstream Btu** | **Combustion Btu** | **Line-Loss Btu** | **Total Life Cycle Energy Btu** |
|---|---|---|---|---|
| Jan | 18,527,638 | 548,851,925 | 45,390,365 | 612,769,929 |
| Feb | 16,410,904 | 486,147,015 | 40,204,634 | 542,762,553 |
| Mar | 18,392,992 | 544,863,241 | 45,060,499 | 608,316,732 |
| Apr | 18,532,512 | 548,996,297 | 45,402,305 | 612,931,114 |
| May | 19,810,240 | 586,846,961 | 48,532,576 | 655,189,777 |
| Jun | 22,816,979 | 675,916,833 | 55,898,705 | 754,632,517 |
| Jul | 23,483,525 | 695,662,205 | 57,531,658 | 776,677,388 |
| Aug | 23,398,448 | 693,141,945 | 57,323,231 | 773,863,624 |
| Sep | 19,279,706 | 571,130,733 | 47,232,835 | 637,643,275 |
| Oct | 17,861,041 | 529,105,047 | 43,757,287 | 590,723,376 |
| Nov | 17,332,333 | 513,442,903 | 42,462,019 | 573,237,255 |
| Dec | 17,506,370 | 518,598,467 | 42,888,387 | 578,993,224 |
| **Total** | 233,352,689 | 6,912,703,572 | 571,684,501 | 7,717,740,762 |

**Life Cycle Emissions Profile Detroit Grid**

| | **LCA NOx lb/kWh** | **LCA CO2 lb/kWh** | **LCA SO2 lb/kWh** |
|---|---|---|---|
| Coal | 0.0068 | 1.8080 | 0.0000 |
| Nuclear | 0.0001 | 0.0148 | 0.0000 |
| Natural gas | 0.0002 | 0.0491 | 0.0000 |
| Residual fuel oil | 0.0000 | 0.0125 | 0.0000 |
| Hydroelectric | 0.0000 | 0.0000 | 0.0000 |
| Renewables (biomass, solid waste) | 0.0000 | 0.0018 | 0.0000 |
| **Total** | 0.0071 | 1.8862 | 0.0000 |

**Life Cycle Emissions of Detroit Grid to Meet Needs of NextEnergy Facility**

| **Month** | **LCA NOx lb** | **LCA CO2 lb** | **LCA SO2 lb** |
|---|---|---|---|
| Jan | 371 | 98,208 | 0 |
| Feb | 329 | 86,988 | 0 |
| Mar | 368 | 97,494 | 0 |
| Apr | 371 | 98,233 | 0 |
| May | 397 | 105,006 | 0 |
| Jun | 457 | 120,944 | 0 |
| Jul | 470 | 124,477 | 0 |
| Aug | 469 | 124,026 | 0 |
| Sep | 386 | 102,194 | 0 |
| Oct | 358 | 94,674 | 0 |
| Nov | 347 | 91,872 | 0 |
| Dec | 351 | 92,794 | 0 |
| **Total lbs** | 4,675 | 1,236,909 | 0 |
| **Total tons** | 2.34 | 618.45 | 0.00 |

## Appendix 5: Original Specification Sheets for Microgrid Technologies