How well could a DG-based microgrid perform compared with conventional energy supplies? Using life-cycle analysis on an upcoming Detroit microgrid, Scott Baron shows that in terms of energy, efficiency and emissions, the microgrid can score far higher.

Motown microgrid

life-cycle analysis rates energy and environmental performance

Microgrid systems powered with distributed generation (DG) technologies offer an alternative to the conventional system of centralized power and on-site thermal heating and cooling. A microgrid is defined here as a system of multiple power sources of potentially different sizes and technologies for serving aggregated electrical and thermal loads, where the power and thermal energy can be produced at or near the locations of the users. The potential benefits of microgrids are greater efficiency, reduced emissions, and lower cost (both social and financial).

The analysis presented here uses the framework of life-cycle analysis (LCA) to determine the magnitude of the total fuel cycle use and emissions impact of a proposed microgrid system in Detroit, compared with the conventional system of grid-based electricity and on-site thermal heating and cooling. This analysis is a result of a partnership between NextEnergy and the University of Michigan's Center for Sustainable Systems (CSS). NextEnergy provided a grant to CSS to build an analytical tool for evaluating the life-cycle performance of its microgrid system.

BACKGROUND

NextEnergy, based in Detroit, Michigan, is a corporation founded to advance Michigan as a leader in alternative energy, by supporting research, design, manufacturing, commercialization and education of alternative energy technologies. Currently under construction, the state-of-the-art NextEnergy Center will be the Michigan headquarters of NextEnergy, dedicated to research and development, testing, demonstration and public education. Features of the Center will include office and laboratory space, training rooms, public demonstration space and auditorium. NextEnergy's laboratory is available to companies developing alternative energy technologies for stationary, automotive, portable, or micro-power use.

A Microgrid Power Pavilion is being built to power the

The NextEnergy Center and Microgrid Power Pavilion under construction in Detroit, Michigan

Table 1. Microgrid distributed generation technologies

DG unit	Description	Size (kW)	Fuel source	Net electrical efficiency (%)
ENF-7 (four)	Proton exchange membrane (PEM) fuel cells	5 (each)	Hydrogen	35
ENX-55	External combustion (Stirling cycle), induction genset	52	Natural gas	31
ENI-85	Automotive derivative internal combustion, synchronous genset	85	Natural gas	31
ENI-150	Automotive derivative internal combustion, synchronous genset	150	Natural gas	33
Stuart IC	Automotive derivative internal combustion, synchronous genset	120	Hydrogen	32
Unisolar	Thin-film, photovoltaic system	30	Sunlight	389[a]

[a] Estimated efficiency for solar systems (ratio of electricity generated/life cycle energy for PV manufacture) in the Detriot area, assuming a 20-year life of continuous operation

Center and related developments, with a target completion date of spring 2005. NextEnergy is constructing alternative energy technology (AET) infrastructure that will push the demonstration of AET to a higher level. With the assistance of a US Department of Energy grant, the company is constructing infrastructure to generate and store hydrogen for the micro-grid, fuel cell vehicle fuelling, and for use in laboratory testing. Companies and researchers are invited to exhibit and test their DG technologies and on-site hydrogen generation systems in this high-visibility application. Regulatory agencies and independent research institutions are invited to utilize the facility to advance AET codes and standard work.

The NextEnergy microgrid is being developed in partnership with DTE Energy Technologies, a subsidiary of DTE Energy, and is partially funded by a grant from the Michigan Public Service Commission. The microgrid will be powered by an integration of diverse fuel infrastructure: hydrogen, natural gas and biofuels. The base DG units in the microgrid include fuel cells, internal and external combustion engines, and photovoltaic cells. It also includes underground electrical and thermal distribution systems to provide power, heat and cooling to the NextEnergy Center. The microgrid will be built on a flexible, 'plug-and-play' basement foundation to easily accommodate the addition or replacement of new DG units.

For more information regarding NextEnergy's infrastructure and services available to AET developers, visit: www.nextenergy.org.

The Center for Sustainable Systems is an interdisciplinary research centre based at the University of Michigan's School of Natural Resources and the Environment. CSS develops life-cycle-based models and metrics to evaluate the performance and enhance the sustainability of products and technology for

Table 2. Detroit grid fuel mix characteristics, 2001

Source	DTE fuel mix (%)
Coal	76.7
Nuclear	18.1
Gas	3.2
Oil	0.6
Hydroelectric	0.1
Renewables	1.3

meeting societal needs. Systems studied range from renewable energy technologies, hydrogen infrastructure, and alternative vehicle technology to green buildings and consumer products and packaging.

SYSTEM BOUNDARIES

The 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 electrical 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.

The microgrid system is based on a proposed set of distributed generation technologies chosen by NextEnergy – see Table 1. Many of the units are prototypes; therefore, the system has a larger capacity than required for meeting the expected building energy loads, in case some units are either going through tests or are down for repair. It is important to note that the results presented in this analysis are based on the expected operational performance of each of the distributed generation units. All conversion and emissions data are taken based on preliminary stoichiometric specifications.

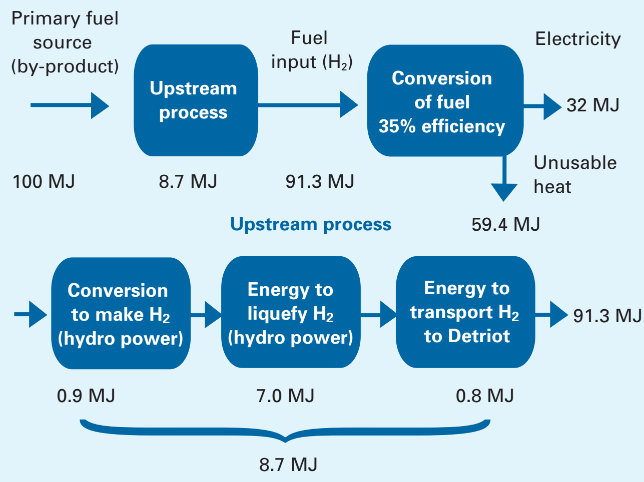

Figure 1. Hydrogen fuel cell energy flow chart

The Detroit grid is modelled based on the current generation

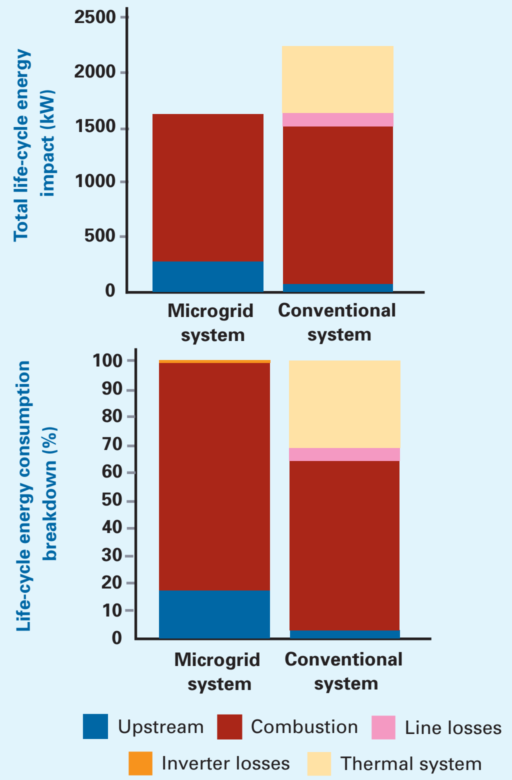

Figure 2. Microgrid system life-cycle assessment – energy performance

mix of coal, nuclear, natural gas, oil, hydro electric, and a small percentage of renewable energy – see Table 2.

LIFE-CYCLE ANALYSIS

Life-cycle analysis is used to measure the total fuel cycle energy and environmental impact of the microgrid and conventional energy systems. LCA is an analytical tool, based on ISO 14040 standards, that characterizes the full energy and environmental consequences of a system. Environmental impacts examined are emissions of NOx and carbon dioxide. These 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 energy and environmental accounting provides a comprehensive set of metrics for evaluating and comparing the energy efficiency and environmental performance of both systems.

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 is generally reformed or extracted from other energy carriers (e.g. natural gas, methane), the energy required to extract and convert the hydrogen must be considered for measuring the life-cycle efficiency of the fuel cell device.

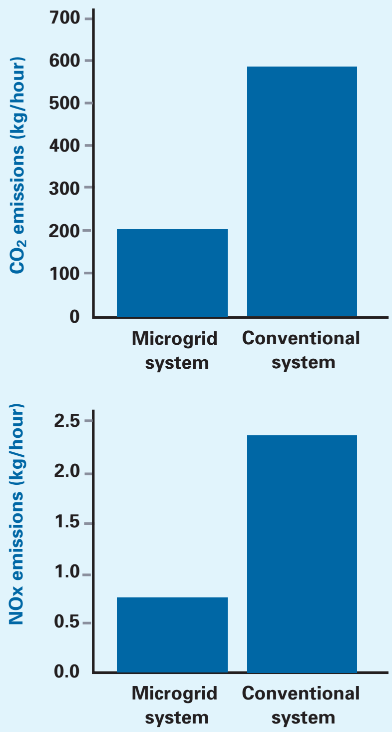

Figure 3. Microgrid system life-cycle assessment – emissions

LCA METHODOLOGY EXAMPLE – PEM FUEL CELL STACK

The value of LCA is apparent when considering the efficiency of hydrogen fuel cells. How the hydrogen is derived (e.g. natural gas reformation, electrolysis) greatly affects the life-cycle efficiency of fuel cell systems. The hydrogen system modelled for NextEnergy is unique because the hydrogen is a by-product from another process (chlorine manufacturing), where it is recovered, liquefied, and shipped to NextEnergy via diesel trucks. Hydro power generates the electricity supplied to this process (the production facility is near Niagara Falls). The utilization of renewable hydro power minimizes the use of fossil fuels relative to other hydrogen production routes.

Praxair Inc. receives the hydrogen gas from the by-product processes by pipeline, which it then converts to liquid hydrogen for transport. 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%. Once the hydrogen is liquefied, it is put on diesel trucks and shipped to NextEnergy (160 km one-way). Figure 1 shows the life-cycle flow diagrams for the complete process, normalized to 100 MJ.

MICROGRID SYSTEM ANALYSIS

The life-cycle model created for NextEnergy compares the life-cycle performance of the microgrid against the conventional system. The model produces three main outputs for each system that allow for this comparison: system efficiency, total

Table 3. Microgrid system life-cycle assessment results

Life-cycle metric		Conventional system			Microgrid system
		Grid electricity	Thermal	Total	
Total upstream energy use	kW	45	67	112	275
Total combustion energy use	kW	1342	601	1946	1333
Total line losses energy use	kW	111	0	110	0
Total inverter energy use	kW	0	0	0	6
Total life-cycle energy use	kW	1500	668	2168	1614
Total NOx emissions	kg/hour	1.8	0.5	2.3	0.8
Total carbon dioxide emissions	kg/hour	481	108	586	184
Total electrical energy produced	kWh				435
Total heat energy produced	MJ				1624
Microgrid system efficiency	%				54.9
Conventional system efficiency	%		40.9		–

life-cycle energy use and total emissions for NOx and carbon dioxide. Figures 2–3 and Table 3 summarize the results of the analysis.

System efficiencies are calculated based on the total energy output of the system divided by the life-cycle input into the system. Thermal energy and heat energy are combined in order to compare equivalent systems. Although heat and electricity have different thermodynamic qualities, this technique is useful for comparing overall performance. The results are based on an *average* hour of operation for the microgrid and the conventional system, with each unit running at 100% capacity (e.g. PV performance is based on annual average solar irradiation, and microgrid is not displacing peak power).

KEY FINDINGS

The key finding is that, in general, the microgrid has lower emissions than the conventional system and uses less primary energy, due to capturing waste heat and avoiding losses from power transmission over long distances. The NextEnergy microgrid modelled in this analysis shows a 34% reduction in total life-cycle energy and greater than 65% reduction in NOx and carbon dioxide emissions when compared with the conventional system.

The following findings were reached from analysing the specific mix of generating technologies and fuels for the microgrid and the conventional system as defined above.

- The microgrid system has 34% greater life-cycle efficiency than the conventional system under the anticipated microgrid configuration.
- The microgrid system has 66% lower total NOx emissions and 69% lower carbon dioxide emissions than the conventional system. The microgrid system operates based on cleaner technologies and fuels than the conventional system.
- The life-cycle energy consumption of the microgrid system is reduced by avoiding line losses from long-distance transmission of power. Line losses for a conventional system typically account for 8% of the life-cycle energy.
- The microgrid system has higher upstream energy consumption than the conventional system. The microgrid is fuelled 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.

CONCLUSION

The implication of this research for the cogeneration and on-site power industry and policymakers is that there is a methodology available for quantifying the full potential benefits of distributed generation and microgrids. This analysis quantifies and compares the total fuel cycle energy and two pollutant emissions on a life-cycle basis for microgrid and conventional systems. The current life-cycle model can also be adapted to determine life-cycle costs, including both financial and social costs. Most importantly, the industry should start using life-cycle metrics for measuring comparative efficiencies between systems. This holistic approach provides a more complete picture, and is the type of thinking necessary for moving towards a more sustainable energy future.

The full report, Life Cycle Energy and Environmental Analysis of the NextEnergy Microgrid Power Pavilion, can be downloaded from the Center for Sustainable Systems website: www.css.snre.umich.edu.

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