Energy Conversion Options for Energy-efficient Controlled Environment Agriculture

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***Summary*. One of the deterrents to the commercial adoption of controlled-environment agriculture (CEA) on a broad scale is the significant energy cost for lighting and thermal environmental control. Advances in energy conversion technologies, such as internal combustion engines (ICs), microturbines and fuel cells, offer the potential for combined heat and power (CHP) systems, which can be matched with the needs of CEA to reduce fossil-based fuels consumption. A principal concept delineated is that an integrated entrepreneurial approach to create business and community partnerships can enhance the value of energy produced (both electrical and heat). Energy production data from a commercial dairy farm is contrasted with energy use data from two greenhouse operations with varying energy-input requirements. Biogass produced from a 500-cow dairy combined with a 250-kW fuel cell could meet nearly all of the energy needs of both the dairy and an energy-intensive 740-m^2 CEA greenhouse lettuce facility. The data suggest CEA greenhouses and other closely compatible enterprises can be developed to significantly alter agriculture, as we have known it.**

This paper begins with the premise that agriculture is much more than food production, but is also a major source of natural raw materials for bioindustries and energy and thus, a significant engine to drive our transition to a sustainable world. We start with the concept of sustainable development as the driving force in suggesting a vision for change to integrated energy and entrepreneurial agricultural enterprises. We will illustrate the potential opportunity to develop a real system by providing data and analysis for an integration of a dairy farm with a controlled-environment agriculture (CEA) greenhouse.

Sustainable Development

The world is in transition to one where there will be more people, greater consumption of materials and resources, more connectivity and a need to reduce poverty without destroying the environment. Over the past 2 decades, sustainability has become a principal concept to integrate technological, economic, social and political issues to address environmental protection and economic development.

Hatch (1992) wrote, "Sustainable development is the dominant economic, environmental and social issue of the 21st century." It is an idealistic concept, which has its origins in the report, *Our Common Future*, by the United Nation's World Commission on Environment and Development (1987) (chaired by Gro Brundtland): sustainability means, "meeting the needs of the present without compromising the ability of future generations to meet their own needs." Many have suggested definitions building upon this report. We particularly like Weston's (1993) description of the concept and impetus for action: "Sustainable development is a process of change in which the direction of investment, the orientation of technology, the allocation of resources, and the development and functioning of institutions meet present needs and aspirations without endangering the capacity of natural systems to absorb the effects of human activities, and without compromising the ability of future generations to meet their own needs and aspirations."

Thus, sustainable development is a process of redirection, reorientation and reallocation—an evolving one rather than a definition. As we see it, it is a fundamental redesign of technological, economic and sociological processes to address change. We emphasize that the design of processes, at all levels, is absolutely essential to the concept of cradle to cradle thinking that is inherent to sustainable development (McDonough and Braungart, 2002).

A sustainable system will require integration of many sectors. To develop our thesis that agriculture will be an increasingly important part of any scenario, domestic or international, in transitioning toward a sustainable world, we address the concept of industrial ecology. A network of material and energy flow resembles an industrial ecology where the resources are optimized by integrating the entire process, minimizing the waste generated at each step of the process, and maximizing the reuse of waste at each step of the process. Graedel and Allenby (1995) developed the first textbook on industrial ecology with a focus on lifecycle assessment and design for environment. Indigo Development, a development division of RPP

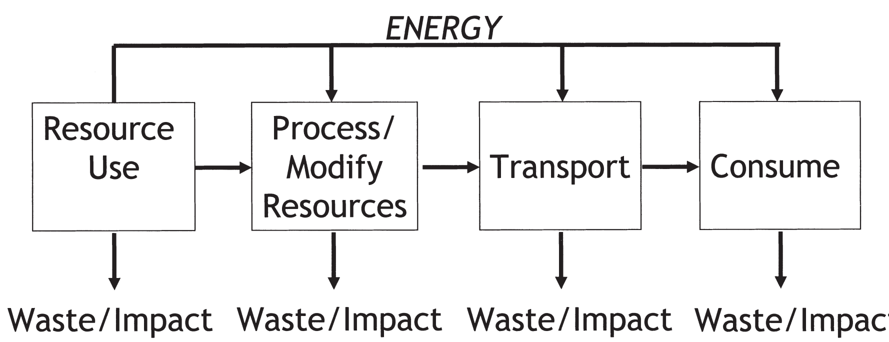

Fig. 1. Linear systems approach (Roberts, 1994).

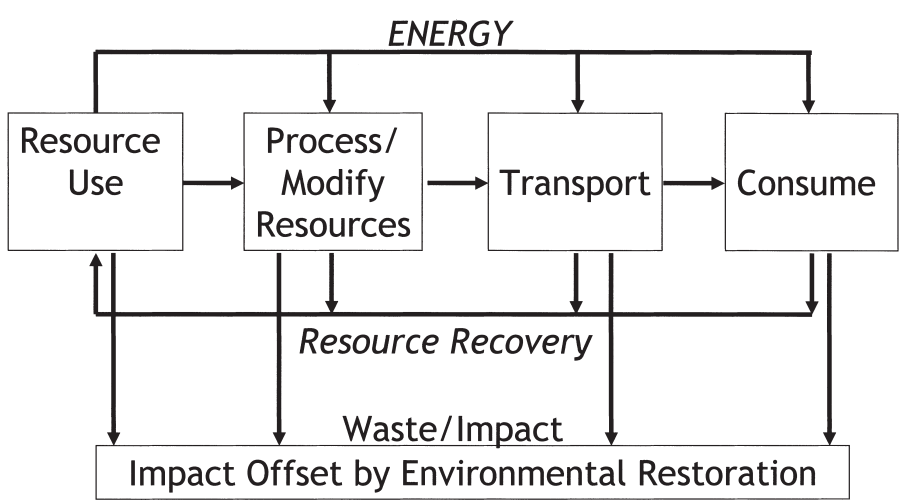

Fig. 2. Incorporating concepts of sustainability (Roberts, 1994).

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International (1998) has summarized over 25 definitions and developed a list of common themes. These themes form a framework for the concept of sustainable agriculturally-based communities.

Historically, CEA greenhouses have been viewed as being so energy-intensive as to be limited to use in research settings. We will present data to demonstrate that protected horticulture technologies, such as CEA, might play an integral role in an industrial ecology system by increasing the value of energy produced by another component of the system.

Systems Thinking

Typically the developed world has used a linear approach to use and management of resources (Roberts, 1994). Natural resources have been extracted without serious consideration of their long-term availability. These resources have been processed into products, which are transported to consumers where all too often their disposal has been without consideration of environmental impact (Fig. 1). Unlike ecosystems we have operated as an open loop where resources are unlimited, there is an unlimited ability to produce products and a limitless source for waste disposal.

Roberts (1994) suggests that we must function like an ecosystem where use, processing, transportation and consumption of resources flow as a closed loop with feedback (Fig. 2). Throughout the process, wastes are minimized and by-products are recycled as recovered resources. Energy is minimized by improvements in efficiency and increasingly non-fossil sources should be developed. Engineering design is the crucial piece in this whole process to create new innovative processes and products.

Global Biologically Integrated Sustainable Communities (GBISCs)

Throughout the history of humankind agriculture has been the source for food and natural raw materials to sustain humans. However, in much of the developed world, during the 20th century, a major shift to a petroleum-based economy lead to the present dependency on fossil fuels for energy and raw materials for industry and agriculture. The time is right to begin the transition to sustainability by re-engineering our supply for raw materials and energy from biobased sources (NRC, 1999). Sustainable agricultural and rural development in the developing world is also an issue of great urgency and concern. The agricultural sector, more than any other, is critical to economic success because of huge pressures on the natural resource base in addition to social and institutional stresses. The challenge is to rethink how the material needs of society can be met by using agriculturally based systems. This rethinking involves an integration of science and engineering with an emphasis on ecological processes and socio-economic phenomena.

The challenge is to create a sustainable entrepreneurship at the local community scale that integrates energy, environmental, agricultural and industrial innovation. It is out of this context that we (Scott, 1992) propose the concept of global biologically integrated sustainable communities (GBISCs). A GBISC is a community with characteristics of biologically derived fuels; renewable energy systems; total recycling; energy conservation; low-energy and close proximity transportation for the work and living environment; managed ecosystems for treatment of waste water, retention of wetlands and promotion of landscape ecology; sustainable enterprises developed from agriculturally-based bioindustries, including both new molecular technologies as well as new bioindustries compatible with community resources; and infrastructure development to take advantage of the advances in information technologies for communication, both internal and external to the community.

Example of Integration of Technologies

The following example analyzes the potential integration of a dairy farm with a CEA greenhouse. Using the systems approach, waste from the dairy farm is recovered to produce energy. The energy is used to run the dairy operation and excess energy is used as a source to run greenhouse operations. Using the energy for greenhouse operation rather than selling excess energy back to the grid increases the value of the waste-energy by decreasing the cost of the greenhouse operation.

Dairy farm as energy source

Inappropriate technologies are frequently

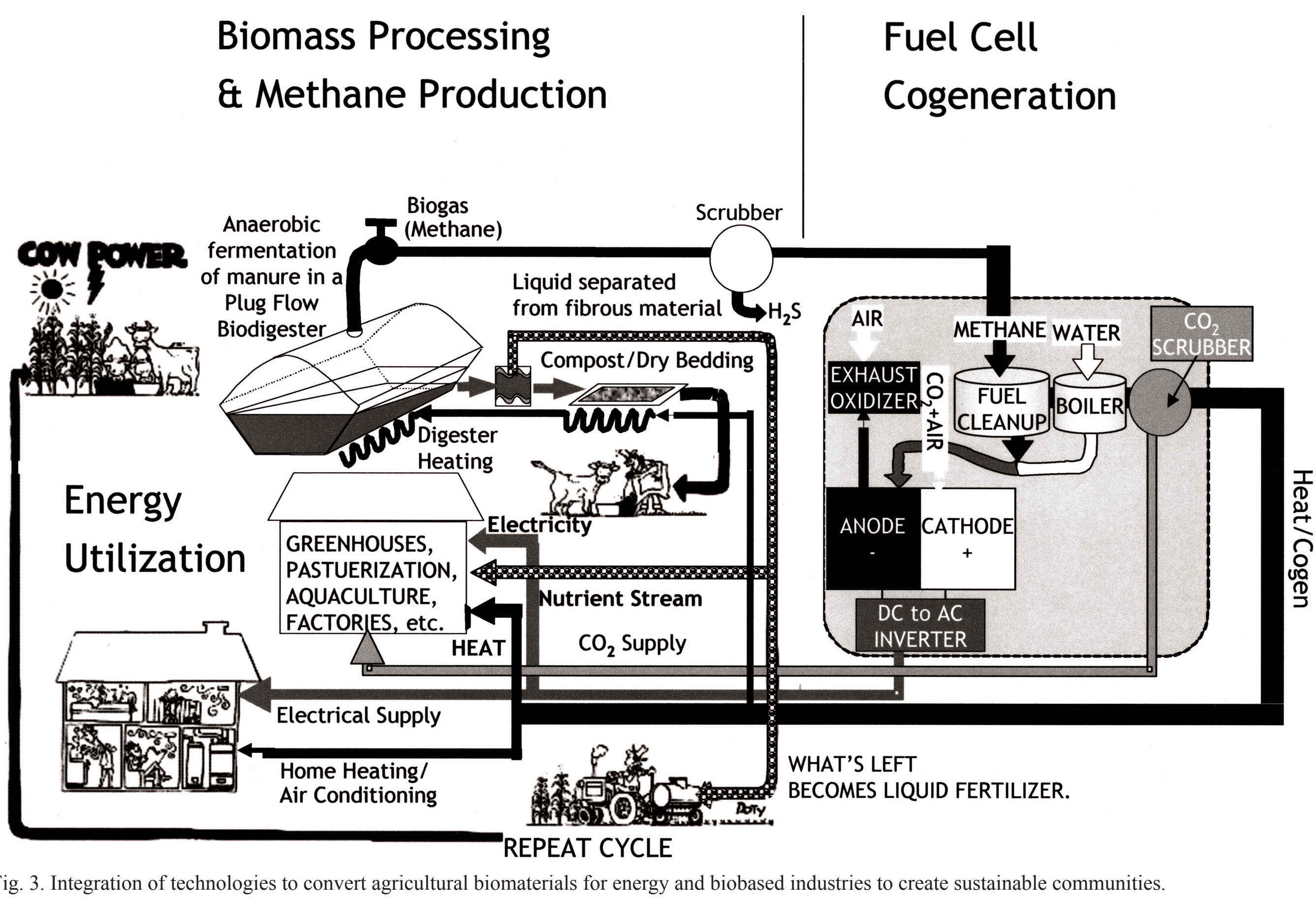

Fig. 3. Integration of technologies to convert agricultural biomaterials for energy and biobased industries to create sustainable communities.

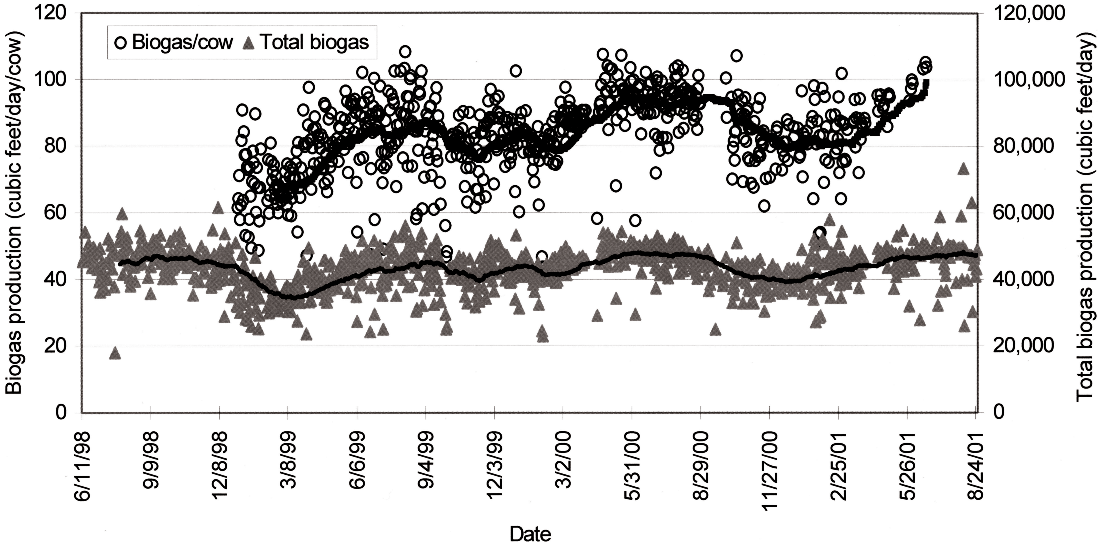

Fig. 4. Total biogas production and biogas production per cow per day at AA Dairy (1999–2001).

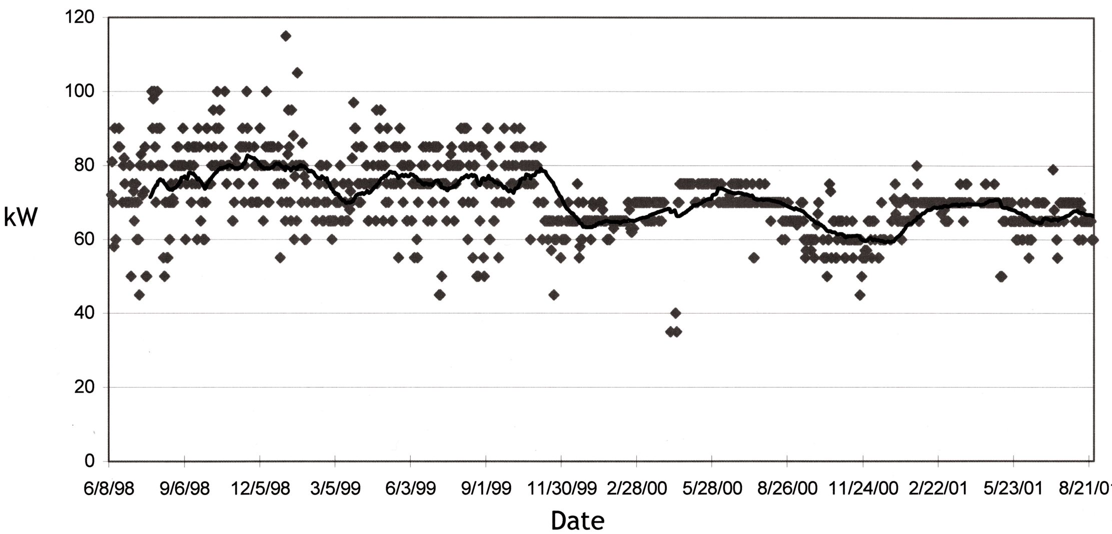

Fig. 5. IC engine-generator performance indicates that electricity produced on the AA Dairy farm ranged from about 60 to 80 kW (1400 to 2000 kW-h·d^{-1}).

blamed for the failures of environmental and agricultural systems. For far too long waste disposal has been a primary mode of management when, instead, the focus should be on a total resource recovery approach. An example of an innovative potential technology that should be investigated as a centerpiece of a total resource recovery system is the possible use of energy conversion technology to convert biogas directly into electrical and thermal energies for both on-farm uses and to supply community energy needs (Fig. 3). This figure captures the vision of the dairy farm as a system of material and energy flows. It is predicated on the principle of total resource recovery and manure management with respect to energy generation and effluent management of the flow of liquids and solids. Such an approach offers the opportunity to expand agricultural operations (in this case a dairy) from just a farm product (milk) to a contemporary system of 1) producing other bioproducts, 2) developing energy which can drive more integrated food and fiber production systems, as well as, 3) generating energy for enterprises on or near the farm or for energy needs of a surrounding community. Figure 3 assumes the energy converter is a fuel cell, although the basic function of producing CHP can be accomplished with an IC engine-generator set or a microturbine, albeit with significant differences in energy conversion efficiencies among these devices.

Anaerobic digestion

To illustrate the realism of these ideas, we use AA Dairy (Candor, N.Y.) as our example in order to use real data for an analysis linked to a CEA greenhouse. A plug flow digester with a 1,000-cow capacity designed by RCM Digesters, Inc. is installed at AA Dairy. It is a buried concrete manure storage structure, 40 m long × 9 m wide × 4.5 m deep. The digester is equipped with an airtight expandable black rubberized dome to trap biogas consisting of methane, carbon dioxide, hydrogen sulfide, and other trace gases from the digesting manure. The manure is kept at about 38 °C in the digester for optimal biogas production. A solids-liquid separator, a 130-kW Caterpillar 3306 modified diesel engine connected to a generator, and a lined liquid-waste storage lagoon are features of the current resource recovery system. Thermal and electric energy generation, digested fiber for compost, and liquid fertilizer are byproducts of the existing digestion system.

Data have been collected daily and the average biogas flow from the digester at AA Dairy (herd size of 500 cows) has been between 990 to 1415 m^3·d^{-1}, or about 1.7 to 2.8 m^3/cow/day (Fig. 4). The gas is collected, filtered, measured and slightly pressurized before being used to fuel a 130kW (3306 Caterpillar) engine. The engine is a diesel block with a natural gas head that has been converted to run on methane. The engine runs an induction generator to produce electrical energy at the current average of about 70 kW (about 613,000 kW-h·year^{-1}) with downtime about 5%. Electricity produced meets the electricity needs for the dairy farm and provides some excess electrical power for sale to the local utility (New York State Electric & Gas (NYSEG)) at wholesale prices. IC engine-generator performance is shown in Fig. 5 and indicates that electricity produced on the farm ranges from about 1400 to 2000 kW-h·d^{-1} (about 60 to 80 kW).

Table 1. Shushan Underwood Farms Greenhouse energy use for production of about 100,000 pounds of tomatoes per year before and after the installation of supplemental lighting.

Year	12-month electricity (kWh) Before lamps	After lamps	12 month coal + heating oil (therms)[z]
1999	73,040		Not available
2000	77,320		77,000
2001	81,560		78,000
2002		197,240	67,000
2003		238,160	103,000[y]
Average per year	77,307	217,700	81,250
Average per Month	6,442	18,142	6,771
Average per Day	212	596	223
Average per Hour	9	25	9
Average per pound of tomatoes (‘Trust’)	0.7	1.7	0.7
Average per kg of tomatoes	1.6	3.7	1.5
Average per square foot production area per year	7.3	20.6	7.7

[z]Estimated based on 24 million Btu/ton bituminous coal, and 139,000 Btu/gallon heating oil.
[y]2003 record cold winter season.

Another option for use of excess low-cost electrical power is to use the electricity to power another facility that 1) would be cost-prohibitive to run with power purchased directly from the grid and 2) can produce a product of higher value than the value of the excess electrical power alone. To assess whether this may be feasible, we examined two greenhouse operations with widely varying power-consumption rates.

Energy requirements in two New York greenhouse facilities

Energy requirements from two greenhouses in New York were estimated for this analysis. The first greenhouse is a family owned operation that uses a small amount of supplemental lighting and temperature control for tomato production. This greenhouse will be considered under two conditions: before and after the installation of supplemental lighting. The second greenhouse, the Cornell CEA Greenhouse is more energy-intensive and uses CEA technology to control several aspects of the environment.

Underwood Farms (Shushan, N.Y.) greenhouse. The Underwood Farms Greenhouse in Shushan is an example of a family owned and operated tomato production greenhouse with lower energy use than the Cornell CEA greenhouse. The Underwood Farms facility used about 77,000 kW-h·year^{-1} before installing supplemental lighting and uses about 218,000 kW-h·year^{-1} using supplemental lighting only during night (off-peak) hours. The facility provides production of 100,000 lb of high quality tomatoes from February through November from an area of 980 m^3 or about 0.1 ha. The facility requires the labor of 2 persons for 8 h·d^{-1}. A supplemental lighting array (144 high-pressure sodium, 600-W lamps) was installed in the facility and is powered only after cloudy days and only during off-peak hours using a simple on/off timer. The owners estimate a 14% increase in tomato production with the use of supplemental lighting (data not shown). Although the cost to produce a pound of tomatoes increased with supplemental lighting, the increase in pounds of tomatoes produced economically justified the additional production cost. Electricity usage (kW-h) was obtained for five years (1999–2003) from utility billing statements (Table 1).

The average energy used per kg of tomato was 3.7 kW-h (electricity) and 1.5 therms (coal and heating oil). We would expect to observe a reduction in heating fuels after the HPS lamps were installed. After the supplemental lighting installation, the 2002 data show a reduction in the heating fuel used compared to 2001 and 2000. However the 2003 winter season was unusually cold in the region, as reflected in the Therms of coal and heating oil required. Electricity usage data for Underwood Farms was collected from utility billing statements (1999–2004). As expected, use of supplemental lighting during the winter months changed the seasonal electricity usage patterns of the farm (Fig. 6).

Cornell CEA greenhouse. The Cornell CEA Greenhouse is an example of a production greenhouse with high energy use. The Cornell CEA facility uses about 600,000 kW-h of electricity per year and provides year-round production of high quality leafy greens including ‘Boston Bibb’, ‘Romaine’, ‘Red Leaf’, and several other unique varieties of lettuce in Ithaca, New York. This hydroponic facility produces 1200 heads of lettuce per day, year round in an area of 740 m^2 or about 0.07 ha. The facility was sized specifically for operation by a single-family farm and requires the labor of 2.5 persons for 8 h·d^{-1}.

CEA greenhouse technology permits precise matching of environmental parameters with plant requirements (Albright, 1997, Both et al., 1998). Initial work on Cornell CEA lettuce led to a commercial scale CEA food production prototype module. Currently producing high quality lettuce, a crop that meets Food Safety (HACCP) standards with no post-harvest treatment, the CEA Lettuce Greenhouse Module is demonstrating exceptional productivity (500 tons/acre/year). Integral to the CEA production method is a proprietary algorithm developed by Albright (1998). This algorithm regulates production to a constant daily rate by providing precisely the correct amount of light for maximum photosynthetic activity. Further, it maximizes use of natural light, controlling shades and supplemental light according to minimum total cost economic rules. The effect is a year round, constant daily rate of production (Ferentinos et al., 2000; Albright et al., 2000). Continued optimization work is leading to additional sophisticated computer control algorithms able to adjust the daily light integral, carbon dioxide concentration, supplemental cooling, and ventilation control to maximize plant productivity while simultaneously minimizing the energy costs of environmental modification (Albright et al., 2004). Central to the work is a focus on creating for each plant, its ideal microclimate in an economical way.

Electricity usage (kWh) and natural gas

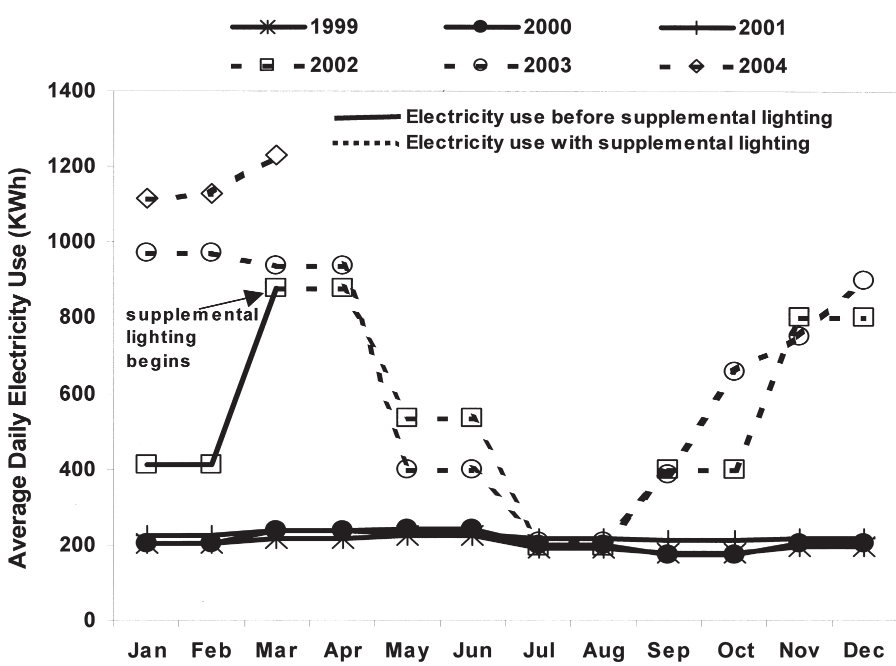

Fig. 6. Average daily electricity usage data from 1999–2004 show that after supplemental tomato greenhouse lighting begins (2002), there is a significant change in the seasonal electricity consumption patterns.

Table 2. CEA Greenhouse energy use for production of 1200 heads of lettuce per day.

Year	12-month kW-h (electricity)	12-month therms (natural gas)
2000	663,680	38,544
2001	608,165	26,821
2002	515,360	28,898
2003	595,440	27,950
Average per year	595,661	30,554
Average per month	49,638	2,546
Average per day	1,632	84
Average per hour	68	3
Average per 150 g head of lettuce (about 5 oz)	1.4	0.1
Average per pound lettuce	4.4	0.2
Average per kilogram lettuce	2.0	0.1
Average per square foot production area per year	74.5	3.8

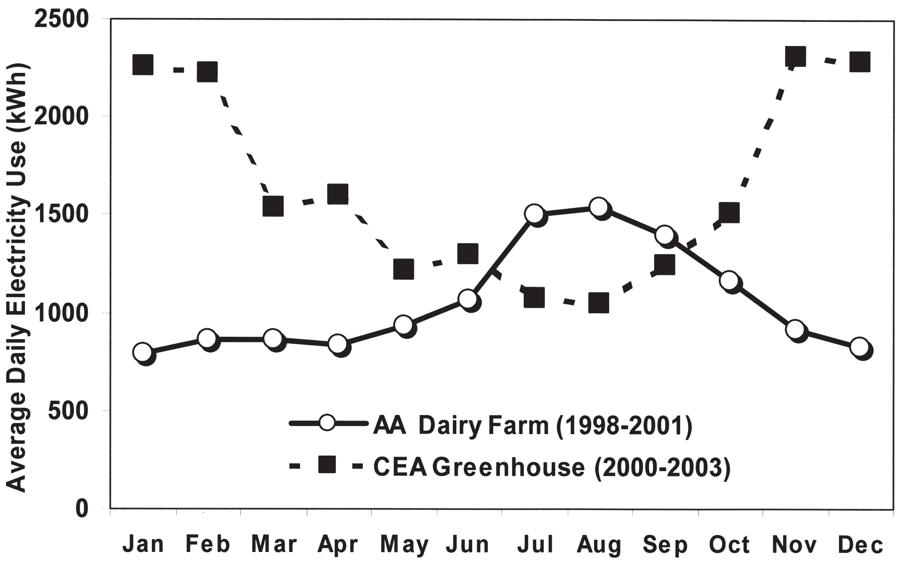

Fig. 7. The average daily energy used on the AA Dairy Farm (from 1998–2001) compared to average daily energy used by the Cornell CEA Greenhouse (from 2000–03) shows seasonal peaks occurred in summer for the dairy farm and in winter for the greenhouse.

usage (therms) were obtained for four years (2000–03) from monthly utility billing statements (Table 2). The average energy use per 150 g (5 oz.) head of lettuce was 1.4 kWh (electricity) and 0.1 therms (natural gas). When CEA greenhouse electricity usage was plotted on a monthly basis and compared to the AA Dairy electricity usage, it can be seen that the highest usage months were during winter and the lowest usage months were during summer. This is the opposite of the usage pattern of the dairy farm, suggesting the two systems may be a good complement to one another (Fig. 7) from an industrial ecology perspective.

Integrating the Systems

Three scenarios will be considered in integrating the AA Dairy farm energy data set with greenhouse energy data. In the first scenario, the least energy intensive (about 80,000 kW-h·year^{-1}) Underwood Farms tomato greenhouse before supplemental lighting installation is considered. In the second scenario, the more energy-intensive (about 225,000 kW-h·year^{-1}) Underwood Farms year-round tomato greenhouse with supplemental lighting is considered. In the third scenario, the energy-intensive (about 600,000 kW-h·year^{-1}) CEA greenhouse is considered.

Scenario 1. Before the supplemental greenhouse lighting was installed, the data show the combined (greenhouse + dairy) energy use varied seasonally (Fig. 8) from about 1000 kW-h·d^{-1} in December through April to about 1700 kWh per day in August. Without supplemental lighting, the greenhouse could not produce tomatoes in the winter months, thus the combined usage patterns follow the usage pattern of the Dairy Farm alone.

For the analysis, if we assume that a 250 kW fuel cell operates at 50% efficiency, then the daily (24 h) potential supply would be (50% × 250 kW × 24 h) 3000kWh. An IC engine operating at a typical 20% efficiency could provide (80 kW × 24 h) 1960 kW-h·d^{-1}. The IC engine system would be sufficient to supply the combined energy needs of the Dairy farm and this summer-production greenhouse.

Scenario 2. Considering the combined electricity requirements of the AA Dairy Farm and the Underwood Farms Greenhouse WITH supplemental lighting, the combined (greenhouse + dairy) energy use varied seasonally from about 1400 kW-h·d^{-1} in May to about 1900 kW-h·d^{-1} in February (Fig. 9). The supplemental lighting of the greenhouse allows winter production (when growers can obtain a higher price per pound of tomato from the market). This scenario suggests that an IC engine would be sufficient to supply the electricity needs of both the AA Dairy and the Underwood Greenhouse throughout the year, with excess energy production in most months of the year.

Scenario 3. Bringing the AA Dairy farm and CEA greenhouse facility 4-year data sets together (Fig. 10) demonstrates that the AA dairy farm combined with the energy used by a CEA greenhouse ranged seasonally from about 2200 kW-h·d^{-1} in May to about 3200 kW-h·d^{-1} in November through February. The data suggest a 250-kW fuel cell will almost meet the energy needs of both facilities. An IC engine also will meet a significant portion of the electrical energy needs of both operations.

Conclusions

The combined dairy and greenhouse system may provide an efficient energy-integration that allows excess energy produced by a dairy operation to be used by a greenhouse operation. The data presented suggest both businesses may benefit from such an integration. Selling electricity to a neighboring greenhouse rather than selling it back to the local utility's power grid could increase the value of the excess energy produced by the dairy farm. The greenhouse would also benefit from a lower-cost energy source. Three levels of greenhouse electricity-use were considered: 1) The Underwood Farms summer production greenhouse without supplemental lighting (consuming about 80,000 kW-h·year^{-1}); 2) The Underwood Farms year-round production greenhouse with supplemental lighting (consuming about 225,000 kW-h·year^{-1}); and 1) The Cornell CEA greenhouse (consuming about 600,000 kW-h·year^{-1} for year-round production).

The data suggest the integration of a 500 head dairy farm with a greenhouse would be beneficial across the range of greenhouse energy-use scenarios presented. An IC engine would be sufficient to meet the energy requirements of the combined AA Dairy and Underwood Greenhouse (summer or year-round production greenhouse). A 250-kW fuel cell will meet most of the electrical energy needs of the combined AA Dairy and the Cornell CEA Greenhouse. We suggest a potentially innovative and economically successful route to creating sustainable business and community partnerships is to enhance the value of energy produced, both electrical and thermal.

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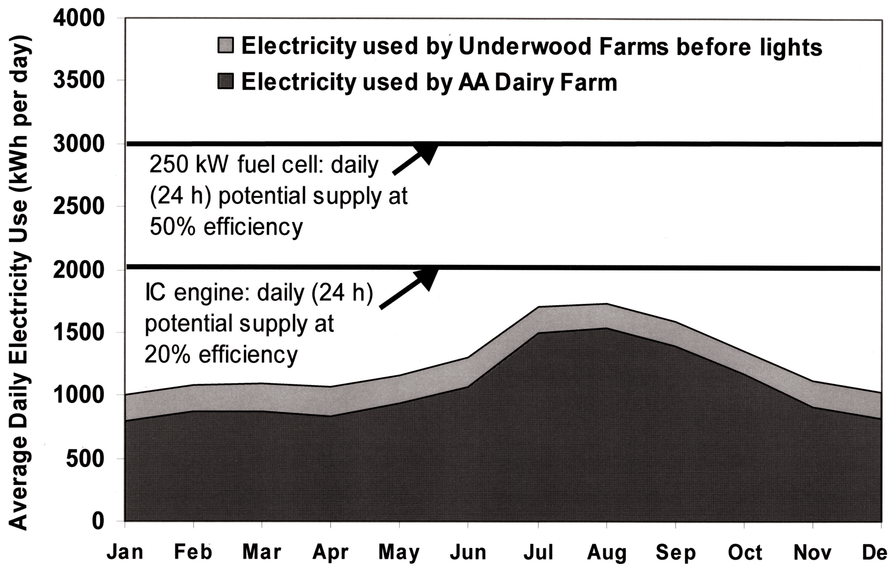

Fig. 8. Combined average daily energy use of the AA Dairy Farm and the Underwood Farms greenhouse BEFORE supplemental lighting was installed suggests an IC engine will meet the electricity needs of this type of greenhouse-dairy combination.

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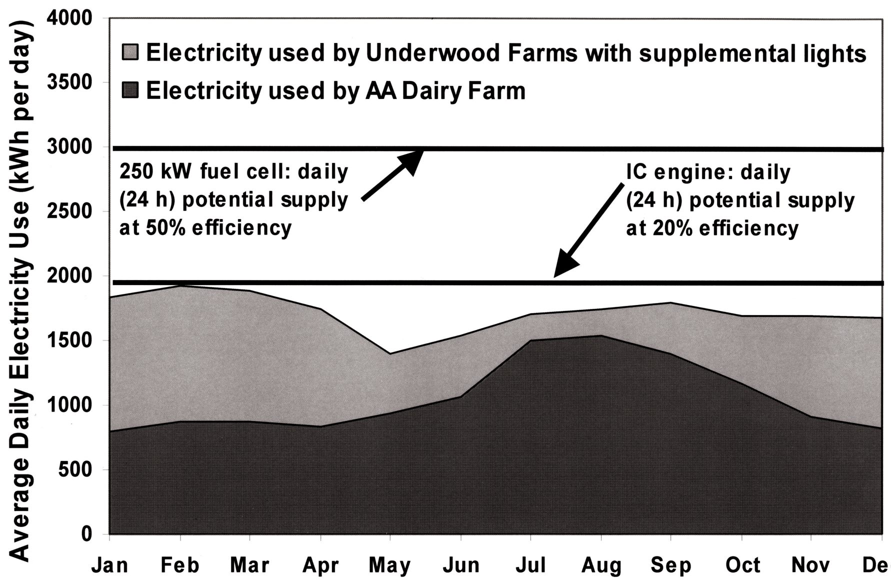

Fig. 9. Combined average daily electricity use of the AA Dairy Farm and the Underwood greenhouse WITH supplemental lighting (allowing winter production) suggests an internal combustion (IC) engine is sufficient for the electrical energy needs of both facilities.

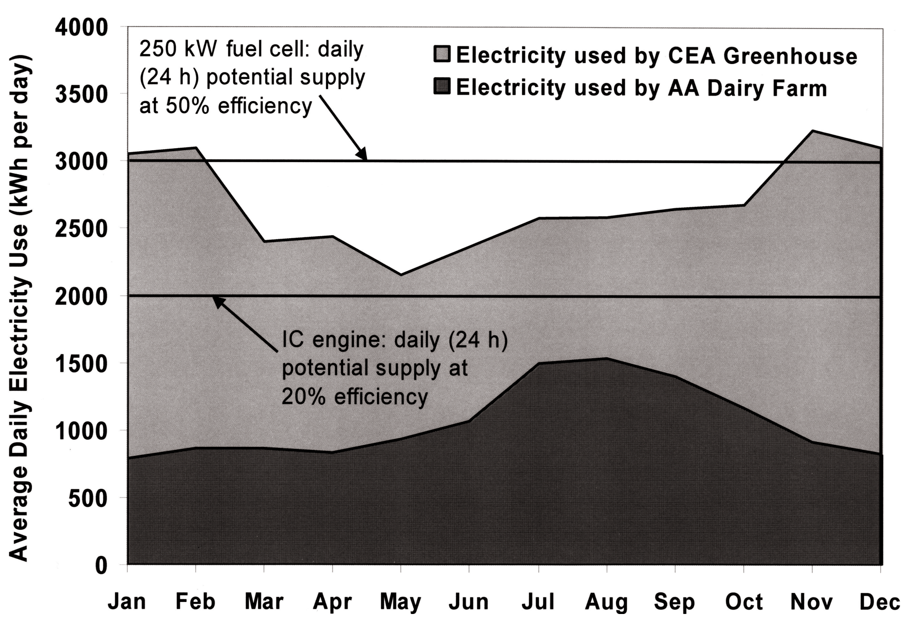

Fig. 10. Combined average daily electricity use of the AA Dairy farm and the Cornell CEA greenhouse suggests a 250-kW fuel cell operating at 50% efficiency will almost meet all of the electrical energy needs of both facilities. An internal combustion (IC) engine also will meet a significant portion of the electrical energy needs of both facilities.