Alternative greenhouse heating systems

Bryan M. Jenkins

Biomass and cogeneration systems offer potential for savings

Greenhouses are the fifth largest energy user in California agriculture, accounting for almost 7 percent of agricultural energy demand. Conventional heating systems utilize direct combustion of natural gas, liquefied petroleum gas, or fuel oil to provide heat for boilers, water heaters, and unit heaters. Several alternatives to conventional heating methods are heat pumps, biomass systems, and cogeneration systems. A comparison of these to conventional systems indicates that biomass and cogeneration systems offer substantial benefits throughout the state, while the feasibility of heat pumps depends on electricity rates and, hence, on the geographic location of the greenhouse.

Heat pumps

Heat pumps use electricity to transfer heat from the outside environment to the inside of the greenhouse. An organic fluid such as dichlorodifluoromethane (R-12) or monochlorodifluoromethane (R-22) is passed through a heat exchanger, where it absorbs energy from the outside environment and vaporizes. This vapor is compressed and then passed through a second heat exchanger (condensor) inside the greenhouse. The vapor condenses and releases heat. The high-pressure liquid returns to a reservoir and then through an expansion valve back to the evaporator. Electricity drives the compressor, fans, and pumps in the heat pump system.

The thermal energy source can be the outside air, groundwater, surface water, the soil, or direct solar energy. Groundwater-source heat pumps are suitable for California because of the high groundwater temperatures, ranging from 56°F in the north to 74°F in the south. The ability of a heat pump to extract energy from the environment, as measured by the coefficient of performance (COP), improves as the source temperature approaches the temperature of the space to be heated. The coefficient of performance is defined as the ratio of the heat energy delivered by the heat pump (H_{out}) to the electrical energy used to drive the compressor, fans, and pumps in the system (E_{in}):

$$COP = H_{out}/E_{in}$$

With source temperatures at 60° to 70°F, the COP is typically in the range of 3.5 to 4. When the source temperature drops to 0° to 10°F, the COP falls to about 1, and the heat pump has no advantage over electrical resistance heating. The groundwater-source heat pump in California achieves a higher coefficient of performance for heating than an air-source heat pump. Heat from the pump can be produced in the form of heated air or hot water.

Because most heat pumps use electricity, their widespread adoption could induce a load shift for electric utilities, increasing electricity demand at night and in the winter, and reducing natural gas consumption. As will be seen later, time-of-use rates would be required to induce a shift to this technology.

Heat pumps save energy when compared with conventional systems only if operated at a high coefficient of performance. For example, if the value is 3 and the utility is generating and transmitting electricity at an average efficiency of 25 percent, the heat pump is equivalent to a natural gas boiler operated at 75 percent thermal efficiency. Large-scale energy savings are not likely to occur as a result of the use of heat pumps. In fact, the opposite may occur if air-source heat pumps without solar assist are used to a large degree. The utility may, however, be capable of burning other types of fuels that the greenhouse operator may not want to use, and the heat pump would allow the grower to continue using a convenient energy source for heating.

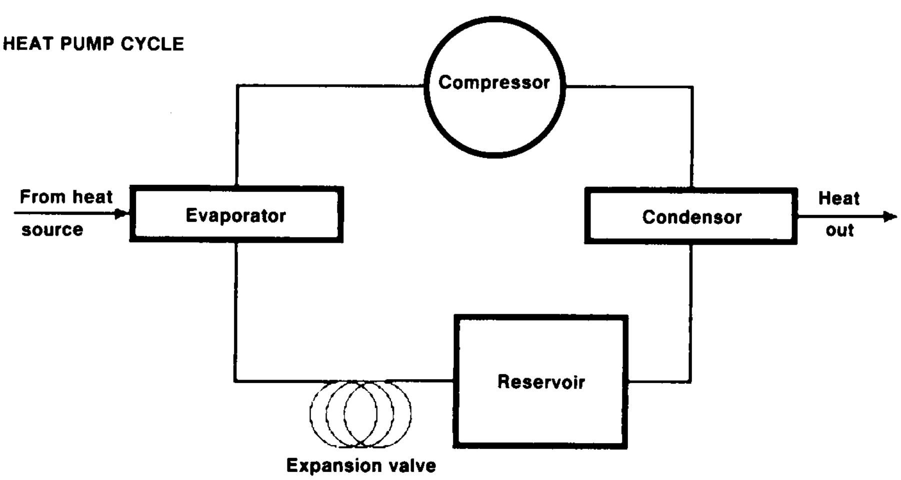
Biomass systems

Biomass can be used in a number of ways to provide greenhouse heating. Direct combustion and gasification systems are currently being tested on commercial greenhouses in California. Wood is the primary fuel considered for these systems, but other forms of biomass are also available. Peach pits are being used in a gasification system with subsequent combustion of the low-energy gas in a water tube boiler.

Biomass is an inexpensive source of energy: at $30 a ton delivered to the greenhouse, it is equivalent to 18 cents a therm, or about one-third the current cost of natural gas. Biomass systems usually operate at lower thermal efficiencies than natural gas systems. One ton of dry wood will provide approximately the same heat as 16,000 cubic feet of gas, or 160 therms.

Biomass is by no means as convenient to use as natural gas. Storage is required, preferably covered storage, and additional management time is needed. As development continues, automatic control systems will reduce management requirements. Emissions from biomass systems are more of a problem, and systems to

HEAT PUMP CYCLE



Heat pumps extract warmth from outside air by passing a fluid through a heat exchanger, where it absorbs energy and vaporizes. When the vapor is compressed and passes through a second heat exchanger inside the greenhouse, it condenses and releases heat.

control particulates may need to be installed.

The heating value of biomass fuels is a measure of the energy released during combustion. The heating value of field crop residues varies from 6,500 to 7,500 British thermal units (Btu) per pound dry basis, wood fuels from 8,000 to 9,500 Btu per pound, and fruit pits and nut shells from 8,500 to 10,000 Btu per pound. The ash content of biomass varies from a low of less than 0.5 percent for high-quality wood chips, to over 30 percent for cotton gin trash and poorly handled fuels with large amounts of dirt. The low ash levels are preferred, not only because there is less ash to dispose of, but also because they reduce the tendency for slagging, or melting, of the ash. Slagging is a serious problem with high-ash fuels in combustors and gasifiers. Research is under way on design and operation of biomass conversion systems to avoid these problems.

Cogeneration

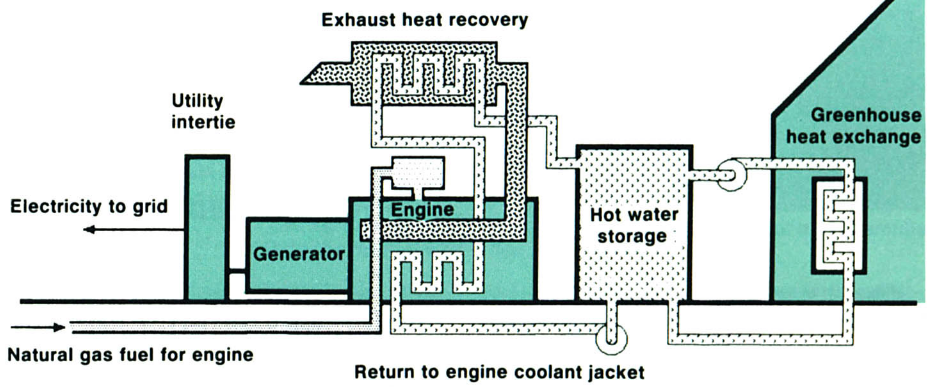
Cogeneration refers to the simultaneous generation of heat and electricity and, in the case of greenhouse cogeneration, to the use of waste heat from an engine. The engine, fueled by natural gas, drives a generator, and electricity is sold to the local utility. The Public Utilities Regulatory and Policy Act of 1978 (PURPA) stimulated commercial development of cogeneration systems in the United States. PURPA requires utilities to offer to buy electricity from qualified cogenerators and pay the cogenerator the "avoided" cost for the power produced. For almost every utility in California, the marginal energy source for power generation is natural gas, and the avoided cost is based on the cost of natural gas for utility power generation.

Cogeneration is a way to insulate the greenhouse heating operation from fluctuations in the price of natural gas, even though the greenhouse is essentially still being heated with natural gas. If the system is operated at high efficiency, the revenue from the sale of electricity will pay for the natural gas fuel. The major constraint on cogenerators using natural gas for the engine relates the useful energy produced by the system to the fuel energy consumed. Specifically, the ratio of the sum of the total annual electrical energy produced (E_p) and one-half the useful thermal energy used in the greenhouse (E_t) to the total annual fuel energy consumed by the engine (E_f) must be equal to or greater than 0.425:

$$(E_p + \tfrac{1}{2} E_t)/E_f \geqslant 0.425$$

This constraint limits the size of the engine that can be used and requires careful matching of the thermal demand in the greenhouse and the electrical production of the generator. The design of a cogeneration system is further complicated by contractual arrangements with the utility. Most utilities offer additional benefits in the form of capacity payments if the cogeneration system is dispatchable, which means that the system must be operated if the utility desires it to be on line during times of peak electrical demand. The capacity payments are a substantial source of revenue, but the peak electrical demand occurs in the summer when heating may not be needed in the greenhouse. Operation of the system to meet the dispatch requirement when there is no useful thermal demand for the waste heat may result in the above ratio being less than 0.425 over the course of a year, and the cogenerator would not qualify for the avoided cost rates. The selection of a cogeneration system requires careful evaluation of all these factors.

GREENHOUSE COGENERATION SYSTEM



A cogenerator engine uses natural gas to produce electricity that can be sold to a local utility and uses the waste heat to heat a greenhouse. If the system is operated efficiently, the sale of electricity pays for the natural gas fuel used.

Cogenerators can purchase natural gas at a lower rate than they would pay for it in direct greenhouse heating; it is essentially the same cost the utility pays (or charges itself) for gas to run its power plants. Because natural gas is the marginal energy source for most utilities in California, the avoided cost can be computed directly from the cost of gas to the cogenerator. The avoided cost is calculated by multiplying the price of gas by the heat rate of the utility. The utility heat rate is the amount of fuel energy used to produce one unit of electrical energy. If a utility is operating at a system average efficiency of 25 percent, the heat rate is:

$$\text{Heat rate (Btu/kWh)} = 3{,}413/0.25 = 13{,}652$$

This means that the utility uses 13,652 Btu of fuel to produce 1 kilowatt-hour (kWh) (3,413 Btu) of electrical energy. If the same utility pays 55 cents per therm for natural gas used in its power plants, the avoided cost is:

$$\text{Avoided cost} = [(\$0.55/\text{therm})/100{,}000\ \text{Btu/therm}] \times 13{,}652\ \text{Btu/kWh} = \$0.075/\text{kWh}$$

The avoided cost varies among utilities because of differences in the heat rate and the price of gas. The heat rate depends on the time of year and the type of plants being used (peaking plants are generally less efficient than base-load or intermediate-load plants).

Cogeneration can result in substantial energy savings. One therm of natural gas used in a cogeneration plant will produce 8.8 kWh of electricity and 0.35 therm of useful heat for the greenhouse, assuming that the thermal efficiency of the engine/generator is 30 percent and half of the engine waste heat is recovered. To produce the same amount of energy separately would require 1.5 therms, or 50 percent more natural gas.

The adoption of a cogeneration system may require some changes in the existing greenhouse heating system. Hot water or steam can be produced, but hot water is easier to handle, because some storage is necessary to meet peak heat demands. Additional piping may be required to increase heat transfer if the greenhouse previously had a steam system. The engine should be placed so that exhaust gases do not enter the greenhouse, but should not be placed so far from the house that excessive heat losses occur.

Comparison of heating systems

Heat pump, biomass, and cogeneration systems were compared with the use of a computer model developed to size and cost each system. The size of the heat pump and biomass systems is based on peak heat demand of the greenhouse. The size of a cogeneration system is based on both peak heat demand and the annual heat demand profile. Peak heat demand is computed from the geometry of the greenhouse, the cover type, the location, and the minimum night temperature desired inside. A comparison of systems is included here for a greenhouse range consisting of 16 gutter-connected doublepolyethylene-covered houses. Houses are assumed to be of gable type, 21 feet wide by 144 feet long, with a 10-foot-high gutter and 16-foot-high ridge. Total floor area is 48,384 square feet. Total volume of the range is 628,992 cubic feet. Minimum inside night temperature was assumed to be 65°F. Heat demand was calculated from surface losses and an assumed infiltration rate of 0.7 air changes per hour.

Comparison of peak heat demand for the greenhouse in three locations shows that Sacramento has the lowest design outdoor temperature and the highest peak demand (table 1). Annual heat demand is highest in San Francisco with its cool, coastal weather conditions. A conventional gas-fired boiler system was used for comparison with the alternative systems. Natural gas consumption was computed for a boiler efficiency of 70 percent. The cost of heating the range varies from about $18,000 in San Diego to almost $37,000 in San Francisco with natural gas at 65 cents per therm.

Annual savings resulting from the installation of heat pump systems at the three locations are listed in table 2. The size of each system is based on groundwater heat pumps. A coefficient of performance of 3.6 was used for the San Francisco and Sacramento conditions, and of 4 for San Diego. The heat pump systems are characterized by fairly long payback periods, particularly in San Diego where electricity rates are high and annual heat demand is low. Operating the system to take advantage of time-of-use rates would reduce the payback period, but thermal storage would be required.

Savings from biomass systems are listed in table 3. Peak and annual fuel demands were determined for wood with a higher heating value of 8,500 Btu per pound dry basis and a furnace efficiency of 65 percent. The installed capital cost of biomass systems currently operating has been approximately $40,000 per million Btu per hour of rated output. Fuel costs are typically on the order of $30 per ton dry basis for clean wood chips. The fuel price is site-specific. Payback periods for biomass systems are short. As mentioned earlier, biomass technologies are not yet fully developed. Management requirements are higher for biomass systems than for other systems.

The size of a cogeneration system depends on how the system is operated. If it is operated continuously (neglecting minor downtime for maintenance), the size of the engine must be reduced to meet the qualifying requirements, because greenhouse heat demand is nonuniform over the year. As a result, the system may not meet the peak heat demand of the greenhouse. The engine size can be increased when the system is operated to balance heat demand against dispatch requirements. If carefully managed, the system can be sized to provide virtually all the heating required. Thermal storage is needed, however. Payback periods for cogeneration systems are relatively short (table 4), and they are reasonably insensitive to the price of gas when that is the marginal fuel for utility power generation. Cogeneration is an effective way of insulating the greenhouse from natural gas price fluctuations as long as the system is operated at high efficiency. Summertime uses for thermal energy from the engine, such as absorption cooling, could reduce payback periods and help to keep the engine in continuous operation.

TABLE 1. Greenhouse heating requirements and costs for a conventional gas-fired boiler heating system

Location	Peak demand*	Annual demand	Annual natural gas use†	Annual natural gas cost‡
	therms/hour	*therms*	*therms*	*$*
San Francisco	14.9	39,700	56,700	36,900
Sacramento	19.3	32,000	45,700	29,700
San Diego	12.7	19,300	27,600	17,900

* Outside minimum temperatures are: San Francisco, 38°F; Sacramento, 30°F, and San Diego, 42°F.
† At 70 percent furnace efficiency
‡ At 65 cents per therm.

TABLE 2. Heat pump system size and payback

Location	Total heat pump capacity*	Number of heat pumps	Peak electrical demand	Annual savings	Simple payback
	tons		*kW*	*$*	*years*
San Francisco	124	16	125	16,800†	5.9
Sacramento	161	16	156	14,150†	9.1
San Diego	106	16	95	2,300‡	36.5

* One ton = 12,000 Btu/hr.
† Electricity at 6¢/kWh, natural gas at 65¢/therm, COP = 3.6.
‡ Electricity at 11¢/kWh, natural gas at 65¢/therm, COP = 4.

TABLE 3. Biomass system size and payback

Location	Peak biomass fuel demand*	Annual fuel demand*	Annual savings†	Simple payback‡
	lb/hr	*tons*	*$*	*years*
San Francisco	270	360	25,900	2.3
Sacramento	350	290	20,900	3.7
San Diego	230	175	12,700	4.0

* Wood at 8500 btu/lb dry basis, 65% thermal efficiency.
† Biomass at $30/dry ton, natural gas for conventional heating at 65¢/therm.
‡ Installed cost of $40,000 per MMBtu/hr rated output.

TABLE 4. Cogeneration system size and payback

	100% operation time*			100% heating requirement†			
Location	Maximum generator size	Annual savings & revenue‡	Simple payback	Maximum generator size	Total operating time	Annual savings & revenue‡	Simple payback
	kW	*$*	*years*	*kW*	*%*	*$*	*years*
San Francisco	145	44,400	3.6	240	66	56,700	4.5
Sacramento	-0-	—	—	255	50	51,900	5.2
San Diego	30	7,500	4.4	145	52	25,800	6.2

* Engine operated 8,760 hours/year (neglecting minor downtime for maintenance).
† Engine sized to provide all heat for greenhouse (storage required) and meet cogeneration and utility dispatch criteria.
‡ Utility heat rate of 13,089 Btu/kWh except for San Diego at 11,858 Btu/kWh, $1,000/kW installed, additional costs of $15,000 for grower modifications to the existing heating system, natural gas for conventional heating at 65¢/therm, natural gas fuel for cogeneration at 55¢/therm.

Conclusions

Biomass and cogeneration systems appear to offer greenhouse operators substantial potential for reducing heating costs. Heat pump systems are marginally attractive where electricity rates are low and annual heat demand is high. Thermal storage and time-of-use rates can improve the economic feasibility of heat pump systems. Biomass and cogeneration systems require more management than conventional systems do, but improved automatic control systems and continued development will probably reduce management requirements in the future.

Bryan M. Jenkins is Assistant Professor, Department of Agricultural Engineering, University of California, Davis.