When, and by how much, can cogeneration and trigeneration plants cut carbon dioxide emissions from buildings? Danny Harvey suggests that modern low-energy building design and improving the efficiencies of centralized power plants make the situation more complex than many assume. He concludes that larger, district-scale heating and cooling systems are best.

Clean building

contribution from cogeneration, trigeneration and district energy

Alongside the reduction of building energy loads using low-energy design, the other way of optimizing energy use is to employ efficient on-site energy systems such as cogeneration and trigeneration plants, or to connect the building to a local district heating and/or district cooling plant. The effectiveness with which these technologies deliver reductions in overall carbon emissions requires a study of how energy supply systems interact with the building energy loads.

COGENERATION

Cogeneration, the simultaneous production of electricity and useful heat, can be carried out at the scale of individual buildings using reciprocating engines (either spark or compression ignition), microturbines (gas engines with an electrical power output of 50–500 kW), or fuel cells (electrochemical conversion devices that run on natural gas and, in the future, possibly on hydrogen produced using renewable energy). Cogeneration can be performed using simple-cycle gas turbines at a scale of 1 MW but, at a scale of ≥ 25 MW, cogeneration can be economically achieved using combined gas and steam turbines. The fuel energy supplied to a cogeneration unit, or to the separate boiler for heating and power plant for electricity generation (which cogeneration can replace), is referred to as primary energy.

For cogeneration to represent an improvement in the efficiency of using primary energy compared with separate production of heat and power, a use has to be found for a substantial portion of the waste heat produced through electricity generation. Potential heating loads in buildings include:

CHP at a bank. The use of CHP is especially advantageous for sites with large heating loads (Capstonen Turbines)

- space heating
- domestic hot water
- reheating after overcooling air for dehumidification in summer
- heat for regenerating solid or liquid desiccants in desiccant dehumidification systems.

This requirement poses a problem with space heating loads, which are seasonal in character and can dominate all the other heating loads. What does one do with the surplus heat during the summer when there is no space heating load?

Use of surplus heat

In buildings with a high-performance envelope (high levels of insulation, high-quality windows, minimal uncontrolled leakage, heat recovery from ventilation exhaust), peak space heating loads can be reduced by 50%–90% compared with typical practice in new construction, thus reducing the seasonal variability in the total heating load but also reducing the overall scope for cogeneration. Therefore insulation should be a priority consideration. Upgrades in the thermal envelope of existing buildings can achieve substantial reductions in their existing heating loads, but normally need to be combined with required renovations and so might not coincide with the establishment of, or connection to, a district heating system. Reducing the space heating load also reduces the required distribution temperature for heating, which leads to improvements in boiler or cogeneration efficiencies and reduces heat losses in the district heating network (if present).

From the point of view of reducing the use of primary energy, the critical parameters involving cogeneration are the overall efficiency in using the fuel, the proportion of the output as electricity, and the *marginal efficiency* of electricity generation. The latter is the electricity produced divided by the extra fuel energy used compared with the generation of heat alone. The term ‘marginal’ is used in the sense used by economists – in reference to the benefits and costs of the last unit of production. The marginal efficiency can also be thought of as an effective efficiency and is given by the following equation:

$$\eta_{marginal} = \frac{\eta_{el}}{1 - \eta_{th}/\eta_b}$$

where η_{el} and η_{th} are the cogeneration electric and thermal efficiencies, and η_b is the boiler efficiency. The more efficient the system for stand-alone heat production, the greater the additional fuel use by cogeneration compared with heating alone, and the lower the marginal efficiency of electricity production.

Let me illustrate this with an example. Suppose that 100 units of fuel are used in a cogeneration system that produces 30 units of electricity and 35 units of useful heat (for an overall efficiency of 65%, typical of microturbines). To produce the same amount of heat in a condensing boiler at 92% efficiency would require 38 units of fuel. Thus, an extra 62 units of fuel are used to produce 30 units of electricity, giving a marginal or effective efficiency of 30/62 = 48.4%. If the efficiency of the central power plant times the transmission efficiency is smaller than this, cogeneration will result in a saving in primary energy. Thus, computation of the marginal or effective efficiency of electricity production in cogeneration and comparison with that of the central power plant (multiplied by transmission efficiency) automatically takes into account the energy that would otherwise be used for heating and the savings in primary energy at the central power plant resulting from cogeneration.

In an existing building, it may not be possible to use a condensing boiler (which requires sufficiently low return temperatures in the hydronic heating system), so the appropriate boiler efficiency (η_b) is smaller. Thus, more fuel would have been required to produce the heat supplied by cogeneration; the extra fuel use in cogeneration is smaller and the marginal efficiency for electricity production larger, increasing the attractiveness of cogeneration. In new buildings, condensing boilers are an option.

But should the marginal efficiency be compared with the efficiency of existing central power plants (which tend to be 33%–35%, with 5%–10% transmission loss or 95%–90% transmission efficiency) or with the efficiency of new state-of-the-art power plants (38%–42% using coal, 55%–60% in combined-cycle plants using natural gas)? The answer depends on whether the effect of cogeneration will be to allow the early retirement of existing, inefficient power plants or, at least, less use of these power plants, or whether it will delay the addition of new, efficient power plants.

Fuel and efficiency considerations

Another consideration is that the central power plant might be burning coal while the cogeneration system might be burning natural gas. Natural gas has just over half the carbon dioxide (CO_2) emission per unit of fuel energy as coal, as well as resulting in much smaller emissions of conventional pollutants.

Table 1 gives marginal efficiencies for a variety of different cogeneration systems using natural gas and assuming a boiler at 92% efficiency as the alternative for heating. It also gives electricity generation efficiencies, overall efficiencies, heat:power ratios, illustrative costs, and pollutant emissions. As mentioned above, cogeneration reduces the fuel use associated with electricity production if the marginal efficiency of electricity production is greater than that of the central power plant that it displaces multiplied by the transmission efficiency. Greater overall benefits accrue if the cogeneration system has a larger electricity:heat production ratio (so that more inefficiently generated central electricity can be displaced in matching a given building heating load).

From Table 1 it can be seen that:

- electricity generation efficiencies are lowest for microturbines (23%–26%) and simple-cycle gas turbines (22%–37%), intermediate for reciprocating engines (30%–37%) and fuel cells (36%–46%), and highest for combined-cycle cogeneration (47%–55%) (all efficiencies given here are on a higher heating value (HHV) basis)
- overall efficiencies ($\eta_{el} + \eta_{th}$) are also lowest for microturbines and small gas turbines (61%–67%), intermediate for reciprocating engines and fuel cells, and largest for combined cycle systems (90%)
- as a result of the above, marginal efficiencies for electricity production are not large (around 40%–45% for microturbines, 52%–62% for fuel cells and 56%–63% for reciprocating engines), with the exception of combined-cycle cogeneration systems (88%–90%)
- the power:heat ratio tends to increase with increasing size and is largest for fuel cells and combined-cycle systems
- costs fall dramatically with increasing size
- reciprocating engines are the least expensive building-scale option but involve comparatively high pollutant emissions.

The marginal efficiency using building-scale cogeneration is less than that of state-of-the-art natural gas combined-cycle power plants (55%–60%) and is substantially less than what can

Table 1. Characteristics of cogeneration technologies available for use at the scale of individual large buildings (microturbines, fuel cells, reciprocating engines) and in district heating networks (simple- and combined-cycle turbines). Source: Lemar 2001[2] and Goldstein et al 2003[3]

	Cost ($/kW)		Efficiency (%, HHV basis)			Power-to-heat ratio	O&M (US cents/kWh)	Emissions (gm/kWh)		
Capacity	Electricity only	CHP	Electrical	Overall	Marginal			NOx	CO	Hydrocarbons
Microturbines										
30 kW	2263	2636	23	67	44	0.52	2.0	0.23	0.63	< 0.08
70 kW	1708	1926	25	61	41	0.70	1.5	0.20	0.12	< 0.08
80 kW	1713	1932	24	63	42	0.63	1.3	0.57	0.69	< 0.08
100 kW	1576	1769	26	62	43	0.73	1.5	0.33	0.20	< 0.08
Fuel cells										
200 kW PAFC	–	5200	36	72	59	1.00	2.9	0.02	0.02	< 0.01
5–10 kW PEMFC	–	5500	30	69	52	0.79	3.3	0.05	0.03	< 0.01
150–250 kW PEMFC	–	3800	35	72	59	0.95	2.3	0.05	0.03	< 0.01
250 kW MCFC	–	5000	45	65	58	1.95	4.3	0.03	0.02	< 0.01
2000 kW MCFC	–	3250	46	70	62	1.92	3.3	0.02	0.02	< 0.01
100–250 kW SOFC	–	3620	45	70	62	1.79	2.4	0.02	0.02	< 0.01
Reciprocating engines										
100 kW	1030	1350	30	78	63	0.61	1.8	20.9	16.8	1.0
300 kW	790	1160	31	77	62	0.67	1.3	2.8	2.8	1.4
1 MW	720	945	34	71	57	0.92	0.9	1.4	2.8	1.4
3 MW	710	935	35	69	56	1.04	0.9	1.0	3.5	1.8
5 MW	695	890	37	73	61	1.02	0.8	0.7	3.4	0.7
Gas turbines (simple-cycle cogeneration)										
1 MW	1403	1910	22	65	41	0.51	1.0	1.09	0.32	2–3
5 MW	779	1024	27	67	48	0.68	0.6	0.50	0.27	2–3
10 MW	716	928	29	69	51	0.73	0.6	0.50	0.23	2–3
25 MW	659	800	34	70	56	0.95	0.5	0.41	0.18	2–3
40 MW	592	702	37	72	60	1.07	0.4	0.36	0.18	2–3
Gas and steam turbines (combined-cycle cogeneration)										
20–50 MW	–	860	47	90	88	1.09	0.5	0.33	0.15	1–2
50–100 MW	–	770	49	90	88	1.20	0.5	0.30	0.15	1–2
> 100 MW	–	600	55	90	90	1.57	0.5	0.13	0.08	1–2

PAFC = phosphoric acid fuel cell
PEMFC = proton exchange membrane fuel cell
MCFC = molten carbonate fuel cell
SOFC = solid oxide fuel cell

be achieved in large-scale combined-cycle cogeneration (88%–90%). Thus, although any form of small-scale cogeneration represents a significant improvement in electrical efficiency compared with present typical power plants, none of them represents the most efficient use of natural gas for electricity generation available today

The useful thermal energy obtainable from cogeneration systems is constrained by the fact that not all the waste heat can be extracted at temperatures high enough to be put to use in most applications. If building systems can be designed to be able to make more use of lower-temperature heat (using, for example, low-temperature radiators for heating), then the useful thermal heat extraction and, by extension, the marginal and overall efficiencies would be larger. This in turn could increase the attractiveness of small-scale cogeneration compared with large-scale cogeneration or compared with central combined-cycle power plants. But collaboration between architects, building services engineers and manufacturers of cogeneration equipment would certainly be required.

One of the advantages of building-scale cogeneration is that it provides power where it is needed, thereby reducing transmission bottlenecks and energy losses. However, cogeneration at the scale of small district heating systems (≥ 25 MW) provides essentially the same benefits but with much greater savings in primary energy.

In short, unit costs and pollutant emissions per kWh of electricity generated are smaller and the marginal efficiency, overall efficiency, and electricity:heat production ratio are larger at the scale of small district heating systems than at the scale of individual buildings. Furthermore, these parameters all improve as the scale increases in the 20–100 MW range. This in turn favours cogeneration as part of a district heating system rather than in individual buildings wherever this is feasible.

TRIGENERATION

Trigeneration is the simultaneous production of heat, chilled water and electricity. It is commonly carried out using waste heat from a gas turbine to make steam and to drive an absorption chiller, or using waste heat from a steam turbine. The production of chilled water using absorption chillers thus provides a use for waste heat during the summer months when

Trigeneration uses waste heat to drive absorption chillers (Yazaki Energy Systems)

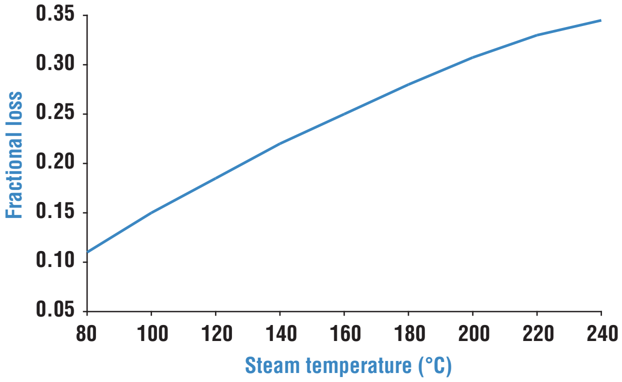


Figure 1. Loss of electricity generation when thermal energy is extracted from a steam turbine, as a fraction of the amount of energy extracted. Source: Bolland and Undrum1999[1]

there is no space-heating load. It represents a good use of waste heat in a simple-cycle gas cogeneration system but, as discussed above, a simple-cycle cogeneration is inefficient compared with the combined-cycle cogeneration system.

In a conventional condensing steam turbine, steam is generated in a boiler, enters a turbine at high pressure, and leaves the turbine at low pressure (a high vacuum) for a condenser, where it condenses to water (at 40º–50ºC) before returning to the boiler. The high vacuum allows maximal extraction of mechanical energy from the steam (to rotate a turbine), but the exhaust is of too low a quality (pressure and temperature) to be useful in most cases. To be useful, steam must be extracted at higher temperature (and pressure), but this reduces the production of electricity. Figure 1 gives the ratio of lost electricity production to extracted heat, as a function of the temperature at which heat is extracted.

The ratio of cooling provided (joules or kWh of heat removed) to energy input to a chiller is called the coefficient of performance (COP). For electrical chillers, COPs range from about 4–5 for small reciprocating chillers (up to 1.5 MW cooling capacity) to about 5–8 in large centrifugal chillers (up to 35 MW cooling capacity). Absorption chillers can be either single effect (COP = 0.7) or double effect (COP = 1.2). They require a minimum input temperature of about 80ºC (single effect) or 120ºC (double effect).

Figure 1 shows that, for every unit of thermal energy withdrawn at 80ºC, about 0.11 units of electricity production will be lost; at 120ºC, 0.185 units of electricity production are lost. From this it follows that one will achieve more cooling for a given energy input if electricity production is maximized, the low-grade waste heat is thrown away and the extra electricity production is used in an electrical chiller (as long as the electric chiller COP is about 6.4 or more). This result does not account for the fact that both electric and absorption chillers require electricity to operate the cooling tower, but this auxiliary electricity requirement is 2–2.5 times larger for the absorption chiller. As a result, the break-even electric chiller COP is only 5.3–5.8, something that can easily be exceeded with large centrifugal chillers. These in turn will be more often available as part of a centralized district cooling system.

An interesting alternative to electric vapour compression chillers for cooling and dehumidification, especially in humid climates, is desiccant cooling and dehumidification. Desiccant systems require heat input at a lower temperature than absorption chilling – about 50º–70ºC – and thus represent a possible use for relatively low-temperature waste heat such as can be supplied from combined-cycle cogeneration with no or minimal penalty in terms of electricity production. However, desiccant systems produce cool and dry air, not chilled water, and so could be used only at individual building sites instead of as part of a centralized district cooling system. On the other hand, a separate district cooling grid would not need to be constructed – the desiccant chillers could be powered with heat from the district heating grid in summer. Complicating the picture would be a situation where some customers have absorption chillers and therefore need heat at a higher temperature.

DISTRICT HEATING

As outlined above, district heating networks offer the prospect of significant savings in energy use for electricity production if they are combined with combined-cycle cogeneration. However, if electricity is already supplied from non-fossil fuel energy sources such as hydro electric power, then one is in effect replacing a non-fossil energy source with a fossil fuel energy source for the electricity portion of the cogeneration system (unless the cogeneration system is also powered with a non-fossil fuel energy source such as biomass). One would be better off in terms of CO_2 emissions by producing heat alone and as efficiently as possible. So are there efficiency benefits to district heating when the heat to the network is not supplied from cogeneration?

One of the arguments in favour of district heating systems is their ability to achieve better part-load efficiencies in heating compared with individual boilers in each building. A typical practice in the latter case might be to install two identical boilers, one serving as a backup. Non-condensing boilers (the norm in most parts of the world) have lower efficiency at part load than at full load and, most of the time, the boiler is operating at only a small fraction of full load (especially if the boiler is grossly

District heating pipes being installed. When combined with cogeneration, DH offers significant energy saving (Løgstør Ror)

oversized, as is normally the case). In summer, when the only load might be a small domestic hot water load, the part-load penalty will be particularly severe.

In a centralized heating system with many boilers collectively serving the network, all the boilers except one can be operated at full load and those not needed can be shut down. The annual energy savings can be 10%–20%. However, in district heating networks, the net loss during distribution can be 5%–10% or even more if the system is old and poorly maintained. In addition, modern condensing boilers have constant or even higher efficiency at part load, down to 10%–30% of full load, so the efficiency gain from centralized heating is reduced. In any case, the net efficiency gain through district heating – in the absence of cogeneration – is not large.

However, the district heating network supplying heat to the buildings in a community could be used to collect heat from scattered sources. Examples include sewage treatment works, bakeries, some manufacturing facilities and electrical transformer stations. Since the heat from these sources will usually be at a lower temperature than that at which heat is distributed by the district heat system, heat pumps will be needed to transfer heat from these heat sources to the heat distribution grid.

In Tokyo, sewage has a stable temperature of about 16ºC in February and is used as a heat source for production of hot water at 47ºC with a COP of 3.9 in one small district heating network. Over 20% of the heat for district heating in Gothenburg, Sweden, is extracted from waste water. Heat that is rejected by chillers in ice arenas or district cooling systems could also be supplied to the district heating system (to the extent that the timing of the loads matches). In effect, the district heating system would serve as a heat energy broker, collecting it where there is an excess and supplying it where there is a deficit. About half of the total heat output from heat pumps in Sweden comes from units in district heating systems, usually to upgrade the heat from lake water and sewage water. In addition, steam from incineration plants is used with 6 MW absorption heat pumps to extract heat from the exhaust gas for district heating; the exhaust gas is cooled from 70ºC to 30ºC in the process.

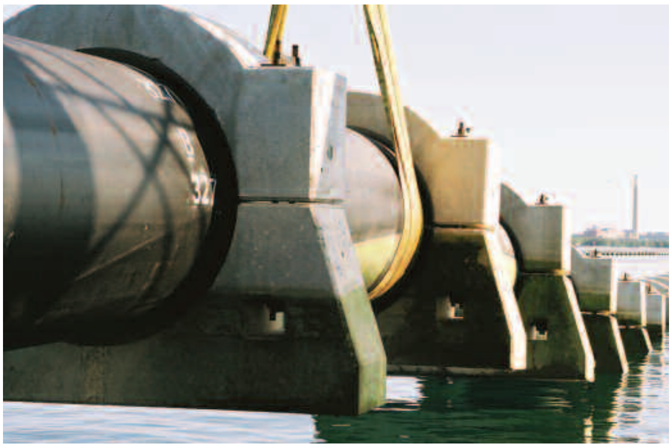
Finally, district heating systems lend themselves easily to alternative fuel sources (biomass in some cases, perhaps eventually hydrogen produced in sunny or windy areas using solar or wind energy). District heating system designed for relatively low distribution temperatures (35º–70ºC) can also make use of solar thermal energy and lend themselves to seasonal underground storage of thermal energy collected during the summer – as in many projects in Europe and the Drake Landing Solar Community in Canada (see www.dlsc.ca).

DISTRICT COOLING

Centralized chilling with electric chillers is usually highly favourable in terms of energy efficiency compared with on-site chilling. It can be economically attractive in spite of the network costs and provides a number of advantages to building owners (such as elimination of on-site cooling towers and freeing up of roof space for other purposes). The efficiency gains arise from the greater efficiency of large units (easily a factor of 2–3 compared with small room air conditioners) and from the ability to avoid inefficient part-load operation. As an example, the central chilling plant built for the Expo '98 project in Lisbon reduced chilling energy use by 45% compared with meeting the same loads with chillers in each building.

Additional efficiency benefits of district cooling arise from the use of heat sinks that could not otherwise be used. In a conventional cooling system, the heat extracted from a building is rejected to the atmosphere through a cooling tower on the roof of the building or through the air-cooled condensers of roof-top chillers. Air-cooled condensers must be warmer than the ambient air in order to reject heat. This is more difficult the warmer the air, so the efficiency of the cooling system decreases (at the same time that the amount of heat that needs to be removed from the building increases). If cooling towers are used, the cooling water supplied to the condenser will be 2–4ºC warmer than the ambient wet-bulb temperature, which depends on ambient temperature and relative humidity, and the condenser must be slightly warmer than the cooling water in order to reject heat. If the heat in the cooling system can be rejected to a colder medium, the system efficiency can be improved.

Centralized chilling with electric chillers can be economically attractive in spite of network costs



Toronto's Deep Lake Water Cooling project uses the cooling ability of the icy cold lake water for air conditioning downtown buildings (Enwave Energy Corporation)

Potential media for receiving the heat from a cooling system include sewage water, lake water or seawater, or the ground itself. However, the majority of buildings in a region are not likely to be situated where they are able to use these heat sinks. By linking the buildings in a district cooling network, it may become possible to utilize heat sinks that could not otherwise be used. District cooling networks can also be linked to large above- or below-ground cold water tanks that can be used to store chilled water produced at nights, when electricity rates are lowest and the efficiency in generating electricity from fossil fuels the highest.

CONCLUDING REMARKS

The optimization of electricity production, heating and cooling requires consideration of many interacting factors. The first priority in any case is to reduce heating and cooling requirements through the use of a high-performance envelope and optimization of the building form, shape and internal ventilation system. Current small-scale, on-site cogeneration systems have smaller overall efficiencies compared with large, combined-cycle cogeneration systems. Thus, they are generally not the most attractive option from an energy efficiency point of view unless a use can be found for a greater portion of the waste heat than is normally the case. This in turn requires consideration of the cogeneration device and building as a complete system.

Cogeneration at the scale of district heating systems is highly attractive using combined-cycle power plants whenever electricity would otherwise be produced from fossil fuels. Even in the absence of cogeneration, district heating networks can save energy by tapping heat sources that could otherwise not be used. Trigeneration using absorption chillers is less efficient for cooling compared with maximizing the electricity production with combined-cycle power generation and using the extra electricity thus produced in large (and highly efficient) electric chillers. District cooling networks using large electric chillers can provide significant energy savings compared with the use of chillers or air conditioners in individual buildings. These savings are amplified further when dispersed heat sinks (such as sewage water) can be utilized.

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NOTES

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