# Assessment of Replicable Innovative Industrial Cogeneration Applications

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# Executive Summary

U.S. industrial facilities utilize a wide array of thermal process equipment, including:

- Hot water heaters,
- Thermal liquid heaters,
- Ovens,
- Furnaces,
- Kilns,
- Dryers,
- Chillers, and
- Boilers.

In most industrial facilities, process heating is provided by direct or indirect heat exchange from fossil fuel-fired combustion systems. Process heating may also be provided by the direct or indirect use of steam supplied by central boiler systems. Many of these systems could be retrofit to become part of integrated distributed generation (DG) cogeneration systems. Cogeneration, or Combined Heat and Power (CHP) systems, generate electricity on-site using turbines, reciprocating engines, or fuel cells and use the "waste" heat from the prime mover to supply some or all of the energy required by thermal processes. Cogeneration systems have high overall efficiencies and, for some facilities, will have lower life cycle costs than conventional solutions.

There has been considerable interest shown in the distributed generation field over the past 5 years. This market movement has gained credence with the distributed generation equipment manufacturers, and they have made substantial investments in the development of new power generation technologies. However, little is being spent to develop innovative industrial cooling and thermal systems and less on how to integrate distributed generation equipment within manufacturing processes, where the greatest opportunity to use waste heat can be found. Adaptation of innovative cogeneration systems is more advantageous from a national energy and environmental policy standpoint than other distributed generation applications because of the high overall efficiency of these systems.

Conventional large cogeneration systems are well developed, widely deployed, and utilize readily available thermal technologies. Their use and benefits are well documented. The thrust of this effort is to look beyond these beneficial and economically-attractive conventional technologies and identify very replicable and innovative cogeneration approaches integrated with selected industrial process operations.

One of the guiding principals of applying cogeneration is the efficient utilization of all energy input to the process. To accomplish this, thermal energy normally rejected needs to be recovered to the maximum extent possible. This can be achieved by recovering heat from the DG equipment exhaust stream, and for engine system, heat can also be recovered from the water jacket, oil cooler, and aftercooler.

This report provides a market assessment of innovative industrial DG cogeneration systems that are less than 1 MWe. The market assessment was developed by:

- Analyzing industrial thermal processes on an industry-by-industry basis and determining annual energy consumption for each industry/process combination,
- Using a methodology to choose five leading thermal processes that can be easily integrated into a cogeneration system and that offer large energy-saving potential,
- Developing integrated DG cogeneration process schematics, and

- Assessing the potential market for these systems by comparing their economics with the economics of conventional solutions.

Electricity rates used in this market assessment were based on actual utility electricity rate structures gathered in 1999. Gas rates are based on state average industrial gas rates from 1999, as reported by DOE's Energy Information Administration (EIA). Escalation rates for electricity and gas are based on 1999 EIA regional projections. Using these values eliminates the gas price spikes of 2000 and uncertain projections regarding electricity rates for the West Coast that surfaced in 2000-2001. If emerging energy price trends and escalation rates are incorporated in a subsequent analysis of the industrial cogeneration opportunities examined in this study, market penetration rates would likely change.[1]

The five leading cogeneration systems identified are:

- Direct contact water heaters fed directly with engine/turbine exhaust,
- Indirect liquid heating using air-to-liquid heat exchangers fed with engine/turbine exhaust,
- Convection ovens used for metals fabrication preheating fed directly with engine/turbine exhaust,
- Indirect air heating using air-to-air heat exchanges fed with engine/turbine exhaust, and
- Central boiler systems using turbine exhaust gas as a combustion oxidant.

The market assessment analysis shows 11 GW of economic market potential for these cogeneration applications. Figure 1 shows the total economic market potential by system type.

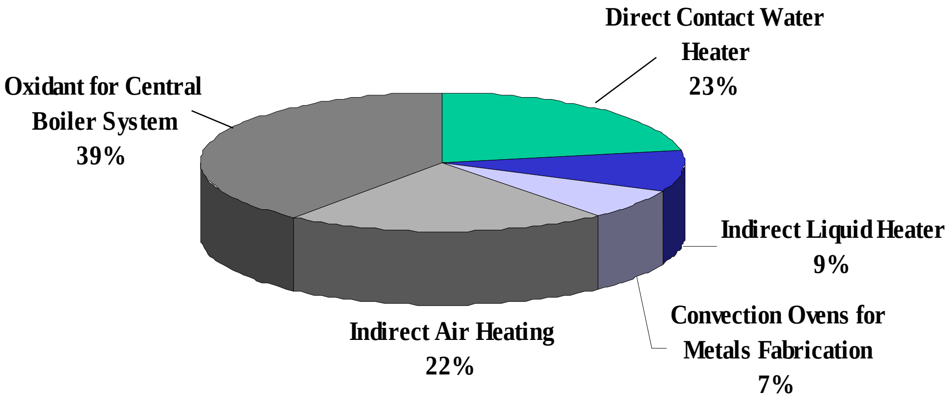

**Figure 1. Summary Results by System Type - 11 GW Total Economic Market Potential**

Factors that influence economic market potential by system type include:

- Number of facilities in the U.S. with matching thermal processes (there are more facilities with central boiler systems that could be retrofit with cogeneration than potential facilities with convection ovens for metals fabrication),
- Thermal system cogeneration retrofit cost, which affects the total installed cost of the cogeneration system (lower installed cost improves project economics and market potential),
- Existing thermal system efficiency (the lower the existing thermal system efficiency, the more cost-effective the project – indirect air heating efficiency is often below 50%, while convection ovens exceed 85%), and

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[1] Analysis of the impacts of these recently emerging price trends was outside the scope of this effort.

- System sizes for each type (system types where there are more potential facilities with matching thermal processes in the larger size ranges – retrofit, engineering, and installation costs are lower in terms of dollars per kW in the larger sizes).

The 10 states showing the highest economic market potential are shown in Figure 2.

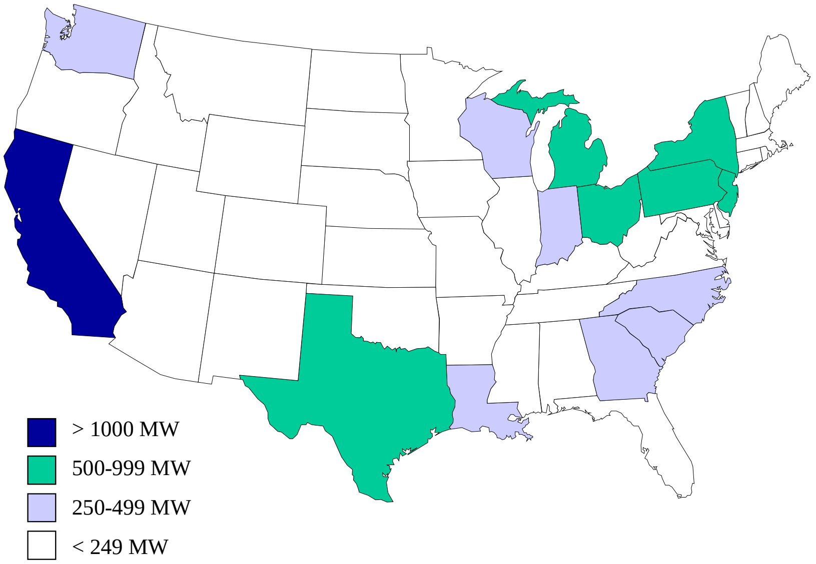

**Figure 2. Summary Results by State - 11 GW Total Economic Market Potential**

Factors that influence market economic market potential by state include:

- Size of the state and industry mix within the state,
- Industrial electric rates within the state, and
- Industrial natural gas rates within the state.

California has the most applications, because it has the highest number of industrial facilities with matching thermal processes, and also relatively high industrial electricity rates.

Economic market potential broken down by prime mover size range is shown in Figure 3.

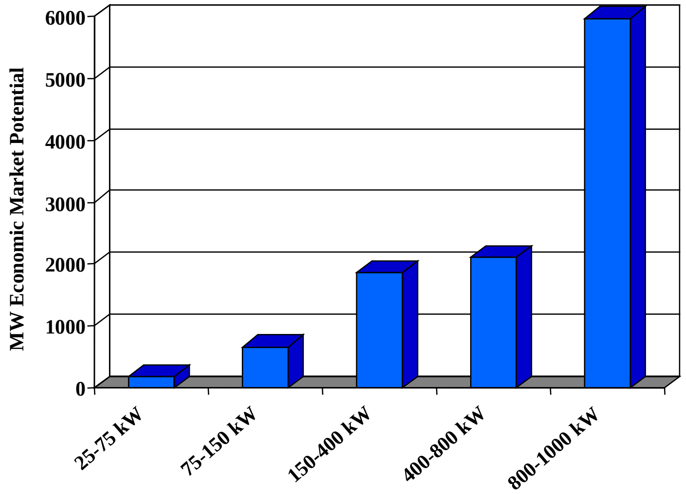

**Figure 3. Summary Results by Size Range**

Factors that influence market economic market potential by prime mover size range include:

- Number of potential facilities in each size range (most industrial facilities have electric demands greater than 75 kW), and
- Installation costs (costs are lower as the size ranges increase, because retrofit, engineering, and installation costs are lower in terms of dollars per kW, so this favors the larger size ranges).

Economic market potential broken down by prime mover type is shown in Figure 4.

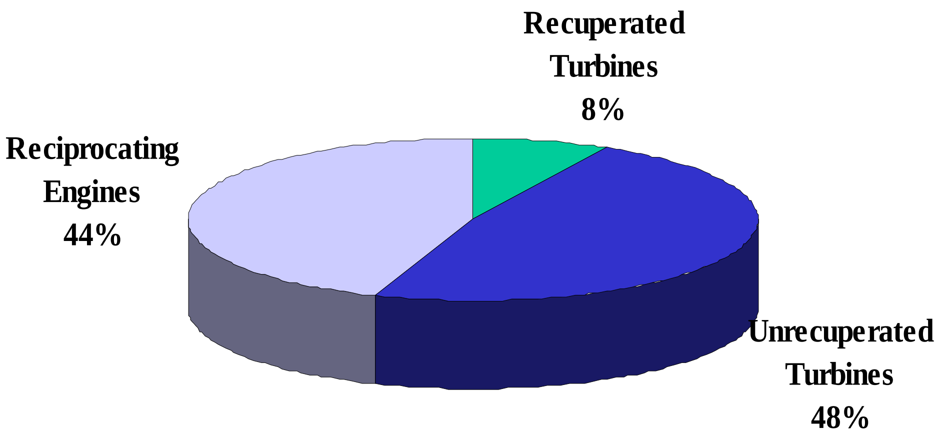

**Figure 4. Summary Results by Prime Mover Type**

Factors that influence market potential that vary by prime mover type include:

- Prime mover electric efficiency (for most size ranges, reciprocating engines have the highest electric efficiency),
- Available usable thermal output from the prime mover (unrecuperated turbines have the highest), and
- Prime mover installed cost (reciprocating engines and unrecuperated turbines are less expensive than recuperated turbines in all size ranges – for example, the installed costs for a 70-100 kW direct contact water heater system using a recuperated turbine is over $2,400 per kW, but this decreases to under $1,000/kW in the 800-1000 kW size range),

The results shown in this assessment show the economic market potential. There are a number of barriers that may limit applications of these technologies. Some of these barriers may be regional in nature. The barriers include:

- Product performance and availability,
- Lack of off-the-shelf integrated systems,
- Presence of a supporting market infrastructure,
- Awareness, information and education of end users,
- Demonstration of successful case studies,
- Environmental regulations,
- Planning, zoning, and codes, and
- Tax treatment.

There clearly exists a need for a structured approach to assist with the development and deployment of innovative cogeneration systems in the industrial sector. This approach needs to foster the development of industrial cooling and heating systems that can easily be integrated with distributed generation equipment. The approach should demonstrate these systems in industrial settings and then develop case studies around these demonstrations. These case studies need to include validated and verified data on the systems' operation and performance. In addition, the structured approach also needs to address the potential barriers and how to overcome them.

Acknowledgement: The report was supported by the Industrial Center Distributed Generation Consortium and the Oak Ridge National Laboratory/U.S. Department of Energy Office of Power Technologies' Distributed Energy Resources Program, and was developed for the Industrial Center, Inc. by Resource Dynamics Corporation and CSGI, Inc.

# Introduction

## Background

The U. S. Department of Energy's Office of Power Technologies (OPT) and the Industrial Center, Inc. sponsored this work in keeping with their joint goal to significantly improve the resource efficiency and productivity of industries in the United States. In support of this goal, this project will help industries develop technological solutions to critical energy and environmental challenges. Among the solutions being pursued are innovative applications of distributed generation technologies in industrial and institutional cogeneration applications. These technologies have the potential to reduce national energy use and emissions.

A number of trends have surfaced that may lead to growth in industrial cogeneration including:

1. Global concern over greenhouse gas emissions has meant an increased emphasis placed on total energy efficiency, which would favor combined heat and power over utility central plant generation. This outlook may create interest in changing environmental regulations to be less emission based, and more output based, thus favoring the more efficient cogeneration. Furthermore, creation of a global carbon permit trading market would provide new incentives for cogeneration.
2. Electric utility restructuring has heightened concerns over grid reliability and thus is renewing interest in on-site generation. Stranded cost treatment, including exit fees, threatens to counter this interest by deterring non-grid sources of power.
3. New technologies are surfacing, including microturbines and fuel cells. In addition, a new generation of reciprocating engines is entering the market, with higher efficiencies, decreased costs, and lower emissions. In combination, these technologies provide smaller facilities with an unprecedented set of options from which to potentially satisfy their needs for both thermal and electric energy on-site.

## Objectives

The purpose of this study is to assess the market for innovative and replicable applications of small cogeneration technologies in the U. S. industrial sector. Specific objectives of this study are to:

- Review distributed generation technologies in the 25-1000 kWe size range,
- Examine industrial thermal processes that can be integrated with cogeneration systems,
- Select the top five innovative and replicable industrial cogeneration technologies in the 25-1000 kWe size range, and
- Assess the potential market for these technologies.

## Approach

This report is the first task of a larger project that will demonstrate innovative applications of industrial cogeneration systems in actual manufacturing facilities. In order to ensure replicability, this first task will assess the market for cogeneration applications in the 25-1000 kWe size range.

This study identifies five highly replicable innovative cogeneration technologies and assesses their domestic market potential. A five-step approach is used to identify these opportunities and estimate the potential market.

**Step 1.** Analyze and group industrial thermal processes into seven broad categories, including:

- Hot water,
- Indirect liquid heating,

- Direct heating and drying,
- Indirect air heating,
- Refrigeration and freezing,
- Dehumidification, and
- Furnaces and boilers.

This is done by examining each specific industry within the manufacturing sector (4 digit Standard industrial classifications (SIC) with SICs 20-39), and looking at each of their significant thermal processes.

**Step 2.** The seven broad categories of thermal processes are broken into more specific categories (e.g., *direct heating and drying* can be broken into subcategories such as *spray drying*) and replicability is assessed by estimating the total U.S. annual energy consumption of each specific process. This is done for each industry at the 4-digit level, and the results are aggregated to obtain totals for each subcategory.

**Step 3.** The top five applications are chosen because of their replicability (energy savings across all applicable SICs) and ease of integration into a cogeneration systems. The five applications selected for the market assessment are:

- Direct contact water heaters,
- Indirect liquid heating,
- Convection ovens used for metals fabrication preheating,
- Indirect air heating, and
- Exhaust gas as an oxidant for central boiler systems.

**Step 4.** Cogeneration system price and performance information is gathered for these five applications.

**Step 5.** An economic analysis (market assessment) is performed to determine the number of potential applications for these five innovative industrial cogeneration systems. The analysis determines the number of facilities, by 4 digit SIC, size range, and state, where using the cogeneration application is more cost effective than purchasing electricity from the grid and using conventional thermal processes.

# Distributed Generation Technologies

A summary of each commercial and near-commercial DG technology is provided below. Included are the technology's history and current status, operational process, and detailed information on industrial cogeneration potential.

## Reciprocating Engines

### *History and Status*

Reciprocating engines, developed more than 100 years ago, were the first of the fossil fuel-driven DG technologies. Both Otto (spark ignition) and Diesel cycle (compression ignition) engines have gained widespread acceptance in almost every sector of the economy and are in applications ranging from fractional horsepower units powering small hand-held tools to 60 MW baseload electric power plants. Reciprocating engines are machines in which pistons move back and forth in cylinders. Reciprocating engines are a subset of internal combustion engines, which also include rotary engines. Small to medium sized engines are primarily designed for transportation applications and are converted to power generation units with little modification. Larger engines are, in general, designed for power generation, mechanical drive, or marine propulsion. Reciprocating engines are currently available from many manufacturers in all DG size ranges, and can use gasoline, diesel, natural gas, or waste fuels.

### *Operation*

Almost all engines used for power generation are four-stroke and operate in four cycles (intake, compression, combustion, and exhaust). The process begins with fuel and air being mixed. Some engines are turbocharged or supercharged to increase engine output, meaning that the intake air is compressed by a small compressor in the intake system. The fuel/air mixture is introduced into the combustion cylinder, then compressed as the piston moves toward the top of the cylinder. In diesel units, the air and fuel are introduced separately with fuel injected after the air is compressed by the piston in the engine. As the piston nears the top of its movement, a spark is produced that ignites the mixture (in most diesel engines, the mixture is ignited by the compression alone). Dual fuel engines use a small amount of diesel pilot fuel in lieu of a spark to initiate combustion of the primarily natural gas fuel. The pressure of the hot, combusted gases drives the piston down the cylinder. Energy in the moving piston is translated to rotational energy by a crankshaft. As the piston reaches the bottom of its stroke the exhaust valve opens and the exhaust is expelled from the cylinder by the rising piston.

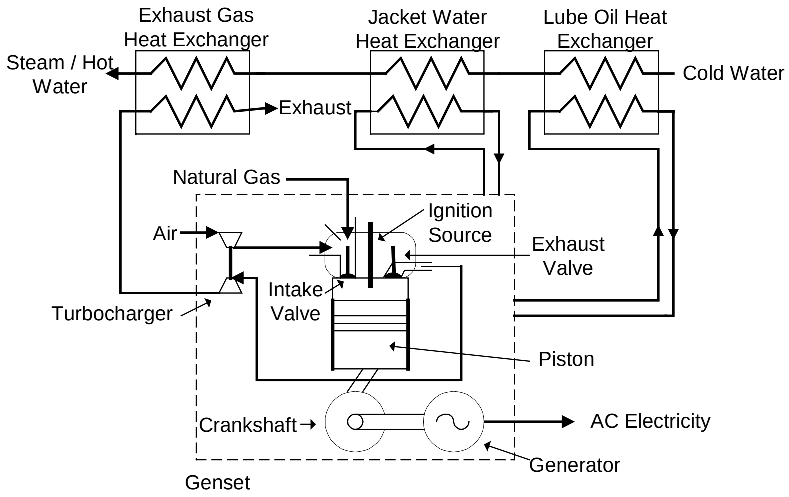

**Figure 5. Reciprocating Engine**

### *Industrial Cogeneration Potential*

Reciprocating engines can be used in three different types of industrial cogeneration applications:

- To produce hot water at around 195° F,
- To produce low temperature steam at around 265° F, and
- To produce heat at higher temperatures, e.g. for drying processes, exhaust gases with temperatures of 930 to 1,000° F can be used directly or by means of a heat exchanger.

The following chart shows the electric efficiencies, thermal output, and potential overall efficiency:

| | Electric Efficiency (% LHV) | Thermal Output (% LHV) | Overall Efficiency (% LHV) |
|---|---|---|---|
| Hot Water | 31-38 | 47-54 | 80-85 |
| Low Temperature Steam | 31-38 | 18-25 | 80-85* |
| High Temperature Heat | 31-38 | 18-34 | 80-85* |

*also includes potential hot water production

## Microturbines

### *History and Status*

The technology used in microturbines is derived from aircraft auxiliary power systems, diesel engine turbochargers, and automotive designs. A number of companies are currently field testing demonstration units for small-scale distributed power generation in the 30-400 kW size range. Several units are available commercially, and more are slated to enter the market in 2001 and 2002.

### *Operation*

Microturbines consist of a compressor, combustor, turbine, and generator. The compressors and turbines are typically radial-flow designs, and resemble automotive engine turbochargers. Most designs are single-shaft and use a high-speed permanent magnet generator producing variable voltage, variable frequency alternating current (AC) power. An inverter is employed to produce 60 Hz AC power. Most microturbine units are currently designed for continuous-duty operation and are recuperated to obtain higher electric efficiencies. Non-recuperated engines have lower electric efficiencies, but higher exhaust temperatures, which makes them better for some industrial cogeneration applications.

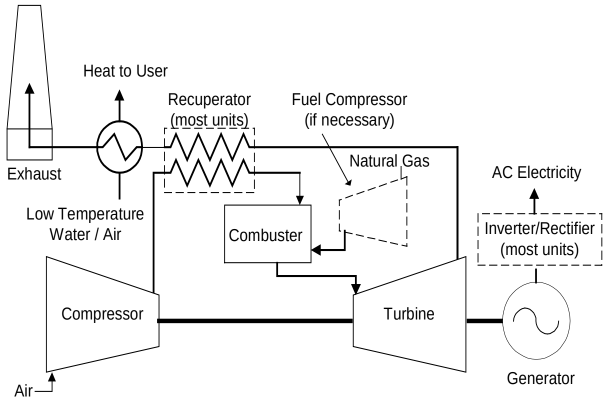

**Figure 6. Microturbine**

### *Industrial Cogeneration Potential*

Microturbines can be used in three different types of industrial cogeneration applications:

- To produce hot water at around 195-205° F,
- To produce low temperature steam at around 265° F, and
- To produce heat at higher temperatures, e.g. for drying processes, exhaust gases with temperatures of 600 to 1,000° F can be used directly or by means of a heat exchanger.

The following charts shows the electric efficiencies, thermal output, and potential overall efficiency for each type of system:

**Recuperated Microturbine**

| | Electric Efficiency (% LHV) | Thermal Output (% LHV) | Overall Efficiency (% LHV) |
|---|---|---|---|
| Hot Water | 25-27 | 40-55 | 65-80 |
| Low Temperature Steam | 25-27 | 40-55 | 65-80 |
| High Temperature Heat | 25-27 | 50-68 | 75-93 |

**Unrecuperated Microturbine**

| | Electric Efficiency (% LHV) | Thermal Output (% LHV) | Overall Efficiency (% LHV) |
|---|---|---|---|
| Hot Water | 13-15 | 52-72 | 65-85 |
| Low Temperature Steam | 13-15 | 52-72 | 65-85 |
| High Temperature Heat | 13-15 | 72-80 | 85-93 |

## Industrial Combustion Turbines

### ***History and Status***

Combustion turbines have been used for power generation for decades and range in size from units starting at about 1 MW to over 100 MW. Units from 1-15 MW are generally referred to as industrial turbines, a term which differentiates them from larger utility grade turbines and smaller microturbines. Combustion turbines have relatively low installation costs, low emissions, high heat recovery, and infrequent maintenance requirements. With these traits, combustion turbines are typically used for large cogeneration systems, as peakers, and in combined cycle configurations. Industrial turbines sized below 1 MW are rare.

### ***Operation***

Historically, industrial turbines have been developed as aero derivatives using jet propulsion engines as a design base. Some, however, have been designed specifically for stationary power generation or for compression applications in the oil and gas industries. A combustion turbine is a device in which air is compressed and a gaseous or liquid fuel is ignited. The combustion products expand directly through the blades in a turbine to drive an electric generator. The compressor and turbine usually have multiple stages and axial blading. This differentiates them from smaller microturbines that have radial blades and are single staged. The intercooler shown in Figure 7 is generally reserved for larger units that can economically incorporate this improvement.

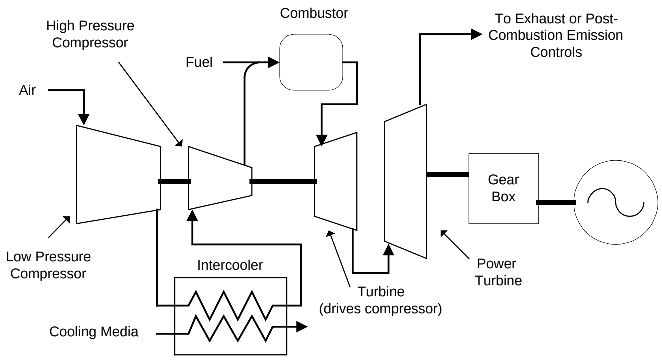

**Figure 7. Turbine**

### ***Industrial Cogeneration Potential***

Industrial turbines can be used in two types of industrial cogeneration applications:

- To produce steam over a range of pressure and temperatures, and

- To produce heat at higher temperatures, e.g. for drying processes, exhaust gases with temperatures of 900 to 1,000° F can be used directly or by means of a heat exchanger.

The following chart shows the electric efficiencies, thermal output, and potential overall efficiency for industrial turbines below 1 MW:

| | Electric Efficiency (% LHV) | Thermal Output (% LHV) | Overall Efficiency (% LHV) |
|---|---|---|---|
| Steam | 25-27 | 45-55 | 70-80 |
| High Temperature Heat | 25-27 | 59-68 | 84-93 |

## Phosphoric Acid Fuel Cells

### *History and Status*

Although the first fuel cell was developed in 1839 by Sir William Grove, the technology was not put to practical use until the 1960's when NASA installed fuel cells to generate electricity on Gemini and Apollo spacecraft. There are many types of fuel cells currently under development, including phosphoric acid, proton exchange membrane, molten carbonate, solid oxide, alkaline, and direct methanol. However, fuel cells are not generally commercially available, except for a 200 kW phosphoric acid unit made by International Fuel Cells.

### *Operation*

There are many types of fuel cells, but each uses the same basic principle to generate power. A fuel cell consists of two electrodes (an anode and a cathode) separated by an electrolyte. Hydrogen fuel is fed into the anode, while oxygen (or air) enters the fuel cell through the cathode. With the aid of a catalyst, the hydrogen atom splits into a proton (H+) and an electron. The proton passes through the electrolyte to the cathode, and the electrons travel through an external circuit connected as a load, creating a DC current. The electrons continue on to the cathode, where they combine with hydrogen and oxygen, producing water and heat.

The main differences between fuel cell types are in their electrolytic material. Each different electrolyte has both benefits and disadvantages based on materials and manufacturing costs, operating temperature, achievable efficiency, power to volume (or weight) ratio, and other operational considerations. The part of a fuel cell that contains the electrodes and electrolytic material is called the "stack," and is a major component of the cost of the total system. Stack replacement is very costly but becomes necessary when efficiency degrades as stack operating hours accumulate.

Fuel cells require hydrogen for operation. However, it is generally impractical to use hydrogen directly as a fuel source; instead, it is extracted from hydrogen-rich sources such as gasoline, propane, or natural gas using a reformer. Cost effective, efficient fuel reformers that can convert various fuels to hydrogen are necessary to allow fuel cells increased flexibility and commercial feasibility.

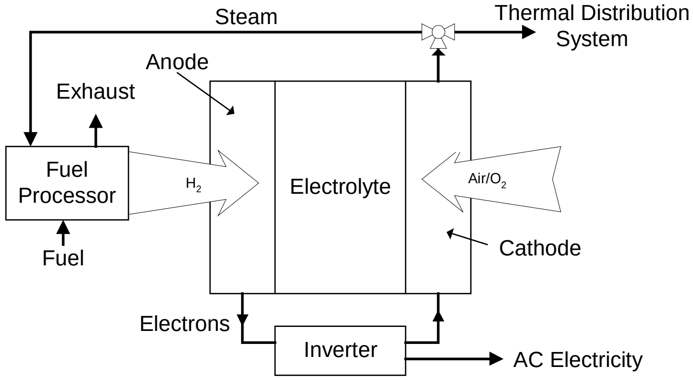

**Figure 8. Fuel Cell**

### ***Industrial Cogeneration Potential***

The phosphoric acid fuel cell can be used in two different types of industrial cogeneration applications:

- To produce hot water at around 140° F, and
- To produce hot water at around 140° F and low temperature steam at 250° F.

The following charts shows the electric efficiencies, thermal output, and potential overall efficiency for the 200 kW phosphoric acid fuel cell:

| | Electric Efficiency (% LHV) | Thermal Output (% LHV) | Overall Efficiency (% LHV) |
|---|---|---|---|
| Hot Water | 37 | 50 | 87 |
| Hot Water Plus Low Temperature Steam | 37 | 50 | 87 |

## DG Technology Cost and Performance

Table 1 shows cost and performance parameters for the each of the generation technologies described. These numbers are used as input data into the model that develops the market assessment presented later in this report. Installation costs and prices for heat recovery equipment depend on the specific thermal application that the generation technology is integrated with, and are presented in later sections of this report.

**Table 1. DG Cost and Performance Tables**

**Recuperated Turbines**

| | 25-75 kW | 75-150 kW | 150-400 kW | 400-800 kW | 800-1000 kW |
|---|---|---|---|---|---|
| Packaged Cost ($/kW) | 800 | 800 | 700 | 700 | 700 |
| Maintenance ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.009 |
| Heat Rate | 13,200 | 13,200 | 13,200 | 10,434 | 10,434 |
| Max. Thermal Output Exhaust (mBtu/hr/kW) | 8.94 | 8.94 | 8.94 | 6.76 | 6.76 |
| Max. Thermal Output Water (mBtu/hr/kW) | 0 | 0 | 0 | 0 | 0 |

**Unrecuperated Turbines**

| | 25-75 kW | 75-150 kW | 150-400 kW | 400-800 kW | 800-1000 kW |
|---|---|---|---|---|---|
| Packaged Cost ($/kW) | 600 | 600 | 500 | 500 | 350 |
| Maintenance ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.004 |
| Heat Rate | 26,246 | 26,246 | 26,246 | 14,519 | 13,123 |
| Max. Thermal Output Exhaust (mBtu/hr/kW) | 21.52 | 21.52 | 21.52 | 10.38 | 9.05 |
| Max. Thermal Output Water (mBtu/hr/kW) | 0 | 0 | 0 | 0 | 0 |

**Reciprocating Engines**

| | 25-75 kW | 75-150 kW | 150-400 kW | 400-800 kW | 800-1000 kW |
|---|---|---|---|---|---|
| Packaged Cost ($/kW) | N/A | 530 | 490 | 435 | 390 |
| Maintenance ($/kWh) | N/A | 0.01 | 0.0085 | 0.008 | 0.0075 |
| Heat Rate | N/A | 11,000 | 10,340 | 9,750 | 8,980 |
| Max. Thermal Output Exhaust (mBtu/hr/kW) | N/A | 3.54 | 2.91 | 2.35 | 1.62 |
| Max. Thermal Output Water (mBtu/hr/kW) | N/A | 3.5 | 3.5 | 3.5 | 3.5 |

**Phosphoric Acid Fuel Cells**

| | 25-75 kW | 75-150 kW | 150-400 kW | 400-800 kW | 800-1000 kW |
|---|---|---|---|---|---|
| Packaged Cost ($/kW) | N/A | N/A | 3300 | 3300 | 3300 |
| Maintenance ($/kWh) | N/A | N/A | 0.015 | 0.015 | 0.015 |
| Heat Rate | N/A | N/A | 9,235 | 9,235 | 9,235 |
| Max. Thermal Output Exhaust (mBtu/hr/kW) | N/A | N/A | 0 | 0 | 0 |
| Thermal Water Output (mBtu/hr/kW) | N/A | N/A | 4.5 | 4.5 | 4.5 |

Initial screening ruled out applications using fuel cells. Because of their high capital costs, they cannot currently compete either with other DG technologies or with conventional thermal technologies combined with purchased electricity from the grid. The remainder of this report will focus on turbine- (including microturbine) and reciprocating engine-based cogeneration technologies.

# Potential Industrial Thermal Applications to Integrate with Cogeneration DG Systems

The section describes the generic industrial applications that can use waste thermal energy.
For each generic industrial application, there is a general description, process uses, and details on cogeneration integration. A diagram of the generic process integrated with a microturbine is also included.

## Hot Water/Direct Contact Water Heaters

### *General*

Process hot water often represents the single largest Btu/hr energy requirement for a manufacturer. Development of highly efficient heat exchange concepts for this purpose has resulted in the 'direct contact water heating' scheme. Fundamentally, by raining water down a 'packed' column, which also is the stack for combustion products (natural gas), near ideal heat transfer is achieved. Exhaust leaves the system cooled to less than 10°F above the cool water inlet, and the water is able to reclaim well above 90% of the exhaust energy.

### *Process Uses*

Abundance, availability, safety and experience make hot water a first choice for manufacturing processes requiring:

1. Washing/flushing
   - Equipment "clean-down" and sanitizing in food industries (meat, dairy, sugar refining, etc.), and pharmaceutical and "bio" processes.
   - Continuous washing operations in raw food preparation (cane/beet sugars, meat, etc.), textiles, wood/paper pulp, removing oils and other excess matter (paint, dust etc.) in metals fabrication and molded plastics industries (auto parts, sheet metal, cans, food/beverage containers, etc.), and in synthetic rubber and fiber manufacturing.
   - Flushing process piping and batch equipment (paint blenders, fermentation vessels, etc.), particularly for operations using the same process lines/equipment to produce slightly varying products (paints, candy slurries, pharmaceuticals, etc.).
2. Solvents for raw material preparation, leaching, separations/extractions, and emission control operations. Water is typically chosen when these systems handle general solid inorganics, acids, generally polar fluids, and crystalline salts.
3. Crystallization/fermentation/reaction media for industries including wine/malt-beverage, dairy, pharmaceutical, and inorganic chemicals.
4. Heating jackets for vessels/operations below ~230°F including chocolate tempering, crystallizers, and storage vessels/mixers containing viscous materials.

Hot water generated from direct contact with natural gas derived combustion exhaust has been approved for food manufacturers including dairy, meat plants, and beverages.

### *Integrating for Cogeneration*

To address heat transfer, either more packing media, or extending the height of the column (or both) may be necessary to maintain normal operation (with retrofit systems). Pressure drop and thus back-pressure imposed on the generating system will be a key design element. Special consideration to ensure that no process water enters back into the DG unit's exhaust system is also crucial for practical implementation.

Many industrial facilities may not have a constant hot water demand. However two profiles may describe the demand well (e.g., normal production operation, and "clean-down" or full capacity day shifts with part capacity night shifts). In the latter case, a bypass-recuperator option on a turbine-based cogeneration scheme can be integrated with a variable flow water tower to switch between profiles. Assuming precise hot-water energy requirements are known, a recuperator with bypass can be designed to maintain total system efficiency by diverting some or all of the exhaust past the (turbine) recuperator to boost the hot water delivery to the desired level.

### ***Currently Available Systems***

There are currently two off-the-shelf small industrial cogeneration systems available in the marketplace to generate hot water. The first system is a microturbine-based solution that works like the indirect liquid heating system described later in this report. An air-to-water heat exchanger is used with the turbine exhaust gases to heat water.

The second system is a standard reciprocating engine cogeneration system. These systems use liquid-to-water heat exchangers on the water jacket cooling fluid, the lubricating oil system, and sometimes on the aftercoolers. Some of these systems also use an air-to-water heat exchanges on the engine exhaust.

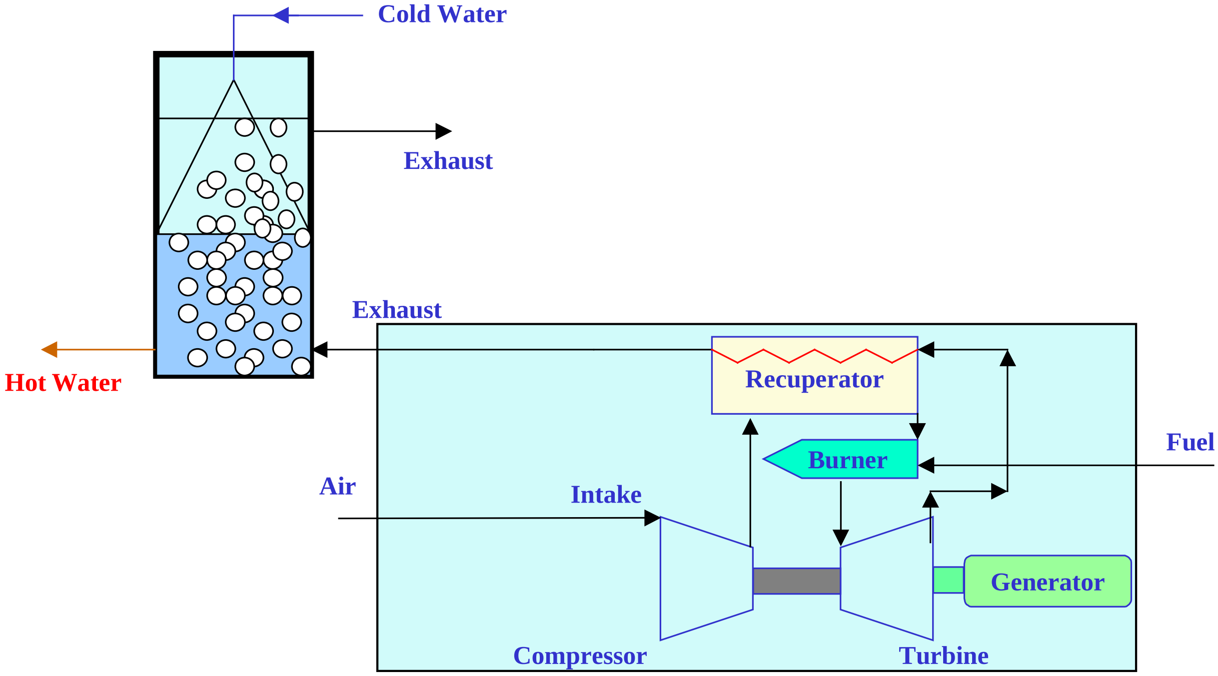

**Figure 9. Direct Contact Water Heater System**

## Indirect Heating of Thermal Fluids

### ***General***

Many operations, requiring energy delivery to a liquid-phase (and/or fluid) stream, require a physical barrier between the fossil burn (energy release) and the process stream. The barrier reduces heat transfer efficiency, but is often necessary. Traditional systems depend upon heat delivery via heat exchangers, fire-tube schemes (heating coils, or multi-pass fluid heaters) and other methods. Many of these systems use flame induced, radiant based heating to rapidly deliver well over 50% of the required energy.

### ***Process Uses***

Situations involving high (and/or variable) pressure systems, separation/purification operations, multi-phase operations, systems impeded by oxidation (or other possibly reactive/degrading components of combustion), and/or strictly maintained closed-loop systems are common boundaries to direct heating of process streams. More specific operations and their manufacturing environments include:

1. Purification, recovery, and separations.
    - Chemicals/refinery distillation (reboilers, etc.), and flash evaporators (polymer processing, slurry separations/purification, brine treatment, etc.).
2. Pressurized process streams (chemical reactors, etc.).
3. Processes/products sensitive to oxidation, other reaction-driven degradation, and/or general fouling (chemical, food, pharmaceutical processing, etc.).
4. Vat or batch systems maintaining a heated fluid (paint/dye blenders, food deep fryers, refinery-bottoms storage and subsequent processing, reactor/fermentation vessels, crystallizers, etc.).
5. Thermal fluid, closed-loop-heating systems for processes, often including those already mentioned, requiring especially high and smoothly controlled temperature profiles.
    - Systems requiring high temperatures over large areas such as calcium chloride crystallizers.
    - Pipe line tracing.
        - Distillation and reactor feed lines whereby preheating feed components simplifies the energy delivery and/or chemistry complexity of that downstream operation.
        - Heat tracing viscous material (crude, confectionery, polymer melts, etc.) pipelines to reduce electric driven pumping.
    - Tool heating (including plastics/rubber extruders, molds), paper mill platens and rollers, metal fabrication equipment, laminate setting, and others.
    - General polymer processing. Polymer processing plants may require high temperature (> 400$^o$F) energy delivery to several unit operations because of high "pure" polymer melting points (maintained for extrusion, molding, etc.), and endothermic and/or equilibrium limited reactions (whereby light byproducts, often water, must be continuously evaporated and removed for effective/efficient reactor output). Polyester and Nylon 6,6 are good examples of major international commodities often utilizing thermal fluids systems throughout their production cycle.

## ***Integrating for Cogeneration***

The wide variety of thermal "fluid" heating applications mentioned above reflects the broad scope in unit operations, engineering techniques, and process chemistries involved in this concept category. For this section, three general interconnection (with cogeneration) systems will be discussed.

1. Systems not relying on radiant energy delivery.

    Systems currently delivering heat to a process fluid via combustion exhaust energy only (or other forced convection media), either through a series of tubes, vessel/pipe jacket, or compact heat exchanger (shell and tube, plate unit, etc.) can be easily adapted to receive cogeneration based thermal energy. Because the majority of a DG unit's thermal output is in the form of hot exhaust, the key concerns would be matching the temperature, gas volume, and pressure parameters to those experienced prior to cogeneration integration. This may require little or no rebuilding of the process heat exchange equipment, but needs to consider the operating tolerance of the DG unit.

2. Systems relying on radiant (flame induced) energy transfer.

    Unless there is little radiant energy transfer contribution (relative to the entire quantity delivered by the process operation) and/or the flame temperatures are low (< 1500$^o$F), even an unrecuperated turbine cannot match the heat transfer characteristics expected in the existing process heat transfer unit. Several combinations may then compete on a cost benefit and space based analysis. Many systems delivering a majority of the energy via high temperature, flame induced radiation leave a significant amount of the unit volume for flame (radiant rays) "space" only. If this space were utilized to generate more passes (fluid tubing), thereby increasing heat transfer area, the operation could be more readily fit by a cogeneration scheme. It may be the case that the original heat transfer unit cannot be properly modified. However, if the feed line to the heater unit is relatively low temperature (70-300°F), a heat exchanger extracting cogeneration energy prior to entering the main heater could result in a sizable turn down of fuel delivery to that unit. Another option would be the use of duct burners to increase the fuel gas temperature to the required levels.

3. Closed loop, thermal fluid heating systems.

   The previous two interconnection categories represent traditional methods of heat transfer to process fluid streams/systems. The second is more common, but also requires a great deal more case by case analysis, because of the variety of techniques and principles incorporated in radiant heat transfer different from those available from cogeneration exhaust (not considering "reburn" technologies). Thermal fluid heating systems however, represent a stronger possibility for a more heterogeneous cogeneration-based heat delivery, retrofit and/or interface system. From a cogeneration standpoint, the only concern is maintaining total heat transfer characteristics to the heat transfer fluid on return from the process unit(s). In other words, a 400,000 Btu/hr Dowtherm® based operation can use the same heater design regardless of whether the system is heating/controlling a polymer reactor or a paper laminate machine. This would allow for more repetitious cogeneration designs across broad categories of process operations and manufacturing sectors.

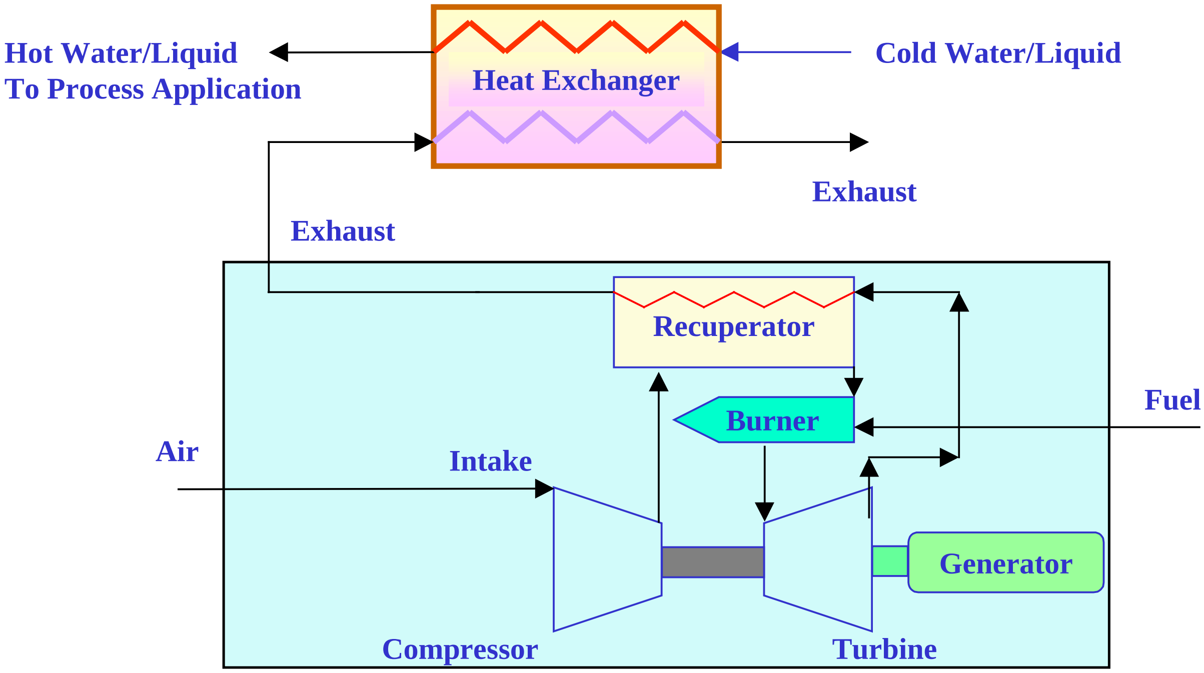

Figure 10. Indirect Fluid Heater System

## Direct Heating/Drying

### ***General***

Direct heating and drying refers to combustion products mixing directly with the process environment (typically process solids and a forced "air" stream). Because radiation transfer is rapid, typically at high temperature, and ceases upon reaching a boundary (the outer layer of process matter), it is often undesirable and unnecessary. Therefore, natural and forced convection heat transfer engineering may dominate dryer design. There are a wide variety of process dryers, kilns, calciners, ovens, etc. that incorporate an even greater range of combinations in forced convection, radiation, and conduction (through the material) heat transfer principles to satisfy the product requirements. In all cases, however, the heat energy supplied to a system must perform the following four tasks:

1. Heat the dryer feed to the "light" component's vaporization temperature.
2. Vaporize and/or free the liquid/byproducts above the solids' surface.
3. Heat the solids to the final desired temperature, and for the desired duration of time.
4. Heat the vapor to the final desired temperature.

### ***Process Uses***

Numerous factors, including production throughput, local steam, natural gas and electricity prices, emissions restrictions, and equipment cost considerations, often result in similar solids being dried in very different ways. However, common direct drying/heating operations and their typical product/process applications include:

1. Bringing variable water-weight percent feeds to a desired initial processing concentration.
    - Mined raw materials and/or prepared mixes fed to cement, gypsum, ceramics, and lime processes require crushing, sizing, and drying. Rotary dryers, impact dryers, drum dryers, and others are used to handle large volume, variable composition slurries. Water removal to organize/homogenize process streams for inorganic chemicals manufacture is also common.
2. More complete drying of slurries containing finer solids within certain size/weight specifications is carried out using spray dryers, thin-film dryers, and drum dryers.
    - Within the Stone, Clay, Glass and Cement manufacturing sector (SIC 32), fine dry powders are desirable for handling, packing, and/or to produce a more consistent product. Specific products include kaolin clay, fluid cracking catalysts and ceramics that may also use this step to introduce property enriching additives/binders to the material.
    - Emulsion PVC and PVP polymer processes often employ spray drying to rapidly remove water without degrading product.
    - Milk/dairy powders.
    - Organic and inorganic dry soaps, detergents, dyes and pigments.
3. Pre-heating/drying materials.
    - Metals fabrication and/or scrap metal industries use direct heat to remove volatile impurities (oils, plastics, paints, etc.) and/or to reduce energy demand of central furnace operations.
    - Large kilns, calciners, and ovens (primarily in SIC 32) also benefit from preheated feeds, often containing preheat sections as part of the primary unit (tunnel kilns, etc.).
    - Coke processes may preheat coal feeds to reduce moisture content.
    - Glass and mineral wool industries utilize many preheat techniques to reduce energy demands or increase throughput on central furnaces systems.
4. Drying and heating meant to relieve chemically bound light components and/or otherwise modify solid structure. Rotary kilns, shaft kilns, kettle calciners, flash calciners, brick ovens/houses, tunnel kilns, regenerative kilns, and others are included in this grouping.
    - Kilns and ovens used for bricks, ceramics, etc. where residence times in hot and dry conditions may last hours to days to obtain desired final qualities in appearance and structure.
    - Kilns and calciners used to produce/process gypsum, plasters, cements, limestone, etc. where energy not only thoroughly removes any remaining water, but also frees intimate impurities, and forces various reactions often resulting in the release of carbon and sulfur oxides. Along with those operations in SIC 32, both the pulp & paper and beet sugar industries use these lime kiln technologies.
5. Drying to remove water (and/or other solvents/chemicals) added, left, or produced during processing.
    - Starch, stalk and husk dryers, and fruit peel and feed dryers, used in beet and cane sugar manufacturing, grain mill products, and other SIC 20 manufacturing sectors.

   - Convection dryers in textile manufacturing.
   - Veneer and other lumber/wood-furniture dryers.
   - Pulp dryers, coated and tissue paper dryers in SIC 26.
   - Dryers including conveyor and tray dryers used in non & cellulosic fibers (rayon, acrylics, etc.) processing, polymer rubbers manufacture, for pharmaceuticals, and latex.
6. Granulators, fluidized bed systems, rotary dryers, and tower dryers often used for producing finished grains, sugar, and fertilizer.

### ***Integrating for Cogeneration***

Many kilns and calciners depend on high temperature (1000-2000°F) exhaust and radiant heating sections that could not be supplied by cogeneration exhaust alone. However, preheating operations can take advantage of cogeneration. Although many “direct” preheating systems recover stack gas from onsite furnaces and central calciners/dryers, the gas often requires filtering or other treatment to remove particles, sulfurous gases, and other components that can otherwise deteriorate equipment and cause health concerns. Sites with successful existing preheating not derived from cogeneration may see additional turndown (on the primary unit’s fuel feed) without high retrofit costs if the system can handle an extra volume of exhaust (from a cogeneration scheme) and assuming temperature conditions are similar to the existing preheater’s hot gas feed. Drying operations at facilities without processing furnaces, (e.g., calciners) could completely supplement a non-radiant based dryer. However, some direct dryers burn cheap fuels (e.g. wood, pulp waste, coal) and so emissions considerations may drive the final decision.

In all cases, drying systems can contain a complex array of blowers and fans to promote improved heat transfer and efficiency. Back pressures on the DG unit may require controls and monitoring at each dryer entry point (of hot gases into the system) depending on the design.

Note: Typical unit operations literature may define direct drying to include solids receiving energy from any heated gas (combustion products/air mixtures, and hot air only are two of the most common media). This report distinguishes between the two, not because the process solid experiences different heat transfer profiles (it, essentially, does not), but because the integration of the cogeneration equipment is different.

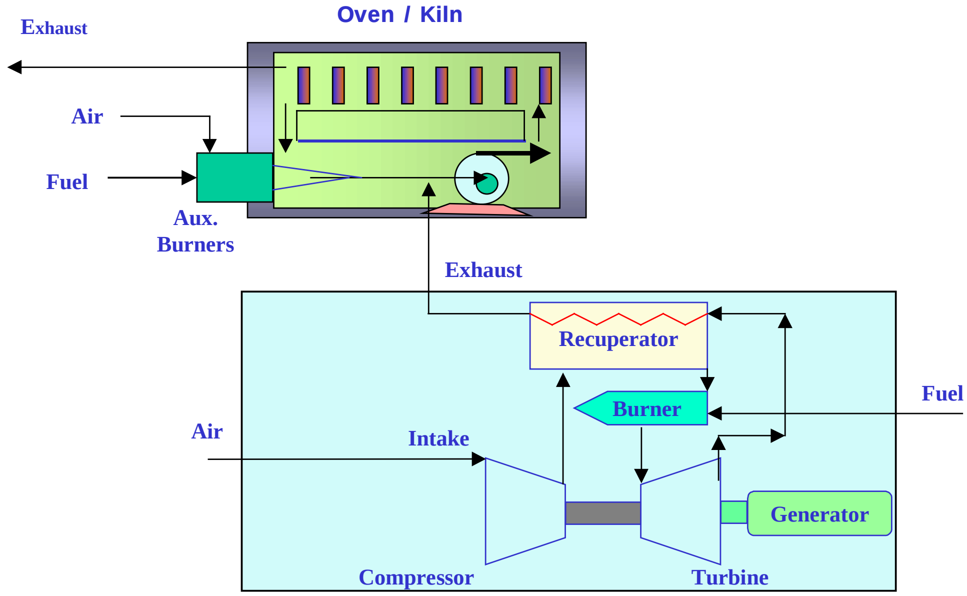

**Figure 11. Direct Heating/Drying System**

# Indirect Air/Gas Heating

## *General*

Air heaters or inert gas heaters are commonly considered when products, process operations, or the facility environment are potentially compromised by using direct drying/heating systems. Because issues including plant layout, local regulations, and fuel type affect these considerations, many of the processes in this section and the preceding section are served by both indirect and direct heating.

## *Process Uses*

Two general processing categories are considered:

1. Food products cooking, baking, and drying.
    - Roasters used in coffee and cocoa processing.
    - Baking ovens used for breads, cakes, etc.
    - Toasting and drying systems for cereals.
2. Finish drying and curing systems.
    - Dryers following painting and or final cleaning operations in furniture and metals fabrication industries (transportation & industrial equipment, beverage cans, etc.).
    - Dryers used in finishing periodicals and newspaper production processes.

## *Integrating for Cogeneration*

Air heaters are often industrial versions of fired furnaces used in HVAC systems. Although many of the operations mentioned above require only modest heat (200-600°F), the heater itself may have radiation-induced "hot side" temperatures above 1500°F. A new type of heat exchanger may be needed for some applications.

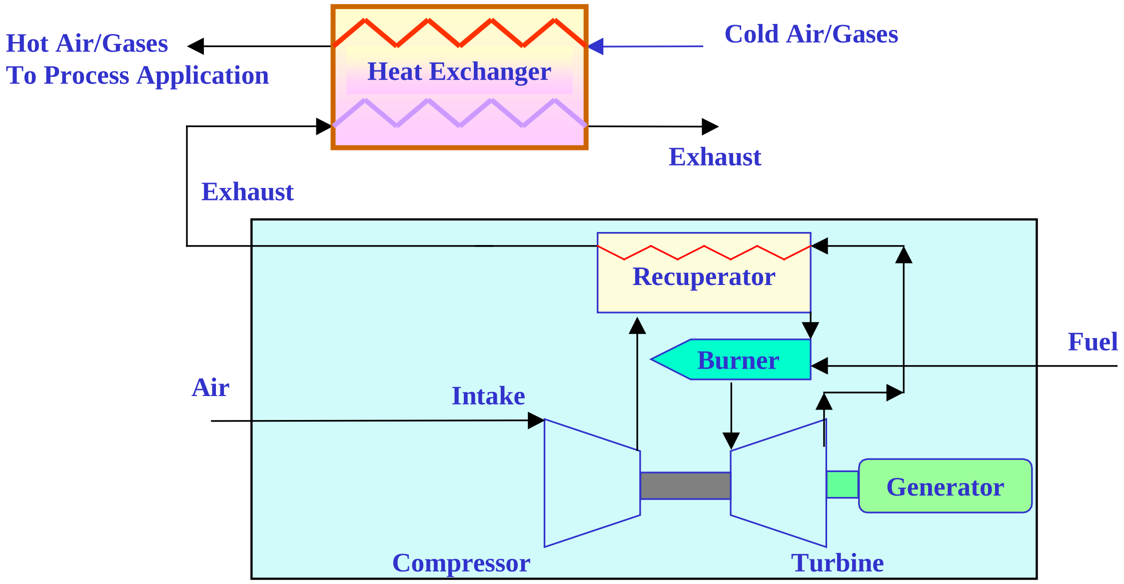

**Figure 12. Indirect Air/Gas Heating System**

## Refrigeration/Freezing (absorption cooling)

### ***General***

Refrigeration/freezing refers to a direct process end use in which energy is used to lower the temperature of substances involved in the manufacturing process. Conventional equipment includes industrial chillers and absorption cooling equipment.

### ***Process Uses***

Major applications of industrial cooling include:

- Refrigerated storage of unfrozen foods,
- Frozen foods,
- Refrigeration to change the chemical structure of food,
- Freeze drying,
- Industrial process air conditioning, and
- Refrigeration in the petroleum and chemicals industries (reaction heat removal, gas separations, condensation of gases, separations, solidifications, humidity control, etc.).

### ***Integration for Cogeneration***

Absorption cooling systems require a source of heat. For an ammonia-water cooling system, the heat is required to separate the water and ammonia. In conventional absorption systems, this heat is supplied by steam heat exchangers, an electrical heater or a gas fired heater. For cogeneration systems, this heat can be supplied by using a heat exchanger where clean exhaust gases from a turbine or other type of prime mover is used as a heat source. The heating gases may have to be mixed with air or other gases to maintain desired heating gas temperature. Such a system will reduce or eliminate heat input for the overall system.

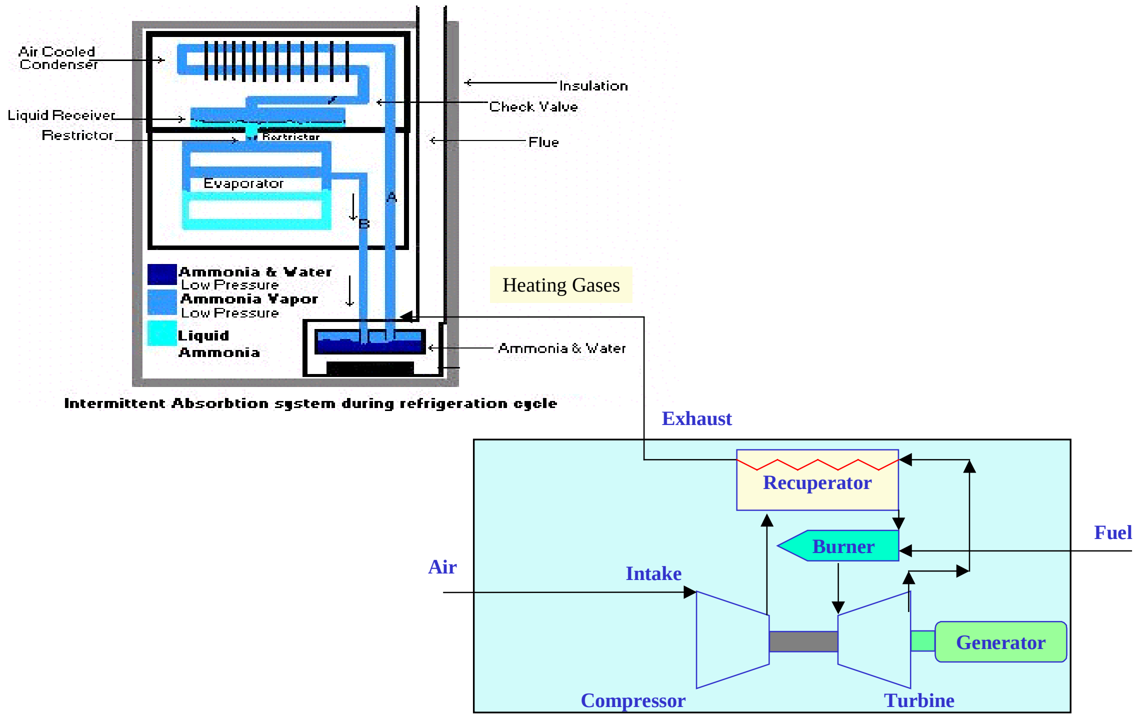

**Figure 13. Refrigeration/Freezing System**

## Dehumidification

### *General*

Desiccant-based dehumidification systems are used extensively for removing moisture from moist air or gases in many industrial applications. Some typical industries where such systems are used include chemical, pharmaceutical, food, semi-conductor manufacturing, and vacuum processing. These systems are also used for climate control applications in commercial buildings. Operation of these systems includes a regeneration step where hot air (or other gases) are used to remove moisture from saturated desiccant media.

### *Process Uses*

Major applications of dehumidification in the manufacturing sector include:

- Pharmaceutical processing,
- Candy coating,
- Storage and packing,
- Conveying of hygroscopic powders,
- Composite manufacturing,
- Semiconductor manufacturing,
- Printing operations,
- Corrosion prevention,
- Molding operations, and
- Drying operations.

### *Integration for Cogeneration*

In the cogeneration system, clean exhaust gases will be mixed with ambient air to raise the temperature to the desired value. Currently, a variety of heating methods and media are used for supplying hot regenerative air. The heating methods include heating by electricity, steam, or a fuel (usually gas) fired burner. Application of such a scheme may require redesign of the regenerative air system for a retrofit application. For a newer application, such changes can be accounted for during the design phase of the project.

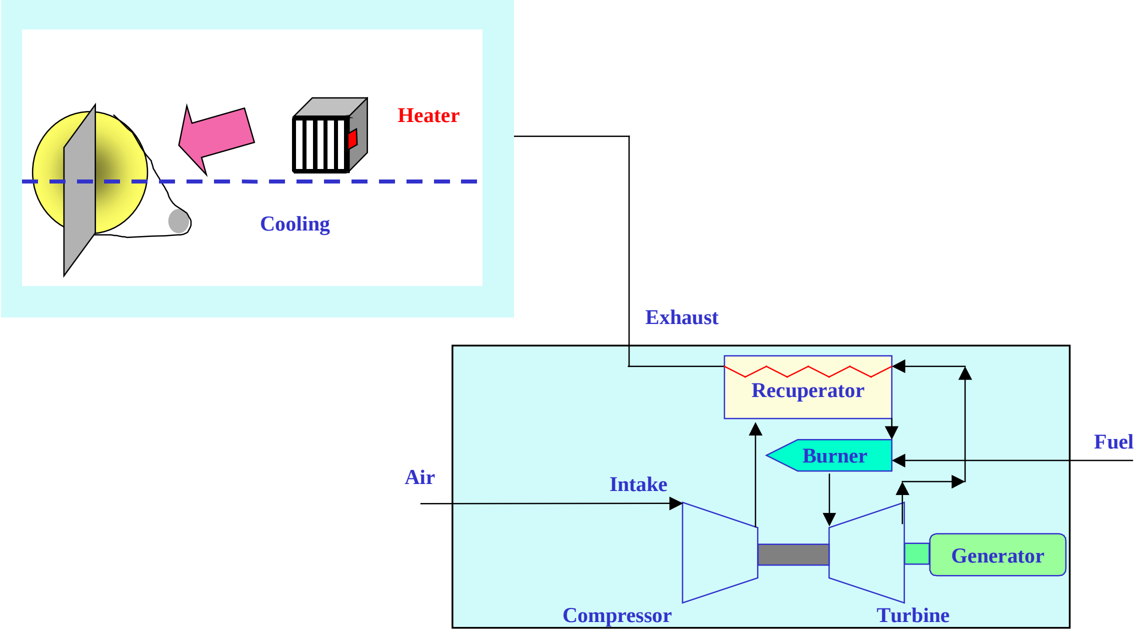

**Figure 14. Dehumidification System**

## Use of Exhaust Gas as an Oxidant (including boiler systems)

### ***General***

Combustion reactions are highly exothermic. However, their reactants (fuel and oxidant) continuously absorb considerable energy to reach proper combustion temperatures. Exhaust gases from a prime mover, particularly from a gas turbine (because of its high oxygen content), provide an excellent preheated oxidant. These gases can be considered as an oxidant source for combustion of fossil fuels used in most heating applications including steam generators or boilers.

### ***Processes Uses***

Applications for using exhaust gases as an oxidant include:

- Central boiler systems,
- Waste VOC incineration systems,
- Kilns,
- Calciners,
- Large ovens,
- Large heat treating operations,
- Large furnaces,
- Forging operations,
- Tempering operations,
- Annealing operations, and
- Cupolas.

### ***Integration of  Cogeneration Systems***

Many engineering techniques addressing the principle of preheating the combustion reactant feed (especially the oxidant, because its volume generally dominates the reactant mixture) are in practice. Three categories represent a majority of these techniques:

1. Using the stack exhaust to indirectly (e.g., with a shell and tube exchanger) heat the air/oxidant feed line.
2. Burner tip techniques that often incorporate ceramics to maintain the final mixing chamber at extremely high temperature, thereby heating the reactants immediately prior to ignition.
3. Using high temperature, high oxygen content, waste-heat streams as a combustion reactant/oxidant (as the DG cogeneration system would offer).

In general the cogeneration based oxidant system is highly competitive for these options when:

1. The process operation is operated such that its own exhaust is either low in temperature or low in excess oxygen.
2. The process operation uses coal (or other fuels releasing soot and sulfur in the exhaust) as a fuel. In such cases cogeneration offers both a relatively clean preheated feed (so as not to foul the burner equipment) and also reduces the amount of sulfur and particulate released (by reducing the amount of coal needed).

If a system's burner was initially designed for low temperature air feeds, more heat durable components may be needed to handle a hot oxidant. The difference in oxygen content also needs careful consideration to properly engineer the combustion system.

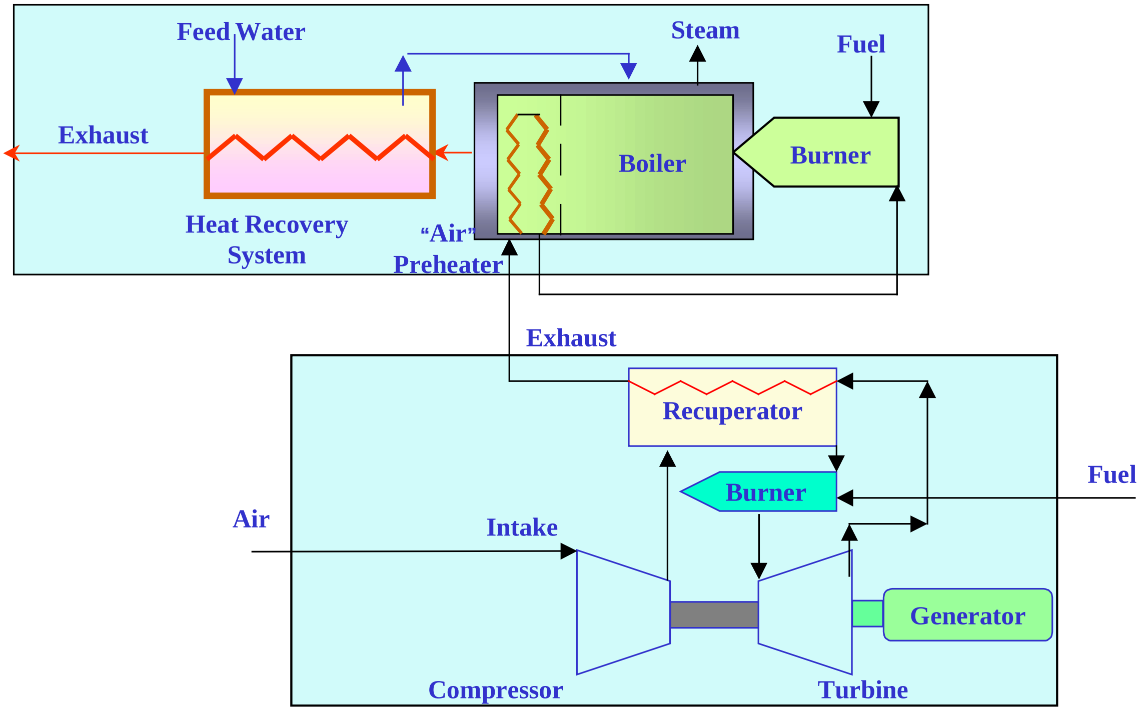

**Figure 15. Exhaust Gas as an Oxidant System for Boiler Systems**

## General Cogeneration Integration Considerations

Integration into a specific manufacturing facility will always require further site-specific analyses. However, there are several general considerations pertinent to determining how a specific existing operation is altered (from an engineering perspective) when driven or partially supported through cogeneration.

1. *Heat transfer rates* to the process media are often reduced when using exhaust (the typical heat media from a cogeneration unit) as opposed to a burner-based operation (e.g., a process furnace). Though the quantity of heat energy available from a DG unit is often sufficient to maintain a process operation from an energy balance standpoint, the dynamics (temperature and energy transfer profiles) can be significantly different. This is because high temperature (1500-4000°F), luminous flames induce radiant based heating (rays of energy moving at the speed of light), whereas cogenerated exhaust energy ranges from 450-1100°F and moves via convection-conduction only. A common remedy is an increase in the heat transfer area (and therefore the equipment size).

2. *Batch systems* and other operations with non-constant temperature/energy requirements, including fermentation, reactor, and mixing vessels, are often dependent upon dynamic heating systems to accommodate "cold" start-ups, and varying endo/exo-therms and temperature profiles. These systems are not always ideal for cogeneration schemes.

3. *Auxiliary burners,* or maintaining the existing burner system (depending on its flexibility), can increase the flexibility and therefore applications of cogeneration systems. The primary driver for investing in a distributed generation (leading to a cogeneration option) unit is the electricity output. Constant electrical delivery typically results in constant heat delivery (although variations in heat recuperation, fuel feed, etc. can allow for some flexibility). However, for a process such as the batch systems addressed above, there may be a row of three burners heating the vessel. If a "batch" cycle

ran one hour, needing all three burners for the first 20 minutes, and one or two thereafter, a steady cogenerated heat stream could replace the “one or two” burners needed constantly, while the third would remain to maintain the initial per-batch heat requirement.

4. *Controls systems* monitoring and maintaining operations incorporating a cogeneration scheme may need to be modified or completely re-engineered. Automated control systems on a typical burner based system will monitor one or more parameters of the process and then adjust fuel/oxidant feeds to the burner accordingly. If a system is heated via exhaust from a cogeneration scheme, the control system might include a by-pass system (e.g., a recuperator) or on/off auxiliary burner concepts.

## Generic Thermal Process by Industry

Table 2 shows the applicability of each generic thermal process to each manufacturing sector.

**Table 2. Thermal Processes by Industry**

| Industry | Direct Contact Water Heater | Indirect Liquid Heating | Direct Heating Drying | Indirect Air/Gas Heating | Refrig Freeze | Dehumid ification | Exhaust Gas Oxidant (non-boiler) | Exhaust Gas Oxidant (boiler) |
|---|---|---|---|---|---|---|---|---|
| 20 – Food | X | X | X | X | X | X | X | X |
| 21 – Tobacco |  |  | X |  | X |  |  | X |
| 22 – Textiles | X |  | X | X |  |  |  | X |
| 23 – Apparel | X |  |  |  |  |  |  | X |
| 24 – Wood | X |  | X |  |  |  |  | X |
| 25 – Furniture | X |  |  |  |  |  |  | X |
| 26 – Paper | X | X | X |  |  |  | X | X |
| 27 – Printing | X | X | X |  | X |  | X |  |
| 28 – Chemical | X | X | X | X | X | X | X | X |
| 29 – Petroleum |  | X | X |  | X | X | X | X |
| 30 - Rubber Plastics | X | X | X | X | X |  |  | X |
| 31 – Leather | X |  |  |  |  |  |  | X |
| 32 - Stone Clay Glass | X | X | X |  |  |  | X | X |
| 33 - Prim Metals | X | X | X |  | X | X | X | X |
| 34 - Fab Metals | X | X | X | X |  |  | X |  |
| 35 – Machinery | X | X | X |  |  |  | X |  |
| 36 – Electronics | X |  |  |  |  |  |  |  |
| 37 – Transport | X |  |  |  |  |  |  |  |
| 38 – Measuring Equipment | X |  |  |  |  |  |  | X |
| 39 - Misc. | X |  |  |  |  |  |  |  |

Table 3 shows significant thermal processes by 4-digit SIC, describes each process step in more detail, and gives an indication of temperature ranges for each process.

## Table 3. Thermal Processes by Industry

| SIC | Industry Sector | Direct Contact Water Heater | | Indirect Liquid Heating | | Direct Heating Drying | | Indirect Air/Gas Heating | | Refrigeration/ Freezing | | Dehumidification | | Exhaust Gas Oxidant | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F |
| 2026 | Fluid Milk | Washing | 90 | Pasteurizing | 165 | | | | | Cooling | 33 | | | | |
| 2026 | Fluid Milk | | | | | | | | | Milk refrig. | 40 | | | | |
| 2026 | Dried/evap milk | | | | | Spray drying | 350-500 | | | Milk product storage | 38 | | | | |
| 2033 | Preserved fruits & vegs. | Washing | | | | | | | | Water cooling | 45-60 | | | | |
| 2040 | Grain mill products | Process (Steeping) Hot Water | 125 - 140 | Process (Steeping) Hot Water | 125 - 140 | Drying/ Roasting for starch, germ | 160 - 250 | Drying/ Roasting for starch, germ. | 160 - 250 | | | | | | |
| 2040 | Grain mill products | Clean-up/ Washing hot water | 140 | | | Drying for feed and product | 300 - 450 | Drying for feed and product | 300 – 450 | | | | | | |
| 2050 | Bakery products | | | | | | | Baking ovens | 400 – 600 | | | | | | |
| 2060 | Sugar & confection. products | Process Hot Water (Mingler, melter etc.) | 165 to 195 | Process Hot water (Mingler, melter etc.) | 165 - 195 | | | | | | | Space conditioning (humidity control) | 75 | | |
| 2060 | Sugar & confection. products | | | | | Drying - granular product | 165 - 250 | Drying for granular product | 165 - 250 | | | | | | |
| 2060 | Viscous materials (molasses, etc.) | | | Hot oil (thermal fluids), storage & pumping | | | | | | | | | | | |
| 2062 | Cane sugar refining | Washing | 140 | | | Charcoal regenerator | 900 | | | | | | | Charcoal regenerator | 900 |
| 2063 | Beet sugar production | | | Process Hot water (Mingler, melter etc.) | 165 - 195 | Kiln dryer | 200 | | | | | | | Lime kiln | 600 |
| 2066 | Chocolate | | | | | | | Cocoa roaster | 500 - 600 | | | | | | |
| 2070 | Fats & Oils | | | | | | | | | | | | | VOCs reduction | |
| 2080 | Malt Beverages | Process Hot Water (pasteurization, filtering, etc.) | 165 | Process Hot Water (pasteurization filtering, etc.) | 165 | Grain dryers | 600-700 | | | Cooling, fermentation etc. | 20 - 60 | | | | |
| 2087 | Extracts & syrups | | | | | | | | | | | | | VOCs reduction | |
| 2090 | Coffee | | | | | | | Roaster | 900 | | | | | | |
| 2000 | Chips, french fries, fish, doughnuts, etc. | | | Oil fryers (thermal fluids) | 400-600 | | | | | | | | | | |
| 2100 | Tobacco Products | Washing | 120-140 | | | Kiln dryer | 180-220 | | | Storage | 40 | | | | |
| | | | | | | Dry and frame | 180 | | | | | | | | |

## Table 3. Thermal Processes by Industry

| SIC | Industry Sector | Direct Contact Water Heater | | Indirect Liquid Heating | | Direct Heating Drying | | Indirect Air/Gas Heating | | Refrigeration/ Freezing | | Dehumidification | | Exhaust Gas Oxidant | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F |
| 2221-62 | Textile mill products | Dye and wash | 140 | | | Singeing | 400 | Singeing | 401 | | | | | | |
| 2221-62 | Textile mill products | Washing | 180 | | | Drying | 250 | | | | | | | | |
| 2400 | Lumber & wood products | | | | | | | | | | | | | Supplemental burn (low emissions) | |
| 2421 | Saw mills etc. | | | | | Kiln drying | 120-180 | | | | | | | | |
| 2430 | Plys & structural | | | Molds/ Presses (thermal fluids) | | | | | | | | | | | |
| 2499 | Fiberboard | | | | | Stabili-zation/ drying | 350 | | | | | | | | |
| 2500 | Furniture | | | | | | | | | | | | | VOCs reduction (paints, solvents, etc.) | |
| 2600 | Paper & allied products | | | | | | | | | | | | | | |
| 2600 | Non-integrated finishing plants | | | | | | | | | | | | | VOCs reduction | |
| 2611 | Pulp Mills (Kraft, sulfite and mechanical process) | Washing of pulp stock | 900-100 | | | Drying | 151-240 | | | | | | | Lime kilns | 1200 |
| 2620-30 | Paper (paper board) mills – integrated plants | Washing of pulp stock | 90-101 | | | Drying | 151-240 | | | | | | | Lime kilns | 1200 |
| 2670 | Coated & laminated | | | Laminate setting/ finish cure (thermals) | | | | | | | | | | | |
| 2710-20-30-40-50 | Newspaper, Periodicals, books, misc. publishing & general printing | General washing | 100-120 | | | Drying | 150-200 | | | Air Cooling | 40-60 | | | Thermal oxidizers | 1400-1600 |
| 2750 | Commercial printing – gravure | | | Finish drying/curing (thermal) | | | | | | | | | | | |
| 2812 | Alkalies and Chlorine | | | Brine heater | 160 | | | | | Chlorine con-denser | | | | Lime kiln | 1600-1800 |
| 2812 | Alkalies and | | | | | Drying | 180 | | | | | | | Calciner for | 650 |

## Table 3. Thermal Processes by Industry

| SIC | Industry Sector | Direct Contact Water Heater | | Indirect Liquid Heating | | Direct Heating Drying | | Indirect Air/Gas Heating | | Refrigeration/ Freezing | | Dehumidification | | Exhaust Gas Oxidant | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F |
| | Chlorine | | | | | | | | | | | | | NAHCO3 | |
| | Anhydrous caustic soda | | | Evaporators (thermal) | 700 | | | | | | | | | | |
| 2813 | H2 generation – steam reformer | | | Ammine solution reactivator | 220 | | | | | | | | | Reformer heating | 1500-1600 |
| 2813 | H2 generation – steam reformer | | | | | | | | | | | | | CO converter | 800 |
| 2816 | Inorganic pigments | Washing | 120-140 | | | Pigment (spray) dryer | 325 - 1200 | | | Chilled water | 40 | | | Ti 02 Heater & Vaporizer | 1120 |
| 2816 | Inorganic pigments | | | | | | | | | | | | | 02 Heater | 1120 |
| 2819 | Inorganic chemicals | Ore leaching | 180 | | | Drying | 250-350 | | | | | | | Calciner – Ti02 | 1500 |
| | Sodium tripolyphos-phate | | | | | Spray dryer | | | | | | | | | |
| 2821 | Plastic resins | | | Hot oil for heating | 400-450 | Drying | 250-350 | | | | | | | | |
| 2821 | PVP & PVC emulsion | | | | | Spray dryers | 300-400 | | | | | | | | |
| 2821 | LDPE, polystyrene | | | Various equipment (thermal fluids) | 600-800 | | | | | | | | | | |
| 2821 | PTA | | | Preheat hydrogener-ation feed (thermals) | 700 | | | | | | | | | CTA & vent gas (VOCs) incineration | |
| 2822 | Synthetic Rubber | | | | | Storage heating | 200-250 | | | Emulsion reactor | 40 | | | | |
| 2822 | Synthetic Rubber | | | | | Drying | 180 | | | Chilled water for extruders mixers etc. | 40 | | | | |
| 2822 | Synthetic Rubber | Preheaters (Ethylene) | 120 | | | Pre-heaters (Ethylene) | 120 | | | | | | | | |
| 2823 | Manmade fibers | Hot water for washing – fibers | 180-200 | | | Drying | 120-200 | | | | | | | | |
| 2823 | Manmade fibers | Pulp preheating | 90-100 | | | Pulp preheating | 90-100 | | | | | | | | |
| 2824 | Organic fibers | | | | | Drying | 120 | | | | | | | Reactor heating | 450-500 |
| 2824 | Polyester, nylon 6-6 | | | Melters, evaps, etc. (thermals) | 400-1000 | Melter | 320 | | | | | | | Polymer melter | 450 |
| 2824 | Polyester, nylon 6-6 | | | | | Drying | 150 | | | | | | | Polymerizer | 540 |

**Table 3. Thermal Processes by Industry**

| SIC | Industry Sector | Direct Contact Water Heater | | Indirect Liquid Heating | | Direct Heating Drying | | Indirect Air/Gas Heating | | Refrigeration/ Freezing | | Dehumidification | | Exhaust Gas Oxidant | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F |
| 2824 | Pharmaceuticals | Container washing | 80-100 | | | Drying | 200-250 | Drying | 200-250 | Production cell atmosphere conditioning | 50-70 | Production cell atmosphere conditioning | 75 | | |
| 2824 | Pharmaceuticals | | | Purification/ recovery of heat-sensitive products (thermal) | | | | | | | | | | | |
| 2841 | Soaps & detergents | | | | | Spray dryers | | | | | | | | | |
| 2850 | Paints etc. | | | Storage & Pumping (thermal fluids) | | | | | | | | | | | |
| 2865 | Cyclic crudes and intermediates | | | | | Pre-heaters | 400-500 | | | Reactor – chiller | -20 | | | Steam heaters/ super heaters | 750-1300 |
| 2865 | Dyes & pigments | | | | | Spray dryers | 350-700 | | | | | | | Reformer (methanol) | 1500 |
| 2865 | Styrene | | | Separations, recovery, etc. (thermals) | 500 | | | | | | | | | Shift reactor | 550-600 |
| 2865 | p-xylene | | | Isomerization & separations (thermals) | 1000 | | | | | | | | | | |
| 2869 | Caprolactam, acryloni | | | | | | | | | | | | | | |
| 2869 | VCM | | | Purification recovery | | | | | | HCl cond. | -22 | | | | |
| 2869 | VCM | | | EDC cracker | 1000 | | | | | Cooling water | | | | | |
| 2869 | Acetic acid | | | Purification recovery | 300 | | | | | | | | | | |
| 2873 | Fertilizer | | | | | Drying | 150-200 | Methane Preheating | 400-500 | Reactor – Chiller | -20 | | | Reformer (methane) | 1500 |
| 2911 | Petroleum refining | | | | | | | | | | | | | | |
| 2911 | Petroleum refining | Preheating of crude | | Preheating | 450-500 | | | | | | | | | Preheating | 450-500 |
| 2911 | Distillation | | | | | | | | | | | | | Heating | 750-780 |
| 2911 | Coking | | | | | | | | | | | | | Heating | 900-1100 |
| 2911 | Vis breaking | | | | | | | | | | | | | Heating | 70-1000 |
| 2911 | Lube oil | | | | | Heating | 200- | | | | | | | | |

# Table 3. Thermal Processes by Industry

| SIC | Industry Sector | Direct Contact Water Heater | | Indirect Liquid Heating | | Direct Heating Drying | | Indirect Air/Gas Heating | | Refrigeration/ Freezing | | Dehumidification | | Exhaust Gas Oxidant | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F |
| | processing | | | | | | 450 | | | | | | | | |
| 2911 | Reforming | | | | | | | | | | | | | Heating | 1100-1400 |
| 2911 | Alkylation | | | | | | | | | Vapor condens. | -10 – 40 | Dehumid of feed | Ambient | | |
| 2911 | Recovery boiler | | | | | | | | | | | | | CO burning | 1000-1600 |
| 2950 | Asphalt | | | Heating | 250-350 | Drying process | 250-400 | | | | | | | VOC reduction | |
| 2990 | Misc. petroleum | | | Heating | 250-350 | | | | | | | | | VOC reduction | |
| 3069 | Fabricated rubber | | | Thermal fluids | 350-600 | Drying | 120-150 | | | Chilled water | 40 | | | | |
| 3069 | Plastics products | | | Thermal fluids | 350-600 | Lamin., cast, mold | 250-350 | | | Chilled water | 40 | | | | |
| 3069 | Tire recycling | | | Melting | | | | | | | | | | | |
| 3221<br>3222 | Glass | | | | | Cullet drying preheating | 250-1000 | | | | | | | Annealing | 900-1000 |
| 3221<br>3222 | Glass | | | | | | | | | | | | | Tempering | 1300-1600 |
| 3221<br>3222 | Glass | | | | | | | | | | | | | Laminating heating | 1000-1100 |
| 3229 | Fiber glass | | | | | Curing ovens | 350-650 | | | | | | | Curing ovens | 350-650 |
| 3240 | Cement | Hot water | 120-140 | | | | | | | | | | | Dryers, clinkers | |
| 3250<br>3260 | Clay products | Hot water | 120-140 | | | Spray dryers | 300-1100 | | | | | | | | |
| 3270 | Concrete, gypsum, plaster | Hot water | 120-140 | | | | | | | | | | | Lime kilns | |
| 3296 | Mineral wool | | | Curing | | Curing ovens | 350-650 | | | | | | | Curing ovens | 350-650 |
| 3296 | Mineral wool | | | | | | | | | | | | | Cupolas | |
| 3310 | Coke from coal | | | | | Pre-drying coal | | | | | | | | | |
| 3310<br>3312 | Blast furnaces steel mills | Pickling | 160 | Pickling | 160 | Scrap drying preheating | 350-600 | Blast furnace stove air preheat | 200-800 | | | Blast furnace dehumid. | 75-90 | Scrap preheat | 1000-1200 |
| 3310<br>3312 | Blast furnaces steel mills | | | | | Load preheating | 250-600 | | | | | | | Direct fired furnaces | 600-2500 |
| 3310<br>3312 | Blast furnaces steel mills | | | | | Ladle drying | 300-400 | | | | | | | | |
| 3313 | Electromet. Products | | | | | Ore drying | 300-400 | | | | | | | Preheating kilns | 1200-1600 |

## Table 3. Thermal Processes by Industry

| SIC | Industry Sector | Direct Contact Water Heater | | Indirect Liquid Heating | | Direct Heating Drying | | Indirect Air/Gas Heating | | Refrigeration/ Freezing | | Dehumidification | | Exhaust Gas Oxidant | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F | Process Step | Temp °F |
| 3321 | Iron foundries | | | | | Mold drying | 500-600 | | | | | | | | |
| 3321 | Iron foundries | | | | | Core baking | 400-450 | | | | | | | | |
| 3321 | Iron foundries | | | | | Sand reclamation | 800-1200 | | | | | | | | |
| 3321 | Iron foundries | | | | | Heat treating tempering | 300-900 | | | | | | | Heat treating hardening forging | 300-1600 |
| 3334 | Primary Al | | | | | | | | | | | | | Anode baking | 500-2000 |
| 3341 | Secondary Al | | | | | Scrap drying preheating | 350-600 | | | | | | | Melting furnace | 1250-1350 |
| 3341 | Secondary Al | | | | | Solution treatment furnaces | 350-400 | | | Quench medium cooling | 40-60 | | | Direct fired homogen. Furnaces | 350-1000 |
| 3341 | Zinc | | | | | Sweating furnace | 1000 | | | | | | | Melting furnace | 1000 |
| 3341 | Zinc | | | | | Mold preheating | 250-400 | | | | | | | Distillation furnace | 2400 |
| 3341 | Copper | | | | | Scrap drying preheating | 350-600 | | | | | | | Sweating furnace | 1000-1100 |
| 3341 | Copper | | | | | | | | | | | | | Melting refining furnace | 2000-2400 |
| 3353 | Al sheet, plate, foil | | | Preheat with thermal fluids | | | | | | | | | | Melting refining furnace | 1200-1400 |
| 3353 | Al sheet, plate, foil | | | | | Annealing | 400-700 | | | | | | | Annealing | 400-1000 |
| 3460 | Forging | | | | | Preheat | 600-1400 | | | | | | | Preheat | 600-1400 |
| 3460 | Forging | | | | | Annealing | 400-700 | | | | | | | Heat treatment | 1000-1600 |
| 3479 | Metal coating | | | | | Sheet drying | 150-200 | | | | | | | | |
| 35 | Machinery | | | | | Paint drying | 200-350 | | | | | | | Heat treatment | 1000-1600 |
| 35 | Machinery | | | Parts washing and rinsing | 140-160 | Parts drying | 160-200 | | | | | | | VOC reduction (painting) | |
| 36 | Electronics | | | | | | | | | | | Clean rooms | Ambient | | |

# Selecting the Top 5 Cogeneration Applications

The seven broad categories of thermal applications were broken into more specific categories (e.g., breaking *direct heating and drying* into subcategories such as *spray drying*) so that replicability could be estimated by approximating the total U.S. annual energy consumption of each specific process. Table 4 ranks the specific thermal process categories by total U.S. annual energy consumption.

**Table 4. U.S. Annual Energy Consumption for Each Process**

| Technology Group | Process Step Aided | SIC | Product | Tbtu per year |
|---|---|---|---|---|
| (1) exhaust as oxidant | heating | 2911 | atm & vacuum distillation | 113.50 |
| | methane reformer | 2873 | ammonia | 71.49 |
| | H2 feedstock reformers | 2911 | refineries | 66.17 |
| | heating | 2911 | catalytic reforming | 52.00 |
| | heating | 2911 | coking | 25.75 |
| | lime kilns | 2611-30 | paper mills integrated | 22.00 |
| | reformer heating | 2813 | merchant inorganics gases | 22.00 |
| | reformer | 2869 | methanol | 17.74 |
| | melting/refining furnace | 3353 | aluminum sheet, foil, etc | 5.55 |
| | slab/billet/etc. preheat | 3354 | aluminum sheet, foil, etc | 2.99 |
| | melting furnace | 3341 | secondary aluminum | 2.27 |
| | annealing | 3221 | container glass | 1.64 |
| | preheating kilns | 3313 | electrometallurgical prods | 1.45 |
| | tempering | 3211 | flat glass | 1.20 |
| | heating | 2911 | vis breaking | 1.00 |
| | Lime kiln | 2063 | beet sugar | 0.76 |
| | Annealing | 3211 | flat glass | 0.38 |
| | Laminating/heating | 3211 | flat glass | 0.18 |
| | | | **Category (1) Total** | 408.06 |
| (2) direct contact water heater | Pulp wash | 2620-30 | integrated paper mills | 227.43 |
| | Mingle, melt, etc | 2060 | sugar & confectionery | 48.16 |
| | pickling op. | 3312 | blast furnace steel | 32.37 |
| | container wash | 2834 | pharmaceutical | 22.00 |
| | process water | 2082 | malt beverages | 21.26 |
| | dye/wash | 2200 | textile | 18.28 |
| | pulp wash | 2611 | pulp mills | 13.77 |
| | ore leaching | 2819 | inorganic chemicals | 6.06 |
| | washing | 2026 | fluid milk processing | 3.92 |
| | | | **Category (2) Total** | 393.25 |
| (3) indirect liquid heating - thermal fluid systems | setting laminates | 2670 | coated & laminated paper | 49.24 |
| | isomerization/separations | 2865 | para xylene | 31.43 |
| | molds/cures | 3080 | misc plastic products | 24.74 |
| | various | 2824 | nylon 6,6 | 23.20 |
| | hot rolls | 3350 | nonferrous roll/draw | 16.12 |
| | recovery, purify | 2834 | pharmaceutical preps | 14.21 |
| | molds/cures | 3010 | tires & tubes | 12.74 |
| | hydrogenation feed | 2821 | terephthalic acid (PTA) | 11.70 |
| | separations/recovery | 2865 | styrene | 10.73 |

| Technology Group | Process Step Aided | SIC | Product | Tbtu per year |
|---|---|---|---|---|
| | high T calenders/rollers | 2600 | pulp finishing | 10.00 |
| | fryer | 2096 | potato/corn chips | 9.97 |
| | heater/melter | 2824 | polyester fiber | 9.47 |
| | hot rolls/ink press | 2754 | gravure, comm. printing | 5.84 |
| | various | 2821 | LD polyethylene | 4.24 |
| | various | 2821 | polystyrene | 4.17 |
| | curing/finishing | 3296 | fiberglass insulation | 2.68 |
| | evaps/crystallizers | 2819 | calcium chloride, anhyd. | 2.16 |
| | storage/pumping | 2950 | asphalt | 1.16 |
| | evaps/crystallizers | 2812 | caustic soda, anhydrous | 0.64 |
| | fryer | 2099 | french fries | 0.61 |
| | melters/heaters | 2869 | caprolactam | 0.56 |
| | storage/pumping | 2080 | beverages | 0.48 |
| | fryer | 2092 | prepared fish | 0.45 |
| | fryer | 2051 | doughnuts | 0.39 |
| | storage/pumping | 2060 | sugar and confectionery | 0.28 |
| | storage/pumping | 2070 | fats and oils | 0.19 |
| | fryer | 2051 | snack pies | 0.10 |
| | storage/pumping | 2850&91 | paints & allied products | 0.06 |
| | | | Category (3) Total | 247.56 |
| (4) exhaust as oxidant - mixing with combustion air &/or apart of an air/fuel staging scheme all for energy savings and lower emissions | dryers and clinkers | 3240 | cement manufacture | 41.50 |
| | Kilns | 3270 | lime (dolomite, etc) | 21.60 |
| | central furnaces/boilers & dryers | 2400 | lumber and wood products | 4.24 |
| | cupolas | 3296 | mineral wool | 0.40 |
| | central boilers | 2600 | pulp mills | 116.40 |
| | | | **Category (4) Total** | 184.14 |
| (5) indirect air heating - process 'ovens' | baking ovens | 2050 | bakery goods | 33.68 |
| | finish drying (paint) | 3700 | transportation equipment | 30.00 |
| | finish drying and curing | 3470 | coating, engraving etc | 18.09 |
| | finish drying | 3500 | industrial machinery | 18.00 |
| | finish drying (paint) and curing | 3411 | metal cans | 17.08 |
| | coffee roaster | 2090 | coffee manufacture | 3.29 |
| | cocoa roaster | 2060 | chocolate manufacture | 3.10 |
| | finish drying | 3600 | electronics, etc. | 3.00 |
| | | | **Category (5) Total** | 126.24 |
| (6) direct dry - spray drying | Spray drying | 3255 | kaolin clay | 37.60 |
| | Spray drying | 2023 | dried milk | 9.79 |
| | Spray drying | 3253 | ceramic slips | 9.32 |
| | Spray drying | 2841 | soaps & detergents | 9.30 |
| | Spray drying | 2816 | inorganic pigments | 4.75 |
| | Spray drying | 2819 | Na tripolyphosphate | 1.76 |
| | Spray drying | 3255 | fluid cracking catalysts | 0.80 |
| | Spray drying | 2865 | inorganic dyes/pigments | 0.50 |
| | Spray drying | 2821 | emulsion PVC | 0.30 |
| | Spray drying | 2821 | PVP | 0.01 |
| | | | **Category (6) Total** | 74.13 |

| Technology Group | Process Step Aided | SIC | Product | Tbtu per year |
|---|---|---|---|---|
| (7) direct dry - conveyor | drying | 2822 | PBR | 16.44 |
| | drying | 2822 | BR | 13.00 |
| | drying | 2822 | PI | 4.89 |
| | drying | 2822 | EPR | 2.27 |
| | drying | 2822 | SBR | 2.04 |
| | | | **Category (7) Total** | 38.64 |
| (8) direct dry - metals drying | parts drying | 3479 | metal services | 21.56 |
| | scrap/load dry/preheat | 3312 | blast furnace steel | 8.30 |
| | scrap dry/preheat | 3341 | secondary aluminum | 4.69 |
| | ore drying | 3313 | electrometallurgicals | 0.73 |
| | scrap dry/preheat | 3341 | copper | 0.34 |
| | | | **Category (8) Total** | 35.63 |
| (9) indirect liquid heating - chemicals reactor | cracker furnace, recovery, etc | 2869 | vinyl chloride monomer | 23.50 |
| | reactor furnace | 2869 | methanol | 6.00 |
| | | | **Category (9) Total** | 29.50 |
| (10) indirect liquid heating - chemical separations | distillation, recovery equipment | 2865 | p-xylene | 3.69 |
| | distillation, recovery equipment | 2865 | styrene | 7.00 |
| | distillation, recovery equipment | 2869 | acetic acid | 10.24 |
| | distillation, recovery equipment | 2869 | propylene oxide | 3.30 |
| | heaters and separation equip. | 2869 | acrylonitrile | 1.00 |
| | heaters and separation equip. | 2869 | caprolactam | 0.67 |
| | heaters | 2824 | olefin fibers | 1.00 |
| | | | **Category (10) Total** | 26.90 |
| (11) preheating VOC exhaust prior to incineration | distillation & reactors off vents | 2800 | organic chemicals | 11.81 |
| | solvents, laminates, inks | 2600 | non-integrated paper finishing mills | 2.43 |
| | finishing' process vents | 2821-24 | resins and manmade fibers | 1.79 |
| | VOCs off paint-label dryers | 30 | plastic/rubber products finishing | 1.45 |
| | VOCs off finishing op's | 3710 | motor vehicles | 1.18 |
| | cleaning/paints solvent VOCs | 3400 | fabricated metal products | 0.83 |
| | VOCs off dryers, storage, etc | 2950/90 | asphalt roofing materials | 0.76 |
| | odors, cleaning solvents | 2000 | foods manufacture | 0.74 |
| | solvent, paint, coating | 2500 | furniture finishing | 0.66 |
| | solvents, laminates | 2700 | printing/publishing establishments | 0.31 |
| | coating/finishing solvents | 2200 | textile manufacturing | 0.24 |
| | general VOCs reduction | 2851 | paints & varnishes | 0.11 |
| | glues, solvents | 2400 | lumber and wood products | 0.11 |
| | paints | 3600 | electronics, etc. | 0.09 |
| | | | **Category (11) Total** | 22.52 |
| (12) direct dry - curing | curing ovens | 3296 | mineral wool, etc | 10.11 |
| | curing ovens | 3229 | fiber glass | 7.92 |
| | | | **Category (12) Total** | 18.03 |
| (13) direct dry - kiln | kiln dryer | 2063 | beet sugar | 16.23 |
| | | | **Category (13) Total** | 16.23 |

| Technology Group | Process Step Aided | SIC | Product | Tbtu per year |
|---|---|---|---|---|
| (14) direct dry | drying | 2834 | pharmaceutical preps | 12.71 |
| | | | **Category (14) Total** | 12.71 |
| (15) refrigeration and freezing | cool after pasteurizing & storage | 2026 | fluid milk processing | 4.67 |
| | cooling, fermentation, etc | 2082 | malt beverages | 3.22 |
| | cooling & refrigeration | 2822 | synthetic rubber | 1.29 |
| | storage | 2100 | tobacco products | 0.12 |
| | | | **Category (15) Total** | 9.30 |
| (16) direct dry - pulp drying | infrared drying | 2600 | paper finishing mills | 2.00 |
| | | | **Category (16) Total** | 2.00 |
| (17) direct dry - storage conditioning | storage heating | 2822 | SBR | 0.75 |
| | | | **Category (17) Total** | 0.75 |
| (18) direct dry | ethylene preheaters | 2822 | EPR | 0.44 |
| | | | **Category (18) Total** | 0.44 |
| (19) direct dry - granulators/dryers | granulator/dryers | 2063 | beet sugar | 0.25 |
| | granulator/dryers | 2062 | cane sugar refining | 0.09 |
| | | | **Category (19) Total** | 0.35 |
| (20) desiccant based dehumidification | space conditioning | 2060 | sugar & confect. prods. | |
| | QC | 2834 | pharmaceutical prep | |
| | feed dehumidification | 2911 | alkylation step | |
| | blast-furnace air feed | 3312 | steel mills (blast based) | |
| | | | **Category (20) Total** | Data not available |

Central boiler systems are not included in Table 4, but initial estimations show they offer the largest energy savings opportunity. The top five applications were determined in terms of replicability (energy savings across all applicable SICs), innovation, and ease of integration into a cogeneration systems. The five cogeneration systems that will be analyzed in the market assessment are:

- Direct contact water heaters,
- Indirect liquid heating,
- Convection ovens used for metals fabrication preheating,
- Indirect air heating, and
- Exhaust gas as an oxidant for central boiler systems.

# Market Assessment Model Input Parameters

A number of input parameters are required by the model to estimate the economic market potential for each application. The following tables summarize these parameters for each application.

## Direct Contact Water Heaters

For this application, a direct contact water heater fired with the turbine/engine exhaust is replacing a conventional water heater. For the reciprocating engine-driven system, engine jacket cooling water is also used to supply hot water.

**Table 5. Direct Contact Water Heater – Input Parameters**

| | **Size Range (kW)** | | | | |
|---|---|---|---|---|---|
| | 25-75 | 75-150 | 150-400 | 400-800 | 800-100 |
| **Recuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 2,410 | 1,565 | 1,203 | 1,053 | 994 |
| Heat Rate (Btu/kW) | 13,200 | 13,200 | 13,200 | 10,434 | 10,434 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.009 |
| Usable Exhaust Energy (mBtu/hr/kW) | 7.5 | 7.5 | 7.5 | 5.72 | 5.72 |
| | | | | | |
| **Unrecuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 2,070 | 1,318 | 978 | 838 | 620 |
| Heat Rate (Btu/kW) | 26,246 | 26,246 | 26,246 | 14,519 | 13,123 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.004 |
| Usable Exhaust Energy (mBtu/hr/kW) | 20.80 | 20.80 | 20.80 | 8.62 | 8.62 |
| | | | | | |
| **Reciprocating Engine** | | | | | |
| Installed Cost ($/kW) | N/A | 1,237 | 961 | 772 | 671 |
| Heat Rate (Btu/kW) | N/A | 11,006 | 10,340 | 9,748 | 8,978 |
| O&M ($/kWh) | N/A | 0.01 | 0.0085 | 0.008 | 0.0075 |
| Usable Exhaust Energy (mBtu/hr/kW) | N/A | 3.33 | 2.58 | 2.16 | 1.45 |
| Usable Cooling Water Energy (mBtu/hr/kW) | N/A | 3.5 | 3.5 | 3.5 | 3.5 |
| | | | | | |
| Existing Thermal System Eff. | 0.85 | | | | |

## Indirect Liquid Heating

For this application, an indirect liquid heating system fired with turbine/engine exhaust replaces a conventional burner-fed system. For the reciprocating engine driven system, engine jacket cooling water is used to supply hot water to other applications at the site.

**Table 6. Indirect Liquid Heating – Input Parameters**

| | **Size Range (kW)** | | | | |
|---|---|---|---|---|---|
| | 25-75 | 75-150 | 150-400 | 400-800 | 800-100 |
| **Recuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 1,700 | 1,196 | 950 | 870 | 839 |
| Heat Rate (Btu/kW) | 13,200 | 13,200 | 13,200 | 10,434 | 10,434 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.009 |
| Usable Exhaust Energy (mBtu/hr/kW) | 5.08 | 5.08 | 5.08 | 4.54 | 4.54 |
| | | | | | |
| **Unrecuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 1,380 | 954 | 728 | 657 | 467 |
| Heat Rate (Btu/kW) | 26,246 | 26,246 | 26,246 | 14,519 | 13,123 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.004 |
| Usable Exhaust Energy (mBtu/hr/kW) | 17.94 | 17.94 | 17.94 | 8.46 | 7.32 |
| | | | | | |
| **Reciprocating Engine** | | | | | |
| Installed Cost ($/kW) | N/A | 874 | 711 | 590 | 518 |
| Heat Rate (Btu/kW) | N/A | 11,006 | 10,340 | 9,748 | 8,978 |
| O&M ($/kWh) | N/A | 0.01 | 0.0085 | 0.008 | 0.0075 |
| Usable Exhaust Energy (mBtu/hr/kW) | N/A | 2.83 | 2.09 | 1.79 | 1.18 |
| Usable Cooling Water Energy (mBtu/hr/kW) | N/A | 3.5 | 3.5 | 3.5 | 3.5 |
| | | | | | |
| Existing Thermal System Eff. | 0.66 | | | | |

## Convection Ovens

For this application, a convection oven system direct-fired with the turbine/engine exhaust replaces a conventional burner-fed system. For the reciprocating engine driven system, engine jacket cooling water is used to supply hot water to other applications at the site.

**Table 7. Convection Oven – Input Parameters**

| | **Size Range (kW)** | | | | |
|---|---|---|---|---|---|
| | 25-75 | 75-150 | 150-400 | 400-800 | 800-100 |
| **Recuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 1,050 | 905 | 764 | 743 | 735 |
| Heat Rate (Btu/kW) | 13,200 | 13,200 | 13,200 | 10,434 | 10,434 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.009 |
| Usable Exhaust Energy (mBtu/hr/kW) | 5.08 | 5.08 | 5.08 | 4.54 | 4.54 |
| | | | | | |
| **Unrecuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 810 | 691 | 557 | 538 | 377 |
| Heat Rate (Btu/kW) | 26,246 | 26,246 | 26,246 | 14,519 | 13,123 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.004 |
| Usable Exhaust Energy (mBtu/hr/kW) | 17.94 | 17.94 | 17.94 | 8.46 | 7.32 |
| | | | | | |
| **Reciprocating Engine** | | | | | |
| Installed Cost ($/kW) | N/A | 615 | 542 | 473 | 421 |
| Heat Rate (Btu/kW) | N/A | 11,006 | 10,340 | 9,748 | 8,978 |
| O&M ($/kWh) | N/A | 0.01 | 0.0085 | 0.008 | 0.0075 |
| Usable Exhaust Energy (mBtu/hr/kW) | N/A | 2.83 | 2.09 | 1.79 | 1.18 |
| Usable Cooling Water Energy (mBtu/hr/kW) | N/A | 3.5 | 3.5 | 3.5 | 3.5 |
| | | | | | |
| Existing Thermal System Eff. | 0.88 | | | | |

## Indirect Air Heating

For this application, an indirect air heating system using an air to air heat exchanger fired with the turbine/engine exhaust replaces a conventional burner-fed system. For the reciprocating engine driven system, engine jacket cooling water is used to supply hot water to other applications at the site.

**Table 8. Indirect Air Heating – Input Parameters**

| | **Size Range (kW)** | | | | |
|---|---|---|---|---|---|
| | 25-75 | 75-150 | 150-400 | 400-800 | 800-100 |
| **Recuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 1,641 | 1,176 | 940 | 865 | 836 |
| Heat Rate (Btu/kW) | 13,200 | 13,200 | 13,200 | 10,434 | 10,434 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.009 |
| Usable Exhaust Energy (mBtu/hr/kW) | 5.08 | 5.08 | 5.08 | 4.54 | 4.54 |
| | | | | | |
| **Unrecuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 1,341 | 943 | 722 | 654 | 469 |
| Heat Rate (Btu/kW) | 26,246 | 26,246 | 26,246 | 14,519 | 13,123 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.004 |
| Usable Exhaust Energy (mBtu/hr/kW) | 17.94 | 17.94 | 17.94 | 8.46 | 8.46 |
| | | | | | |
| **Reciprocating Engine** | | | | | |
| Installed Cost ($/kW) | N/A | 864 | 706 | 589 | 517 |
| Heat Rate (Btu/kW) | N/A | 11,006 | 10,340 | 9,748 | 8,978 |
| O&M ($/kWh) | N/A | 0.01 | 0.0085 | 0.008 | 0.0075 |
| Usable Exhaust Energy (mBtu/hr/kW) | N/A | 2.83 | 2.09 | 1.79 | 1.18 |
| Usable Cooling Water Energy (mBtu/hr/kW) | N/A | 3.5 | 3.5 | 3.5 | 3.5 |
| | | | | | |
| Existing Thermal System Eff. | 0.48 | | | | |

## Exhaust Gas as an Oxidant to Boiler Systems

For this application, exhaust gases from the turbines are used as an oxidant for the boiler burners and are retrofitted to conventional boilers.

**Table 9. Exhaust Gas as an Oxidant to Boiler Systems – Input Parameters**

| | **Size Range (kW)** | | | | |
|---|---|---|---|---|---|
| | 25-75 | 75-150 | 150-400 | 400-800 | 800-100 |
| **Recuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 2,195 | 1,454 | 1,127 | 998 | 948 |
| Heat Rate (Btu/kW) | 13,200 | 13,200 | 13,200 | 10,434 | 10,434 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.009 |
| Usable Exhaust Energy (mBtu/hr/kW) | 8.73 | 8.73 | 8.73 | 6.4 | 6.4 |
| | | | | | |
| **Unrecuperated Turbine** | | | | | |
| Installed Cost ($/kW) | 1,865 | 1,210 | 904 | 785 | 576 |
| Heat Rate (Btu/kW) | 26,246 | 26,246 | 26,246 | 14,519 | 13,123 |
| O&M ($/kWh) | 0.01 | 0.01 | 0.009 | 0.009 | 0.004 |
| Usable Exhaust Energy (mBtu/hr/kW) | 21.33 | 21.33 | 21.33 | 10.28 | 8.96 |
| | | | | | |
| Existing Thermal System Eff. | 0.85 | | | | |

***Installed Costs*** are based on packaged generator cost (shown earlier in the report), thermal system retrofit, engineering, and installation. Cost is also based on the following assumptions.

- In all cases, except direct contact water heating, the system will be retrofitted to an existing host system.
- A "standard" engineering package is available for the replicable applications. This package includes a bill of material, component sizing methodology or tool, and a list of suppliers for necessary components.
- Installation of the system does not require significant changes in installation drawings and design.
- Installation does not require major structural change for the host system or the plant itself.
- It will not be necessary to spend significant resources for permits or variances from the regulatory agencies or utility companies.

In each case the hardware cost estimates are based on information obtained from the equipment or hardware supplier. Installation cost includes cost of minor changes of standardized installation engineering drawings and labor cost for the retrofit. This cost is obtained from several sources such as the equipment supplier, engineering consulting companies and installation contractors.

In case of direct contact water heater, a new water heater is used to accommodate larger mass flow compared to that in case of a direct fired unit, where a small burner is used to supply heat. The installation cost includes water piping, safety system installation, controls and other hardware.

Direct injection of gases in an oven requires installation of duct work to an existing oven, a pressure control system, and a gas by-pass system together with modification to the oven walls to allow for the gas introduction.

For the indirect (water) liquid and gas heating system, the system cost includes purchase of an appropriate heat exchanger, exhaust gas connections, the fluid exit-entry connections, and associated control system.

In case of boiler applications, the cost includes modifications to the existing burner and air supply system to allow for introduction of turbine exhaust gases, proper piping systems, changes in the control system for air-fuel ratio, and pressure control system if necessary.

The cost numbers for hardware and installation should be considered as “typical”, and should not be used as "standard" costs. The cost can vary significantly depending on the type of host process and its operating parameters, location of the system, and age of the system. It is necessary to carry out such a cost analysis for each individual application.

Engineering cost is based on the assumption that a "standard" engineering package is available for the replicable applications. This package includes a bill of material, component sizing methodology or tool and a list of suppliers for necessary components.

**Heat Rate** and **O&M** data is based on data from equipment manufacturers.

**Usable Exhaust Energy** is calculated by making a comparison between the performances of two self-standing systems, (i) gas turbine and (ii) process heating system - termed as the "host" system, with an integrated system in which turbine exhaust gases are used to supply additional process heat and reduce heat input in the host system. Turbine performance data is supplied by manufacturers and is used to calculate the following parameters for the turbine exhaust gases:

- Mass flow rate,
- Heat content,
- Oxygen content, and
- Power generated by the turbine.

In case of the host system, the following parameters are used to calculate heat demand and efficiency of the system:

- Process temperature,
- Process heat demand,
- Process exhaust gas oxygen (or excess air used for combustion), and
- Combustion air temperature.

Heat (fuel) consumption calculations for the host system used in the combined system assume that net heat supplied to the process is the same as in the case of the self standing heating system. These calculations involve heat balance for the host system, accounting for additional heat from the turbine exhaust gases and allowances for efficiency of the host system.

# Market Assessment Methodology

The analysis was performed using Resource Dynamics Corporation's DIStributed Power Economic Rationale SElection (DISPERSE) model, which estimates the achievable economic potential for cogeneration by comparing the on-site generation economics with competing grid prices. The analysis determines whether on-site cogeneration appears to be more cost effective than purchasing from the grid, and also which technology and size appears to be the most economic for a given application. This model has been developed over the past ten years, and has been applied on a variety of projects for utilities, equipment manufacturers, and research organizations. The following key inputs are used by the model:

1. **Technology price and performance parameters**. The model requires price and performance data on the mix of technologies that are available for each cogeneration application being analyzed. This data includes the technology's installed cost, fuel type, heat rate, electrical efficiency, useable thermal output, fixed and variable operating and maintenance costs, and other key parameters.

2. **Database of industrial sites**. Data on industrial sites by SIC, size, and utility service area come from the County Business Patterns.

3. **Database of fuel prices**. Natural gas costs are based on state prices for the industrial sector, as reported by the Department of Energy's Energy Information Administration (EIA). Base rates are from 1999. Natural gas escalation rates are based on regional EIA projections from the 1999 Annual Energy Outlook. Using 1999 base and escalation rates eliminates the price spikes of 2000. Rates range from a high of $8.24/MCF for Hawaii to a low of $1.25/MCF for Alaska. Annual escalation rates range from a high of 5.72% for states in the Mountain region to a low of 0.58% for states in New England.

4. **Financial parameter assumptions**. Ownership parameters are based on RDC experience with typical DG projects and expectations for financial structures of projects in the future.

5. **Site characteristics**. Site characteristics include electric and thermal load profiles from RDC databases.

6. **Database of grid prices**. Rate schedules of the 68 largest electric utilities (in terms of GWh sales to industrial customers) representing over two-thirds of deliveries to the industrial sectors were utilized and are shown in Table 11. Rate structures are from 1999. Customers in counties not served by the largest utilities were assigned a regional rate schedule derived from schedules of major utilities within that region. Escalation rates are based on regional EIA projections from the Supplement to the Annual Energy Outlook, as projected in 1999. Backup charges are included at $50/kW annually (or $4.20/kW/month). Since actual rate structures were used, rates differ depending on customer size and load profile. For a customer in SIC 20 (Food) with a peak demand of 1.5 MW, rates range from just over $0.03/kWh in low priced areas to over $0.08/kWh. Annual escalation rates range from 0.48% to a high of 2.35%.

7. **Financial parameter assumptions**. Table 10 contains a list of financial assumptions. A project life of 10 years is assumed, reflecting the anticipated life of smaller DG projects and conservative financial planning from customers. Units are expected to be funded by the customer from their operations. Taxes and insurance are included, as well as costs of standby power. There are no sales of excess electricity back to the grid.

**Table 10. Financial Parameter Assumptions**

| | |
|---|---|
| Project Length (years) | 10 |
| Federal Income Tax (%) | 35 |
| State Income Tax (%) | 5 |
| Property Tax and Insurance (%) | 2 |
| Discount Rate (%) | 8 |

The model run begins with a database of industrial sites, which are organized by utility service area, SIC code, and size. In addition, based on the site SIC code/building type, a load profile (both thermal and electric) that is representative of that segment is assigned. The size of the facility is used to scale up or down the magnitude of the load profile.

Using data on number of facilities in each size range in each utility service area, the number of potential applications is determined. Results are aggregated and summarized to show key information on where the potential applications are. Figure 16 provides an overview of the model inputs, analysis, and outputs.

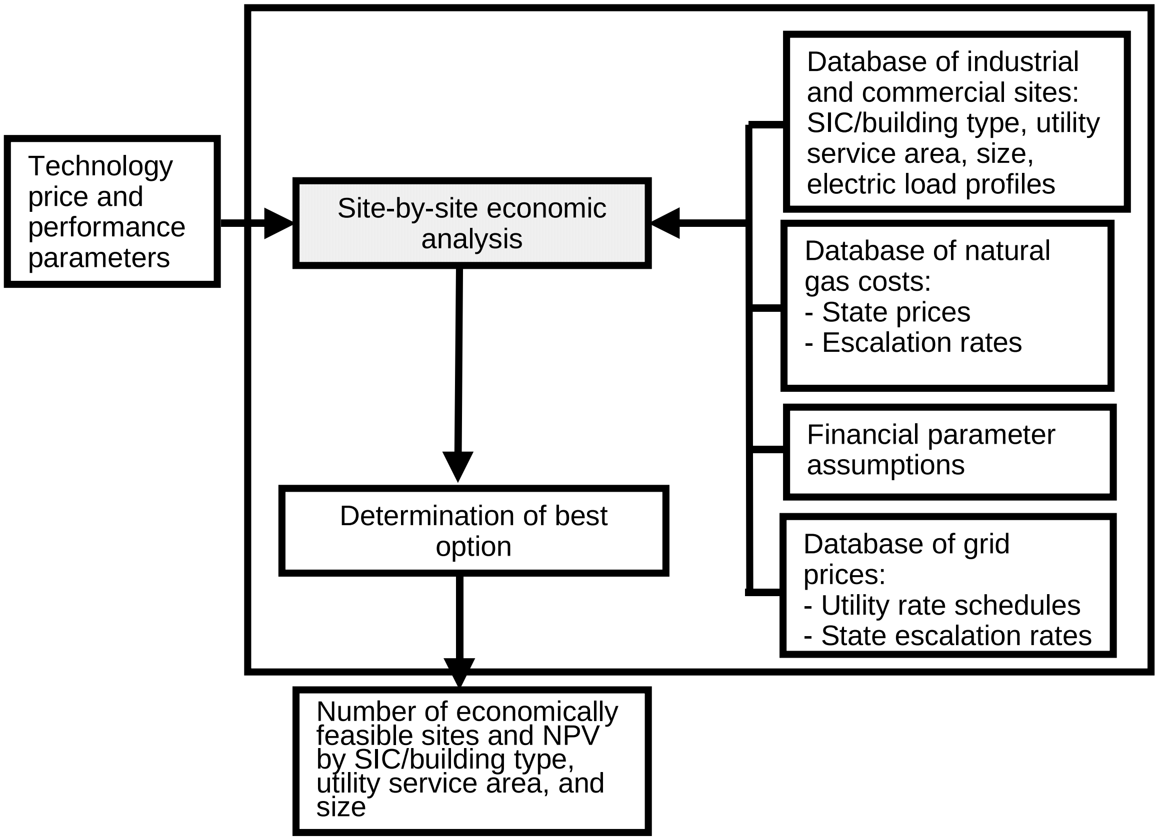

**Figure 16. DISPERSE Model**

Using this information, combined with the unit price and performance data, the model performs a life-cycle cost economic analysis, based on the unit life, electric utility rate schedules, and state fuel prices. The model determines whether the cogeneration system can beat the base case in which all power is purchased from the host utility. The best technology option is selected based on highest net present value (NPV). This process occurs for each group of sites within each combination of the same utility service area/size range/sector in the database of industrial sites, and the results are then aggregated to obtain market potential.

To give an example of the competing grid prices and natural gas prices that were used in the assessment, for a customer in SIC 20 (Food) in Illinois Power Company’s service territory with a peak demand of 700 kW, competing grid prices were $0.055/kWh and gas prices were $4.06/MCF.  Annually escalation rates were 1.33% for electricity and 3.66% for gas.

**Table 11.  Utilities Included in DISPERSE**

Alabama Power Co
Appalachian Power Co
Baltimore Gas & Electric Co
Carolina Power & Light Co
Central Power & Light Co
Cincinnati Gas & Elec Co
Cleveland Electric Illum Co
Commonwealth Edison Co
Connecticut Light & Pwr Co
Consumers Energy Co
Dayton Power & Light Co
Detroit Edison Co
Duke Energy Corp
Entergy Arkansas Inc
Entergy Gulf States Inc
Entergy Louisiana Inc
Florida Power and Light
Florida Power Corp
Georgia Power Co
Green River Electric Corp
Houston Lighting & Pwr Co
Idaho Power Co
IES Utilities Inc
Illinois Power Co
Indiana Michigan Power Co
Indianapolis Pwr & Light Co
Kentucky Utilities Co
Massachusetts Electric Co
Memphis City of
Metropolitan Edison Co
MidAmerican Energy Co
Minnesota Power Inc
Mississippi Pwr Company
Monongahela Power Co
Nevada Power Co
Niagara Mohawk Pwr Corp
Northern Indiana Pub Serv
Northern States Power Co
Ohio Edison Co
Ohio Power Co
Oklahoma Gas & Elec Co
Pacific Gas & Electric Co
PacifiCorp
PECO Energy Co
Pennsylvania Electric Co
Potomac Edison Co
PP&L Inc
PSI Energy Inc
Pub Service Co of Colorado
Pub Svc Co of Oklahoma
Pub Svc Co of New Mexico
Pub Svc Electric & Gas Co
Puget Sound Energy Inc
Sacramento Municipal Util
Salt River Project
San Antonio Pub Svc Bd
South Carolina Elec&Gas
S. Carolina Pub Svc Auth
Southern California Edison
Southwestern Electric Pwr
Texas Utilities Electric Co
Toledo Edison Co
Tucson Electric Power Co
Union Electric Co
Virginia Electric & Pwr Co
West Penn Power Co
Wisconsin Electric Pwr Co
Wisconsin Pwr & Light Co

# Market Assessment Results

The model used to assess the total potential market for these system solutions shows the following economic market potential:

**Table 12. Summary Results by System Type**

| Cogeneration Package Systems | Economic Market Potential (MWe) |
|---|---:|
| Direct Contact Water Heater | 2,435 |
| Indirect Liquid Heaters | 1,010 |
| Convection Ovens for Metal Fab. Preheating | 760 |
| Indirect Air Heating | 2,332 |
| Central Boiler Systems | 4,251 |
| **Total** | 10,789 |

The 10 states showing the highest economic market potential are:

**Table 13. Summary Results by State**

| State | Economic Market Potential (MWe) |
|---|---:|
| California | 1,862 |
| Texas | 689 |
| New Jersey | 637 |
| Michigan | 624 |
| New York | 589 |
| Ohio | 516 |
| Pennsylvania | 501 |
| Louisiana | 410 |
| Georgia | 364 |
| North Carolina | 335 |
| **Total** | 6,527 |

Economic market potential broken down by prime mover size range is:

**Table 14. Summary Results by Size Range**

| Size Range | Economic Market Potential (MWe) |
|---|---:|
| 25-75 kW | 181 |
| 75-150 kW | 664 |
| 150-400 kW | 1,868 |
| 400-800 kW | 2,106 |
| 800-1000 kW | 5,970 |
| **Total** | 10,789 |

Economic market potential broken down by prime mover type is:

**Table 15. Summary Results by Prime Mover Type**

| Prime Mover Type | Economic Market Potential (MWe) |
|---|---:|
| Recuperated Turbines | 829 |
| Unrecuperated Turbines | 5,166 |
| Reciprocating Engines | 4,794 |
| **Total** | 10,789 |

Economic market potential for the top four digit SIC codes by size range and top four-digit SIC codes by state are shown in Table 16.

**Table 16. Detailed Results by SIC/State (10 Sub-tables)**

### Direct Contact Water Heating Systems

| | | | MW Potential per DG Size Range | | | | |
|---|---|---|---|---|---|---|---|
| **SIC** | **Sector Description** | **Total MWs** | **25 - 75 kW** | **75 - 150 kW** | **150 - 400 kW** | **400 - 800 kW** | **800 - 1000kW** |
| 2819 | Inorganic Chemicals, NEC | 263 | 0.0 | 3.6 | 9.7 | 30.7 | 219.2 |
| 3465 | Automotive Stampings | 157 | 0.0 | 6.6 | 18.7 | 60.0 | 71.2 |
| 2026 | Fluid Milk | 110 | 0.1 | 4.4 | 13.4 | 63.3 | 28.4 |
| 2834 | Pharmaceutical Preparations | 106 | 0.7 | 7.4 | 20.0 | 29.4 | 48.6 |
| 3089 | Plastic Products, NEC | 102 | 0.0 | 7.3 | 11.5 | 41.2 | 42.0 |
| 2037 | Frozen Fruits, Vegetables, & Juices | 95 | 0.0 | 0.0 | 8.6 | 0.0 | 86.6 |
| 2086 | Soft Drinks & Carbonated Water | 75 | 0.3 | 8.2 | 22.0 | 31.8 | 12.6 |
| 3312 | Steel Works & Mills | 75 | 0.0 | 0.1 | 0.5 | 2.8 | 71.2 |
| 3471 | Fabricated Metals: Plating, Polishing | 67 | 0.4 | 23.4 | 36.0 | 0.0 | 7.4 |
| 2011 | Meat Packing Plants | 66 | 0.2 | 2.9 | 5.3 | 10.4 | 47.0 |
| 2676 | Sanitary Paper Products | 56 | 0.0 | 1.2 | 3.2 | 9.9 | 41.8 |
| 3625 | Electronics: Relays & Controls | 55 | 0.0 | 0.8 | 7.7 | 6.5 | 40.4 |
| 2048 | Prepared Animal Feeds | 55 | 0.9 | 0.0 | 40.1 | 12.0 | 1.5 |
| 3674 | Semiconductors | 52 | 0.0 | 1.9 | 1.3 | 9.4 | 39.1 |
| 2262 | Finishers of Synthetic Fibers & Silk | 50 | 0.0 | 1.2 | 3.4 | 24.1 | 21.4 |

| **SIC** | **Top Five States, per SIC, by Total Number of Potential Units** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2819 | CA | 41 | NJ | 31 | LA | 26 | SC | 25 | TX | 23 |
| 3465 | MI | 165 | OH | 43 | IN | 20 | NY | 8 | PA | 6 |
| 2026 | CA | 42 | NY | 26 | MA | 17 | PA | 14 | TX | 13 |
| 2834 | NJ | 46 | CA | 39 | NY | 35 | CT | 20 | PA | 10 |
| 3089 | CA | 147 | NJ | 91 | AZ | 17 | CO | 8 | SC | 6 |
| 2037 | CA | 27 | ID | 22 | WA | 20 | FL | 12 | OR | 8 |
| 2086 | CA | 45 | NY | 18 | TX | 14 | GA | 12 | NJ | 11 |
| 3312 | PA | 19 | MI | 9 | TX | 7 | NY | 6 | IN | 6 |
| 3471 | CA | 177 | NY | 40 | CT | 30 | NJ | 29 | MI | 28 |
| 2011 | CA | 12 | TX | 9 | NE | 7 | CO | 5 | PA | 5 |
| 2676 | GA | 8 | WA | 8 | PA | 8 | WI | 8 | CA | 7 |
| 3625 | CA | 33 | WI | 17 | NY | 15 | NJ | 6 | OH | 5 |
| 2048 | CA | 47 | TX | 20 | NY | 20 | GA | 16 | AR | 10 |
| 3674 | CA | 58 | AZ | 9 | NJ | 3 | WA | 0 | OH | 0 |
| 2262 | SC | 22 | NC | 12 | NJ | 10 | MA | 9 | CA | 6 |

## Indirect Fluid Heating Systems€

| | | | MW Potential per DG Size Range | | | | |
|---|---|---|---|---|---|---|---|
| **SIC** | **Sector Description** | **Total MWs** | **25 - 75 kW** | **75 - 150 kW** | **150 - 400 kW** | **400 - 800 kW** | **800 - 1000kW** |
| 3080 | Plastic Products | 218 | 1.7 | 17.0 | 33.4 | 92.4 | 75.4 |
| 2670 | Converted Paper & Paperboard | 214 | 3.3 | 30.5 | 66.8 | 58.8 | 58.4 |
| 2834 | Pharmaceuticals | 109 | 1.8 | 7.0 | 20.8 | 32.6 | 48.9 |
| 3350 | NonFerrous: Rollling, Drawing, Extruding | 77 | 0.0 | 0.0 | 13.2 | 26.2 | 37.2 |
| 2430 | Veneer, Ply, & Structural Wood | 69 | 0.7 | 0.0 | 37.9 | 15.7 | 15.0 |
| 2650 | Paperboard Boxes | 36 | 0.0 | 5.4 | 23.2 | 4.2 | 3.0 |
| 2096 | Potato & Corn Chips | 33 | 0.9 | 2.9 | 5.8 | 6.4 | 18.2 |
| 2080 | Beverages | 32 | 0.0 | 0.0 | 9.5 | 0.0 | 22.2 |
| 2754 | Commercial Printing: Gravure | 28 | 0.1 | 2.4 | 2.2 | 8.4 | 15.2 |
| 2620 | Paper Mills | 21 | 0.0 | 0.0 | 0.0 | 0.4 | 20.1 |
| 2676 | Sanitary Paper Products | 56 | 0.0 | 1.2 | 3.2 | 9.9 | 41.8 |
| 3625 | Electronics: Relays & Controls | 55 | 0.0 | 0.8 | 7.7 | 6.5 | 40.4 |
| 2048 | Prepared Animal Feeds | 55 | 0.9 | 0.0 | 40.1 | 12.0 | 1.5 |
| 3674 | Semiconductors | 52 | 0.0 | 1.9 | 1.3 | 9.4 | 39.1 |
| 2262 | Finishers of Synthetic Fibers & Silk | 50 | 0.0 | 1.2 | 3.4 | 24.1 | 21.4 |

| **SIC** | **Top Five States, per SIC, by Total Number of Potential Units** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 3080 | CA | 267 | NJ | 163 | NY | 49 | AZ | 29 | WI | 23 |
| 2670 | CA | 104 | NY | 63 | NJ | 62 | PA | 53 | OH | 49 |
| 2834 | NJ | 71 | CA | 39 | NY | 35 | CT | 20 | NC | 11 |
| 3350 | CA | 29 | NY | 20 | NJ | 16 | AZ | 10 | IN | 6 |
| 2430 | CA | 56 | AZ | 28 | WI | 20 | UT | 12 | ID | 11 |
| 2650 | NJ | 43 | CA | 37 | NY | 21 | UT | 8 | CT | 7 |
| 2096 | CA | 18 | PA | 12 | TX | 5 | OH | 5 | NY | 5 |
| 2080 | CA | 28 | NJ | 12 | CO | 7 | AZ | 5 | UT | 2 |
| 2754 | CA | 8 | NY | 6 | GA | 6 | VA | 5 | IN | 4 |
| 2620 | WI | 12 | CA | 3 | NJ | 3 | WA | 1 | OH | 1 |
| 2676 | GA | 8 | WA | 8 | PA | 8 | WI | 8 | CA | 7 |
| 3625 | CA | 33 | WI | 17 | NY | 15 | NJ | 6 | OH | 5 |
| 2048 | CA | 47 | TX | 20 | NY | 20 | GA | 16 | AR | 10 |
| 3674 | CA | 58 | AZ | 9 | NJ | 3 | WA | 0 | OH | 0 |
| 2262 | SC | 22 | NC | 12 | NJ | 10 | MA | 9 | CA | 6 |

## Convection Oven Systems€

| | | | MW Potential per DG Size Range | | | | |
|---|---|---|---|---|---|---|---|
| **SIC** | **Sector Description** | **Total MWs** | **25 - 75 kW** | **75 - 150 kW** | **150 - 400 kW** | **400 - 800 kW** | **800 - 1000kW** |
| 3714 | Motor Vehicle Parts | 197 | 0.3 | 5.5 | 8.6 | 35.3 | 147.1 |
| 3312 | Steel Works & Mills | 127 | 0.2 | 0.9 | 1.4 | 7.1 | 116.9 |
| 3728 | Aircraft Parts, NEC | 36 | 0.2 | 4.0 | 3.6 | 9.4 | 19.1 |
| 3452 | Bolts, Nuts, Screws, etc | 28 | 4.2 | 0.0 | 14.4 | 3.6 | 5.5 |
| 3599 | Indust./Comm. Equipment, NEC | 25 | 2.0 | 10.3 | 13.0 | 0.1 | 0.0 |
| 3841 | Surgical & Medical Instruments | 24 | 0.0 | 2.9 | 5.1 | 5.4 | 10.1 |
| 3462 | Iron & Steel Forgings | 20 | 0.1 | 0.8 | 1.9 | 2.4 | 14.9 |
| 3499 | Fabricated Metal Products, NEC | 20 | 0.8 | 5.1 | 6.9 | 3.2 | 3.8 |
| 3443 | Fabricated Plate Work | 17 | 0.8 | 3.7 | 8.3 | 2.5 | 2.1 |
| 3531 | Construction Equipment | 15 | 0.1 | 0.0 | 7.1 | 2.2 | 5.3 |
| 2676 | Sanitary Paper Products | 56 | 0.0 | 1.2 | 3.2 | 9.9 | 41.8 |
| 3625 | Electronics: Relays & Controls | 55 | 0.0 | 0.8 | 7.7 | 6.5 | 40.4 |
| 2048 | Prepared Animal Feeds | 55 | 0.9 | 0.0 | 40.1 | 12.0 | 1.5 |
| 3674 | Semiconductors | 52 | 0.0 | 1.9 | 1.3 | 9.4 | 39.1 |
| 2262 | Finishers of Synthetic Fibers & Silk | 50 | 0.0 | 1.2 | 3.4 | 24.1 | 21.4 |

| **SIC** | **Top Five States, per SIC, by Total Number of Potential Units** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 3714 | MI | 118 | CA | 69 | NY | 31 | OH | 28 | IN | 25 |
| 3312 | PA | 36 | OH | 18 | IN | 11 | MI | 11 | TX | 10 |
| 3728 | CA | 63 | AZ | 12 | NJ | 8 | CT | 6 | UT | 4 |
| 3452 | CA | 72 | CT | 16 | NJ | 15 | NY | 10 | OH | 8 |
| 3599 | CA | 91 | NJ | 59 | AZ | 20 | CT | 10 | OH | 9 |
| 3841 | CA | 41 | UT | 7 | NJ | 6 | CT | 4 | CO | 3 |
| 3462 | CA | 8 | WI | 7 | OH | 7 | TX | 4 | MI | 3 |
| 3499 | CA | 37 | NJ | 12 | NY | 9 | UT | 7 | PA | 6 |
| 3443 | CA | 34 | NJ | 13 | OK | 11 | NY | 6 | UT | 5 |
| 3531 | WI | 10 | OK | 7 | CA | 5 | PA | 3 | NJ | 2 |
| 2676 | GA | 8 | WA | 8 | PA | 8 | WI | 8 | CA | 7 |
| 3625 | CA | 33 | WI | 17 | NY | 15 | NJ | 6 | OH | 5 |
| 2048 | CA | 47 | TX | 20 | NY | 20 | GA | 16 | AR | 10 |
| 3674 | CA | 58 | AZ | 9 | NJ | 3 | WA | 0 | OH | 0 |
| 2262 | SC | 22 | NC | 12 | NJ | 10 | MA | 9 | CA | 6 |

## Indirect Air Heating Systems€

| | | | MW Potential per DG Size Range | | | | |
|---|---|---|---|---|---|---|---|
| **SIC** | **Sector Description** | **Total MWs** | **25 - 75 kW** | **75 - 150 kW** | **150 - 400 kW** | **400 - 800 kW** | **800 - 1000kW** |
| 3411 | Metal Cans | 151 | 0.5 | 1.5 | 4.2 | 21.2 | 124.1 |
| 3479 | Coating & Engraving, NEC | 136 | 7.4 | 41.7 | 31.3 | 40.2 | 15.9 |
| 3625 | Electronics: Relays & Controls | 130 | 0.0 | 4.3 | 13.5 | 19.5 | 92.8 |
| 3714 | Motor Vehicle Parts | 115 | 0.0 | 1.7 | 5.3 | 13.8 | 94.3 |
| 3564 | Indust./Comm. Fans, Blowers, etc | 111 | 0.4 | 2.8 | 10.6 | 28.3 | 68.5 |
| 2752 | Commercial Printing: Lithographic | 96 | 2.8 | 26.4 | 34.7 | 17.4 | 14.2 |
| 3711 | Motor Vehicle Bodies | 93 | 0.3 | 2.4 | 2.4 | 7.7 | 80.4 |
| 3585 | HVAC & Refrigeration Units | 88 | 0.7 | 0.0 | 22.2 | 21.4 | 43.6 |
| 3469 | Metal Stampings, NEC | 77 | 5.2 | 19.9 | 30.7 | 13.8 | 7.0 |
| 2051 | Bread/Bakery Products | 76 | 5.2 | 0.0 | 42.8 | 20.4 | 7.4 |
| 3674 | Semiconductors | 68 | 0.0 | 2.1 | 5.3 | 18.9 | 41.6 |
| 2048 | Prepared Animal Feeds | 66 | 0.1 | 0.0 | 48.1 | 16.0 | 1.5 |
| 3429 | Hardware, NEC | 59 | 1.9 | 5.0 | 11.5 | 17.2 | 23.1 |
| 3444 | Sheet Metalwork | 58 | 26.8 | 0.0 | 27.2 | 2.8 | 1.0 |
| 3679 | Electronics Components, NEC | 51 | 0.0 | 4.4 | 17.1 | 11.6 | 17.6 |

| **SIC** | **Top Five States, per SIC, by Total Number of Potential Units** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 3411 | CA | 37 | OH | 18 | IL | 13 | GA | 9 | WI | 9 |
| 3479 | CA | 153 | MI | 72 | NY | 50 | OH | 46 | MA | 38 |
| 3625 | CA | 52 | NY | 37 | WI | 24 | MA | 17 | OH | 15 |
| 3714 | CA | 46 | MI | 45 | OH | 16 | NY | 13 | AZ | 9 |
| 3564 | CA | 21 | NY | 16 | OH | 14 | NC | 13 | WI | 11 |
| 2752 | CA | 212 | NY | 72 | NJ | 60 | WI | 29 | AZ | 24 |
| 3711 | MI | 29 | OH | 17 | GA | 7 | CA | 7 | IN | 6 |
| 3585 | TX | 19 | NY | 18 | GA | 17 | CA | 15 | NJ | 12 |
| 3469 | CA | 103 | CT | 51 | NJ | 37 | NY | 29 | OH | 25 |
| 2051 | CA | 124 | NY | 27 | NJ | 22 | TX | 13 | UT | 12 |
| 3674 | CA | 78 | AZ | 12 | NJ | 3 | ID | 2 | NM | 2 |
| 2048 | TX | 30 | CA | 27 | AR | 22 | NY | 20 | GA | 16 |
| 3429 | CA | 46 | CT | 21 | MI | 16 | NY | 10 | IN | 8 |
| 3444 | CA | 281 | NY | 54 | NJ | 52 | WA | 43 | MA | 39 |
| 3679 | CA | 94 | NJ | 23 | NY | 12 | CO | 11 | AZ | 10 |

## Exhaust Gas As Oxidant Systems€

| | | | MW Potential per DG Size Range | | | | |
|---|---|---|---|---|---|---|---|
| **SIC** | **Sector Description** | **Total MWs** | **25 - 75 kW** | **75 - 150 kW** | **150 - 400 kW** | **400 - 800 kW** | **800 - 1000kW** |
| 2911 | Petroleum Refining | 638 | 1.4 | 0.0 | 58.0 | 0.0 | 578.1 |
| 2621 | Paper Mills | 604 | 0.6 | 0.0 | 38.3 | 0.0 | 564.6 |
| 2869 | Industrial Organic Chemicals, NEC | 382 | 0.0 | 18.2 | 28.3 | 146.5 | 188.5 |
| 3312 | Steel Works & Mills | 322 | 1.7 | 0.0 | 37.4 | 0.0 | 283.0 |
| 2821 | Plastic Mat'ls, Resins, & Elastomers | 248 | 1.1 | 0.0 | 26.8 | 43.3 | 177.0 |
| 2819 | Industrial Inorganic Chemicals, NEC | 244 | 0.0 | 8.6 | 0.0 | 72.4 | 162.5 |
| 2631 | Paperboard Mills | 207 | 0.2 | 0.0 | 16.9 | 25.6 | 164.3 |
| 2611 | Pulp Mills | 190 | 0.3 | 0.0 | 4.4 | 34.5 | 150.9 |
| 3711 | Motor Vehicle Bodies | 94 | 0.2 | 0.0 | 24.3 | 0.0 | 69.6 |
| 2436 | Softwood Veneer & Plywood | 80 | 0.0 | 0.0 | 16.8 | 0.0 | 63.1 |
| 2812 | Alkalies & Chlorine | 72 | 0.0 | 0.0 | 0.1 | 0.0 | 72.1 |
| 2824 | Manmade NonCellulosic Fibers | 71 | 0.0 | 0.0 | 6.3 | 16.3 | 48.6 |
| 3714 | Motor Vehicle Parts | 51 | 0.0 | 8.8 | 9.8 | 23.4 | 8.7 |

| **SIC** | **Top Five States, per SIC, by Total Number of Potential Units** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 2911 | TX | 160 | CA | 154 | LA | 138 | PA | 56 | NJ | 34 |
| 2621 | ME | 82 | NY | 61 | WI | 49 | MI | 42 | MN | 39 |
| 2869 | TX | 192 | LA | 128 | NJ | 82 | AR | 32 | NY | 28 |
| 3312 | PA | 98 | OH | 65 | IN | 36 | MI | 31 | TX | 28 |
| 2821 | TX | 95 | LA | 47 | NJ | 40 | MI | 36 | SC | 34 |
| 2819 | CA | 43 | LA | 39 | TX | 34 | NJ | 33 | NC | 28 |
| 2631 | GA | 32 | WA | 19 | LA | 19 | VA | 16 | OR | 15 |
| 2611 | GA | 72 | FL | 58 | NC | 39 | WA | 35 | AK | 17 |
| 3711 | MI | 40 | OH | 21 | GA | 11 | CA | 10 | NJ | 8 |
| 2436 | OR | 33 | LA | 21 | AR | 16 | WA | 15 | TX | 11 |
| 2812 | NY | 12 | LA | 11 | TX | 10 | KS | 7 | WY | 6 |
| 2824 | SC | 36 | NC | 21 | VA | 15 | GA | 10 | AL | 9 |
| 3714 | MI | 63 | CA | 18 | IN | 17 | OH | 15 | NY | 12 |

## Sensitivity Analysis

Installed costs for the innovative cogeneration equipment decrease in terms of dollars per kW as the equipment size increases. This is because packaged reciprocating engine and turbines prices, thermal system retrofit, engineering, and installation costs decrease in terms of dollars per kW as the equipment size increase. As an example, the installed cost for the 25-75 kW indirect air heating system using a recuperated turbine is $1,641/kW, but in the 800-1000 kW size range is only $836/kW.

Thermal system retrofit, engineering, and installation cost were determined by specifying a base case for the smallest size range, and then using a multiplier to estimate costs for larger size ranges. The equation takes the following form: cost multiplier (absolute $) = (size multiplier)^n, where n is between 0.20 to 0.60. A sensitivity analysis was performed using n = 0.75 for retrofit, engineering, and installation. This lead to a smaller decrease in installed cost as the equipment size increased. For example, the 25-75 kW indirect air heating system using a recuperated turbine is $1,641/kW, but in this sensitivity analysis now decrease to $1,043/kW in the 800-1000 kW size range (instead of $836/kW). The following tables show the results using this less aggressive installed cost reduction scenario.

**Table 17. Less Aggressive Installed Cost Reduction - System Type**

| Cogeneration Package Systems | Economic Market Potential (MWe) |
|---|---:|
| Direct Contact Water Heater | 1,741 |
| Indirect Liquid Heaters | 835 |
| Convection Ovens for Metal Fabrication Preheating | 648 |
| Indirect Air Heating | 1,865 |
| Oxidant for Central Boiler Systems | 2,865 |
| **Total** | 7,954 |

The 10 states showing the highest economic market potential are (sensitivity analysis):

**Table 18. Less Aggressive Installed Cost Reduction - State**

| State | Economic Market Potential (MWe) |
|---|---:|
| California | 1,649 |
| New Jersey | 607 |
| New York | 486 |
| Texas | 440 |
| Michigan | 419 |
| Pennsylvania | 383 |
| Ohio | 338 |
| Louisiana | 278 |
| Wisconsin | 258 |
| Georgia | 224 |
| Other States | 2,873 |
| **Total** | 7,954 |

Economic market potential broken down by prime mover size range is (sensitivity analysis):

**Table 19. Less Aggressive Installed Cost Reduction - Size Range**

| Size Range | Economic Market Potential (MWe) |
|---|---:|
| 25-75 kW | 149 |
| 75-150 kW | 439 |
| 150-400 kW | 1,193 |
| 400-800 kW | 1,280 |
| 800-1000 kW | 4,893 |
| **Total** | 7,954 |

Economic market potential broken down by prime mover type is (sensitivity analysis):

**Table 20. Less Aggressive Installed Cost Reduction - Prime Mover**

| Prime Mover Type | Economic Market Potential (MWe) |
|---|---:|
| Recuperated Turbines | 478 |
| Unrecuperated Turbines | 4,023 |
| Reciprocating Engines | 3,454 |
| **Total** | 7,954 |

# Conclusions

This assessment shows there is a potentially significant market for small innovative industrial cogeneration technologies. These units can beat conventional solutions in:

- Applications where the thermal systems retrofit cost is low,
- Larger sizes applications, because retrofit, engineering, and installation costs are lower in terms of $ per kW than in the smaller sizes,
- Applications where most or all of the waste heat is being used,
- Applications where the existing thermal system efficiency is low, and
- Applications in areas with high electric rates.

Lowering the installed cost for the smaller size ranges (especially installation and retrofit) would increase the market potential even further.

## Benefits

Innovative industrial cogeneration systems can help industrial end users reduce air emissions, lower costs, and make their plants more competitive. This study examined retrofit opportunities, but economic benefits to end users would likely be greater if innovative cogeneration solutions were adopted in plants with failed thermal equipment that needed to be replaced anyway.

From a national perspective, innovative industrial cogeneration solutions will provide the following benefits:

- Increased overall system efficiency for some processes in the industrial sector,
- Reduced air emissions,
- A more competitive industrial base, and
- Reduced demand on the electricity grid.

This report gives important information to cogeneration project developers and technology funders such as the U.S. Department of Energy on the overall magnitude of the market and also provides critical data on the top application types, size ranges, and states.

## Barriers

The results shown in this assessment show the economic market potential. There are a number of barriers that may limit applications of these technologies. Some of these barriers may be regional in nature. The barriers include:

- Product performance and availability,
- Lack of off-the-shelf integrated systems,
- Presence of a supporting market infrastructure,
- Awareness, information and education of end users,
- Demonstration of successful case studies,
- Environmental regulations,
- Planning, zoning, and codes, and
- Tax treatment.

There clearly exists a need for a structured approach to assist with the development and deployment of innovative cogeneration systems in the industrial sector. This approach needs to foster the development of industrial cooling and heating systems that can easily be integrated with distributed generation equipment. The approach should demonstrate these systems in industrial settings and then develop case studies around these demonstrations. These case studies need to include validated and verified data on the systems' operation and performance. In addition, the structured approach also needs to address the potential barriers and how to overcome them.

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