Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments

Additive Manufacturing

Advanced Materials Manufacturing

Advanced Sensors, Controls, Platforms and Modeling for Manufacturing

Combined Heat and Power Systems

Composite Materials

Critical Materials

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Materials for Harsh Service Conditions

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Process Intensification

Roll-to-Roll Processing

Sustainable Manufacturing - Flow of Materials through Industry

Waste Heat Recovery Systems

Wide Bandgap Semiconductors for Power Electronics

U.S. DEPARTMENT OF ENERGY

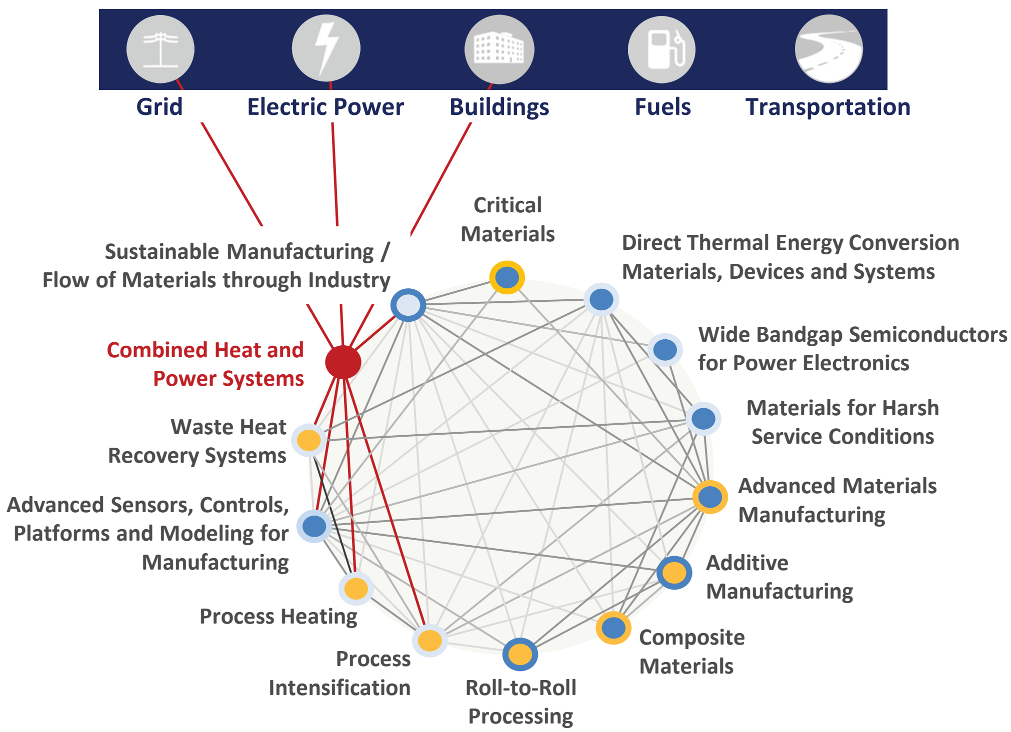
Quadrennial Technology Review 2015

Combined Heat and Power

Chapter 6: Technology Assessments

*NOTE: This technology assessment is available as an appendix to the 2015 Quadrennial Technology Review (QTR). **Combined Heat and Power (CHP)** is one of fourteen manufacturing-focused technology assessments prepared in support of Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. For context within the 2015 QTR, key connections between this technology assessment, other QTR technology chapters, and other Chapter 6 technology assessments are illustrated below.*

Connections to other QTR Chapters and Technology Assessments



Representative Intra-Chapter Connections	Representative Extra-Chapter Connections
■ **Sustainable Manufacturing / Advanced Materials Manufacturing:** modular design of CHP systems for easier reconfiguration, upgrade and repair ■ **Waste Heat Recovery:** heat recovery for CHP systems ■ **Process Heating:** integration of CHP with manufacturing process heating equipment ■ **Advanced Sensors, Controls, Platforms and Modeling for Manufacturing:** models to support development of high-efficiency CHP configurations; improved controls for grid integration	■ **Grid:** CHP for distributed generation ■ **Electric Power:** CHP for distributed generation ■ **Buildings:** CHP for commercial, institutional, and multi-family residential buildings, and data centers

Introduction to Combined Heat and Power

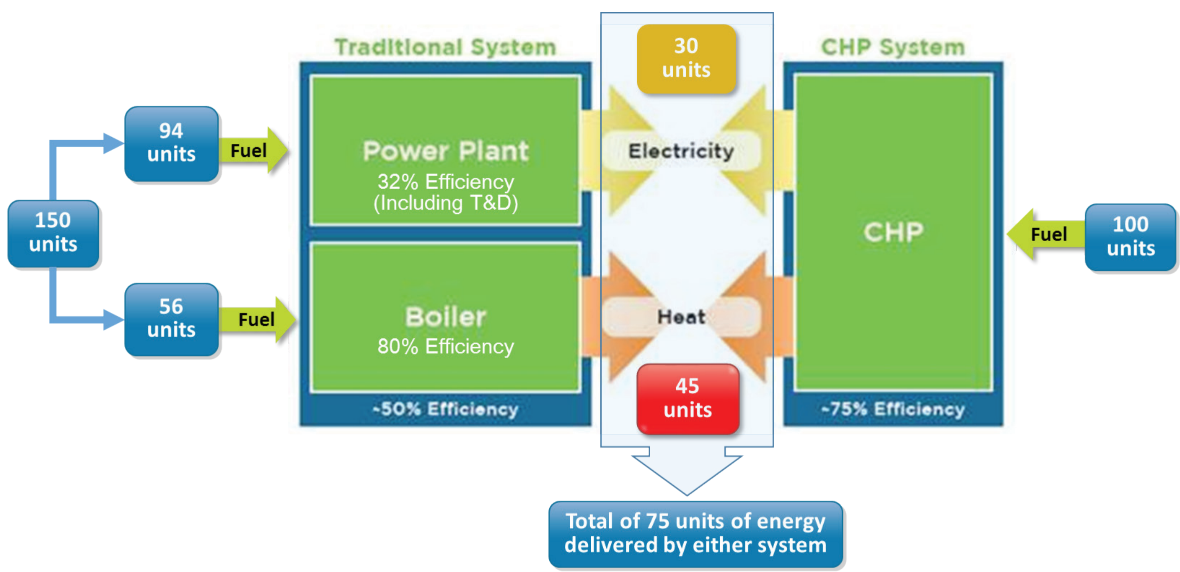
What Is Combined Heat and Power?

Combined heat and power (CHP) is the concurrent production of electricity or mechanical power and useful thermal energy (heating, cooling, and/or process use) from a single energy input. CHP technologies provide manufacturing facilities, commercial buildings, institutional facilities, and communities with ways to reduce energy costs and emissions while also providing more resilient and reliable electric power and thermal energy.[1] CHP systems use less fuel than when heat and power are produced separately. CHP can operate in one of two ways as follows:

- **Topping cycle:** Engines, turbines, microturbines, or fuel cells generate electricity and the waste heat is used for heating, cooling, and/or process use.
- **Bottoming cycle:** Waste heat from an industrial or other source with sufficiently high temperature is used to drive an electricity generator, frequently a steam turbine or organic Rankine cycle (ORC). Bottoming cycle CHP is often referred to as waste heat to power (WHP) and is one way to use waste heat recovered at industrial facilities. (See the "Waste Heat Recovery" technology assessment for additional details.)

The efficiency of a CHP system is most commonly calculated by dividing the total usable energy output (electrical and thermal) by the total fuel input to the system. Today's CHP systems are generally designed to meet the thermal demand of the energy user. CHP systems can achieve energy efficiencies of 75% or more compared to separate production of heat and power, which collectively averages about 50% system efficiency (Figure 6.D.1).[2]

Figure 6.D.1 CHP systems produce thermal energy and electricity concurrently from the same energy input and can therefore achieve higher system efficiencies than separate heat and power systems. In a traditional (separate) system, waste heat from the power generation cycle is discharged to the environment and provides no useful energy service.



CHP systems can be used in a range of settings and power levels, ranging from multifamily residential and commercial/light industrial systems typically producing as little as 50 kW of power to large industrial systems that produce more than 20 MW of power. Applications include the following:[3]

- Industrial (e.g., chemical production plants, refineries, pulp and paper manufacturing facilities, and biorefineries)
- Critical infrastructure (CI) (e.g., emergency services facilities, hospitals, and water and wastewater treatment plants)
- Institutional (e.g., retirement homes, research institutions, and government buildings)
- Commercial (e.g., hotels, airports, and office buildings)
- District energy (e.g., colleges and university campuses, urban centers, and military bases)
- Residential (e.g., single and multifamily housing)

The Value Proposition of CHP

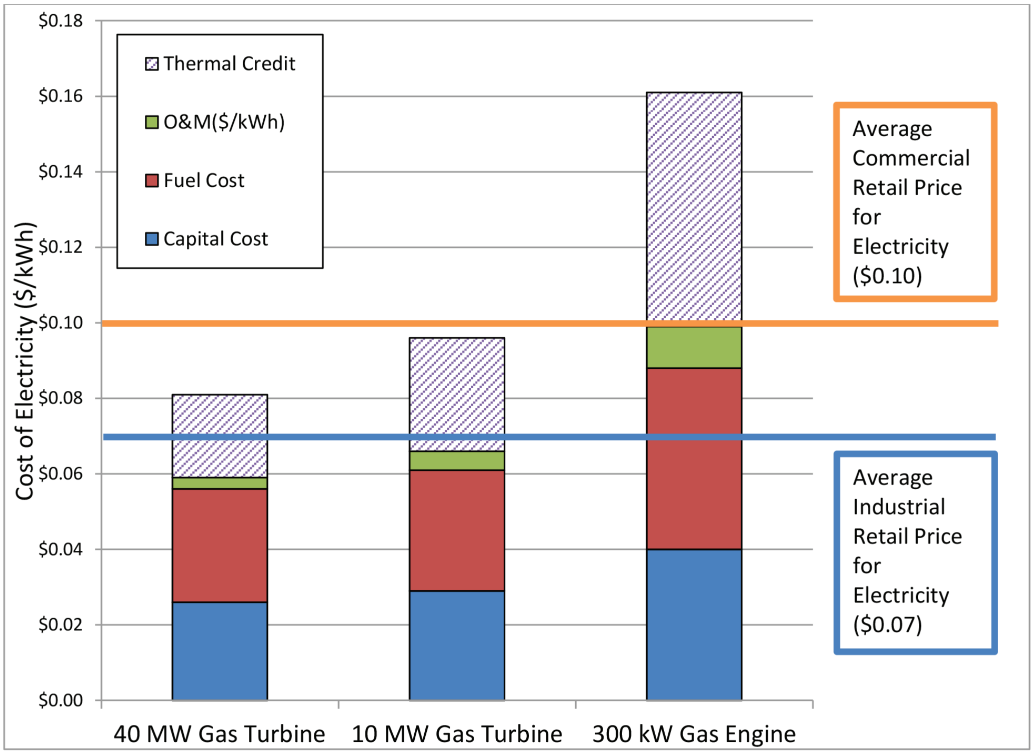
CHP is a commercially available technology that provides a fuel-flexible source of clean electricity and thermal energy, and the expanded use of CHP in the U.S. can offer benefits from greater efficiency to improved grid stability. In 2012, an executive order set a national goal of deploying 40 GW of new, cost-effective CHP (capacity) by the end of 2020, a nearly 50% increase from the 2012 baseline installed CHP capacity of 82 GW.[4] Additionally, as of May 2013, 34 states and the District of Columbia have incentives or regulations encouraging the deployment of CHP and district energy, though the approach is not integrated at the national level.[3]

CHP is first and foremost an energy-efficiency resource and provides efficiency, performance, and reliability advantages. It allows users to produce needed electricity, heat, cooling, and mechanical energy while minimizing fuel consumption. CHP can lower overall energy demand, reduce reliance on traditional energy supplies, make businesses more competitive, cut greenhouse gas (GHG) emissions,[5] and reduce the need for capital-intensive utility infrastructure improvements.

CHP can be a cost-effective solution in many applications, particularly in large, thermally-intensive process facilities. When using the following assumptions, Figure 6.D.2 shows an example of the overall cost of electricity (COE) for three CHP systems when compared to the average retail price of electricity for industrial and commercial facilities. The total COE, including capital, operations and maintenance, and fuel for a large CHP system is $0.080 per kWh (however, the net COE is $0.058 per kWh because less fuel is being used by the on-site boiler system).[6] The net COE for the large CHP system is $0.058 per kWh, and the medium CHP system is $0.067 per kWh, which is slightly less than the typical price paid by industrial customers ($0.070 per kWh). The small CHP system COE is $0.099 per kWh, which is just below the average price paid by commercial customers ($0.103 per kWh).

Figure 6.D.2 demonstrates the current value proposition for CHP and shows potential opportunities to reduce system capital costs, particularly in smaller size ranges. The natural gas and electricity prices used in this analysis are based on typical retail prices from 2010–2015.[7] Although the COE of CHP compares favorably with grid prices for electricity, costs can vary substantially by site and application. Also, the gap between CHP COE and grid prices is narrow, and such narrow margins alone may not be attractive to those considering CHP. The value proposition for CHP is improved when ancillary benefits such as increased reliability and resiliency, emissions reductions, and other benefits are included. CHP is typically most cost-effective in an environment where electricity prices are high relative to natural gas or other fuel prices (sometimes called the "spark spread").

Figure 6.D.2 CHP Cost of Electricity (COE) Relative to Retail Prices.[8] The thermal credit is the value of the displaced energy (e.g. boiler fuel) not needed in a CHP system.



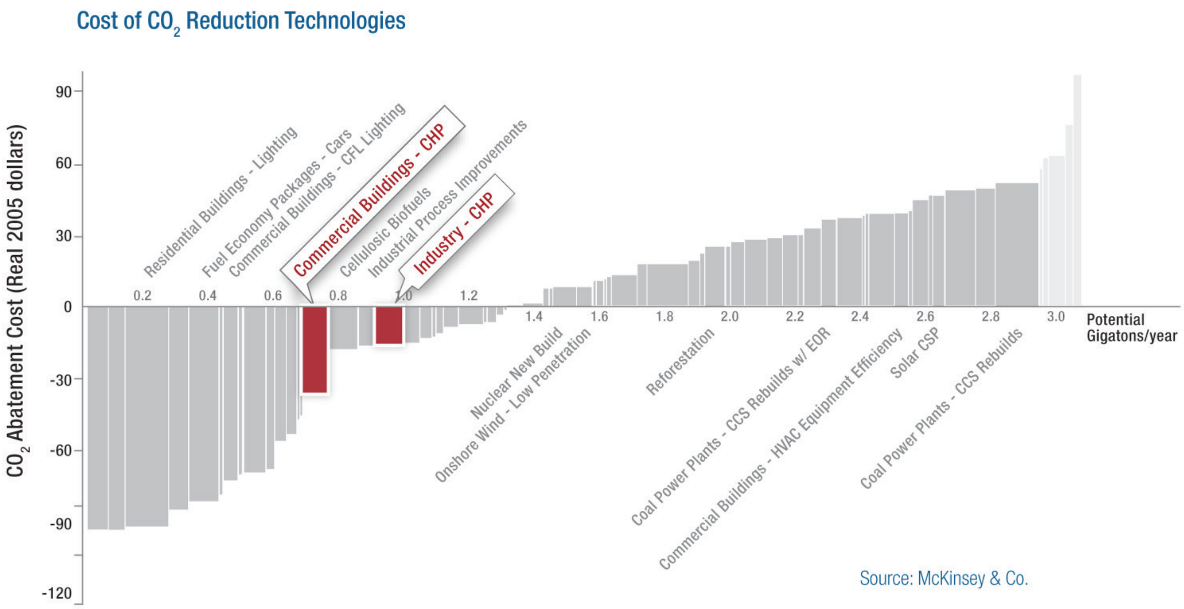
Benefits of CHP

Achieving national goals for climate, competitiveness, energy security, and resiliency will require a broad-reaching strategy addressing both energy supply and end-use efficiency, including CHP. A significant portion of United States electricity generation does not make effective use of waste heat. Electricity is also typically generated far from the point of use, resulting in additional losses during transmission and distribution. The average efficiency of utility generation from fossil fuels has increased from roughly 32% in the early 1960s to nearly 36% today.[9] Despite these efficiency gains, the energy lost in the United States from wasted heat in the power generation sector is still greater than the total energy use of Japan.[10] CHP is a technology pathway to use otherwise wasted energy.

Installing an additional 40 GW of CHP (about 50% more than the current levels of U.S. CHP capacity) would save approximately one quadrillion Btu (one quad) of energy annually and eliminate over 150 million metric tons of CO_2 emissions each year. The additional CHP capacity would save energy users $10 billion a year relative to their existing energy sources. Achieving this goal would also result in $40–$80 billion in new capital investment in manufacturing and other U.S. facilities over the next decade.[11]

CHP systems can provide effective, efficient, reliable, and less costly power to businesses across the nation. Figure 6.D.3 shows the relative cost per ton of potential CO_2 abatement of CHP compared with other energy efficiency and renewable energy technologies. These estimates are interpreted as the additional cost of producing electricity for technologies when compared to a "business-as-usual" baseline of conventional fossil fuel technologies. Given the high efficiency of CHP, these technologies can provide an economic pathway to CO_2 emissions reductions.

Figure 6.D.3 Cost of CHP for CO_2 Abatement Relative to Other Efficiency and Renewable Technologies[12]



CHP can provide a variety of benefits as follows:

- Improved resiliency to electric grid disruptions, enhancing energy reliability and allowing for business continuity in the event of a man-made or natural disaster.
- Stability in the face of uncertain electricity prices.
- Improved U.S. manufacturing competitiveness by lowering energy operating costs to manufacturers. In many parts of the country, CHP provides not only operating savings for the user but also represents a cost-effective supply of new power generation capacity.
- A path to lower GHG emissions through increased energy efficiency. Use of CHP currently avoids 248 million metric tons of carbon dioxide per year.[13]
- Lessened need for new transmission and distribution infrastructure and enhanced power grid security.
- Use of abundant domestic energy sources. Over 83% of CHP capacity is fueled by natural gas, biomass, or waste fuels.

Resiliency and Security

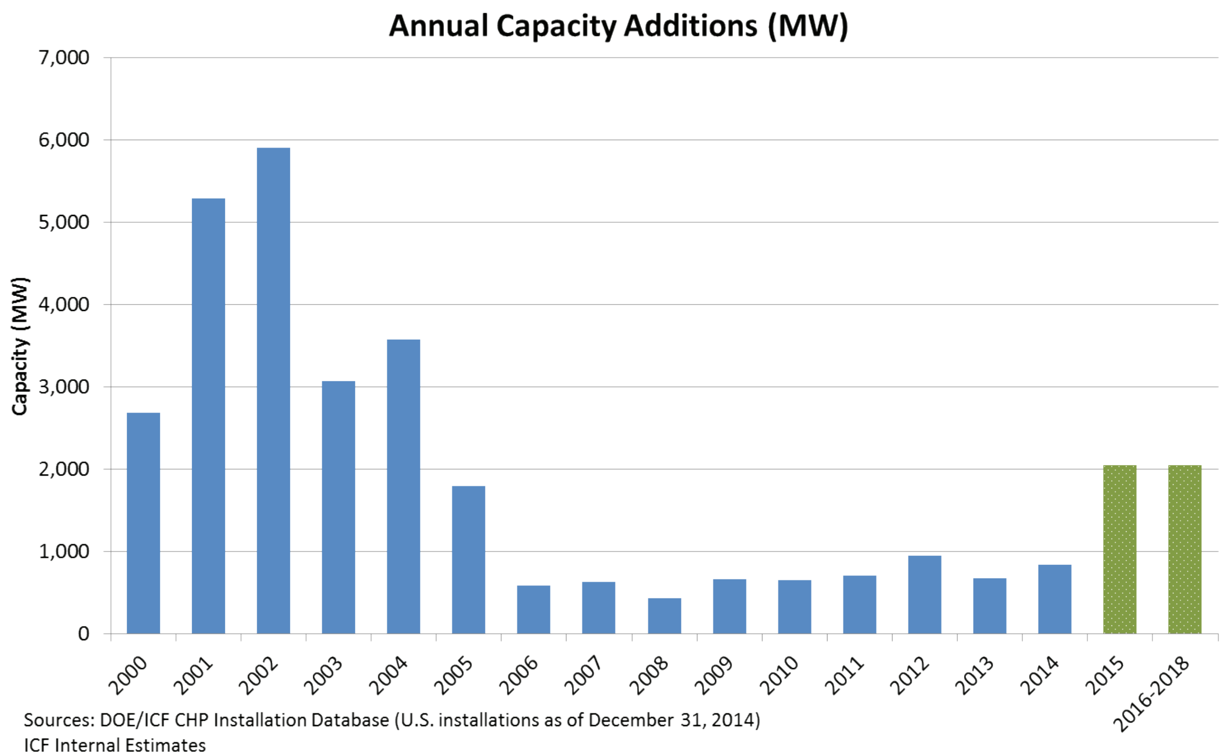
CHP systems, when designed to operate independently from the grid, can provide critical power reliability for a variety of businesses and organizations while providing electric and thermal energy to the sites on a continuous basis, resulting in daily operating cost savings. A CHP system that runs every day and saves money continuously is often more reliable in an emergency than a backup generator system that only runs during emergencies.[14]

By installing properly sized and configured CHP systems, critical infrastructure facilities can effectively insulate themselves from a grid failure, providing continuity of critical services and freeing power restoration efforts to focus on other facilities. The use of CHP systems for critical infrastructure CI facilities can also improve overall grid resiliency[15] and performance by removing significant electrical load from key areas of the grid. This is possible when CHP is installed in areas where the local electricity distribution network is constrained or where load pockets exist. The use of CHP in these areas eases constraints by reducing load on the grid. For this reason, CHP placement can be coordinated with the utility; this allows CHP design to be based on the conditions and needs of the host facility and also on the conditions and needs of the local grid system.

State of the CHP Market

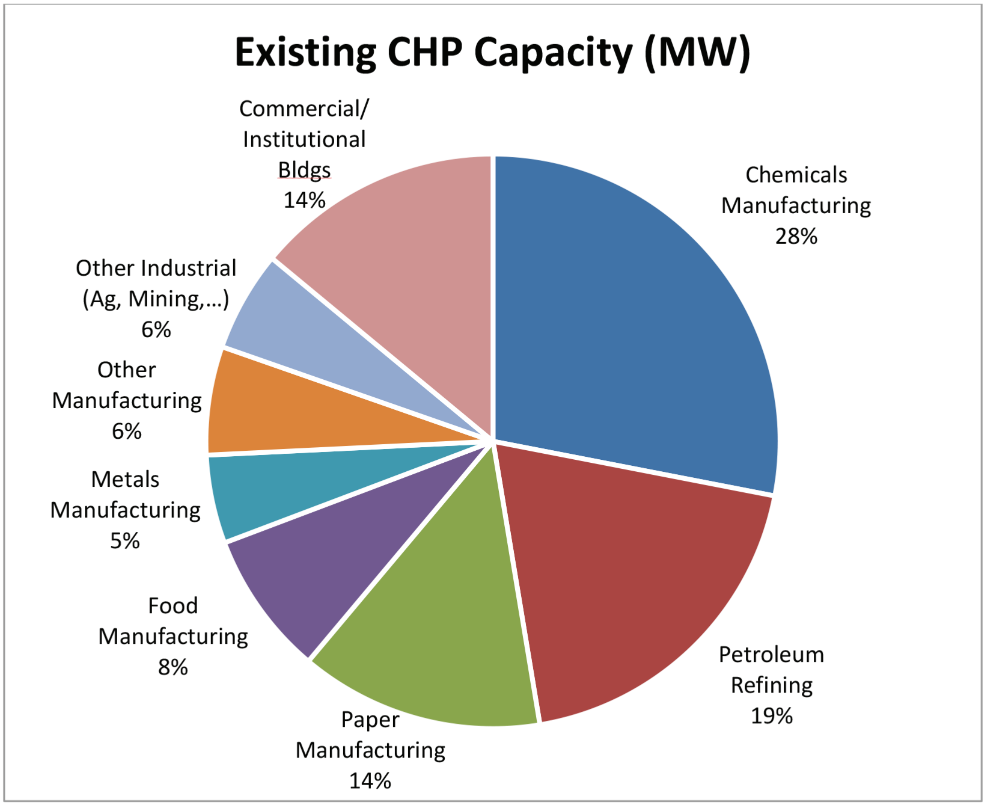
The United States currently has an installed CHP capacity of over 82 GW of electric capacity at over 4,400 facilities, which represents 8% of current U.S. electricity generating capacity (by MW).[16, 17] More than two-thirds of these facilities are fueled with natural gas, but renewable biomass and process wastes are also used. CHP capacity growth has been slow since the early 2000s; however, 2012 had the most new installed capacity since 2005, with 955 MW of installed CHP capacity added (see Figure 6.D.4).[18] Interest in CHP in the United States is rising primarily owing to growth in U.S. manufacturing[19] and growing awareness of the value of energy resiliency. This can also be seen in Figure 6.D.4, where a considerable increase in CHP deployment is expected in 2015 and 2016.

Figure 6.D.4 Annual U.S. CHP Capacity Additions[20]



In the United States, the greatest use of CHP in terms of capacity is in the industrial sector, which accounts for approximately 86% of the CHP capacity (see Figure 6.D.5). CHP has traditionally been deployed most frequently in the manufacturing and commercial/institutional markets. These traditional applications typically enjoy an energy use profile with high thermal demands relative to electrical demands, making them an attractive match for traditional CHP. As shown in Figure 6.D.5, CHP can be very cost-effective for large, thermally driven applications typical in paper and chemical manufacturing and petroleum refining.

Figure 6.D.5 Existing CHP Capacity in the United States by Sector[21]



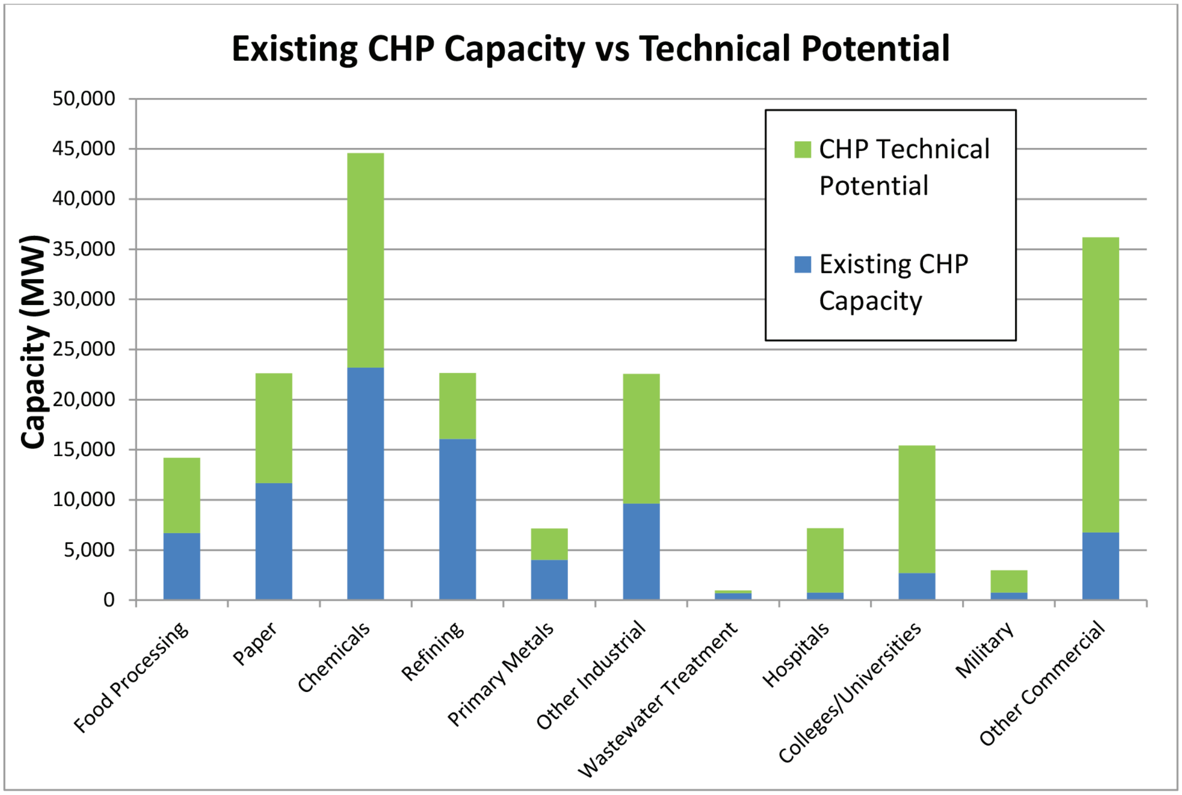
Applications with CHP Opportunities

Significant opportunities remain to improve performance and efficiency of CHP systems and to reduce costs in smaller size ranges, typically under 5 MW. CHP research and development (R&D) will continue to focus on technologies benefiting industrial, large-scale residential, and commercial/institutional facilities. The focus of these activities will shift to address the needs of those markets where large CHP potential exists but has been untapped; namely, 1–5 MW scale CHP systems with higher power to heat ($\frac{P}{H}$) ratios. Standardized, "package" systems for commercial buildings with similar characteristics, such as hospitality and hospitals, are under review and consideration. To more effectively deploy CHP into underserved markets, the following areas have been identified.

Single Buildings/Facilities

Figure 6.D.6 shows existing CHP capacity compared to the total technical potential in a variety of industries and sectors. There still remains significant untapped potential in all market sectors. CHP systems are typically custom-designed and installed. This makes sense in the industrial sector, where many larger projects can support site-specific design and construction costs. For single buildings and smaller facilities, on-site engineering and design costs increase hurdles for the end user. R&D activities should continue to focus on cost reductions and efficiency improvements to improve technology deployment in all market areas.

Figure 6.D.6 Existing CHP versus CHP Technical Potential by Sector[22]



District Energy with CHP

District energy systems typically distribute thermal energy (such as steam, hot water, or chilled water) from a central plant to a number of facilities connected through a pipe distribution system. In a recent analysis, the International District Energy Association (IDEA) has identified 601 district energy systems in the United States, 289 of which were found to not include CHP.[23] CHP installed as part of district energy systems has grown in recent years. There is currently 6.6 GW of CHP generating capacity at district energy sites, including 55 city and 153 university campus district energy systems. There are increasing interest and opportunities to deploy CHP in new mixed-use developments and dense urban sites. Owing to their resiliency and reliability benefits, many universities and cities are interested in district energy systems with CHP. Given that district energy systems connect and aggregate sizable thermal loads, which are important to highly efficient CHP, the U.S. district energy sector holds strong potential for CHP deployment.

Microgrids with CHP

Federal, state and local public-private partnerships[24] can help coordinate and advance the uptake of CHP and are particularly important to encourage the adoption of microgrid technology. Microgrids typically integrate small-scale distributed energy resources into low-voltage electricity systems within clearly defined boundaries that act as a single controllable entity with respect to the grid. One example of federal/state coordination is the transit system in New Jersey, where an agreement was announced in 2013 to develop a microgrid that would help ensure continued operation of the New Jersey Transit rail system after a major disaster, such as Hurricane Sandy.[25] In addition, the state of Connecticut established the nation's first statewide microgrid pilot program in 2013.

Microgrids with CHP offer two primary benefits: (1) assurance that diverse energy supplies will be provided to sites deemed critical for public services or safety even during wide-scale outages or natural disasters; and (2) enhanced reliability and resilience for high-priority sites where outages can cause serious disruptions, risks, or financial costs. Prime candidates for microgrids include hospitals, military bases, police and fire services, and other key government facilities as well as university campuses, schools, and large commercial or industrial facilities that require uninterrupted power supplies.[26]

Microgrids with CHP may also help enable the following:

- **Clean energy development:** Establishing CHP as an enabler of other intermittent sources such as renewables, and reducing GHG and other emissions
- **Disruptive technologies and forces:** Transformative industry trends that make distributed generation, energy storage, and energy management technologies more useful and cost-effective for a wider range of applications

Facilitation of Cost-Effective CHP

While CHP can be a highly effective and efficient electricity and thermal energy generation technology, there still exist significant technical barriers to its adoption. The set of circumstances that would allow CHP to obtain as much of its technical potential as possible includes the following:

- Cost to install and operate CHP technology is less than the cost to purchase electricity and create on-site thermal energy separately (from the least expensive U.S. utility plus the most efficient boiler)
- Efficiency that exceeds the best combination of purchased electricity plus on-site produced thermal energy (i.e., 75%+,[27] a combined efficiency that exceeds current combined efficiency for combined cycle electricity generation and most efficient boiler configurations in most applications)
- Higher power-to-heat ratios (~1.5) while maintaining cost, performance, and efficiency targets (70%+)[28] to allow broader adoption in all end-use sectors
- Fuel flexibility that allows for a variety of locally produced input fuels (such as municipal waste gases and solid fuels, biofuels, methane from animal wastes, and digester gases) and also renewable energy sources, such as solar and geothermal energy
- Reliability, availability, maintainability, and durability that meet and exceed the best comparable technologies (such as electricity derived from highly efficient central-station combined cycle plants plus thermal energy from the most efficient boilers)
- Packaging systems into easy-to-select-and-install (plug and play) modules, including standardized technologies for similar building characteristics
- Technological advances that enable microgrids with distributed energy resources, including CHP, to autonomously and safely switch between grid connected and island mode operation.

Technology Assessment and R&D Potential

The Department of Energy (DOE) has focused on eliminating the technological and market hurdles to the adoption of CHP technologies through a combination of R&D and technical assistance. CHP has a long history of providing both electricity and thermal energy to cities, manufacturers, and other commercial entities. While the technology and its traditional applications are well understood, there still remains an untapped opportunity for R&D both within and outside of the traditional applications and markets.

Near-Term Opportunities

The DOE CHP Technical Assistance Partnerships (CHP TAPs)[29] have been working to promote and assist in transforming the market for CHP, district energy with CHP, and waste heat-to-power (WHP) CHP technologies throughout the United States. The CHP TAPs work closely with end users and other stakeholders to identify opportunities and provide technical assistance. Through this work, DOE has gathered information on many of the near-term barriers to broader implementation of CHP. Most of the near-term research opportunities focus on reducing first cost and simplifying system design and installation for existing traditional markets and applications (typically with power-to-heat ratios under 0.75). The following are five areas where near-term needs have been identified:

- **Single buildings/facilities—packaging:** Development and demonstration of cost-effective CHP package systems requiring less on-site engineering and design that would reduce hurdles for the end user
- **District energy with CHP:** Development and demonstration of technologies bringing down the first cost of installed district energy systems with CHP
- **Microgrids with CHP:** Development and demonstration of enabling technologies for energy management, including advanced controls, distributed generation (including renewables), and energy storage
- **Flexible fuel CHP:** Development and demonstration of technologies reducing the first cost of fuel treatment as well as development of corrosion-resistant materials
- **Grid integration—sizing beyond the facility:** Development and demonstration of control technologies that would allow for seamless integration of both local grid and facility cluster operations

Long-Term Opportunities

Longer-term CHP research will focus on expanding markets and applications for CHP technologies, outside of traditional thermally driven processes and facilities. These activities should focus on improving system efficiencies considering both the first and second laws of thermodynamics. While first-law analysis accounts for conservation of energy flows, second-law analysis addresses the quality of energy utilization. In systems with multiple outputs such as electrical and mechanical power as well as usable heat energy, optimization can be guided by a second-law analysis which considers the maximization of available energy, both in energy inputs such as fuel chemical availability as well as internal energy flows among components. Maximizing $\frac{P}{H}$ generally is a more efficient use of fuel available energy, and flexible systems which can produce higher $\frac{P}{H}$ are desirable.[30]

Long-term opportunities include the development of even higher electric efficiency CHP systems, high-efficiency single and combined cycle prime movers, WHP systems for low-temperature waste heat, and "smart" CHP systems that integrate with the U.S. electric grid. These opportunities are explored in this section. Improvements in low-temperature thermal recovery and prime mover efficiencies will enable CHP to move to higher $\frac{P}{H}$ applications, while smart CHP systems will enable flexibility of use and enhanced revenue opportunities.

Research in these areas can yield fuel and carbon emission reductions as well as open new markets for CHP technologies. The result of these activities will be to make efficient CHP of all $\frac{P}{H}$ ratio ranges cost-competitive with purchased grid electricity.

Opportunity for High Power-to-Heat CHP

While existing thermally driven CHP systems sized to supply 100% of a facility thermal demand (with a low $\frac{P}{H}$ ratio, typically below 0.75) are currently cost-effective in many markets and applications, there still remains a significant unserved market with smaller thermal demand relative to electrical ($\frac{P}{H}$ up to 1.5) in the industrial, commercial/institutional, and residential sectors. An enormous energy and cost savings opportunity could be realized by increasing $\frac{P}{H}$ while maintaining the high efficiencies that thermally sized CHP systems enjoy (the potential is examined in later sections of this document). Increasing $\frac{P}{H}$ without loss of efficiency would entail the development of ultra-high-efficiency electrical generation technologies (these are discussed in the following section).

In order to better understand the opportunity for high $\frac{P}{H}$ CHP, a preliminary analysis evaluated the opportunities to deploy highly efficient CHP to applications that fall outside of the traditional thermally driven systems.[31] The analysis examined the technical potential and energy savings that could be captured if CHP systems were deployed in applications with a power-to-heat ratio of up to 1.5 (current power-to-heat ratios in existing CHP systems are closer to 0.75). The following system characteristics were assumed for existing CHP systems:

- **For 50–1,000 kW systems:** 30.5% electrical efficiency (η_e) and 79.6% overall efficiency (η)
- **For 1–5 MW systems:** 34.8% electrical efficiency and 77.7% overall efficiency[32]

The $\frac{P}{H}$ can be shown to be as follows[33]:

$$\frac{P}{H} = \frac{\eta_e}{\eta_h} = \frac{\eta_e}{\eta - \eta_e}$$

Where η_h = the thermal efficiency of the heat portion of the system. Thus, for the smaller system case, $\frac{P}{H}$= 0.62, and for the larger system, $\frac{P}{H}$= 0.81.[34] Table 6.D.1 lists the sectors included in the analysis.[35]

Table 6.D.1 Sectors and subsectors/facility types included in high power-to-heat CHP opportunity analysis

Manufacturing	Commercial/Institutional
Textiles	Commercial Buildings
Plastics	Schools
Fabricated Metals	Retail Stores
Machinery, Electrical, Computers, and Electronic Equipment	Restaurants
Transportation Equipment	Grocery Stores
	Government Buildings
	Prisons
	Wastewater Treatment Facilities
	Refrigerated Warehouses
	Airports
	Post Offices
	Museums

This analysis indicates that expanding the market applications for CHP systems to those driven more by electrical rather than thermal output could save an additional 1.3 quads of energy compared with existing CHP technologies alone, as shown in Table 6.D.2.

Table 6.D.2 Technical potential and energy and cost savings for high power-to-heat CHP operation

	Energy Benefits for High Power-to-Heat CHP Operation		
	Manufacturing Sector	Commercial/ Institutional Sector	**Total**
Incremental Capacity Potential (GW)*	4.7 GW	45.1 GW	**52.9 GW**
Incremental Annual Primary Energy Savings (TBtu)**	140 TBtu	1,160 TBtu	**1,300 TBtu**
User Incremental Energy Cost Savings ($ Millions)	$1,320 Million	$8,660 Million	**$9,980 Million**

* Incremental CHP capacity on the basis of a power-to-heat ratio of 1.5.
** Incremental primary energy savings on a basis of 33% average grid efficiency.

High-Efficiency Distributed Electrical Generation

The ultimate extension of high $\frac{P}{H}$ CHP discussed in the previous section occurs when all of the fuel energy is used to generate electricity (i.e., $\frac{P}{H} >> 1$). Such systems might consist of a topping cycle, in some cases a prime mover, combined with one or two additional (bottoming) cycles that also generate electrical power. The combined cycles may offer flexibility in a CHP context. When waste heat is needed, the bottoming cycle or cycles can be bypassed and the heat from the topping cycle used. Similarly, the second or third cycle can be brought online only as electrical demand requires. The "Waste Heat Recovery" technology assessment has additional detail on bottoming cycles.

This section explores the practical thermodynamic efficiency limits of natural-gas-fueled combined cycles for electrical power generation in the 1–10 MW_e range. The 1–10 MW_e range is well suited to many of the industries and commercial sector applications identified in Table 6.D.1. On the basis of a scoping survey, a practical limit of 65%–70% fuel-to-electricity efficiency (higher heating value [HHV] basis) can be achieved by utilizing the fuel exergy (available energy) through combined cycles producing AC power. It is important to note that combined-cycle efficiency is path dependent, depending on the arrangement and configuration of individual components, and that combining cycles usually compromises the optimal operation of the individual cycles, with diminishing returns. However, a systematic approach to optimizing the combined cycles, particularly focusing on reducing irreversibilities, such as in combustion processes, could conceivably result in somewhat higher efficiencies than the projections in this study. However, this will require significant R&D to overcome the many barriers.

The thermodynamic analysis consisted of two components: basic thermodynamic modeling and a literature review.

An exhaustive modeling exercise was not attempted, but rather an approach with some parametric variation was used to gauge sensitivities to primary parameters as well as to ascertain that the preliminary modeling matched other studies.

A combined cycle involves the generation of electricity with a topping cycle (the upstream generator) and a bottoming cycle (the downstream generator), which uses residual fuel and/or heat from the topping cycle. The combined-cycle engine converts fuel exergy to electrical power through a combination of chemical engines (such as fuel cells, reciprocating internal combustion engines, and gas turbines) and heat engines (such as waste-heat Rankine or Stirling-cycle engines). Some systems recover exhaust heat to increase internal efficiencies of the primary cycles; for instance, to heat incoming flow streams with a recuperator. It is increasingly common to find references in the literature to add a third waste-heat recovery (WHR) cycle to produce additional electrical power. Additional cycles not only increase capital and operating cost but are also an exercise in balancing returns, so such systems must be carefully considered and designed.

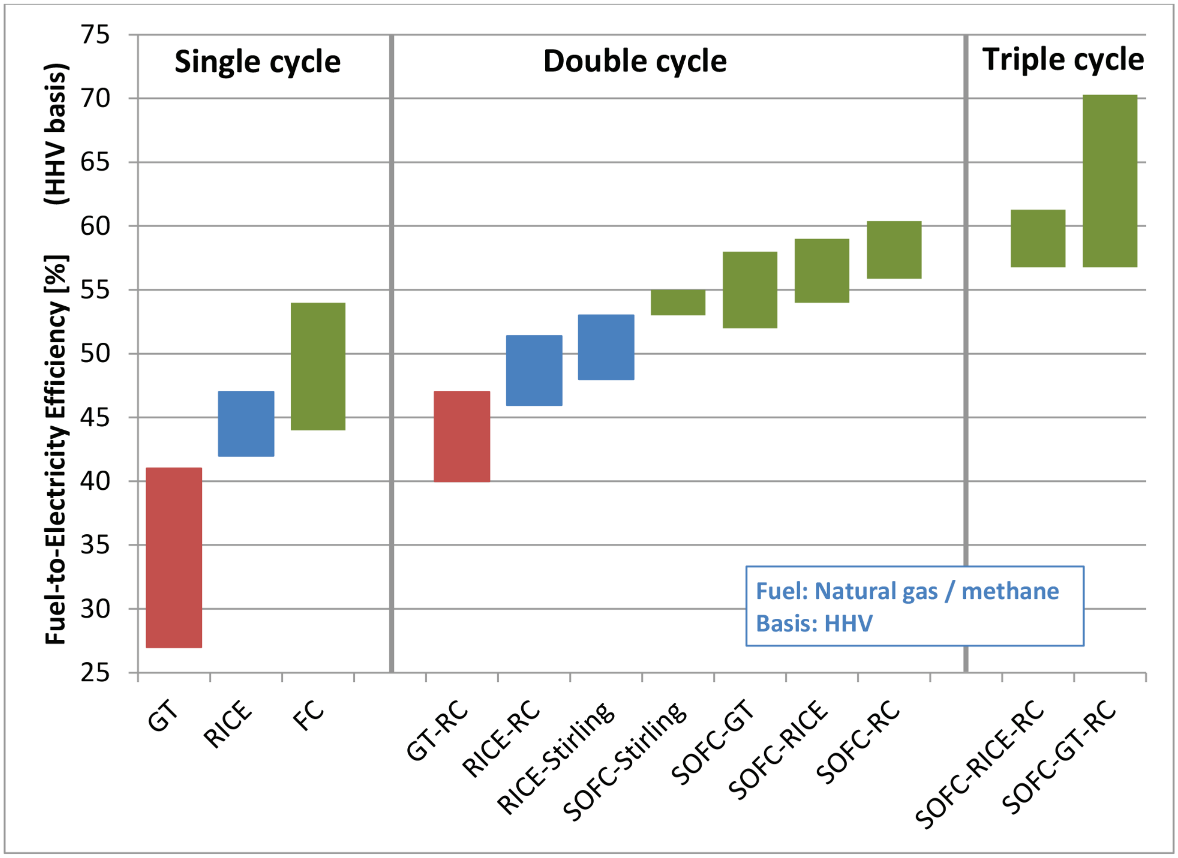
Table 6.D.3 and the accompanying chart, Figure 6.D.7, summarize the range of expected combined-cycle fuel-to-electricity efficiencies (FTEEs) for various technologies and combinations of cycles. Most of the reported efficiencies come from the literature and some solely from modeling analyses. The first column specifies the number of power-generating cycles in the system, and the next three columns specify the different configurations (as applicable). The overall thermal efficiency is based on fuel energy input to electrical power generation output, with no other significant energy inputs (such as solar or heat sinks); the overall system scale is on the order of 1 MW_e but can be expected to be descriptive of systems in the 1–10 MW_e range. In all cases, the fuel is natural gas, usually approximated as methane. Electrical power is generated from mechanical power and/or converted from DC to AC where necessary, so FTEE values include inverter and generator losses as appropriate, typically assuming 95% efficiency for inverters and 94% for electrical generators.[36] Fuel energy was accounted on a lower heating value (LHV) basis, which is acceptable (and standard practice) when comparing systems using a single fuel and descriptive of most fuel-conversion systems with vapor-phase water products exhausted to the surroundings or into a second, non-condensing engine. The HHV basis was obtained by scaling efficiencies by the ratio of LHV/HHV, which is approximately 0.9 for methane and most domestic natural-gas mixtures. Because different fuels have different chemical energies, the HHV is used for calculating and displaying FTEE values in order to facilitate comparison to other fuel-combustion systems. As with most literature studies, the energy inputs to pressurize the fuel to operating pressures along with other small parasitic loads and other losses are neglected in this analysis. The "Notes" column refers to the Appendix at the end of this assessment, with more complete explanations of the assumptions made. In addition, the Appendix contains the descriptions and equations used for the modeling of the different cycles.

Table 6.D.3 Estimated practically achievable fuel-to-electricity efficiencies for selected technologies in combined cycles.

N	Cycle 1	Cycle 2	Cycle 3	FTEE (%) (LHV basis)	FTEE (%) (HHV basis)	Sources	Notes
1	GT	—	—	30–46	**27–41**	L&M	A
1	RICE	—	—	47–52	**42–47**	D	B
1	SOFC/MCFC	—	—	49–60	**44–54**	L	
2	GT	RC	—	44–52	**40–47**	M	A
2	RICE	RC	—	51–57	**46–51**	L&M	B
2	RICE	Stirling	—	53–59	**48–53**	M	C
2	SOFC	Stirling	—	60	**54**	L	D
2	SOFC	GT	—	58–64	**52–58**	L&M	E
2	SOFC	RICE	—	60–65	**54–59**	L	F
2	SOFC	RC	—	62–67	**56–60**	L	G
3	SOFC	RICE	RC	63–68	**57–61**	L	H
3	SOFC	GT	RC	63–78	**57–71**	L&M	I

Key: **GT** = gas turbine; **RICE** = reciprocating internal combustion engine; **SOFC** = solid oxide fuel cell; **MCFC** = molten carbonate fuel cell; **RC** = Rankine cycle using either water or refrigerants (for organic RC); **Stirling** = Stirling cycle engine. Sources: **D**=data; **L**=literature; **M**=modeling; HHV-based efficiencies estimated from LHV-based values. The HHV basis is used to facilitate comparison between fuels. For "Notes," see the Appendix.

Figure 6.D.7 Fuel-to-electricity efficiency on a HHV basis of various technologies in combined cycles as summarized in Table 1.



Key: **GT** = gas turbine; **RICE** = reciprocating internal combustion engine; **FC** = fuel cell (molten carbonate or solid oxide); **SOFC** = solid oxide fuel cell. The Appendix provides background on how these efficiencies were calculated.

CHP systems can achieve very high system efficiencies (>80%, at times). These high efficiencies are typically found only in low $\frac{P}{H}$ systems. Maintaining high system efficiencies while increasing $\frac{P}{H}$ requires the development of highly efficient prime movers (as described above) along with improved thermal recovery. Specific research areas that were identified are listed in Table 6.D.4.

Table 6.D.4 Technical areas for improvement of high $\frac{P}{H}$ CHP and ultra-high-efficiency generation

Component Development	Prime Mover Technology (engines, turbines, microturbines, fuel cells)
	Heat Recovery, Heat Exchanger Materials, and Thermally Activated Utilization
	Combustion, including fuel compression and temperature
	Fuel Collection, Handling, Composition Monitoring, & Treatment
	Materials capable of withstanding extreme temperatures and pressures
Systems Development	Thermodynamic Cycles
	System Engineering/Packaged Design
	Process, Facility, and Utility Integration
Technology Validation	Full-Scale Evaluation
	Pre-Commercial Demonstration
	Innovative Applications and Performance Monitoring

Low-Temperature Heat Recovery and Waste Heat-to-Power (WHP)

Waste heat from generation technologies (engines and turbines) and from industrial processes can be used in several ways. The waste heat can be used to directly produce hot water or steam or can be used to produce electricity. When waste heat from an industrial or other source with sufficiently high temperatures is used to drive an electricity generator, it is called "bottoming cycle" CHP. A recent Oak Ridge National Laboratory (ORNL) study of WHP opportunities found that 14 GW of technical potential and 7 GW of economic potential for WHP exist.[37] Increased capability and efficiency of heat recovery in CHP systems from exhaust gas will increase CHP electricity generation efficiency. A major challenge for low temperature heat recovery from exhaust gases is the condensation and corrosion caused by cooling exhaust gases below their dew point temperature. Condensation heat recovery requires significantly higher capital and operating costs, which are typically not worth the energy-saving benefits. While condensing economizers are commercially available, capital costs can be as much as three times that of conventional boilers. Alternate technologies, such as transport membrane condensers, are being developed and may have lower costs.[38]

There are a number of advanced technologies in the R&D stage that could provide additional options for direct power generation from waste heat sources. These technologies include thermoelectric generators, piezoelectric generators, thermionic devices, thermo-photovoltaic generators, Stirling engines, and innovative concepts for steam engines (see "Direct Thermal Energy Conversion Materials, Devices, and Systems" technology assessment for further information). These systems range in terms of commercial readiness in the United States, although some—such as the Kalina Cycle—have achieved relative success in other countries. A few have undergone prototype testing in applications such as heat recovery in automotive vehicles and from coproduced liquid in oil and gas wells.

Recovery at low temperatures (typically lower than 400°F) becomes increasingly challenging with chemically laden gas streams. These waste heat sources will have greater limitations that prevent cooling flue gases to low temperatures. To enable expansion of low temperature heat recovery (with the goal of improving CHP efficiencies), additional research will involve the following:

- Improving methods for cleaning exhaust streams
- Developing low cost advanced heat exchangers that can withstand corrosive environments

- Developing heat exchangers that can be easily cleaned
- Modifying process technologies to inhibit the introduction of chemicals that would prevent heat exchange

A challenge for heat exchangers when working with low temperature fluids is the large heat transfer area required, especially if heat is to be recovered from gaseous exhausts. Developments that increase heat transfer coefficients in heat recovery systems could partially address this issue. Some examples of commercially available technology for improving heat technology coefficients are ceramic inserts used in radiant heating tubes, dimpled or finned tubes, and heat pipes. Further information on research needs for low temperature waste heat recovery can be found in the "Waste Heat Recovery" technology assessment.

Smart CHP Systems

CHP has the potential to play a significant role in the modern smart grid. Integrating manufacturing operations and CHP into the modern grid system will allow manufacturers to enjoy the cost savings from increased energy efficiency and will also provide the potential to realize additional revenue streams. The focus of longer-term research on grid integration and smart CHP systems will be to fully incorporate smart manufacturing operations, including smart CHP, into an optimized grid. This will involve examining industrial electrical and thermal loads and how they can be incorporated into electricity markets, with the objective of optimizing system efficiency, utilization, and cost-effectiveness.

Program Considerations to Support R&D

Historical Investments in CHP

The DOE CHP R&D portfolio has included the following:

Advanced reciprocating engine systems (ARES): The goal of the ARES program was to deliver a technologically advanced engine/generator system that combined high specific power output and low exhaust emissions with world-class overall efficiency while maintaining excellent durability, all at a low installed cost. This program demonstrated improved engine electrical efficiencies, increasing from ~35% at project start to 50% on project closure—a nearly 50% increase.

Packaged CHP systems: The development of packaged CHP systems suitable for smaller industrial facilities can enable users to avoid complicated and costly system integration and installation but still maximize performance and increase efficiency. The projects included the following:

- High efficiency microturbine with integral heat recovery[39]
- Flexible CHP system with low NO_x, CO, and VOC emissions[40]
- Low-cost packaged CHP system[41]
- CHP integrated with burners for packaged boilers[42]

High value applications: New high-value CHP technologies and applications can offer attractive end-user economics and significant energy savings with reproducible results as follows:

- Flexible distributed energy and water from waste for the food and beverage industry
- Microchannel high-temperature recuperator for fuel cell systems
- Novel controls for economic dispatch of combined cooling, heating, and power systems
- Residential multifunction gas heat pump
- Ultraefficient combined heat, hydrogen, and power system

Fuel-flexible CHP: Accelerating market adoption of emerging technology and fuel options can improve industry competitiveness through more stable energy prices, cost savings, and decreased emissions. Examples of these technology and fuel options include biomass gasifiers, gas turbines utilizing opportunity fuels, landfill gas cleanup and removal systems, and desulfurization sorbents for fuel cell CHP as follows:

- Adapting on-site electrical generation platforms for producer gas
- Development of an advanced CHP system utilizing off-gas from coke calcination
- Development of fuel-flexible combustion systems utilizing opportunity fuels in gas turbines
- Integrated CHP/advanced reciprocating internal combustion engine system for landfill gas to power applications
- Fuel-flexible microturbine and gasifier system for CHP
- Low-NO_x gas turbine injectors utilizing hydrogen-rich opportunity fuels
- Novel sorbent to clean biogas for fuel cell CHP

Demonstrations: The installation of innovative technologies and applications that offer the greatest potential for replication can provide compelling data and information to foster market uptake in manufacturing and other applications as follows:

- ArcelorMittal USA blast furnace gas flare capture[43]
- BroadRock renewables combined cycle electric generating plants fueled by waste landfill gas[44]
- Texas A&M University CHP system[45]
- Thermal Energy Corporation Combined Heat and Power Project at the Texas Medical Center[46]
- Frito-Lay CHP system demonstration[47]

R&D opportunities and research targets for the development of CHP and ultrahigh efficiency generation technologies are shown in Table 6.D.5.

Table 6.D.5 Strategic R&D Opportunities and Performance Targets for CHP

Near-Term Areas (<5 years)		**Long-Term Areas (>5 years)**	
R&D Opportunity	Goals	R&D Opportunity	Goals
CHP Packaging for Single Buildings/Facilities: packaged systems to avoid need for custom equipment design and on-site engineering expertise	■ Target equipment size range 1–5 MW ■ Capital cost less than $1,500/kW ■ "Levelized" cost of electricity less than $0.10/kWh	High Power-to-Heat Ratio CHP: systems with efficient on-site electricity generation for facilities dominated by electrical loads	■ Target equipment size range 1–10 MW ■ 65% electric generation efficiency, with high (>75%) overall CHP efficiency ■ Power-to-heat ratio up to $\frac{P}{H} = 1.5$
Grid Integration: technical solutions to enable grid interconnection, demand response, and ancillary services	■ Facility needs met while safely and seamlessly providing grid support	WHR and WHP: technologies for improved thermal recovery in CHP	■ Improved reliability, availability, maintainability, and durability for low-temperature recovery
Microgrids with CHP: small-scale autonomous energy grids with CHP generation and possible facilitation of intermittent renewable sources, storage, energy efficiency measures, etc.	■ Improved synchronization, controls, and cyber security	Smart CHP: full integration of on-site generation and CHP into a smart grid	■ Specific technical goals in development
District Energy with CHP: systems to enable use of rejected heat from CHP facilities to provide steam, and heated or chilled water to network buildings	■ Reduced system capital and installation costs ■ Deliver electricity and thermal needs to facility loops		
Fuel-Flexible CHP: systems that can operate from various on-site, renewable, and opportunity fuels	■ Capital cost less than $1,500/kW (not including fuel treatment) ■ Levelized cost of electricity less than $0.10/kWh		

Risk, Uncertainty, and Other Considerations

Technical Risks

The long-term development of highly efficient and more broadly applicable types of CHP systems and technologies involves several areas of technical risk. Thermodynamic optimization of systems with multiple outputs is challenging, and significant barriers exist. Some of these technical risk areas relate to system size (scale), individual cycle development, and combined cycle integration as follows:

- Scale
  - Scale matters for combustion systems because of fundamental physics or because of economics of optimization. In order to achieve broader adoption of CHP in markets with significant remaining

technical potential (i.e., ~1–5 MW size range), the challenge of maintaining high system efficiency is significant.

- Combustion systems are typically commercially available in a limited set of size increments, with significant development costs for changing sizes.

- Individual cycle development
  - Biggest issues are economical materials that can operate at higher temperatures and resist corrosion. The challenge will involve identifying and developing materials that can withstand these conditions while maintaining competitive system costs.
  - Some devices would need development to pair well with others (e.g., current pressurization levels for molten carbonate fuel cells (MCFC) may be less viable than for solid oxide fuel cells for operation with a gas turbine).
- Combined-cycle integration
  - Balance of power distribution between cycles and optimization of internal mass and heat flows can be challenging.
  - Individual system efficiencies are not superimposable for combined system efficiency.
  - Some cycles may not be at highest individual efficiency when integrated.

Market Risks

While CHP systems sized according to the thermal demand of a facility are cost-effective and have been broadly deployed in the >5 MW size ranges, there are a host of policy and regulatory barriers that limit further deployment in the marketplace.[48] These barriers limit the ability for CHP to succeed in energy services markets. Fully integrating CHP into the modern local grid or facility cluster will allow manufacturers and other facility operators to enjoy the cost savings from reduced on-site fuel consumption and will also provide the potential to realize additional revenue streams. In a truly integrated and smart grid, a facility may be able to participate in ancillary service markets, enhanced demand-response programs, and other alternate revenue-generating schemes. Ultimately, grid integration of next-generation CHP-based distributed generation will result in stronger, more profitable, and more resilient operations for both the utility and end-use sectors.

Furthermore, the ability to size a CHP system to the needs of the local grid system (versus sizing to satisfy the thermal demand of a particular facility) would allow a broader array of facility types to install CHP. This is particularly applicable to some of the larger types of CHP facilities in the manufacturing sector, where very large thermal demands result in systems that produce more electricity than can be used on site. Interconnection rules and reasonable buy-back rates (which were established in 1978 under the Public Utility Regulatory Policies Act – PURPA) can alleviate this situation but only in a limited way that is dependent on local utility and regulatory policy. Additional discussion of barriers and opportunities is found in the subsequent section on "Market Risks."

Case Study

Case Study: CHP in Food Processing Industry—Frito-Lay Demonstration[49]

Frito-Lay North America, Inc., installed a CHP system at its food processing plant in Killingly, Connecticut, in April 2009. The installation was supported by funds from DOE in partnership with the Energy Solutions Center as well as incentives from the State of Connecticut. In order to reduce the energy costs and environmental impact of the Killingly plant while easing congestion on the constrained northeast power grid, Frito-Lay installed the following:

- A 4.6 MW Solar Turbines Centaur® 50 natural gas combustion turbine
- A Rentech heat recovery steam generator equipped with supplemental duct firing
- Combustion air inlet chilling to increase power generation in warm weather
- A selective catalytic emission reduction system

The CHP system, designed to be electric-load following, has the capacity to meet 100% of the plant's electrical power needs and provide a majority of the facility's annual steam needs.

Converting Waste Heat into Steam

Before the installation of the CHP system, the Killingly plant steam requirements were provided by three dual-fired (natural gas and residual oil) boilers. The three boilers were over 30 years old, and if one boiler needed service, the remaining two boilers could no longer meet the plant's peak steam load. The CHP system can now provide about 80% of the steam load for the Killingly facility (Table 6.D.6).

Figure 6.D.6 Estimated benefits from the CHP at the Killingly plant.

Estimated Benefits of CHP System	
Efficiency	70% overall CHP efficiency
Emissions Reduction	93% reduction in overall NOx emissions 89% reduction in site NOx emissions 99% reduction in SO2 emissions 12% reduction in CO2 emissions
Cost Savings	$1 million annually
Reliability	Provides over 90% of the electrical demand and 80% of the steam load for the facility, with an operating availability of 96.4%

Running in Island Mode

The Killingly plant—which operates 24/7—has the capability to run in island mode by using the CHP system if the power grid goes down. In 2009 and 2010, flying squirrels shorted out local service, leaving the entire area without power for hours. However, Frito-Lay's CHP system continued operating—for six hours in the first incident and eight hours in the second—allowing the plant to maintain production. This added power reliability avoided product losses and prevented the need for food safety reinspections, resulting in significant cost savings.

The ability to run in island mode also means that the plant is less susceptible to outages caused by severe storms. The Killingly plant was intentionally powered down one day prior to Tropical Storm Irene in 2011. Three days after the storm, more than 60% of Killingly remained without power, but with the CHP system, Frito-Lay was quickly able to resume production less than 24 hours after the storm had passed.[50] The Killingly plant also remained operational during a late October 2011 snowstorm that had knocked out power to nearby areas. The plant could also have continued operat-ing during Superstorm Sandy in October 2012 and a blizzard in February 2013 if the roads had not been shut down by the governor.

Appendix: High-efficiency distributed electrical generation notes and calculations

Discussion of Table 6.D.3 and Figure 6.D.7

In this CHP Technology Assessment, Table 6.D.3 and Figure 6.D.7 describe a number of different single and combined cycles. The following discussion describes some of the analysis and some of the assumptions made as well as any references. The letter refers to the last column of Table 6.D.1, labeled "Notes."

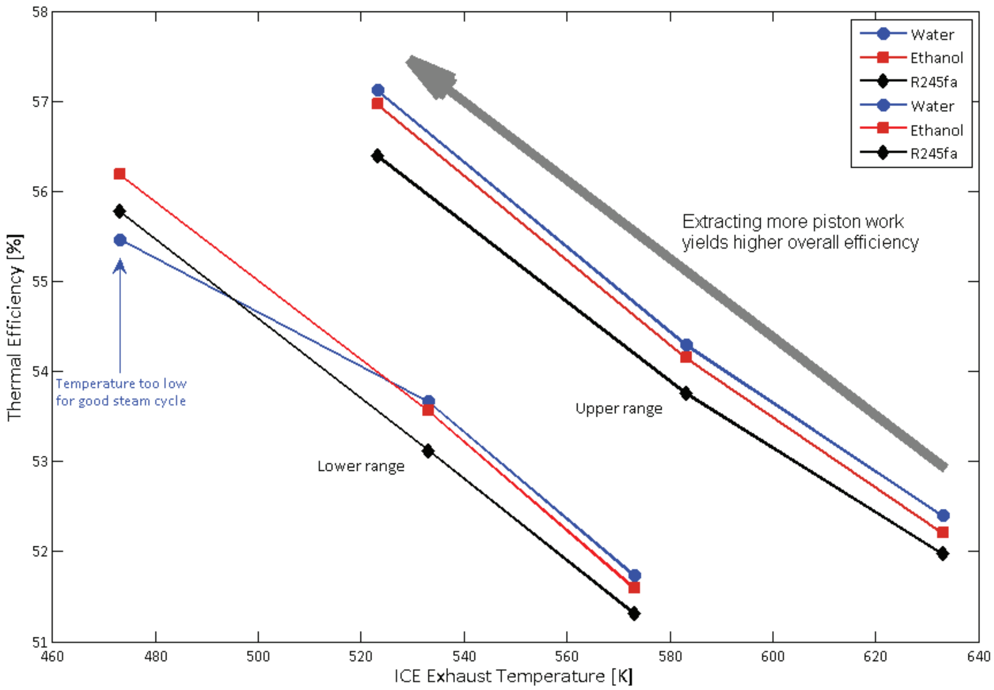
Gas thermodynamic and transport properties were derived from the NIST Reference Fluid Thermodynamic and Transport Properties Database, commonly referred to as REFPROP.[51] These properties were used as inputs into our analysis. In all cases, standard ambient conditions were used as the reference ambient state.

A: Gas turbines (GTs) on the lower end of power output (e.g., <5 MW) are generally less efficient than large-capacity turbines. Large-scale GTs can have 10 percentage points higher efficiency than smaller-scale GT systems; much effort and expense are spent on optimizing the heat balance with techniques such as reheat and recuperation. Several proposals include steam injection (e.g., the humid air turbine), which can increase system efficiency by 5–10 percentage points. However, these can consume large volumes of high-purity water with additional capital and operating costs. The wide range of performance for single-cycle GTs showed results from different operating strategies and design configurations. When coupling a system with a Rankine cycle (RC), it generally is assumed that a hotter input gas stream (i.e., exhaust-gas temperature) yields higher efficiencies.

B: Reciprocating internal combustion engines (RICEs) also present a challenge. Figure 6.D.8 shows the effects of exhaust temperature on overall system thermal efficiencies for a RICE coupled with an RC using various working fluids. The exhaust temperatures vary from hotter (with a 50% brake thermal efficiency baseline engine) to colder (with a 55% brake thermal efficiency stretch engine). Two scenarios are presented: an upper range with higher-efficiency internal RC components and higher exhaust temperatures and a lower range with lower-efficiency RC components and lower exhaust temperatures.

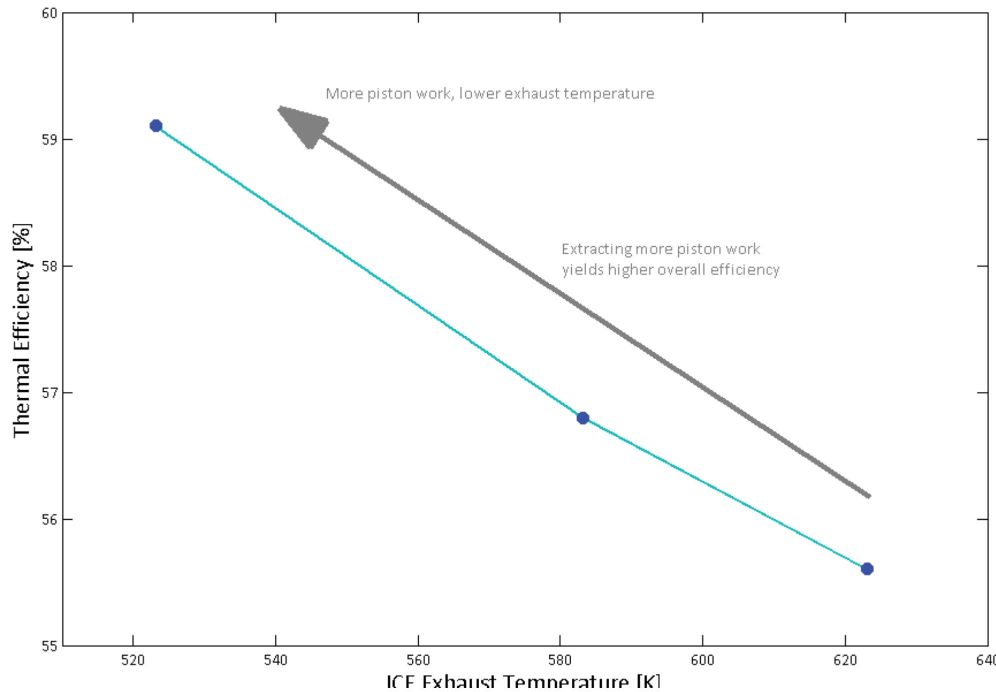
For this combination, efficiency optimization should focus on extracting more piston work, even if doing so reduces the exhaust-gas temperatures and opportunities for waste heat recovery. In some cases, the temperatures may be so low that RCs cannot operate effectively, as seen in Figure 6.D.8 in the steam cycle performance at T_{exh} = 473 K. Cycles not using water might be more advantageous at these scales.

Figure 6.D.8 Overall system thermal efficiencies (lower heating value basis) for reciprocating internal combustion engine (ICE) with Rankine cycles with various working fluids. Extracting more piston work increases overall efficiency. [Oak Ridge National Laboratory analysis]



C: Stirling-cycle engines have been manufactured that operate in the power range (50–60 kW) suitable for waste-heat recovery (WHR). The lower exhaust temperatures from the RICE limit the efficiency of the Stirling engine, and the overall system efficiency improves with more piston work being extracted. This relationship is shown in Figure 6.D.9, where the higher-efficiency RICE leads to lower-temperature exhaust but overall higher combined system efficiency.

Figure 6.D.9 Thermal efficiency (lower heating value basis) as a function of exhaust temperature of a combined RICE and Stirling-cycle engine system for electrical generation. [Oak Ridge National Laboratory analysis]



D: One scheme using a solid oxide fuel cell (SOFC) with a Stirling engine has been proposed[52] for a domestic application in the 10 kW range; this system uses a catalytic burner instead of a GT or RICE to oxidize unreacted fuel in the SOFC exit and can operate at atmospheric pressures.

E: The principle behind using an SOFC as a topping cycle is that while it is an efficient electrochemical power generator, its fuel utilization factor can be less than unity, meaning that some fuel (typically, 15%–35%) passes through to the exhaust unless it is recycled. Adding a combustor and work extractor to the exhaust stream uses some of the chemical exergy. Because of their general robustness, GTs typically have been chosen as the bottoming cycle, and one of the limiting factors for GT systems is the turbine inlet temperature (T_{inlet}). Typically, in combined-cycle operation, the overall system efficiency increases with T_{inlet} in a manner shown in Figure 6.D.10. The sensitivity of efficiency with T_{inlet} (i.e., how much efficiency gain comes with a certain incremental change) is a function of system configuration, such as operating pressures and pressure ratio, use of recuperators or regenerators, and how fuel pressurization and reforming is accounted for in the energy balance.

Figure 6.D.10 Overall system thermal efficiency (lower heating value basis) for an SOFC-GT hybrid system as a function of turbine inlet temperature. [Oak Ridge National Laboratory analysis]

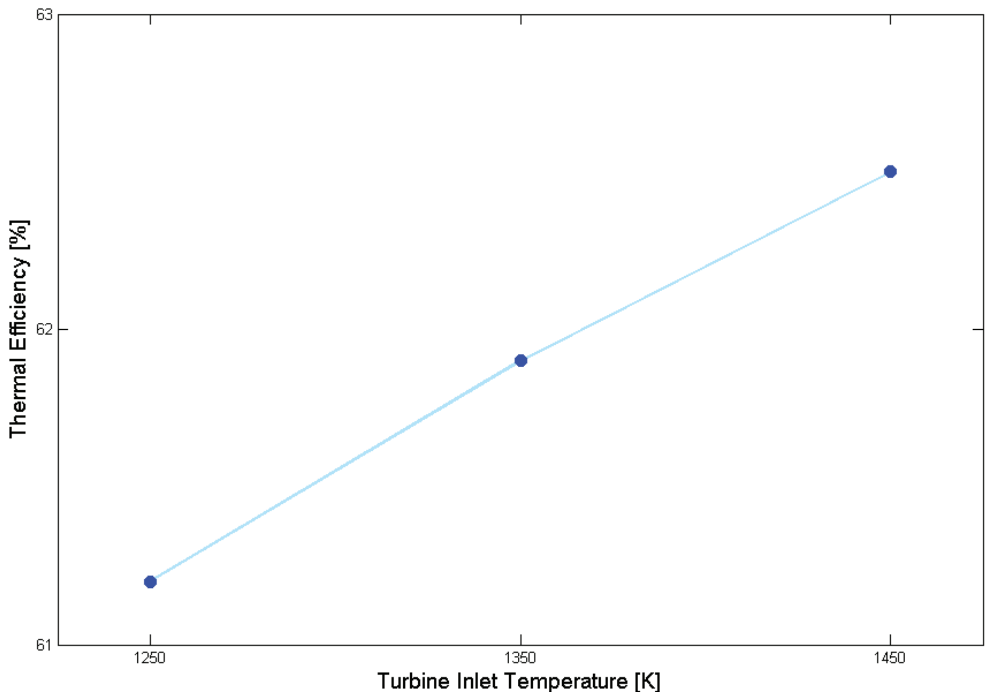


Table 6.D.7 highlights some SOFC-GT combined-cycle configurations and reported efficiencies; the literature base is much wider. Most of these reported values are numerical model-based and not from experimental studies, so while the range generally can be expected to hold, some unrealistic assumptions or design data should be expected; also, some of these values are reported without plant generation capacity.

Table 6.D.7 Efficiencies (lower heating value [LHV] basis) of some SOFC-GT combined cycle approaches to electrical generation.

Configuration	Number of generating cycles	Efficiency, % (LHV)	Source
i. Pressurized SOFC with intercooled reheat GT (baseline for Westinghouse SureCell)	2	66	Rao & Samuelsen[53]
ii. Same as (i), along with humid air turbine (HAT) cycle	3	69	Rao & Samuelsen[53]
iii. Same as (i), with dual SOFC and single HAT	3	76	Rao & Samuelsen[53]
iv. Atmospheric SOFC-GT (and some steam turbine)	3	64–71	Massardo *et al.*[54]
v. Pressurized SOFC-GT (and some steam turbine)	3	74–76	Massardo *et al.*[54]
vi. SOFC-GT with reheat and intercooling	2	65	Palsson *et al.*[55]
vii. SOFC and recuperative GT	2	60.6	Haseli *et al.*[56]
viii. SOFC, GT, recuperator, heat recovery steam generator	3	61.9	Chan *et al.*[57]

F: The principal example of an SOFC+RICE system was a planned system by General Electric (GE), using its Jenbacher reciprocating engine. GE has targeted a system efficiency of 65% (lower heating value [LHV]) for cogeneration and 95% for CHP. Generally, RICEs are easier to scale than GT systems because fewer GT systems are currently on the market, but RICEs can be more sensitive to fueling stoichiometries and must be operated with care.

G: One scheme using an SOFC with an RC cycle has been proposed[58]; this system uses a catalytic burner instead of a GT or RICE to oxidize unreacted fuel in the SOFC exit and can operate at atmospheric pressures.

H: This is the estimation of what is reasonable when the SOFC+RICE system described in (F) is used along with the limits of Rankine-cycle efficiency given expected exhaust properties from the RICE.

I: Triple-cycle systems, typically with SOFC to GT to RC, project efficiencies from 65% up to 78% (LHV) or higher. Most proposed triple-cycle systems include a GT to convert unused fuel from the SOFC, with fuel addition to the GT for proper combustion, and a form of WHR via an RC. The wide range in estimated efficiencies depends on internal thermal optimization of energy flows.

Modeling Methodology

Model complexity is typically described in terms of *dimensionality*, which is a generic description of spatial description and complexity akin to degrees of freedom. For a given flow device such as a turbine or combustor, an imaginary boundary is defined, encompassing the control volume. When all processes within the control volume are lumped and averaged without regard for spatial effects, a zero-dimensional treatment is performed; in the following discussion, this is referred to as simple modeling. When properties are allowed to vary along a single spatial dimension or zone (for instance, from the inlet to the outlet along the flow path), then a one-dimensional treatment is performed. These are examples of low-dimensional modeling. High-dimensional modeling is seen with most computational fluid dynamics simulations, in which a 2-D or 3-D spatial domain is divided into thousands to millions of computational cells and the governing physical modeling equations are solved within each cell.

Generally, the higher the model complexity, the greater the potential for accuracy (with much tuning) but also the higher the cost in modeling effort, sub-model tuning, development time, data validation, and simulation time. With sufficient tuning and validation with carefully crafted experimental data, fairly accurate spatially and temporally resolved predictions of the technology under varying conditions are possible. For scoping analyses such as the present work, low-dimensional treatments are the best means to traverse a range of technologies and configurations. Doing so is a lower-fidelity means than high-dimensional treatments because effects are spatially lumped, time is treated as steady state, and many real processes are not treated in the model. In the present work, simple modeling was used for some systems to gauge a range of performance for given systems to verify that the estimated efficiencies were within the range reported in the literature. The following describes the generic approach employed in the study, except where noted otherwise.

Fluid state properties (e.g., pressure, temperature, enthalpy, entropy, and ratio of specific heats) were obtained by using REFPROP 9.1, a standard software package developed by the National Institute of Standards and Technology.[51] REFPROP has interfaces for calling inside of either spreadsheet programs such as Excel or programming environments such as Matlab. Chemistry was simplified as follows: all fuel was assumed to be natural gas, approximated as methane, to compare with standard literature practice and for fuel uniformity. Combustion was treated as global conversion of fuel and air to carbon dioxide, water vapor with no condensed products, excess oxygen, and nitrogen; because of the state of water vapor, the LHV of the fuel was used for combustion heat (efficiencies were converted to higher heating value [HHV] for reporting as described in the summary). As was typical in the literature, energy required to pressurize the gaseous fuel was neglected (because there are usually different starting pressures and temperatures in practice), and details of any reforming of methane to hydrogen and carbon monoxide for fuel-cell usage were neglected.

Power cycles were constructed by integrating simple models of components at steady state. Where applicable, working-fluid state changes were calculated by using prescribed isentropic efficiencies (for pumps, compressors, and turbines) or effectiveness (for heat exchangers). Flow losses caused by wall friction and geometric effects were neglected, but some flow components had prescribed multiplicative pressure drops defined. Some components were treated as adiabatic (well insulated), with no heat transfer across the boundaries.

The following describes the example formulation of a simple gas-turbine cycle to show the methodology used in GT and RC analysis.

Air starts at the ambient state of pressure P_1 and temperature T_1. For energy-balance considerations, potential-energy and other insignificant effects are neglected, and for air flowing through the control volume, its energy content is described solely by the inlet and outlet specific enthalpy, designated *h*. The incoming air has a mass flow rate $\dot{m}_1$, and by conservation of mass, the outlet mass flow rate is $\dot{m}_2 = \dot{m}_1$. The air enters the compressor, which has an isentropic efficiency η_C. By definition, the state change of air from inlet state 1 to outlet state 2 is defined as follows:

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1}$$

where h_1 is the inlet-specific enthalpy, h_2 is the outlet-specific enthalpy, and h_{2s} is the outlet-specific enthalpy under an isentropic compression process (the ideality). The compressor component is solved as follows—outlet pressure is defined by a parameter called the pressure ratio r_p, which is a key design parameter of the overall system:

$$P_2 = r_p \cdot P_1$$

The inlet ratio of specific heats k_1 and specific enthalpy h_1 for air are obtained using REFPROP. The expected temperature after compression in an isentropic process is defined as follows:

$$T_{2s} = T_1 \cdot r_p^{(k_1-1)/k_1}$$

With P_2 and T_{2s} defined and yielding h_{2s}, and using the definition of isentropic efficiency (above), the specific enthalpy of state 2 is solved as follows:

$$h_2 = \frac{1}{\eta_C}\left[h_{2s} + h_1(\eta_C - 1)\right]$$

and with h_2 and P_2 specified, the temperature T_2 is obtained from REFPROP. The required compressor power is defined as follows:

$$-\dot{W}_C = \dot{m}_1(h_2 - h_1)$$

The fuel stream enters at P_2 and T_2 and combines with the air at the combustor for a total mass flow rate as follows:

$$\dot{m}_3 = \dot{m}_2 + \dot{m}_F$$

The fuel mass flow rate is a global system parameter that is varied until the overall system electrical output is the target power of 1 MW_e. The air flow rate is specified via another control parameter (λ), which is a measure of excess air and is defined as follows:

$$\lambda = \frac{(A/F)_{actual}}{(A/F)_{stoichiometric}}$$

where A/F specifies the air-to-fuel ratio. The stoichiometric A/F for methane, on a molar basis, is obtained from the following global chemical reaction for perfect oxidation of fuel:

$$CH_4 + 2(O_2 + 3.76\ N_2) \rightharpoonup CO_2 + 2H_2O + 7.52\ N_2$$

For methane, the mass-based $(A/F)_{stoichiometric}$ is approximately 17.2. GTs run lean, with $\lambda > 1$, to reduce the combustor exhaust gas temperature entering the turbine, where there is a materials constraint. Knowing $\dot{m}_F$ and λ, $\dot{m}_1$ is defined. By conservation of mass on the combustor, the outlet mass flow rate is $\dot{m}_4 = \dot{m}_3$, and for notational convenience, $P_3 = P_2$ and $T_3 = T_2$.

From an energy balance on the combustor,

$$\dot{m}_4(h_4 - h_3) = \dot{m}_F \cdot LHV$$

where the composition of the outlet state 4 is combustion products, including excess air components with unreacted O_2, and LHV signifies the LHV of the fuel, denoting gaseous state of the water combustion product (ambient air humidity is not examined because effects are insignificant at this level of analysis). The pressure at the combustor outlet is

$$P_4 = \Delta P_B \cdot P_3$$

where ΔP_B is a multiplicative pressure loss across the burner (typically 0.95–0.98). With P_4 and h_4 defined, the turbine inlet temperature T_4 is defined. This is typically limited by materials and in most GTs ranges in 1250–1450 K (with the higher end usually applicable to higher-capacity turbines). Given a chosen $\dot{m}_F$, the excess-air factor λ is adjusted to meet the materials limits at T_4; raising λ reduces overall system efficiency because more power is required to compress the incoming air stream, the power of which is supplied by the GT.

In our analysis, a two-shaft GT is examined, where the first-stage "GT" has a shaft connected to the compressor and only extracts enough power to compress the incoming air stream (from state 1 to 2), and the second-stage power turbine (PT) is connected via a shaft to the generator, which produces electrical power, with a limit being the isentropic turbine efficiency. There are operational and cost trade-offs between one- and two-shaft systems (both of which are generically termed as GTs), but at this level of analysis, there is not much difference except that each turbine is assigned a separate isentropic efficiency with slightly different overall performance.

By conservation of mass, the GT exit mass flow rate is $\dot{m}_5 = \dot{m}_4$, and by definition the required GT power is $\dot{W}_{GT} = \dot{W}_C$ (note the usual sign convention of work output from the component being positive and work input being negative). The gas-specific enthalpy at the GT exit is

$$h_5 = h_4 - \dot{W}_{GT}/\dot{m}_5$$

Given the definition of isentropic efficiency for a turbine,

$$\eta_T = \frac{h_{out} - h_{in}}{h_{out,s} - h_{in}}$$

The GT exit-specific enthalpy for isentropic expansion is as follows:

$$h_{5s} = \frac{1}{\eta_{GT}}[h_5 - h_4\,(1 - \eta_T)]$$

which defines T_{5s}. The outlet pressure from the GT is then as follows:

$$P_5 = P_4 \cdot \left(\frac{T_{5s}}{T_4}\right)^{k_4/(k_4-1)}$$

For the PT, the exit pressure should be close to, but above, ambient as follows:

$$P_6 = \Delta P_{PT} \cdot P_1$$

where ΔP_{PT} is a multiplicative factor (>1) constraining the outlet pressure. By conservation of mass, $\dot{m}_6 = \dot{m}_5$. With solution of k_5, the temperature at the PT exit for isentropic expansion is

$$T_{6s} = T_5 \cdot \left(\frac{P_6}{P_5}\right)^{(k_5-1)/k_5}$$

which fixes the specific enthalpy h_{6s}. On the basis of the definition of isentropic turbine efficiency, the PT exit specific enthalpy is

$$h_6 = h_5 \cdot (1 - \eta_{PT}) + h_{6s} \cdot \eta_{PT}$$

The mechanical power output of the PT is

$$\dot{W}_{PT} = \dot{m}_5(h_5 - h_6)$$

and the electrical power output is

$$\dot{W}_e = \eta_{gen} \cdot \dot{W}_{PT}$$

The overall system efficiency is calculated as follows:

$$\eta_{total} = \frac{\dot{W}_e}{\dot{Q}_{combustion}}$$

The thermal efficiency of the system can be increased with internal heat recovery. For instance, a standard way is to heat the incoming air before the combustor with the exhaust gas downstream of the PT by using a recuperator, whose impact can be quite pronounced for smaller turbines. In a general sense, heat-exchanger performance can be defined with the effectiveness, and this can fix the properties of cold-side and hot-side gas streams; heat exchangers also cause a pressure drop as the fluids pass through them.

The above analysis does not account for other types of internal losses, nor does it account for cost, manufacturability, size, geometric design, material properties, or other relevant design features. This is the type of analysis that was used in this study for analysis of GT and RCs, with the recognition that it represents an optimistic projection.

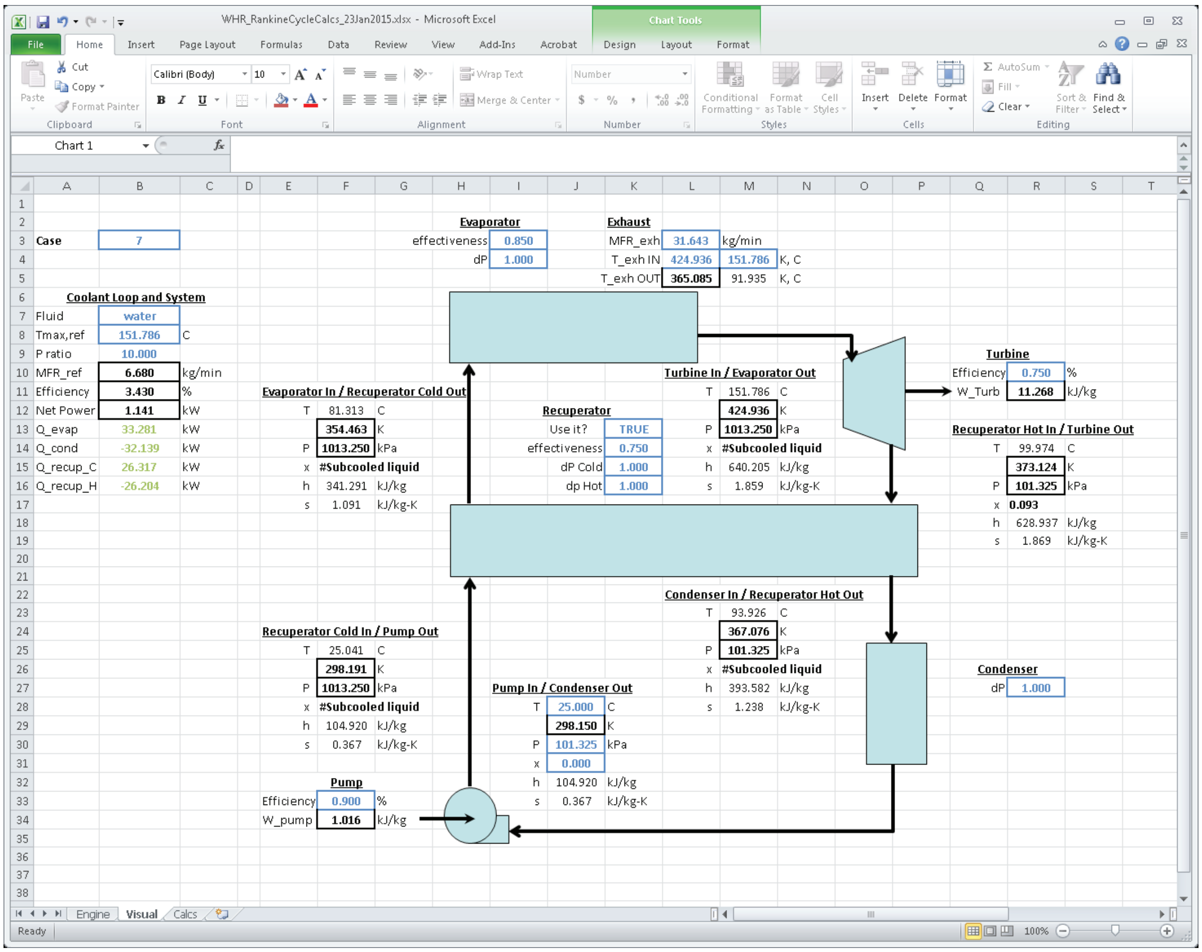
Specific considerations for the analysis of single and combined cycles are as follows:

- **RCs (bottoming):** For this analysis, RC calculations were performed by using a spreadsheet tool developed by Oak Ridge National Laboratory (ORNL) coupled with REFPROP for fluid property calculations. The tool is restricted to evaluating thermodynamic performance, with no consideration given to cost, size, design, or practicality of a real-world system. To evaluate maximum WHR potential, as much heat as possible is extracted from the waste stream, with no consideration of the size, cost, or practicality of the physical system required to do so.

  The Rankine system is modeled as a closed system, consisting of a pump, single-stage evaporator (separate preheater, boiler, and superheater stages are not modeled), generic expander (turbine, scroll expander, or other), condenser, and optional recuperator. Each component is simply modeled by using isentropic efficiency relations for the pump and expander and effectiveness calculations for the heat exchangers. With this approach, losses considered in the model are limited to isentropic efficiency of the pump and expander and the effectiveness and pressure drop of each heat exchanger. No information about component design, size, material, etc., is required for or produced by this model.

Required inputs include working fluid (any fluid or mixture of fluids in the REFPROP library), heat input (composition, flow rate, and temperature of the waste stream), temperature and pressure at the condenser exit, maximum expander inlet temperature (to protect the expander or, for organic cycles, the fluid), expander pressure ratio, and the efficiency, effectiveness, and/or pressure drop for each component. All calculations are automatic and results include required refrigerant flow rate and system power and efficiency. A screenshot of the user input tab of the spreadsheet tool is in Figure 6.D.11.

Figure 6.D.11 User input tab of the spreadsheet tool.



- **RICE:** The baseline efficiencies for RICE are based on a demonstrated brake thermal efficiency of 50% for ARES-class, 1 MW engines at the lower bound and a reasonable stretch goal of 55% at the upper bound. A generator efficiency of 94% was assumed, converting these shaft efficiencies to the fuel-to-electricity efficiency bounds in this report.
- **RICE + RC:** In this combination, the most efficient work extraction device is the RICE. Therefore, priority is given to extracting as much work as possible from the RICE primary cycle with the Rankine bottoming cycle recovering as much additional work as possible. Therefore, the optimized RICE

single-cycle configuration is used as the baseline for the primary cycle. Experimental data (protected under a non-disclosure agreement (NDA)) from an ARES-class, 1 MW engine, including exhaust flow rate and temperature, was used to seed the RC model to determine the additional potential benefit of the secondary cycle. As the secondary cycle, the RC was designed to provide maximum work output, not maximum efficiency. Priority was placed on recovery and extraction of as much additional work as possible, with minimal consideration of cost, size, or practicality of the RC. A spreadsheet tool developed by ORNL was used to evaluate the RC performance. Upper and lower bounds for key component efficiencies determined from experience and engineering judgment were included in the analysis. A generator efficiency of 94% was assumed to convert shaft efficiencies of the RICE and RC turbine to fuel-to-electricity efficiency.

- **RICE + Stirling:** In this combination, the most efficient work extraction device is the RICE. Therefore, priority is given to extracting as much work as possible from the RICE primary cycle with the Stirling bottoming cycle recovering as much additional work as possible. Therefore, the optimized RICE single-cycle configuration is used as the baseline for the primary cycle. Experimental data (protected under an NDA) from an ARES-class, 1 MW engine, including exhaust flow rate and temperature, was used to seed the Stirling cycle model to determine the additional potential benefit of the secondary cycle. An empirically based Stirling-cycle efficiency was used to estimate additional work output based on the quality of the RICE exhaust in the range of 50%–55% brake thermal efficiency.
- **SOFC:** For a zero-dimensional treatment of the SOFC, an approach similar to Haseli et al. was employed.[56] The resulting relation was insensitive to operating pressure, which in SOFCs tends to increase efficiency, and the fuel reforming details were ignored. The fuel-utilization factor in the SOFC varied from 65%–85%, with sufficient fuel in the exhaust to combust in the GT system, with some provision for makeup fuel addition. The air rate was set at $\lambda=2$ nominally.
- **SOFC + RICE:** This value came from GE promotional material found online[59] for a proposed commercial system under development with a projected electrical cogeneration efficiency of 60%–65%.
- **SOFC + RICE + RC:** Using expected qualities of exhaust from the RICE bottoming cycle, the above-described RC model was used to estimate additional power output from the exhaust stream.

Endnotes

1 U.S. Department of Energy (DOE), “CHP Technical Assistance Partnerships.” Available at: http://energy.gov/eere/amo/chp-technical-assistance-partnerships-chp-taps.

2 U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA). “Combined Heat and Power: A Clean Energy Solution.” DOE/EE-0779. August 2012. Available at: http://www.energy.gov/sites/prod/files/2013/11/f4/chp_clean_energy_solution.pdf.

3 “Combined Heat and Power: Pathway to Lower Energy Costs, Reduced Emissions, Secure and Resilient Energy Supply,” Fact Sheet, Environmental and Energy Study Institute. May 2013. Available at: http://www.eesi.org/files/FactSheet_CHP_052113.pdf.

4 The White House. “Executive Order—Accelerating Investment in Industrial Energy Efficiency.” August 30, 2012. Available at: https://www.whitehouse.gov/the-press-office/2012/08/30/executive-order-accelerating-investment-industrial-energy-efficiency.

5 It should be noted that CHP systems that use fossil fuels will often be too widely distributed and too small in scale for cost-effective use of carbon capture and storage (CCS) systems to capture their GHG emissions, thus locking in a reduced but still significant source of carbon emissions as compared to large central power plants with CCS or nuclear or renewable plants.

6 A separate boiler would require $0.022 per kWh worth of fuel to provide the same amount of thermal energy as provided by the CHP system in this example. This is the “thermal credit.” Crediting the cost of the thermal energy allows you to compare the net cost of electricity production from CHP to the cost of purchased electricity.

7 EIA Electric Power Monthly. Available at Table 5.3 in: http://www.eia.gov/electricity/monthly/pdf/epm.pdf.

[8] Sources: Equipment performance on the basis of National Renewable Energy Laboratory, "Gas-Fired Distributed Energy Resource Technology Characterizations." NREL/TP-620-34783. November 2003.

Other general assumptions: 15-year project life, 8% cost of capital, 80% efficient displaced boiler.

Fuel price assumptions as follows:

	Industrial	Commercial
Retail Electricity Price ($/kWh)	$0.070	$0.103
Retail Natural Gas Price ($/MMBtu)	$5.48	$9.88

[9] U.S. Energy Information Administration (EIA). "Monthly Energy Review." Table 7.2b and Table 2.6. June 2015. Available at: http://www.eia.gov/totalenergy/data/monthly/archive/00351506.pdf. EIA "U.S. Electricity Flow." 2014. Available at: http://www.eia.gov/totalenergy/data/monthly/pdf/flow/electricity.pdf.

[10] U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA). "Combined Heat and Power: A Clean Energy Solution." DOE/EE-0779. August 2012. Available at: http://www.epa.gov/chp/documents/clean_energy_solution.pdf.

[11] Ibid.

[12] McKinsey & Co. Cited in: Shipley, A.; Hampson, A.; Hedman, B.; Garland, P.; Bautista, P. "Combined Heat and Power: Effective Energy Solutions for a Sustainable Future." Oak Ridge National Laboratory/DOE EERE. 2008. Available at: http://www1.eere.energy.gov/manufacturing/distributedenergy/pdfs/chp_report_12-08.pdf.

[13] Shipley, A.; Hampson, A.; Hedman, B. Garland, P; Bautista, P. "Combined Heat and Power: Effective Energy Solutions for a Sustainable Future." Oak Ridge National Laboratory/DOE EERE. 2008. Available at: http://www1.eere.energy.gov/manufacturing/distributedenergy/pdfs/chp_report_12-08.pdf.

[14] Hampson, A.; Bourgeois, T.; Dillingham, G.; Panzarella, I. "Combined Heat and Power: Enabling Resilient Energy Infrastructure for Critical Facilities." Oak Ridge National Laboratory, 2013.

[15] Ibid.

[16] DOE Combined Heat and Power Installation Database. Available at: https://doe.icfwebservices.com/chpdb/.

[17] The DOE Combined Heat and Power database contains information on all known CHP systems in operation in the United States today. It the best available comprehensive estimate of the CHP market, but still only an estimate owing to the constantly changing numbers (new additions, existing capacity either shut down or put on standby, or changes in operation [e.g., operating fewer hours per year]). These numbers may differ somewhat from the estimates in the U.S. Energy Information Agency's Manufacturing Energy Consumption Survey (MECS). MECS data does not include third party owned and operated CHP. The MECS estimates also only include CHP in the manufacturing sector and as such do not include CHP in the commercial/institutional, agricultural, or mining sectors.

[18] DOE Combined Heat and Power Installation Database. Available at: https://doe.icfwebservices.com/chpdb/.

[19] CHP systems are typically fueled by natural gas. For discussion, see "Catalog of CHP Technologies," U.S. Environmental Protection Agency Combined Heat and Power Partnership. March 2015. Available at: http://www.epa.gov/chp/documents/catalog_chptech_full.pdf.

[20] Source: DOE Combined Heat and Power Installation Database. Available at: https://doe.icfwebservices.com/chpdb/. Note that 2015 and 2016 are anticipated figures based on ICF International personal communications regarding planned additions; no data is available yet. Note that the ICF analysis did not cover all CHP opportunity in the United States, it focuses on systems <5 MW because of the large untapped technical potential in this size range. System characteristics and other opportunity analysis data are from "The Opportunity for CHP in the United States." ICF International. May 2013.

[21] Source: DOE Combined Heat and Power Installation Database. Available at: https://doe.icfwebservices.com/chpdb/.

[22] Source: ICF International internal estimates. 2014.

[23] Personal communication with Thornton, R., International District Energy Association, and the IEA CHP and DHC Collaborative—CHP/DHC Country Scorecard: United States. August 21, 2015. Available at: http://www.iea.org/publications/insights/insightpublications/US_CountryScorecard_FINAL.pdf.

[24] See, for example, EPA's Combined Heat and Power Partnership. Available at: http://www.epa.gov/chp/aboutus/partners.html.

[25] See the report by the Hurricane Sandy Rebuilding Task Force for approaches to improve grid resiliency, including CHP and microgrids. Available at: http://www.eenews.net/assets/2013/08/19/document_pm_03.pdf.

[26] One advantage of microgrids are that they can decouple from the grid and run in island mode during an interruption (see the Case Study on Island Mode in this Technology Assessment), and then be able to autonomously resynchronize and reconnect with the grid when the disruption is over. For a detailed analysis of challenges and opportunities regarding microgrids, see "The Advanced Microgrid-Integration and Interoperability," Sandia National Lab report 2014-1535, March 2014. Which can be accessed here: http://energy.gov/sites/prod/files/2014/12/f19/AdvancedMicrogrid_Integration-Interoperability_March2014.pdf

[27] Efficiency targets of 75%+, on the basis of higher heating value, are sought for traditional CHP systems that are sized to a facility's thermal demand, with $\frac{P}{H}$ ratios up to ~0.75.

[28] Efficiency targets of 70%+, on the basis of higher heating value, are sought for potential CHP systems that can be sized to meet a facility's electrical demand, with $\frac{P}{H}$ ratios up to ~1.5.

[29] More information about the CHP Technical Assistance Partnerships (TAPs) can be found here: http://www.energy.gov/eere/amo/chp-technical-assistance-partnerships-chp-taps

[30] The First Law of Thermodynamics is an energy accounting, and efficiency is defined as the ratio of useful output to resource input. The Second Law of Thermodynamics defines the maximum useful total output of a system in its environment. That is, all real systems have losses, and Second Law analysis helps to define the upper bounds of efficiency.

[31] Internal DOE analysis to estimate impact of expanded CHP market applications.

[32] This analysis focuses on systems <5 MW because of the large untapped technical potential in this size range. System characteristics and other opportunity analysis data are from "The Opportunity for CHP in the United States." ICF International. May 2013.

[33] Frangopoulos, C. A. "A Method to Determine the Power to Heat Ratio: The Cogenerated Electricity and the Primary Energy Savings of Cogeneration Systems After the European Directive." *Energy* (45:1), 2012; pp.52-61.

[34] In order to achieve a $\frac{P}{H}$ ratio of 1.5 while maintaining the same overall system efficiencies, there would need to be electrical efficiencies of 47.8% and 46.6% for small and large systems, respectively. These efficiency levels are technically achievable with single cycle reciprocating gas engines but fall near the high end of reasonably achievable efficiencies (*High Efficiency Distributed Electrical Generation*). More research will be needed in the areas of low-temperature thermal energy recovery in order to enable high electrical efficiencies in a CHP application.

[35] The sectors in this analysis include those that typically have higher electrical loads relative to thermal loads. Markets such as pulp and paper, chemicals, refineries, hospitals, and universities were not included because they are already well served by CHP technologies.

[36] We adopt conservative literature values for inverter and electrical generator efficiencies. Listed efficiencies for commercial systems are approximately 97-98% for inverters in the 1-5 MW range (e.g., see: Satcon PowerGate Plus PV Inverter (http://www.satcon.com/uploads/products/en/1MW-PG-US-UL.pdf); ABB Central Solar Inverter (https://library.e.abb.com/public/e2508291cc16d124c1257d490049abe5/17237_PVS800_central%20inverters%20flyer%20EN_3AUA0000057380_RevL_lowres.pdf); and GE Brilliance Solar Inverter

(http://site.ge-energy.com/prod_serv/products/solar/en/downloads/GEA18380_1MW_PV_Inverter_r4.pdf)). For generators, efficiencies can run as high as 98-99% (e.g., see: GE generators (https://powergen.gepower.com/content/dam/gepower-pgdp/global/en_US/documents/product/generators/Fact%20Sheet/generator-fact-sheet-2015.pdf); and Siemens generators (http://www.energy.siemens.com/hq/en/fossil-power-generation/generators/)). These efficiency differences could affect the overall FTEE estimates by 1-2%, depending on the system configuration.

[37] Elson, A.; Tidball, R.; Hampson, A. "Waste Heat to Power Market Assessment." ORNL/TM-2014/620. March 2015. Available at: http://info.ornl.gov/sites/publications/Files/Pub52953.pdf.

This report analyzes the technical and economic potential for industrial waste heat to power (WHP) in the United States. The report includes information on WHP technologies, industrial market sectors with significant WHP potential, existing WHP installations, market drivers, and current policies impacting WHP. The primary focus of the report is on waste heat stream temperatures above 450°F, although lower temperature waste heat streams are also considered. The technical potential for WHP above 450°F was determined to be approximately 8.8 GW. On the basis of this technical potential, the economic potential showed an expected market penetration of 2.9 GW of WHP.

[38] Wang, D., "Transport Membrane Condenser for Water and Energy Recovery from Power Plant Flue Gas." Final Technical Report, DOE Award Number DE-NT0005350. Report issued June, 2012. Available at: https://www.netl.doe.gov/File%20Library/Research/Coal/ewr/water/5350-FinalTechReport.pdf

[39] Capstone Turbine Corporation, "Combined Heat and Power Systems Technology Development and Demonstration 370 kW High Efficiency Microturbine." Final Technical Report, DOE Project ID # DE-EE0004258. Report issued October 14, 2015. Available at: http://www.osti.gov/scitech/biblio/1224801

[40] A fact sheet entitled "Flexible CHP System with Low NOX, CO and VOC Emissions" describing the project to develop a flexible CHP system which combines an ultra-low NOX burner, microturbine, and heat recovery boiler can be accessed here: http://www.energy.gov/eere/amo/flexible-chp-system-low-nox-co-and-voc-emissions

[41] Plahn, P., Keele, K., and Pendray, J., "330 kWe Packaged CHP System with Reduced Emissions." Final Technical Report, DOE Award Number DE-EE0003392. Report issued March 31, 2015. Available at: http://www.osti.gov/scitech/biblio/1223435

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[43] Seaman, J., "Recovery Act: ArcelorMittal USA Blast Furnace Gas Flare Capture." Final Technical Report, DOE Award Number DE-EE0002729. Report issued January 14, 2013. Available at: http://www.osti.gov/scitech/biblio/1082429

[44] A case study entitled "Tapping Landfill Gas to Provide Significant Energy Savings and Greenhouse Gas Reductions" describing two Recovery Act funded projects can be accessed here: http://www1.eere.energy.gov/manufacturing/rd/pdfs/chp_landfillgas_casestudy.pdf

[45] A case study entitled "Combined Heat and Power System Achieves Millions in Cost Savings at Large University" describes Recovery Act funded projects at Texas A&M that includes a new CHP system install plus improvements to the campus-wide district energy system can be accessed here: https://utilities.tamu.edu/wp-content/uploads/2014/05/DOE-Recovery-Act-Case-Study.pdf

[46] A project profile entitled "Texas Medical Center and TECO 48-MW CHP System" describing a project that has demonstrated energy cost savings of $6-12 million per year can be accessed here: http://www.southwestchptap.org/data/sites/1/documents/profiles/Texas_Medical_Center-Project_Profile.pdf

[47] A fact sheet entitled "Combined Heat and Power System Increases Reliability and Reduces Emissions" describing a project that demonstrates high potential for CHP in food processing industry can be accessed here: http://www.energy.gov/sites/prod/files/2015/08/f26/PepsiCo%20Frito-Lay%20CHP%20Case%20Study_07.02.15.pdf

[48] For an overview of these barriers, see "Barriers to Industrial Energy Efficiency." Section V. U.S. Department of Energy Report to Congress. June 2015. Available at: http://www.energy.gov/sites/prod/files/2015/06/f23/EXEC-2014-005846_6%20Report_signed_v2.pdf.

[49] For more information on the case study, see: U.S. Department of Energy (DOE), "Combined Heat and Power Case Study: Project Demonstrates High Potential for CHP in Food Processing Industry." Available at: http://www.energy.gov/sites/prod/files/2015/08/f26/PepsiCo%20Frito-Lay%20CHP%20Case%20Study_07.02.15.pdf

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[58] Rokni, M. "Thermodynamic Analysis of an Integrated Solid Oxide Fuel Cell Cycle with a Rankine Cycle." *Energy Conversion and Management* (51:12), 2010; pp. 2724-2732.

[59] See "GE Fuel Cells—The Power of Tomorrow."2015. ; p. 18. Available at: https://www.ge.com/sites/default/files/GE_FuelCells.pdf.

Acronyms

AC	Alternating Current
ARES	Advanced Reciprocating Engine System
CHP	Combined Heat and Power
CI	Critical Infrastructure
COE	Cost of Electricity
DC	Direct Current
IDEA	International District Energy Association
FC	Fuel Cell
FTEE	Fuel-to-Electricity Efficiency
GT	Gas Turbine
HAT	Humid Air Turbine
HHV	Higher Heating Value
ICE	Internal Combustion Engine
LHV	Lower Heating Value
MCFC	Molten Carbonate Fuel Cell
ORC	Organic Rankine Cycle
P/H	Power-to-Heat ratio
PT	Power Turbine
RC	Rankine Cycle
REFPROP	(NIST) Reference Fluid Thermodynamic and Transport Properties Database
RICE	Reciprocating Internal Combustion Engine
SOFC	Solid Oxide Fuel Cell
ST	Steam Turbine
TAP	Technical Assistance Partnership
WHP	Waste Heat-to-Power
WHR	Waste Heat Recovery

Glossary

Bottoming Cycle	CHP configuration in which waste heat from an industrial or other source is used to drive an electricity generator, frequently a steam turbine or organic Rankine cycle. Bottoming cycle CHP is often referred to as waste heat to power (WHP).
Combined Cycle	A system of multiple heat engines that generate electricity from the same heat source. In a typical combined cycle power plant configuration, a gas turbine is used to generate electricity while a steam turbine generates additional energy from the waste heat. Combined cycle CHP operation is also possible, and might involve a single topping cycle working in tandem with one or more bottoming cycles.
District Energy	The production of steam, hot water, and chilled water at a centralized location for a network of buildings connected through underground piping.
Higher Heating Value (HHV)	Also known as gross calorific value, the higher heating value of a fuel is the amount of heat released by combusting a specified quantity of the fuel (initially at 25°C) and returning the combustion products to a temperature of 25°C. The latent heat of vaporization of water in the combustion products is taken into account.
Island Mode	Describes an electricity generator that can operate independently when disconnected from the electricity grid (for example, during a power outage).
Lower Heating Value (LHV)	Also known as net calorific value, the lower heating value of a fuel is the amount of heat released by combusting a specified quantity of the fuel (initially at 25°C) and returning the combustion products to a temperature of 150°C. The latent heat of vaporization of water in the combustion products is assumed to be not recovered.
Microgrid	A local energy grid that can disconnect from the traditional grid and operate autonomously.
Opportunity Fuel	A material from an agricultural or industrial process that might otherwise be wasted, but which is available at or near a CHP site and could be used as a fuel for the CHP system.
Power to Heat (P/H) Ratio	Ratio of electricity (or mechanical energy) to heat energy produced by a CHP system.
Topping Cycle	CHP configuration in which engines, turbines, microturbines, or fuel cells generate electricity and the waste heat is used for heating, cooling, and/or process use.