Combined Heat and Power Technology Assessment

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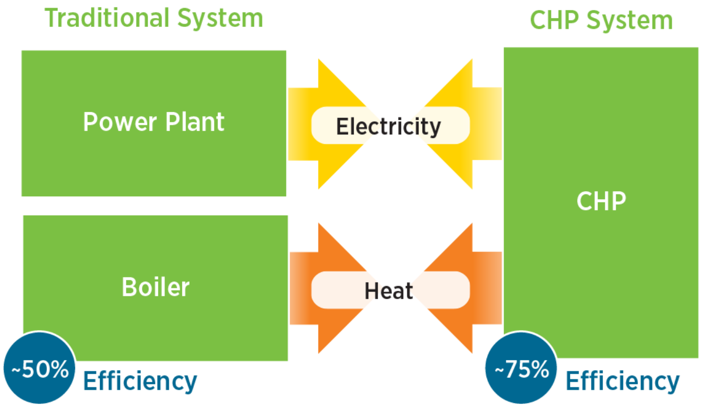
1. Introduction to the Technology/System

1.1 Combined Heat and Power overview

CHP is the concurrent production of electricity or mechanical power and useful thermal energy (heating and/or cooling) from a single source of energy. 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 combine the production of heat (for both heating and cooling) and electric power into one process, using much less fuel than when heat and power are produced separately. CHP can operate in one of two ways: either a “topping” cycle, where engines, turbines, or fuel cells generate electricity and the waste heat is used for either heating or cooling, or a “bottoming” cycle, where waste heat from an industrial or other source is used to drive an electricity generator, frequently a steam turbine.



The efficiency of CHP is most commonly calculated by dividing the total usable 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 – whether at building, plant or city-wide levels – because it maximizes system efficiency and costs less to transport surplus electricity than to pipe surplus heat from a CHP plant[2]. CHP systems can achieve energy efficiencies of 75 percent or more, compared to producing heat and power separately, which is on average less than 50 percent efficient (Figure 1).)[3].

The U.S. currently has an installed co-generation capacity of 82.9 gigawatts (GW) of electric capacity at over 4,300 facilities, which represents 8% of current U.S. electricity generating capacity (by MW)[4][5]. More

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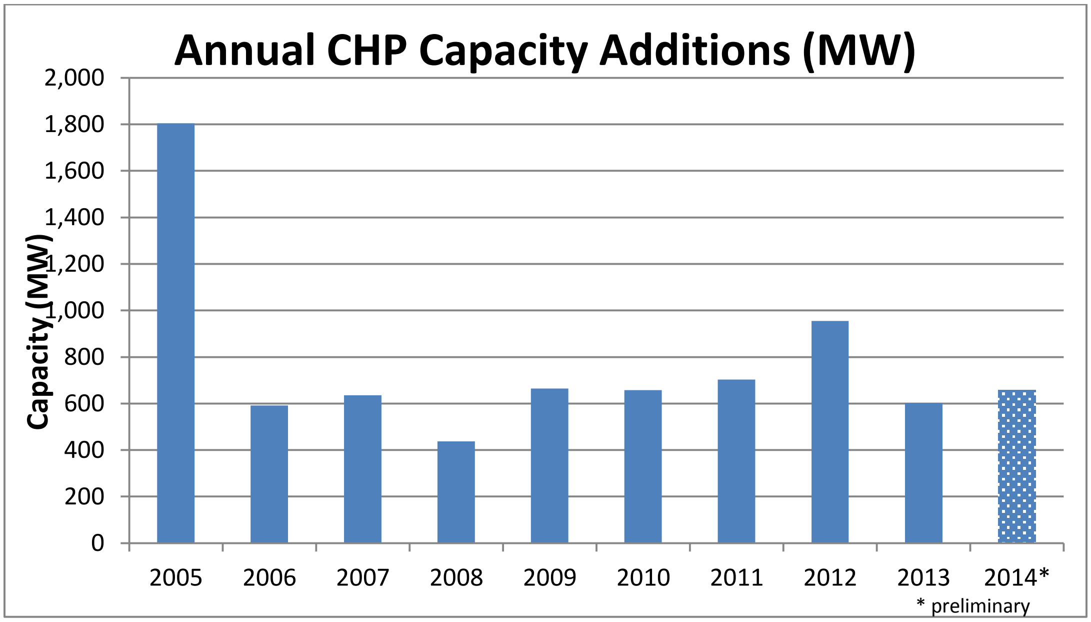
[1] Combined Heat and Power: Pathway to Lower Energy Costs, Reduced Emissions, Secure and Resilient Energy Supply, Fact Sheet, Environmental and Energy Study Institute, May 2013. Available at - http://www.eesi.org/files/FactSheet_CHP_052113.pdf.

[2] Combined Heat and Power – Evaluating the Benefits of Greater Global Investment, IEA 2008. Available at - http://www.iea.org/publications/freepublications/publication/chp_report.pdf.

[3] 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.

[4] ICF Combined Heat and Power database (funded by US DOE and Oak Ridge National Laboratory). http://www.eea-inc.com/chpdata/

than two-thirds 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[6]. Interest in CHP in the U.S. is rising due to low natural gas prices, the increasing return of manufacturing to the U.S., and growing awareness of the value of energy resiliency.



Source: ICF Combined Heat and Power Installation Database

CHP systems can be used in many different settings and many different scales, ranging from the micro, residential scale producing as low as 60 kW to large-scale industrial systems that produce more than 20 megawatts (MW) of power. Applications include[7]:

- Manufacturing (chemicals, refineries, pulp and paper, food processing, pharmaceuticals, biorefineries, etc.)

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[5] The ICF Combined Heat and Power database contains information on all known CHP systems in operation today. It the best estimate we have of the complete CHP market, but still only an estimate due to the constantly changing numbers (new additions, existing capacity either shut down or put on standby, or changes in operation (e.g., less hours per year)). These numbers may differ somewhat from the estimates in the Manufacturing Energy Consumption Survey (MECS). MECS data does not include 3rd party owned and operated CHP. The MECS estimates also only include manufacturing industries, and as such does not include commercial/institutional CHP, agricultural CHP and mining CHP.

[6] ICF Combined Heat and Power database (funded by US DOE and Oak Ridge National Laboratory). http://www.eea-inc.com/chpdata/

[7] 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.

- Critical infrastructure (emergency services facilities, hospitals, water and wastewater treatment plants, etc.)
- Institutional (retirement homes, research institutions, government buildings)
- Commercial (hotels, airports, office buildings)
- District energy (colleges and university campuses, urban centers, military bases)
- Residential (large multi-family units and a small number of individual homes)

The greatest use of CHP is in the manufacturing sector, with approximately 86% of the CHP capacity (see Figure 2).

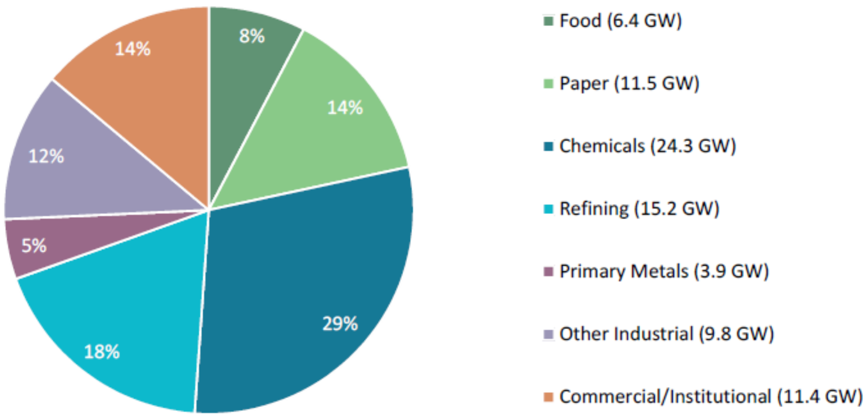

Figure 2 – Existing CHP capacity in the U.S. by sector, 2012 [6].

The International District Energy Association (IDEA) has identified 601 district energy systems in the US, 289 of which are currently district energy-only systems[8] . 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, spread across 55 downtown systems and 153 university campus district energy systems.

The U.S. Federal government has set a target of 40 GW of additional CHP capacity by 2020, an increase of nearly 50% above the 2012 baseline of installed capacity of 82 GW. Additionally, 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[9] .

1.2 Benefits of CHP for the Nation

- Improves U.S. manufacturing competitiveness by lowering energy operating costs to manufacturers
- Offers a low-cost approach to new electricity generation capacity
- Improves resiliency to the local electrical power allowing for business continuity in the event of a man-made or natural disaster

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[8] The IEA CHP and DHC Collaborative – CHP/DHC Country Scorecard: United States. Available at http://www.iea.org/publications/insights/insightpublications/US_CountryScorecard_FINAL.pdf

[9] Ibid

- Provides an immediate path to lower GHG emissions through increased energy efficiency - use of CHP currently avoids 248 million metric tons of carbon dioxide per year
- Lessens the need for new transmission and distribution (T&D) infrastructure and enhances power grid security
- Uses abundant clean domestic energy sources – over 83% of CHP capacity is fueled by natural gas, biomass, or waste fuels
- Uses highly skilled American labor.

1.3 Benefits of CHP for U.S. businesses

Combined heat and power systems provide effective, efficient, reliable, and less costly power to businesses across the nation. CHP has proven to:

- Increase production efficiency, reducing business costs
- Reduces risk of electric grid disruptions, enhances energy reliability and lessens potential impacts on business operations
- Provides stability in the face of uncertain electricity prices
- 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. As an example, Figure 3 compares the cost of electricity generated from small, medium, and large sized CHP projects with delivered electricity costs in New Jersey and the cost of electricity from new central power generation[10] .

1.4 Status of CHP Market

CHP is considered by many to be a "mature" technology. There is significant deployment of the technology in the large industrial and large commercial/institutional sectors. The economies of scale allow CHP to be cost-effective for high-thermal demand applications in the size range above 5MW. 1-5 MW systems are typically cost-effective when sized for thermal demand, but can face significant barriers when interconnecting with their electric utility regarding interconnection standards; utility rates, such as stand-by; and opportunities to sell electricity back to the grid, such as in net-metering. These barriers can influence the systems overall cost-effectiveness.

1.5 Challenges, Policy, and Regulatory

While current thermally-sized CHP technologies are cost-effective and broadly deployed in the medium to large size ranges (>5 MW), there are a host of policy and regulatory barriers that limit its deployment in the marketplace. These barriers limit the ability for CHP to succeed in energy services markets.

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[10] ORNL. Combined Heat and Power, Effective Energy Solutions for a Sustainable Future. 2008. Available at - http://www.energy.gov/sites/prod/files/2013/11/f4/chp_report_12-08.pdf.

Improvements in the following areas have been proposed to maximize the cost-effective penetration of CHP technologies:

- Design of standby rates
- Interconnection standards for CHP with no electricity export
- Excess power sales
- Clean energy portfolio standards (CEPS)
- Emerging market opportunities—CHP in critical infrastructure and utility participation in CHP markets.

1.6 Opportunity

While existing thermally-driven CHP systems sized to fill 100% of a facility thermal demand (low power to heat ratio ($\frac{P}{H}$), typically below 0.75) are currently cost effective in many markets and applications, there still remains a vast unserved market with smaller thermal demand relative to electrical ($\frac{P}{H}$ up to 1.5) in the industrial, commercial/institutional, and residential sectors. By increasing $\frac{P}{H}$ while maintaining the high efficiencies that thermally-sized CHP systems enjoy an enormous energy and cost savings opportunity would be untapped (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 efficient generating technologies. Ultra-efficient electricity generation could be a transformative technology leap for providing power to end-use customers. Combined with increased use of renewables, 70% efficient power generation (an effective doubling of current U.S. average electricity generation efficiency), could lead the U.S. down the path of 80% carbon reductions by 2050[11]. Meeting these aggressive goals will require a transformation both in how energy is produced and consumed. A proposed R&D activity focused on ultra-efficient electricity generation technologies will focus on increasing the CHP electricity generation efficiency.

1.7 Options for CHP on the Electric Side

A rough analysis of the opportunities of deploying highly-efficient CHP to applications that fall outside of the traditional thermally-driven systems was carried out (details in the following sections). The analysis examined how much increased technical potential and energy savings could be captured if CHP systems could be 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).

This analysis showed 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 more than existing CHP technologies alone.

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[11] The White House, Remarks by the President at the Morning Plenary Session of the United Nations Climate Change Conference (Dec. 18, 2009) (online at www.whitehouse.gov/the-press-office/remarks-president-morning-plenary-session-united-nations-climate-change-conference).

1.8 CHP in Grid Integration Scenario

CHP has the potential to play a larger and significant role in the modern smart grid. Integrating manufacturing operations and resources (including CHP) into the modern grid system will allow manufacturers to enjoy the cost savings from reduced on-site fuel consumption and will also provide the potential for the realization of additional revenue streams. In a truly integrated and smart grid, a manufacturer may be able to participate in ancillary services markets, enhanced demand-response programs, and other alternate revenue-generating schemes. The end result of grid integration of electric-driven CHP distributed generation will be stronger, more profitable, and more resilient operations for both the utility and end-use sectors. Additional end-user benefits would include avoidance of lost revenues due to a more reliable, and resilient grid.

2. Technology Assessment and Potential

2.1 Past CHP R&D Portfolio

The DOE CHP R&D Portfolio has included:

- **Advanced Reciprocating Engine Systems (ARES):** The goal of the ARES program was to deliver a technologically advanced engine/generator system that combines high specific power output and low exhaust emissions with world-class overall efficiency, while maintaining excellent durability, all provided at a low installed cost. This program resulted in demonstrated engine efficiencies that increase from ~35% at project start to 50%, a nearly 50% increase in efficiency.

- **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:

    - High Efficiency Micro-turbine with Integral Heat Recovery
    - Flexible CHP System with Low NOx, CO and VOC Emissions
    - Low-Cost Packaged Combined Heat and Power System
    - Combined Heat and Power Integrated with Burners for Packaged Boilers

- **High Value Applications:** New high-value CHP technologies and applications can offer attractive end-user economics, significant energy savings, and with reproducible results.
    - 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 (CCHP) Systems
    - Residential Multi-Function Gas Heat Pump
    - Ultra Efficient 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 a biomass gasifiers, gas turbines utilizing opportunity fuels, landfill gas cleanup and removal systems, and desulfurization sorbents for fuel cell CHP.
  - Adapting On-site Electrical Generation Platforms for Producer Gas
  - Development of an Advanced Combined Heat and Power (CHP) System Utilizing Off-Gas from Coke Calcination
  - Development of Fuel-Flexible Combustion Systems Utilizing Opportunity Fuels in Gas Turbines
  - Integrated Combined Heat and Power/Advanced Reciprocating Internal Combustion Engine System for Landfill Gas to Power Applications
  - Fuel-Flexible Microturbine and Gasifier System for Combined Heat and Power
  - Low-NOx Gas Turbine Injectors Utilizing Hydrogen-Rich Opportunity Fuels
  - Novel Sorbent to Clean Biogas for Fuel Cell Combined Heat and Power

- **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.
  - ArcelorMittal USA Blast Furnace Gas Flare Capture
  - BroadRock Renewables Combined Cycle Electric Generating Plants Fueled by Waste Landfill Gas
  - Combustion Turbine CHP System for Food Processing Industry
  - Texas A&M University CHP System
  - Thermal Energy Corporation Combined Heat and Power Project

Technology Needs

Highly-efficient CHP systems (~90%) are currently possible and deployed in limited applications with very high thermal and low electrical demands (low power to heat ratio ($\frac{P}{H}$). A key area for expanding the market for CHP, while also creating real, tangible thermodynamic improvements, is in pushing the $\frac{P}{H}$ ratio while maintaining high efficiencies. This would involve the development of ultra-high efficient distributed generation technologies.

Ultra-efficient electricity generation technologies (70% efficient power generation on an electric-only basis, an effective doubling of current U.S. average electricity generation efficiency) focus on increasing the CHP electricity generation efficiency.

Several technology configurations are being examined for thermodynamic maximum efficiencies: combine cycle system in the 1 MW range, using natural gas fuel, whose product is AC electricity. These include:

- Fuel cell as topping cycle, reciprocating engine as bottoming cycle.
- Reciprocating engine as topping cycle and Stirling engine as bottoming cycle

- Stirling engine as topping cycle and ORC cycle as bottoming
- Fuel cell as topping cycle and small gas turbine as bottoming cycle

(See analysis in following section for more detail on theoretical efficiencies)

A rough analysis of the opportunities of deploying highly-efficient CHP to applications that fall outside of the traditional thermally-driven systems was carried out.[12] The analysis examined how much increased technical potential and energy savings could be captured if CHP systems could be 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 analysis examined how much increased technical potential and energy savings could be captured if CHP systems could be 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 50-1,000 KW systems : 30.5% electrical efficiency and 79.6% overall efficiency
- For 1-5 MW systems : 34.8% electrical efficiency and 77.7% overall efficiency

The following sectors were included in the analysis[13]:

Manufacturing:	Commercial/Institutional:
- Textiles - Plastics - Fabricated Metals - Machinery, Electrical, Computers and Electronic Equipment - Transportation Equipment	- Commercial Buildings (NEC) - Schools - Retail Stores - Restaurants - Food Stores - Government Buildings - Prisons - Wastewater Treatment - Refrigerated Warehouses - Airports - Post Offices - Museums

This analysis showed 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 more than existing CHP technologies alone.

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[12] This was an internal DOE analysis done to estimate impact of expanded CHP market applications.

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

Benefits	Manufacturing Sector	Commercial/ Institutional Sector	Total
Incremental MW Potential (based on $\frac{P}{H}$ ratio up to 1.5)	4,739 MW	45,128 MW	52,867 MW
Incremental Primary Energy Savings (TBtu) – Assuming 33% average grid efficiency	144 TBtu	1,164 TBtu	1,308 TBtu
User Incremental Energy Cost Savings ($ Millions)	$1,316 Million	$8,660 Million	$9,976 Million

3. Program Considerations to Support R&D

3.1 Theoretical Feasibility of Ultra-High Generation technologies

A basic thermodynamic analysis was conducted to determine theoretical maximum efficiencies of several generation equipment configurations[14]. A combined cycle involves cogeneration of electricity, with a top cycle (the upstream generator) and a bottom cycle (the downstream generator), which makes use of residual fuel and/or heat from the top cycle. Many systems such as with gas turbines or Rankine cycles will use exhaust heat to increase internal efficiencies of the primary cycles (for instance, to heat incoming flow streams), but increasingly common in the literature is to add a third WHR cycle to produce additional electrical power. Adding such third cycles not only adds cost but is also an exercise in balancing returns, so such systems must be carefully considered and designed.

The table below and the accompanying chart summarize the range of expected combined-cycle thermal efficiencies for a range of technologies and combinations of cycles. Most of the reported ranges come from the literature, and some from our DOE internal 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; the overall system scale is on the order of 1 MW_e. In all cases, the fuel is natural gas; most literature studies neglect the energy inputs to pressurize the natural gas to operating pressures[15], but this is a small overall effect.

N	Top	Bottom	Extra WHR	Efficiency [%]
1	RICE (baseline)	—	—	47
1	RICE (stretch)	—	—	52
1	GT	—	—	30-38
1	SOFC	—	—	50-55

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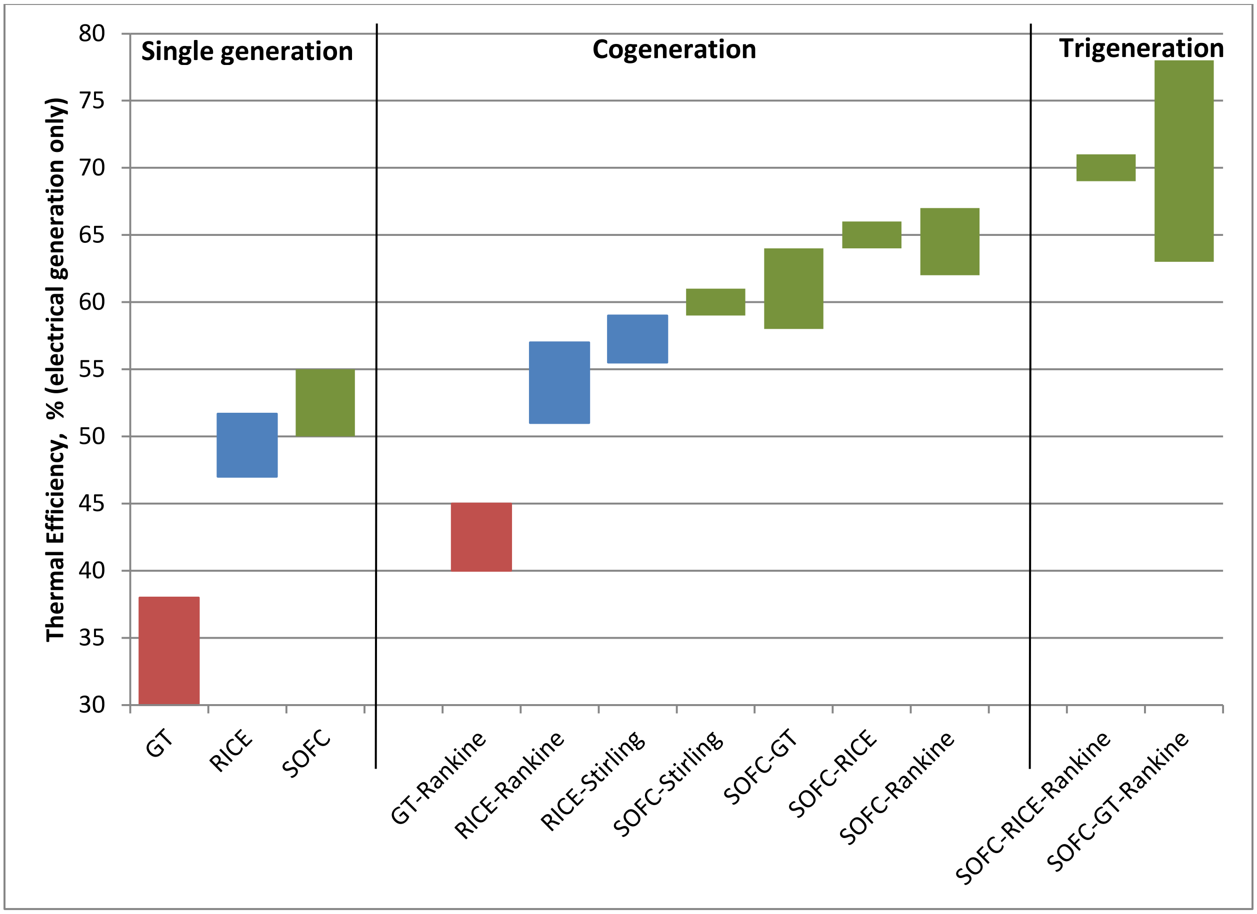
[14] This was an internal DOE review. It has not yet been peer reviewed by stakeholders.
[15] NG was the only fuel included in this analysis.

2	RICE	Rankine	—	51-57
	RICE	Stirling	—	51-59
2	GT	Rankine	—	40-45
2	SOFC	GT	—	58-64
2	SOFC	Stirling	—	60
2	SOFC	RICE	—	65
2	SOFC	Rankine	—	62-67
3	SOFC	GT	Rankine	63-78
3	SOFC	RICE	Rankine	69-71



Key: GT = gas turbine; RICE = reciprocating internal combustion engine; SOFC = solid oxide fuel cell; Rankine = Rankine cycle using either water or refrigerants (for organic Rankine cycle); Stirling = Stirling cycle engine.

Based on this preliminary analysis, it would appear that an aggressive and theoretically possible initial target efficiency for ultra-high efficiency generation is 70%%. . Initial tentative target price of generation is $1/W[16]. Details on milestones, timeline, and metrics are still being developed.

Three main technical areas for development of ultra-high-efficient generation include component development, systems development, and technology validation.

Technology Improvement Areas	
Component Development	Prime Mover Technology (engines, turbines, micro-turbines, 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

4.

Risk and Uncertainty, and Other Considerations

4.1 Barriers and unknowns

While traditional CHP is a fairly mature technology, it remains underutilized for both technical and policy reasons, as well as lack of understanding of CHP. Improving the technology to apply to a broader market will help bring down costs to existing markets as well, making the technology more attractive than it is currently, but will do little to address the policy and regulatory barriers to CHP and other distributed generation technologies.

Additional market uncertainties include the cost escalation of various fuels as well as electricity, effects of GHG reductions and the "greening" of the grid, impacts of policy on the US economy and revitalizing our industrial base.

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[16] This is still tentative, pending a more detailed stakeholder reviews

The activities of the DOE CHP Deployment program, through the DOE CHP Technical Assistance Partnerships (CHP TAPS), are key to continuing to ensure that the benefits of highly-efficient CHP are realized.

5. Sidebars and Case Studies

5.1 CHP in Food Processing Industry – Frito-Lay Demonstration

Frito-Lay North America, Inc. installed a combined heat and power (CHP) system at its food processing plant in Killingly, Connecticut, in April 2009. The installation was supported by funds from the U.S. Department of Energy (DOE) in partnership with the Energy Solutions Center1 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:

- A 4.6 megawatt (MW) Solar Turbines Centaur® 50 natural gas combustion turbine;
- A Rentech heat recovery steam generator (HRSG) equipped with supplemental duct firing;
- Combustion air inlet chilling to increase power generation in warm weather; and
- 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.

5.1.1 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 thirty 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. The unfired steam production from the gas turbine exhaust is approximately 24,000 lb/hour, and maximum supplementary fired steam production is as high as 60,000 lb/hour.

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%

5.1.2 Running in Island Mode

The Killingly plant—a 24/7 operation—has the capability to run in island mode 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 re-inspections, 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.3 The Killingly plant also remained operational during a late October 2011 snowstorm that had knocked out power to nearby areas. The plant would also have continued operating during Superstorm Sandy in October 2012 and a blizzard in February 2013 if the roads had not been shut down by the governor.