ABSTRACT

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| Title of Document: | Combined Heat and Power and Campus Carbon Footprint Reduction |
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Combined heat and power (CHP), the sequential generation of electrical and heat energy in an integrated process, has emerged as an economically viable and immediately effective power generation method to reduce harmful greenhouse gas emissions. CHP systems utilize both the electricity and waste heat created during energy production to increase fuel efficiency and decrease carbon emissions compared to conventional power generation. This research examines the extent to which universities can decrease carbon emissions by identifying strategies for installation and operation of highly efficient, gas-fired CHP. To best identify how to enhance campus CHP, existing university plants were first surveyed to establish a benchmark level of how efficiently universities operate CHP. Strategies for increasing turbine efficiency were then considered. Demand for efficient CHP on university campuses was identified and connected to specific turbine characteristics. Policy frameworks to support the development of efficient CHP implementation and operation were examined and challenges identified. This report provides recommendations for overcoming technical, economic, and policy challenges to attain immediate emissions reductions through university usage of CHP.

# COMBINED HEAT AND POWER AND CAMPUS CARBON FOOTPRINT REDUCTION

By

Team Cogeneration Technology

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# Nomenclature

Alphanumeric Symbols

| | |
|---|---|
| $C_c$ | capital cost of installation, dollars |
| $C_f$ | cost of fuel, dollars |
| $C_o$ | monthly operating expense, dollars |
| $C_C$ | cost of carbon per metric ton, dollars |
| $C_{LC}$ | lifetime cost of carbon, dollars |
| $c_p$ | fluid specific heat at constant pressure, J/kgK |
| $c_v$ | fluid specific heat at constant volume, J/kgK |
| $E$ | emissions, metric tons |
| $F_t$ | lifetime fuel usage, MMBtu |
| $k$ | ratio of specific heats, $c_p/c_v$ |
| $\dot{m}$ | mass flow rate, kg/s |
| $\dot{m}_{air}$ | mass flow rate of air, kg/s |
| $\dot{m}_{fuel}$ | mass flow rate of fuel, kg/s |
| $O_t$ | lifetime operating expenses, dollars |
| $p$ | megawatts produced (cost analysis) |
| $P$ | pressure, Pa |
| $P_i$ | inlet pressure, Pa |
| $P_{amb}$ | ambient temperature, Pa |
| $P_{comp}$ | pressure after compression, Pa |
| $P_{comb}$ | pressure of combustion, Pa |
| $P_{exp}$ | pressure after expansion, Pa |
| $P_o$ | outlet pressure, Pa |
| $\dot{Q}_{thermal}$ | energy leaving plant as heat, kW |
| $\dot{Q}_{fuel}$ | energy added as fuel, kW |
| $R_c$ | compression ratio |
| $R_t$ | expansion ratio or $1/R_c$ |
| $s$ | entropy, J/K |
| $T$ | temperature, K |
| $T_{1a}$ | inlet temperature of stream 'a' in a heat exchanger, K |
| $T_{1b}$ | inlet temperature of stream 'b' in a heat exchanger, K |
| $T_{2a}$ | exit temperature of stream 'a' in a heat exchanger, K |
| $T_{2b}$ | exit temperature of stream 'b' in a heat exchanger, K |
| $T_{amb}$ | ambient temperature, K |
| $T_{comp}$ | temperature of compression, K |
| $T_{comb}$ | temperature of combustion, K |
| $T_{dry\ bulb}$ | dry bulb temperature, K |
| $T_{exp}$ | temperature after expansion, K |
| $T_{EXH}$ | exhaust temperature, K |
| $T_i$ | inlet temperature, K |
| $T_{mw}$ | lifetime megawatts produced |

| | |
|---|---|
| $T_o$ | exit temperature, K |
| $T_{wet\ bulb}$ | wet bulb temperature, K |
| $TIT$ | turbine inlet temperature |
| $u$ | internal energy, J |
| $\dot{W}$ | work, kW |
| $\dot{W}_{C1}$ | work of the first compressor stage, kW |
| $\dot{W}_{C2}$ | work of the second compressor stage, kW |
| $\dot{W}_{net}$ | net work compressor stage, kW |
| $\dot{W}_{T1}$ | work of the first turbine stage |
| $\dot{W}_{T2}$ | work of the second turbine stage, kW |
| $Y$ | years operational |

Greek Symbols

| | |
|---|---|
| $\eta_{compressor}$ | compressor efficiency |
| $\eta_{turbine}$ | turbine efficiency |
| $\rho_{NG}$ | density of natural gas |

Abbreviations

| | |
|---|---|
| ACUPCC | American College and Universities Presidents' Climate Commitment |
| ARRA | American Recovery and Reinvestment Act of 2008 |
| ASME | American Society of Mechanical Engineers |
| BTU | British thermal units |
| CAA | Clean Air Act of 1970 |
| CC | combined cycle |
| CCGT | combined cycle gas turbine |
| CCS | carbon capture and storage |
| $CH_4$ | methane |
| $C_2H_6$ | ethane |
| $C_3H_8$ | propane |
| $C_4H_{10}$ | butane |
| CHP | combined heat and power |
| CLEER | Clean Local Energy Efficiency and Renewables Act |
| $CO_2$ | carbon dioxide |
| CO | carbon monoxide |
| CREB | clean renewable energy bonds |
| DOE | US Department of Energy |
| DP | differential pressure |
| EECBG | Energy Efficiency and Conservation Block Grant Program |
| EES | Engineering Equation Solver |
| EIA | Energy Information Administration |
| EISA | Energy Independence and Security Act of 2007 |
| EPA | US Environmental Protection Agency |
| ESI | energy savings index |
| EPRI | Electric Power Research Institute |
| FERC | Federal Energy Regulatory Commission |
| GDP | gross domestic product |

| | |
|---|---|
| GE | General Electric |
| GSP LE | Gas Turbine Simulation Program |
| GW | gigawatt |
| GWh | gigawatt hour |
| HHV | higher heating value |
| HOQ | house of quality |
| HRSG | heat recovery steam generator |
| HUD | US Department of Housing and Urban Development |
| ICAO | International Civil Aviation Organization |
| ICRH | intercooled reheat |
| IRB | Institutional Review Board |
| IRS | Internal Revenue Service |
| ISO | independent system operator |
| ITC | investment tax credit |
| kWh | kilowatt hour |
| LCOE | levelized cost of energy |
| MACRS | modified accelerated cost-recovery system |
| MCF | thousand cubic feet |
| MMBTU | thousand BTU |
| MMT | million metric tons |
| MTBF | mean time before failure |
| MW | megawatt |
| MWh | megawatt hour |
| $N_2$ | nitrogen |
| NG | natural gas |
| NLR | Dutch national aerospace laboratory |
| $NO_X$ | nitrous oxide |
| NREL | National Renewable Energy Laboratory |
| $O_2$ | oxygen |
| O&M | operation and maintenance |
| SI | système international |
| PDM | positive displacement meter |
| PJM | Pennsylvania, New Jersey, and Maryland RTO |
| PNNL | Pacific Northwest National Laboratory |
| PURPA | Public Utilities Regulatory Policy Act of 1978 |
| PTC | production tax credit |
| PV | photovoltaic |
| REPI | renewable energy production incentive |
| RPS | renewable portfolio standard |
| RTO | regional transmission operator |
| QECB | qualified energy conservation bond |
| QF | qualifying facility |
| Quads | quadrillion BTU |
| TREEA | Thermal Renewable Energy and Efficiency Act of 2010. |
| UHC | unburned hydro carbons |
| UMD | The University of Maryland in College Park |

# 1. Introduction

Recent concern about anthropogenic contributions to climate change has highlighted the need to reduce fossil fuel consumption. A majority of research investigations that target reductions in carbon emissions, a leading driver of climate change, are focused on harnessing alternative energy sources, with minimal research devoted to refining existing power generation processes for emissions reductions. An area with particularly exciting unrealized potential is cogeneration, or combined heat and power (CHP).

Typical users of CHP systems are campus-based organizations, such as large universities, hospitals, and government installations. These organizations represent an untapped potential for immediate, substantive emissions cuts. In particular, many universities across the nation have already taken important steps to translate the goal of reduced carbon emissions into a viable plan of action. The American College & University Presidents Climate Commitment represents a collective commitment to carbon neutrality by the year 2050. While such agreements are integral to reducing carbon emissions, the process is complex and requires an individualized plan of action for each signatory. The widespread usage of CHP on university campuses, coupled with the expectation that colleges remain on the cutting edge of intellectual and social movements, make schools the ideal subjects of this research.

Practicality remains a large factor in determining the method by which a university tackles carbon reduction. Initially, change will be gradual; it would be impossible to abandon fossil fuels immediately since most universities have significant investments in their current energy systems and standing contracts with nearby utility companies. To stay within the confines of university budgets, fossil fuel burning plants continue to grow to satisfy swelling energy needs of college campuses. Although there are a number of clean, carbon neutral energy generation alternatives available in today's market, such as solar, wind, and nuclear systems, CHP systems are more economically and logistically more feasible for universities. Although they are not free of carbon emissions, CHP systems dramatically increase fuel efficiency by capturing energy that would otherwise be wasted as exhaust heat. This increase in efficiency decreases fuel consumption and carbon emissions.

## 1.1. Research Objectives

The research methodology was guided by several overarching and interrelated research questions. First, to what extent can a large university campus with a district heating system in place meet its energy needs through an economical CHP system while minimizing carbon emissions? Second, what is the market for gas turbines and how can it be improved to benefit university consumers? Third, how does policy shape CHP implementation and operation on university campuses? These questions encompass many of the issues faced by potential university plant designers, builders, owners, and operators. As such, this research is built on a framework supported by these three research questions. The technical issues of benchmarking CHP performance and enhancing turbine (and consequently CHP) efficiency are addressed in Section 2, which deals largely with the first research question. The market-oriented research explored in Section 3 is directed at the second research question. The policy research in Section 4 focuses on the third and final research question.

# 2. CHP Engineering

In the CHP industry, the overarching goal of carbon reduction translates into a very specific technical goal – thermal efficiency improvements. The engineering approach to this project aims to understand the current state of CHP on university campuses and demonstrate that the use of improved CHP practices can produce dramatic carbon-reduction results.

## 2.1. Engineering Literature Review

### 2.1.1. Available Energy Sources

First, the value of gas-fired CHP versus competing power generation routes for large university campuses is examined. Natural gas-fired CHP plants face several potential competitors in utility-scale energy markets – namely solar, wind, biomass, nuclear, coal, and simple-cycle natural gas. These six power generation routes are evaluated by cost, suitability for on-campus generation, contribution to the national energy grid mix, and environmental impact. Comparisons are drawn between these fuel sources and gas-fired CHP to determine suitability for campus power generation. Figure 2.1 and Figure 2.2 give a visual summary of the key points discussed in the following section: capital cost and operational considerations. In addition, consideration is given to the importance of reliable thermal energy generation to university campuses, which need steam to heat buildings and drive several other applications. Thus, any alternative energy source must provide considerations for boilers and backup energy sources located on site. These considerations often reduce the desirability of alternative energy sources.

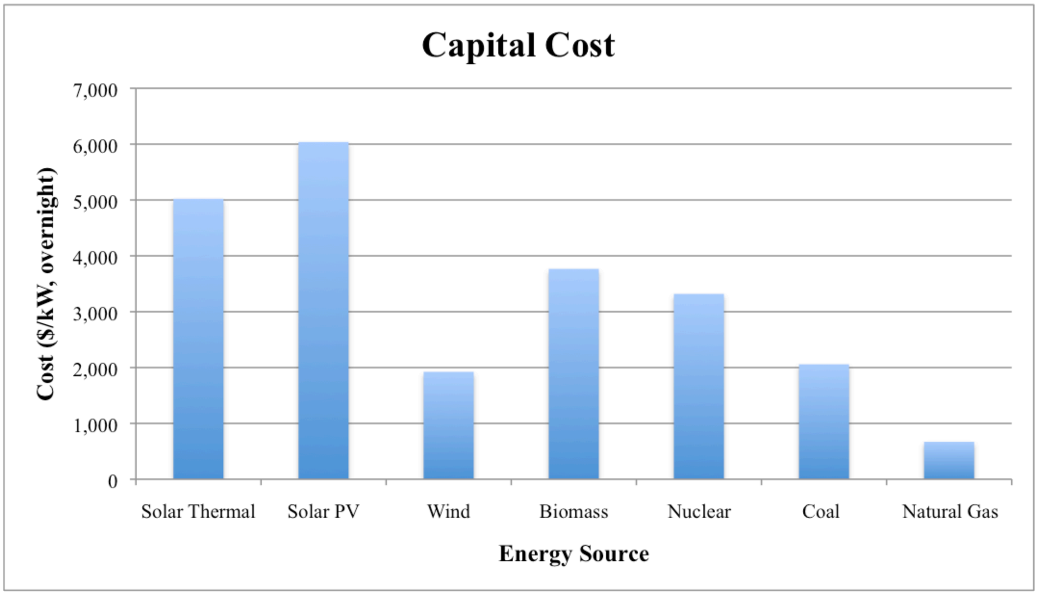



Figure 2.1. Comparison of On-site Capital Costs for the Fuel Sources Considered (in 2007 Dollars) [3].

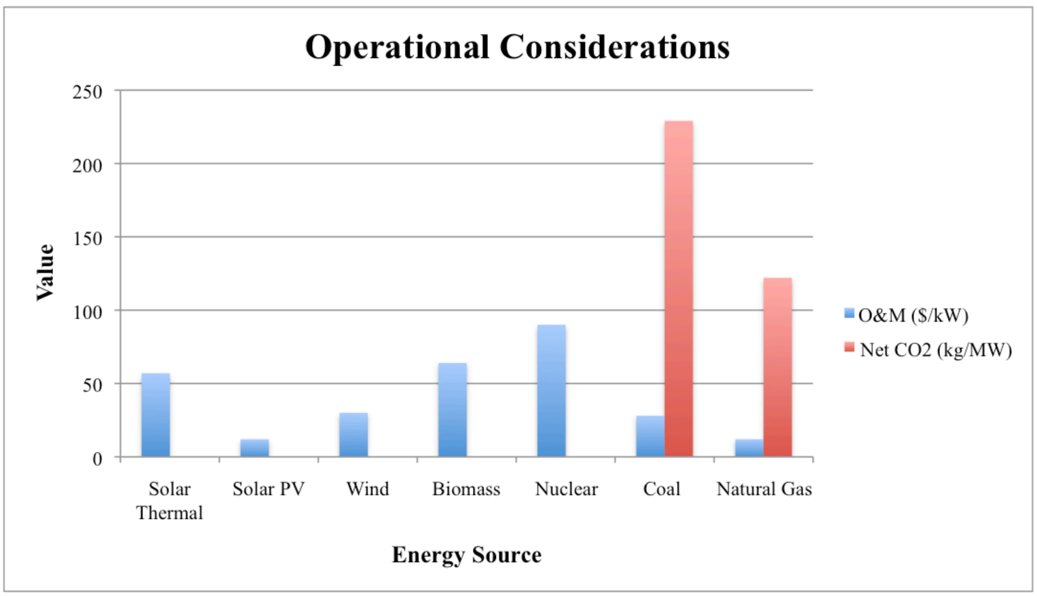



Figure 2.2. Comparison of On-Site Generation Factors (O&M Costs and $CO_2$ Emissions) for the Fuel Sources Considered (in 2007 Dollars) [3].

### 2.1.1.1. Solar

Solar energy encompasses solar thermal technologies, which utilize sunlight to heat up a working fluid and drive a steam power cycle; and photovoltaic (PV) devices, which generates electricity directly from sunlight via the photoelectric effect. High capital costs are the primary limitation in the adoption of solar technology [3].

At a capital cost of $5021/kW and a fixed O&M cost of $56.78/kW, solar thermal may be prohibitively expensive for many universities, especially compared to natural gas. Space requirements are another consideration, as solar projects generate less power per unit of plant area than any competitor. Geographic and temporal variability in solar insolation also require a means of reliable, high-capacity energy storage [4].

The purchase of solar energy from off-site producers is also relatively costly. Figure 2.3 compares the estimated levelized costs – a metric which integrates costs at all stages from generation to transmission – of various technologies in 2016. The estimated levelized cost of producing electricity with a solar plant is more than four times that of an advanced combustion turbine. While a university may be able to purchase limited quantities of solar power, it is highly unlikely that a campus can be powered entirely with solar unless the price of generation decreases.

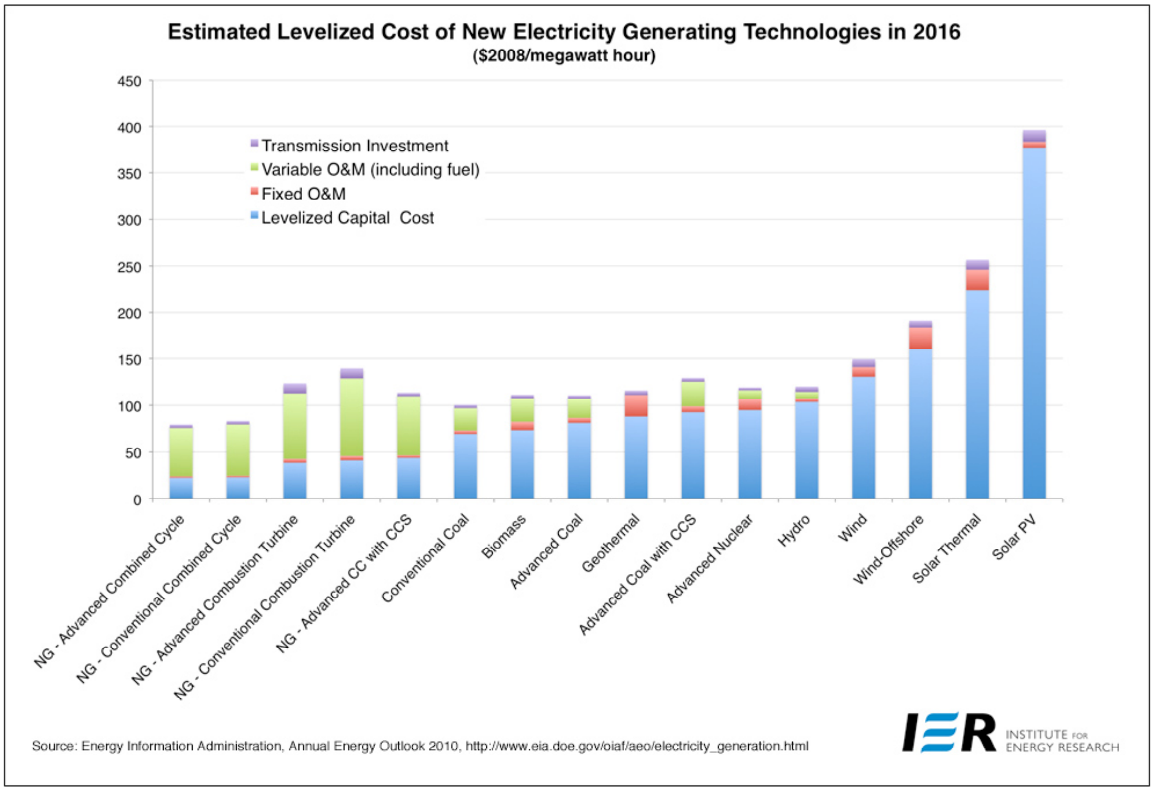



Figure 2.3. Levelized Cost of Electricity Generation by Source [5].

While solar is not currently cost-competitive, its operational production of zero carbon dioxide makes it extremely favorable from the perspective of reducing greenhouse gas emissions. External factors such as carbon tax or cap policies would decrease the monetary gap between solar and fossil fuels by incorporating the social cost of carbon in generation.

#### 2.1.1.2. Wind

The cost of installing and operating wind turbines is almost three times the cost of an advanced combustion turbine. Space requirements are milder than those for solar, with utility-scale wind turbines requiring 0.25-0.5 acres per turbine [6-7]. However, on-site production of wind energy is limited by high temporal variability, the availability of local wind resources, and requisite freedom from obstructions such as buildings and trees, which eliminate the possibility of significant on-site generation for many campuses [8].

Wind farms can produce energy at $150/MWh a substantially larger cost than $125/MWh for advanced combustion turbines and $80/MWh for combined cycles [5].

Like solar power, wind power – ignoring the customary backing by a natural gas generator – emits no carbon during production, making it a favorable choice in a culture that is increasingly worried about growing greenhouse gas emissions. However, wind technology has yet to gain a foothold on university campuses and may be met with some timidity by university energy managers as an on-campus tool.

#### 2.1.1.3. Biomass

Biomass energy systems use combustion of a feedstock – grass, agricultural residue, wood chips, municipal solid waste, etc. – to provide heat for a steam power cycle. Biomass can also be gasified and the resulting gas used either in a boiler or directly in a gas turbine.

Capital costs of a biomass-fueled plant are estimated at $3,766/kW with $64.45/kW fixed O&M, nearly six times the capital investment required for an advanced combustion turbine [3]. The physical size of a typical biomass plant is comparable to that of a gas-fired plant, with feedstock storage requiring additional land area (though not as much as a solar or wind farm). The greatest limitation on biomass power generation is the lack of adequate supply of feedstock in developed areas. Without such a supply, the feasibility of an on-campus biomass plant is doubtful.

While it is unlikely a university will be powered entirely on biomass, it can be used to supplement other fuel sources. Biomass is already being used on some university campuses in co-firing applications with another fuel source [9].

Offsite production of biomass energy is competitive with natural gas and coal at about $100/MWh [9]. Biomass is considered a carbon-neutral fuel because all of the carbon released through its combustion was previously sequestered during plant growth.

#### 2.1.1.4. Nuclear Power

Nuclear energy plants typically provide massive quantities of power (1-2 GW), though it is extremely unlikely that a university would front the capital cost for a nuclear plant of this scale. To build a plant overnight would cost $3,318/kW, greater than that for wind and comparable to biomass, with fixed O&M at $90.02/kW [3]. Nuclear plants require large amounts of space and issues of licensing and permitting would likely prohibit a university from building its own plant for commercial power production. A university and nuclear plant could be collocated such that the campus consumes electrical and steam output from the plant; however, this scenario has yet to occur.

Universities are much likelier, and in many cases do, purchase nuclear energy from an external producer [10]. Nuclear power can be produced for $125/MWh, a price competitive with any fuel alternative. Nuclear power also releases zero carbon emissions during operation.

#### 2.1.1.5. Coal

Coal power is a widely used, nonrenewable, low cost fuel. While many versions of coal power generation exist, all involve combusting coal to produce heat for a steam power cycle. With the exception of natural gas, coal is the cheapest power generation option. Construction of a new coal plant with scrubbers (to remove various pollutants) costs $2,058/kW with a $27.53/kW fixed O&M, a price comparable to that of a wind farm [3]. Coal is widely used on hospital, federal, and college campuses because of its low cost, availability, familiarity, legacy, and low space demands.

The major disadvantage of coal energy is that it releases the highest amount of carbon per unit of energy produced. Pulverized coal combustion releases 229 g of carbon/kWh, with combined cycle and carbon capture modifications capable of reducing carbon emissions to only 40 g/kWh [11]. This lowered carbon output is reflected in the production costs, ranging from $100/MWh for conventional pulverized coal to $150/MWh for advanced coal with carbon sequestration [11].

Coal can also be used in CHP applications, but because of its higher carbon density would still produce more carbon emissions than a gas-fired plant at the same efficiency. When the objective is to decrease carbon emissions, natural gas is preferred over coal.

#### 2.1.1.6. Natural Gas

Power production with natural gas relies mainly on two processes: combusting gas directly in a gas turbine, or combusting gas in a boiler to produce steam for a steam turbine. A simple cycle natural gas plant burns gas in a combustion turbine to produce electricity and exhausts the waste heat out of the plant stack. Advanced combustion turbines come with the lowest capital cost of any fuel source, at $670/kW total overnight cost with a fixed O&M of $12.11/kW. Simple cycle gas turbine generation systems can produce electricity cheaply, at about $75/MWh, while emitting carbon format a rate of

103-122 g/kWh. Carbon capture and storage technologies can reduce the carbon output to 17 g/kWh and increase the generating cost to about $110/MWh [11].

Combined cycle natural gas plants use the waste heat from the gas turbine exhaust to produce steam (occasionally adding additional heat by combusting more fuel between the turbine exhaust and the boiler). The steam is expanded in a steam turbine to produce additional power. CHP can be used with both simple and combined cycles, using leftover heat for nearby heating and cooling applications.

#### 2.1.1.7. Summary and Comparison to CHP

Each of the fuel sources evaluated has major limitations that decrease the potential for on-campus power generation. Solar technologies are prohibitively expensive to deploy at a large scale. Wind is severely limited by wind resource issues and space requirements. Biomass is infeasible except in the rare case when a large quantity of biomass is available cheaply. Utility-scale nuclear power plants are heavily restricted by siting and permitting requirements. Though universities may like to purchase energy from entirely renewable resources, none of these sources has achieved a deep enough market penetration to provide institutions with all of their energy demand [12]. Regarding fossil fuels, natural gas plants are both cheaper and emit less carbon per unit of energy that coal plants.

This research centers around natural gas-fired turbine-based CHP because it is capable of producing power on university scales and emits significantly less carbon than competing fossil fuels. While a CHP system is more expensive to build, it can dramatically reduce carbon output both by reducing the amount of electricity used for heating applications and by increasing the cycle thermal efficiency. By 2008, CHP displaced more than 1.9 Quadrillion British Thermal Units (Quads) of fuel consumption to avoid 248 million metric tons (MMT) of $CO_2$ [14]. CHP relies on proven, familiar technology that is readily deployable in the U.S., and thus presents a more immediate means of reducing carbon output than competing renewable options, which must overcome the inertia of technology demonstrations and market development.

Although the use of CHP is already prevalent – and growing – this research shows that problems with the implementation of this technology has resulted in less than optimum operation of existing campus plants from the perspective of carbon emissions. This study also demonstrates an exciting potential to minimize carbon emissions by improving upon the configuration of existing CHP plants [13].

### 2.1.2. Components of a CHP System

#### 2.1.2.1. Gas Turbine-Component Descriptions and Theory

The gas turbine is very often the prime mover in a campus-based, gas-fired CHP system. It converts the chemical potential energy in natural gas to mechanical torque, which is sent to a generator for the production of electricity. The fundamental power cycle that drives a gas turbine is the Brayton cycle. The three main components of a gas turbine machine are the compressor, combustor, and turbine.

#### 2.1.2.2. Brayton Power Cycle

In a conventional Brayton Cycle, inlet air is compressed, followed by constant pressure heat addition (combustion), expansion through a turbine to extract power, and finally heat extraction. This cycle is depicted on three sets of axes in Figure 2.4. [15].

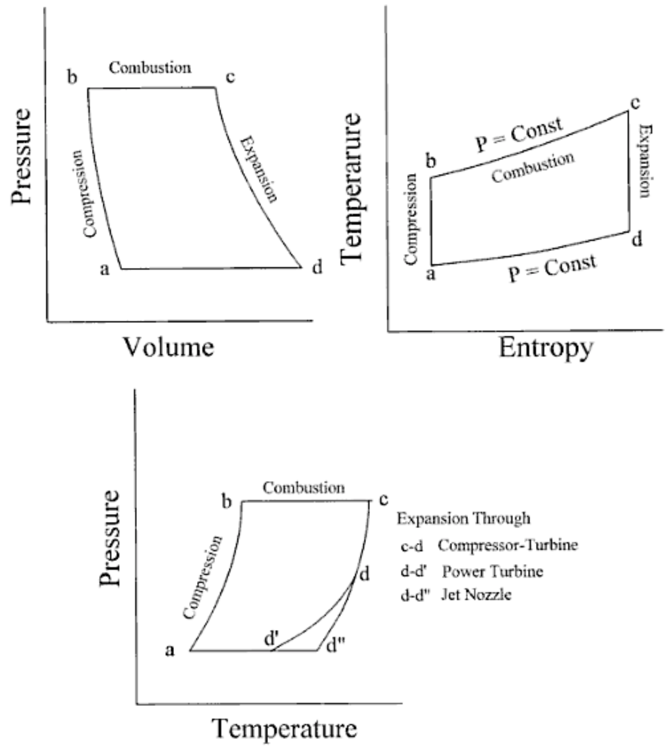



Figure 2.4. Conventional Brayton Cycle.

### 2.1.2.3. Compression

The compressor provides high pressure, high volume air that, when expanded in the turbine, provides mechanical work. Both axial and centrifugal compressors are employed in gas turbines, however only the former is discussed here because it commonly appears on large-scale (5+ MW) gas turbines. Axial compressors are comprised of several rows of airfoil cascades; rows of rotors (airfoils fixed to the rotating shaft of the compressor) alternate with rows of stators (airfoils that are fixed to the compressor casing and do not move). The airflow velocity is increased along the tips of the rotors, which are turning at the same speed as the turbine. When the air passes from the rotors to the stators, the fluid velocity decreases significantly and the kinetic energy that the rotors imparted on the flow is converted to static pressure. Stators also help to align the flow and prevent it from spiraling around the axis [Figure 2.5].

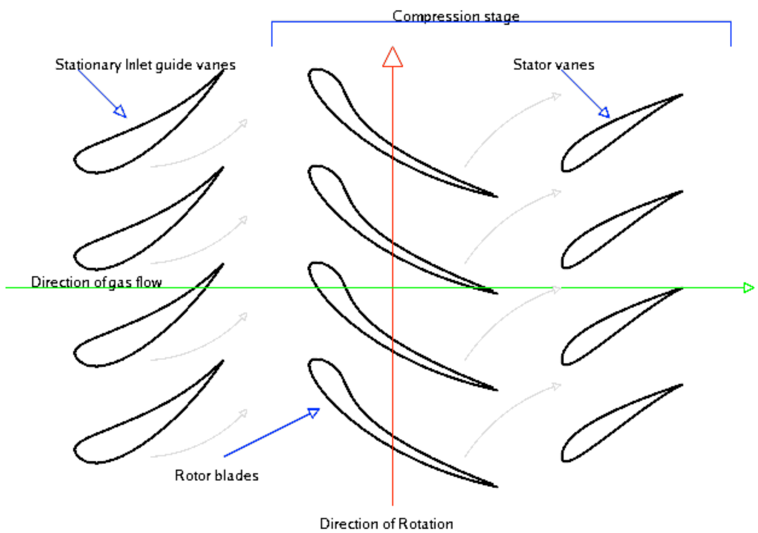



Figure 2.5. Orientation of Compressor Rotors and Stators to Direct Flow [15].

Axial compressors can have several stages (rotor-stator pairs) with overall compression ratios of around 30:1. Compressor efficiencies are measured using the compressor pressure ratio and the inlet/outlet temperature ratio:

$$\eta_{Compressor} = \frac{R_C^{\sigma} - 1}{\frac{T_o}{T_i} - 1} \tag{2.1}$$

where,

$$\sigma = \frac{k-1}{k}$$

$\eta_{Compressor}$ = Compressor efficiency
$R_C$ = Compressor compression ratio (discharge pressure divided by inlet pressure)
$k$ = Ratio of specific heats, $c_p/c_v$
$T_o$ = Exit temperature (absolute scale)
$T_i$ = Inlet temperature (absolute scale) [15]

The required compressor power is calculated using the mass flow rate $\dot{m}$ by:

$$P_{Compressor} = \dot{m} c_p \frac{T_i}{\eta_{Compressor}} \left[ \left( \frac{P_o}{P_i} \right)^{\sigma} - 1 \right] \tag{2.2}$$

where, in addition to the above notations,

$P_i$ = Inlet Pressure (Pa)
$P_o$ = Outlet Pressure (Pa)

#### 2.1.2.4. Combustion

When compressed air flows into the combustion chamber, it mixes with fuel (natural gas) and is burned. When the mixture ignites, it remains at a relatively constant pressure but increases in temperature and volume. This high-temperature, high-pressure gas is forwarded to the turbine section.

The most critical limiting factor to combustion efficiencies is combustion temperature, which is determined by material characteristics. Figure 2.6 shows the decrease in specific fuel consumption with increased turbine inlet temperature and pressure ratio.

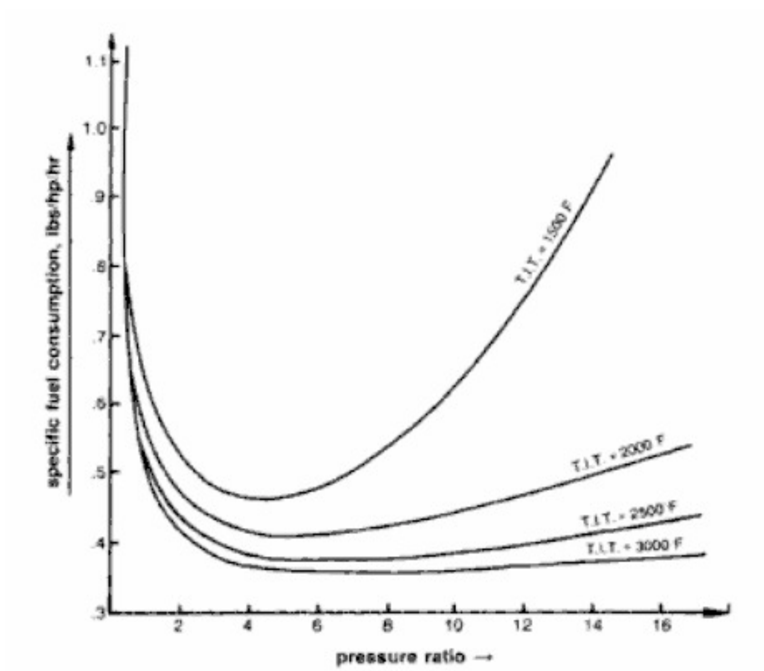



Figure 2.6. Variation of Specific Air Consumption with Turbine Inlet Temperature and Pressure Ratio [16].

The adiabatic flame temperature for the stoichiometric combustion of methane with atmospheric air at equilibrium was determined using ChemCAD to be 1,960 $^{o}$C

(3560 $^{o}$F). However, the most advanced alloys can retain their mechanical properties at temperatures only up to ~1100 $^{o}$C (2012 $^{o}$F) [16]. Significant material advances are required before combustion temperatures nearer the ideal flame temperature can be achieved.

Combustion temperature also plays an important role in emissions. Combustion gas turbines produce two classes of compounds important in emissions considerations: carbon dioxide and NOx. NOx is a term encompassing nitric oxide (NO) and nitrogen dioxide ($NO_2$), both of which contribute to smog formation and the development of tropospheric ozone [114]. Higher combustion temperatures increase combustion efficiencies, which reduces carbon dioxide emissions but increases NOx formation. Emissions constraints must achieve a balance between these two competing considerations. The relationship between NOx and $CO_2$ is explored more fully from a policy perspective in Section 4.1.7.

#### 2.1.2.5. Expansion

Once the high-temperature, high-pressure gas has been combusted, it is expanded in a power turbine, exchanging pressure and volume for kinetic energy of the turbine blades. Expansion is the reverse of the process depicted in [Figure 2.5], so expansion imparts energy to the turbine blades rather than the turbine blades imparting energy to the gas. Like the compressor, the turbine is comprised of rows of airfoil cascades, however there are often fewer stages in turbines than in compressors. The imparted energy manifests as a mechanical torque exerted on the turbine, causing the turbine to rotate on its axis, turning a generator that produces electrical work. The efficiency of the turbine section is:

$$\eta_t = \frac{1 - \frac{T_{EXH}}{TIT}}{1 - R_t^{\sigma}} \tag{2.3}$$

where,

$\eta_t$ = Turbine efficiency
$T_{EXH}$ = Turbine exhaust temperature (absolute scale)
$TIT$ = Turbine inlet temperature (absolute scale)
$R_t$ = 1/$R_c$ [15]

#### 2.1.2.6. Combined Cycle

Combination of a combustion and steam turbine in connected power cycles is often referred to as a combine cycle gas turbine (CCGT)—although originally this phrase was reserved for machines that combined Brayton and Rankine cycles in the same physical housing. The high-pressure steam that exits the heat recovery steam generator is expanded to low-pressure steam before it is used in heating applications (also referred to as a bottoming cycle). This expansion produces additional electric power. The electrical efficiency of a CCGT plant ranges between 35-45%, and can be as high as 58% with more advanced turbines. The total efficiency of a CHP CCGT cycle can be as high as 70-88% [17]. This is compared to a simple cycle gas turbine, which ranges in efficiency from about 25% to 40%. With a single pressure heat recovery steam generator, typically 30% of plant power comes from the Rankine (steam) cycle [18].

### 2.1.3. Cycle Improvements

Modified Brayton cycles with higher thermal efficiencies present opportunities for long-term economic gains and reduced environmental impact through emissions reductions. Of many possible modifications, three are studied extensively in literature: reheat, recuperation, and intercooling.

#### 2.1.3.1. Reheat

Reheat involves processing the exhaust of a first-stage turbine in a second-stage turbine for additional power extraction. Between the two turbines, the exhaust temperature is raised by injecting and combusting supplemental natural gas. The effectiveness of this modification depends on the pressure and oxygen content of the first-stage turbine exhaust stream. A similar addition is called the Brayton-Brayton cycle, in which exhaust from one turbine is sent to a heat exchanger where it raises the temperature of the compressed gas in a second turbine. The reported increase in power in a Brayton-Brayton cycle ranges between 18-30%, with a possible efficiency increase of 10% [18].

#### 2.1.3.2. Recuperation

Recuperation involves heating the compressed air before it is combusted by passing it through a heat exchanger with the turbine exhaust gases. It is a common practice that is often employed in industrial power generation equipment, however less common on smaller turbine models. Recuperation is limited by metallurgical problems in the heat exchangers— high temperature turbine exhaust gas has the potential to melt the exchanger [19]. This restriction limits the compression ratio of the machine, which affects its performance. The Mercury 50, the only commercially available recuperated gas turbine below 20 MW nominal capacity, was developed with a lower compression ratio because of failures with the recuperator in initial testing [19]. Intercooling (discussed below) can be used to address these problems. Raising the initial air temperature decreases the amount of fuel necessary to bring the gases up to the turbine operating temperature, thereby decreasing the running costs and total emissions.

Recuperation can increase the thermal efficiency of a simple cycle gas turbine to 39-43%, well above the standard range of 25-40% [18]. The effectiveness of a recuperator directly affects the increase in cycle efficiency; however a more effective recuperator is larger and requires more material to construct—thus it is more expensive. Several attempts have been made to optimize tradeoffs between efficiency increases and capital expense [20].

#### 2.1.3.3. Intercooling

Thermal efficiency can also be increased by decreasing the required work of compression through a process known as intercooling. Such a process usually involves two stages of compression. The air is water-cooled after the first stage to decrease its volume and thus decrease the work required to compress it further in the second stage. This heat exchange takes place after one stage of compression because energy is more effectively siphoned from the hot high-pressure stream than from the colder inlet stream (because of the higher temperature difference between the air and the cooling water). Intercooling can also be used to increase the effectiveness of recuperation. The temperature of the compressor outlet temperature limits recuperators. Intercooling cools the airflow, allowing higher compression ratios to be obtained without danger of melting the recuperative heat exchanger [18]. Finally, by increasing the density of the air flow, intercooling increases the air mass rate through the turbine and thus increases power output.

#### 2.1.3.4. Combining Cycle Improvements

One way for conducting thermo-economic analyses of cogeneration systems is demonstrated in [21]. They conclude that intercooled reheat (ICRH) recuperated cycles, when compared to nonrecuperated ICRH, simple recuperated, and simple Brayton cycles, present the highest available thermal efficiency and energy savings index (ESI) at full load, in addition to the lowest penalty in electrical efficiency and ESI under partial load operation. For moderate and low-load applications (5-20 MW), the researchers conclude that non-recuperated ICRH cycles provide the highest return on investment under full and partial-load application throughout the range of fuel, steam, and electricity prices considered in the study, despite its poorer thermodynamic performance when compared to the recuperated ICRH cycle. This difference is mainly attributed to higher equipment costs for the recuperated ICRH cycle [21].

Similar articles have developed mathematical models to describe the effects different cycle modifications have on overall thermal efficiency [22-26]. General theoretical tools have been developed to model the operation of power cycles with multi-stage reheating and intercooling that consider compressor and turbine isentropic efficiencies and heat exchanger efficiency. Such designs give optimized pressure ratios, maximum power output, and maximum efficiency for a specific cycle design [22]. Simulations have also been developed for analyzing the efficiency of regeneration in a combined cycle [23]. Such models, which consider the operation of separate cycle components, may be incorporated into a holistic model for this study.

### 2.1.4. Thermodynamic Modeling Software

Thermodynamic modeling software has emerged as a reliable surrogate tool to working with physical machinery and making modifications to test various system configurations and operational parameters. It is true that the most reliable data for research on power generation cycles is produced via performance data from operating gas turbine engines, but such work is expensive, cumbersome, and impractical.

Thermodynamic modeling software is provided in packages that can be either broadly utilized in thermodynamic analysis or specifically focused on turbine system analysis – both provide solid data upon which researchers can draw valid conclusions about innovative theoretical turbine system designs.

Significant improvements have been made to combustion modeling capabilities since the early 1970s in terms of empirical correlations [27]. Computer modeling has not been able to achieve the degree of accuracy that empirical methods (development and testing of either bench-top or full-scale equipment) provide. However, modeling has still been successful in advancing development of cycle technologies while reducing the time and money invested into development of new combustion products [27]. The widespread use of computer modeling in academic research has demonstrated the possibility of significant increases in existing turbine cycle efficiencies. As of February 2008, the most advanced combined cycle power plants in operation can achieve efficiencies of no greater than 60%, but thermodynamic simulations have demonstrated the possibility of achieving efficiencies of over 62% using a variety of equipment modifications and cycle performance enhancements [28]. While this distinction is modest, small increases in efficiency present large opportunities for emissions reduction.

Considering the logistical limitations of redesigning physical turbine systems and the benefits of computer modeling, an improved design for this research project was based on both empirical data and computer modeling simulations. Empirical data was collected from universities across the nation with CHP systems that run on natural gas. Based upon these performance data, an optimized CHP system design for this project was generated, simulated, and tested using 3 simulation software packages: EES (Engineering

Equation Solver), GSP 11 (Gas-turbine Simulation Program), and ChemCAD. This combination of empirical data with computer modeling provides the most comprehensive means of developing a cogeneration system that fits the needs and demands of a generic large university.

#### 2.1.4.1. Engineering Equation Solver

EES is utilized to calculate numerical solutions to general systems of algebraic equations with specific emphasis on thermodynamics and heat transfer simulations. EES is capable of performing thermodynamic system modeling of all stages in the CHP system design with calculations for energy content and energy transfer (heat and work), and corrections for component efficiency. EES was utilized to model CHP system components that function under ideal, steady state conditions.  A sample window produced in EES is shown below in Figure 2.7.

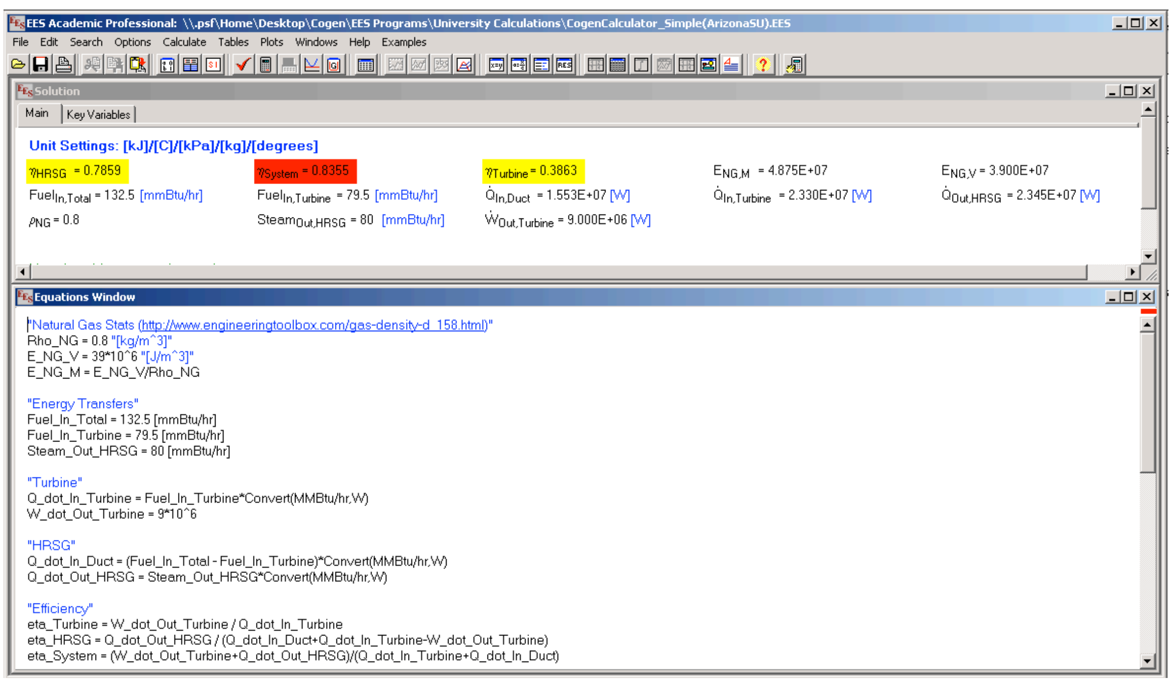



Figure 2.7. EES User Interface with Sample CHP System.

This software has the advantage of providing full control over the design and complexity of the turbine system and all associated calculations. EES is extremely versatile and has the capability of solving over 6,000 simultaneous nonlinear equations while varying the input parameters / boundary conditions over a range of values. EES also utilizes built-in mathematical and thermophysical property functions for many fluids to perform accurate heat transfer calculations (identifying enthalpy, entropy, temperature, pressure, etc). EES can also be programmed to internally convert data among a wide range of measurement systems (including between SI and English units). These capabilities are ideal for performing analysis of individual locations throughout a defined CHP system and calculating the properties of working fluids (air or water) at each location. The development of equations to describe individual elements of a CHP system (compressor, combustor, turbine, heat exchanger, etc) within a single thermodynamic model can also give EES models the versatility to simulate differently designed CHP systems with little additional effort. This is especially useful in standardizing the data collected from the various surveyed plants into a single uniform system of units for comparison.

This software has the disadvantage of requiring detailed coding of all states throughout the turbine or CHP system – effectively the models developed in EES are only as accurate as the equations that the user defines. These models also require detailed data on CHP system performance in order to define the fluid properties at each modeled state (the model cannot be accurately constructed if data is lacking or not provided by plant operators). EES models can readily be developed for ideal and steady state conditions, but it is significantly more challenging to develop non-ideal and transient behavior models of the fluid flows (in which internal losses must be accounted for) as they move through a CHP system. As a result, EES is best utilized to develop simplified approximations of the CHP systems surveyed and calculate general estimates of operational efficiency—to establish broad theoretical trends as it is used in this study.

EES is an established software package that has been utilized for thermodynamics and fluid flow calculations in numerous peer-reviewed research publications and academic textbooks and articles [29-31].

#### 2.1.4.2. Gas Turbine Simulation Program (GSP)

GSP 11 provides for high-level simulations of turbine systems and evaluation of their performance under a variety of conditions. A free, fully functional version of GSP 11 (known as GSP LE) can be downloaded from the NRL GSP website [21]. GSP is a component-based modeling environment that allows for the simulation of a gas turbine / CHP system using predefined system elements (compressor, combustor, turbine, duct burners, heat exchangers, etc) linked together in any user-generated configuration. It calculates solutions to sets of predefined nonlinear differential energy equations for each of the system components and solves them analytically using a "Newton-Raphson based solver optimized for gas turbine models" [21]. These system states and outputs (including temperature, pressure, power, etc.) are calculated from operational parameters and design values defined for the physical components of the CHP system. These values are identifiable via direct measurements in a working CHP system or from published information on existing part performance – manufacturers provide this information in the design specifications.

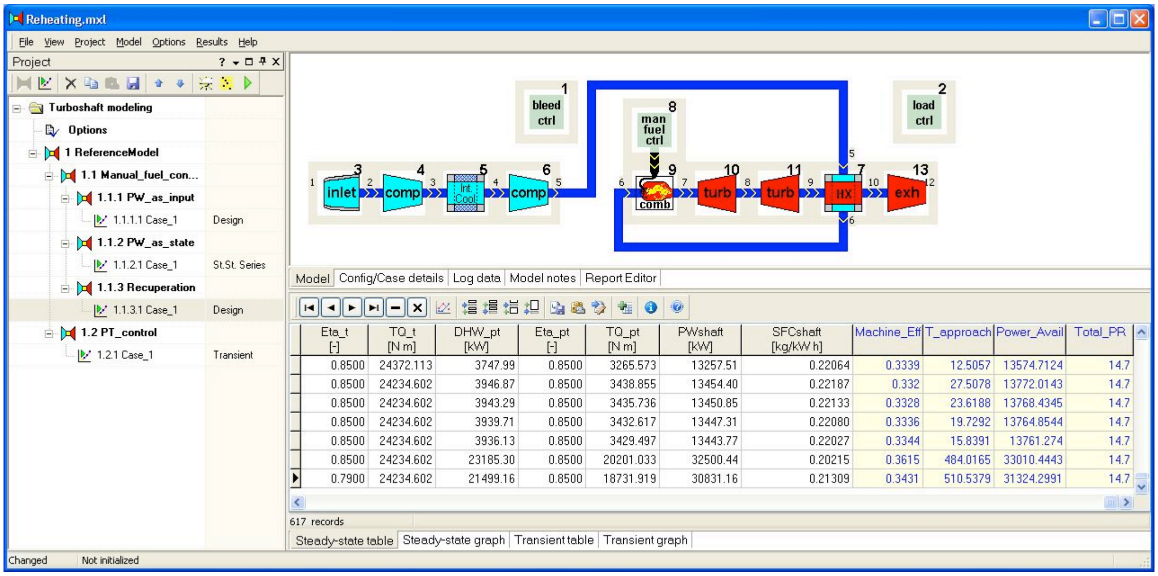



Figure 2.8. GSP LE User Interface with Sample Turbine System.

This software has the advantage of being designed specifically to simulate turbine system operation under a wide range of ambient and design configurations. In GSP, the user does not have to define any energy transfer equations since they are already predefined for each available component. The modeling program is able to simulate combustion reactions (including using both standard turbine fuels and user-defined combustible mixtures) and automatically calculates everything relating to system energy / mechanical output and the properties of working fluids throughout the system. GSP can simulate both steady state and transient operation, and also allows for modeling of non-ideal component performance without substantial or complex user-defined calculations (numerical efficiency values can be independently assigned to each component in a system). Most importantly, GSP was found to be much more flexible than other potential turbine simulation programs in that the attributes (efficiency, operating temperature, etc) of any component are user-defined whereas many programs require the user to select from a list of specific, manufactured components. Turbine simulation programs inspected that fit the latter style include CTI Simulation International's Combined Cycle Gas Turbine Simulator [32] and Thermoflow's GT Pro [33]. These alternative simulation programs can provide more accurate simulations of specific components in a turbine system, but doesn't meet the team's need to model a novel (currently non-existent) CHP system. Finally, GSP incorporates a variety of aerodynamic considerations that EES does not include without direct user input.

This software has the disadvantages of requiring detailed data on CHP system performance and the design parameters for all system components. Initial values are provided for each component, but identifying specific values to change to reflect the true system design takes significant time and effort (specifications like the rotational inertia of the turbine spool, the outlet area, etc.). In situations where CHP systems are located at other universities, it can also prove challenging to identify all component names and operational values and thus develop GSP models. It is also important to note that operational performance of the turbines is often different (less efficient) from the design performance modeled in GSP, thus calculated efficiency values can potentially be higher than the actual values unless proper component efficiencies are factored into the simulations.

GSP 11 / LE and GSP 10 (its predecessor) are established software packages that have been utilized for gas turbine simulations in peer-reviewed research publications and technical reports [34-36]. It is the primary tool for gas turbine performance analysis utilized by (and developed at) the National Aerospace Laboratory (NRL), an independent technological institute that carries out applied research on behalf of aviation and space sectors.

### 2.1.4.3. ChemCAD

ChemCAD is a process flowsheet simulation software used widely in traditional chemical engineering industries to design individual unit operations, larger processes, and entire chemical plants. Simulations are built through an intuitive, drag-and-drop graphical interface. Results are accessed through ChemCAD itself or through reports in Microsoft Word. Figure 2.9 below displays a flowsheet built for this study that simulates a natural gas turbine with part of the extracted power used to power the compressor.

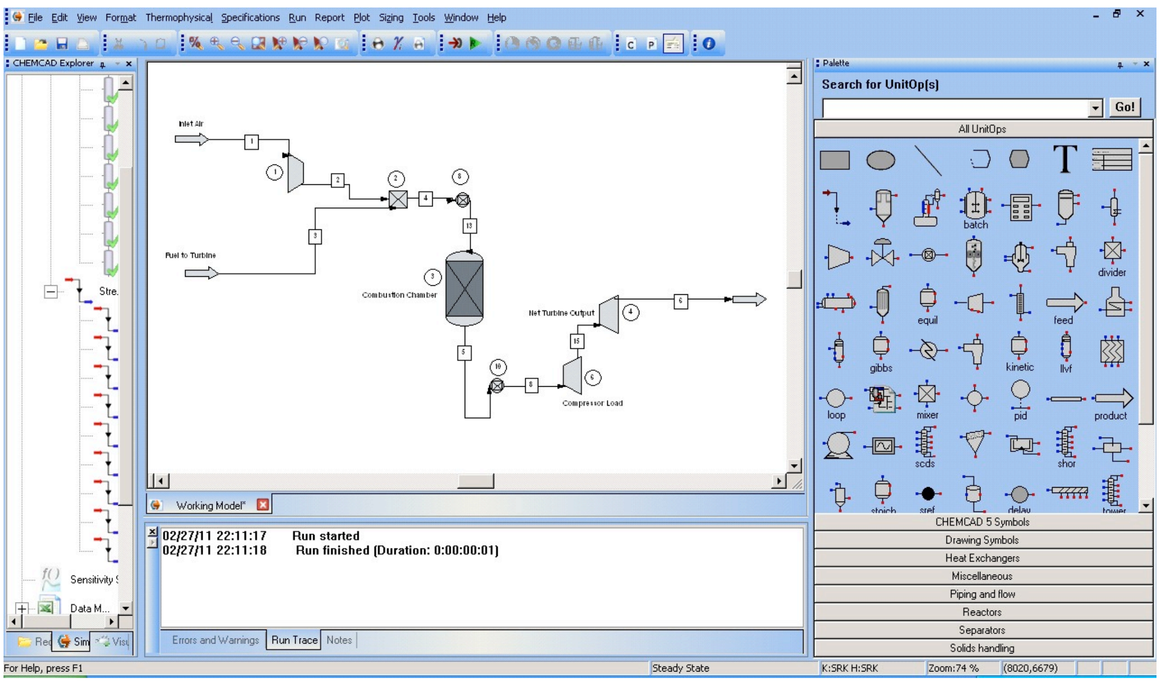



Figure 2.9. Process Flowsheet in ChemCAD Simulating a Natural Gas Turbine.

The primary component of the ChemCAD software is a library of unit operations (reactors, heat exchangers, separation devices, expanders, compressors, controllers, piping, and feed and product flows) that can be connected in any configuration. An extensive library of chemical species and their thermodynamic properties is used to define streams and reactions. Finally, a range of thermodynamic models and computational methods are used to complete the mass and energy balances on the flowsheet.

ChemCAD is used in this study to simulate an entire CHP plant and investigate its performance in response to varying equipment efficiencies. ChemCAD was chosen for this analysis over GSP primarily for its versatility in simulating almost any process or plant. GSP is designed specifically to simulate gas turbines and, while it accounts for certain turbine-specific considerations such as aerodynamics and metallurgy that are lacking in ChemCAD, GSP does not simulate heat exchangers as easily or as fully as ChemCAD. Another feature of ChemCAD that is important to this study is the ability to build sophisticated control and feedback systems into a process.

ChemCAD was chosen over its more popular flowsheet design competitor, Aspen, because of its accessibility and cost. For all the purposes of this research study, there is no difference between the quality of results produced in ChemCAD and Aspen. ChemCAD is an intuitive, freely available, and powerful simulation software that is utilized widely in industry and well-suited for this research study.

### 2.1.5. Novel System Modeling

This research seeks to develop models for improved CHP efficiency through improvements to gas turbine performance. The relationship between these efficiencies is discussed later. Several analytical tools facilitate this process.

#### 2.1.5.1. Pinch Analysis

Pinch analysis is an effective tool for identifying areas that are available for heat recovery improvements. The core of pinch is the process of identifying available hot and cold streams for energy recovery. This project demonstrates the application of the principles of pinch to university-sized CHP plants. These principles are used and extended to identify areas for improvement and where novel heat exchange opportunities lie.

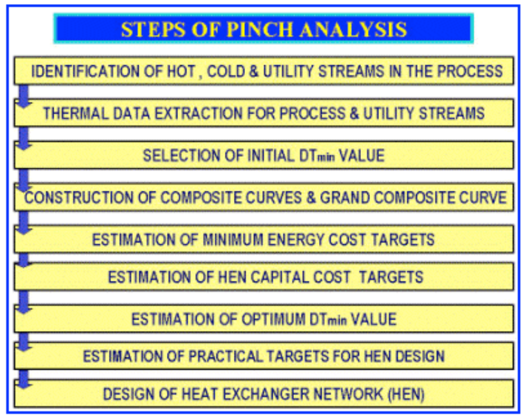



Figure 2.10. Steps in the Conventional Pinch Process [39].

Figure 2.10 shows the basic processes involved in the pinch analysis for an energy plant, a process that has been used many times by various parties to demonstrate potential improvements that can be made using this methodology [40-42]. A central concept to these analyses is the idea of the heat capacity rate [Figure 2.11]. The heat capacity rate is defined as the product of the specific heat of a material and the mass flow of that material. Denoted by the acronym CP, each hot and cold stream in an energy plant is designated a CP value.

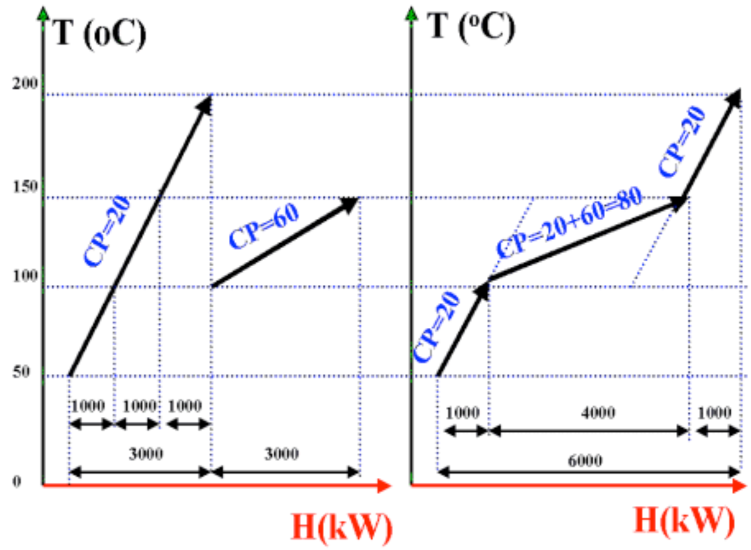



Figure 2.11. Pinch Process Diagrams Showing Heat Capacity.

Figure 2.12 shows how a pinch analysis combines CP values and builds a composite curve. A composite curve can be constructed for both hot and cold energy streams in an energy plant and plotted on the same graph as shown below. At a certain point the hot and cold composite curves reach a point of closest approach, called the pinch point [43].

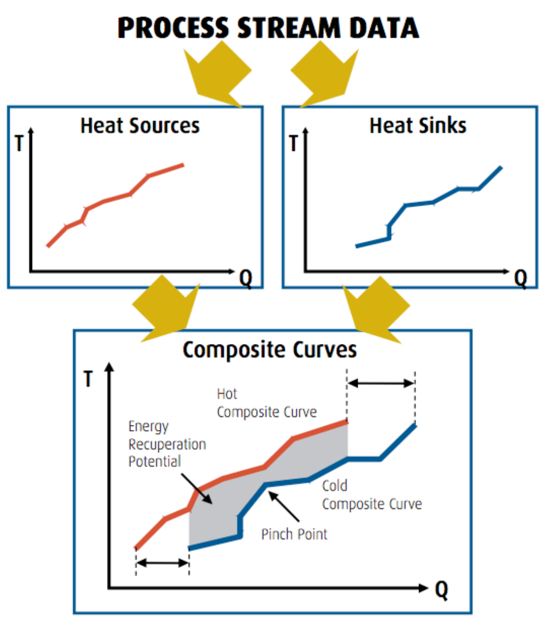



Figure 2.12. Constructing a Pinch Composite Curve.

This composite curve is very useful for identifying areas of potential heat recovery improvements. The shaded area in Figure 2.12 shows the total potential for heat recovery in a system. Effective heat recovery is potential in those regions in which the hot and cold composite curves have a large temperature spread between them. A heat exchanger between the two streams will raise the temperature of the cold stream and lower the temperature of the hot stream. This creates a "pinch" in the graph that results in a net energy savings. This systematic method for identification of potential areas of improvement and quantification of energy savings forms the basis of the novel system changes proposed in this research [43]. It can be observed in cycle enhancements like regeneration, which uses exhaust heat to augment the heat addition process in the combustion can.  Pinch is also visible in the idea of using municipal supply water to provide intercooling, and distributing the heated water in a potable hot water loop.

An area for expansion in traditional pinch analysis is in the relative weighting of different energy streams (the recognition that steam is less valuable per MW than electrical energy because the latter is more versatile). Energy savings have been realized using these principles under a different name: exergoeconomic analysis. A review of these techniques, and an example of its implementation, demonstrate that there is an economic benefit to weighting the relative values of steam versus electrical energy [41-42]. A unification of this idea with the essential elements of pinch analysis will help in the creation of a novel system designs as well as demonstrating potential efficiency gains in small-scale university systems.

#### 2.1.5.2. Approaches to Novel System Designs

One class of novel system design that has been analyzed by many academic papers is combining the thermodynamic cycle of a gas turbine with a renewable energy source to enhance the overall efficiency. One such combination that has been studied and effectively employed [44-46] is the combination of a combined cycle gas turbine engine and a solid-oxide fuel cell. Analysis yields an optimal operating point for the system, and most interestingly, an operating electrical efficiency of 60%. Coupled with a heat recovery system, this means conversion efficiencies over 80% can be realized [47]. This is an impressive result, especially since it is operational on the scale of interest to a university. Other unique cycle combinations explored through academic research that yield similar results include various combinations of wind, solar thermal, photovoltaic, and geothermal power with combined cycle gas turbines [45, 48-50].

Another promising technique for novel realizations of energy savings through the use of pinch techniques is the improved use of natural gas substitutes in existing CHP systems. For a greener fuel to be utilized seamlessly in existing turbine combustion systems it must have all the advantageous qualities of the fuel presently used: natural gas or fuel oil. These fuels have the ability to be compressed, liquefied, and injected into a high-pressure environment. One promising candidate is syngas. Syngas is a synthetic gas produced by gasification of solid-state fuels like biomass and garbage. It has half of the energy density of pure natural gas, but it is easily made and it is easily converted into synthetic biofuels. In addition, syngas is compressible, and suitable for high-pressure gas turbine applications. Along with traditional gasification techniques, two promising modern techniques for production of syngas include direct current plasma gasification and radio- frequency plasma gasification [51-52]. These are new techniques that can be easily implemented at a small-scale installation like a university. Other opportunities for enhancements to the pinch process involve substitution of natural gas for less premium fuels like agricultural waste, in applications amenable to this replacement. Burning wood-derived biogas in a duct burner or boiler, where particulate matter causes fewer complications than it does in a gas turbine, could yield the same energy production values at a lower environmental cost.

### 2.1.6. Measurement Methods and Limitations

Incorrectly measured and reported operational data can have a significant impact on analyses of system efficiency. The following section pairs an overview of basic measurement devices with a discussion of their accuracy and effects on an overall measurement system.

Flows can be described by either volumetric flow rates or mass flow rates. Volumetric flow meters are often accompanied with density meters for conversion to mass flow rate, which is more useful in the context gas turbine power output. Flow rates are often reported in units of energy per time (e.g. Btu/hr), which can be converted to mass or volumetric flow rates if the energy density is known. Flowmeters must be calibrated against a flow of known profile (i.e. fully developed and laminar). Thus an ideal calibration would occur with the working fluid in a straight, smooth pipe of sufficient length to ensure a fully developed flow.

#### 2.1.6.1. Volumetric Flow Measurement

##### 2.1.6.1.1. Differential Pressure

Differential pressure (DP) flowmeters operate by sensing differences in upstream and downstream pressures across a constriction. They have historically been the most widely used flowmeters and are very well-researched [53]. DP devices continue to be fairly dominant in today's flowmeter market despite the availability of more accurate, reliable devices such as ultrasonic and Coriolis meters [54]. Common examples are orifice plates, Venturi tubes, Pitot tubes, and sonic nozzles.

Orifice meters are the most commonly used flowmeter in the natural gas industry [55]. An orifice meter consists of an orifice plate, a thin plate with a hole in the center, inserted into the tube and mounted perpendicular to the direction of measured flow. While the power industry has significant experience with orifice plates, the device presents several difficulties, including the associated pressure loss with the device (which is functionally an obstruction in the flow) and the sensitivity of the device to construction and installation details.

Venturi tubes operate on the same principle as orifice meters, but gradually constrict flow through a pipe of continuously decreasing diameter. With a small enough angle of the diverging conical section, the emerging flow is also fairly unidirectional, as opposed to an orifice tube, where there is a large recirculation/spiraling zone around the *vena contracta*. Thus the pressure loss due to a Venturi tube is less than that of a typical orifice meter, at 5-20% of the measured pressure drop [56].

A Pitot meter also operates by constricting fluid flow and measuring resulting pressure differentials. It consists of a tube that traps the flowing fluid and brings it to rest; the pressure of this resting fluid (the "stagnation pressure" or total pressure) is measured. A second tube is placed in a source of static fluid and the static pressure is measured; since Pitot meters are used commonly in the aerospace industry to measure airspeed, the static source is often the air around the outside of the fuselage [57]. According to

Bernoulli's equation, the difference between stagnation and static pressures is equal to the dynamic pressure of the fluid, which is used to calculate flow rate.

Sonic nozzles constrict the fluid through a short convergent-divergent nozzle. Upstream straighteners/conditioners and an induced turbulence/settling region ensure that upstream effects will have become negligible by the time the fluid reaches the nozzle. At low backpressures, the velocity at the narrowest part of the nozzle is within the sonic range. This effectively "chokes" the flow, preventing any downstream conditions from affecting the flow upstream of the nozzle throat. Sonic nozzles have the most highly controlled flow of any pressure-based flowmeters, with flow in the nozzle being insulated from both upstream and downstream effects. However, the range of flows that a sonic nozzle can measure is limited; multiple nozzles of different throat sizes must be installed to achieve a range comparable to other flowmeters. This in turn means a higher startup cost and greater care required in installing a system of sonic nozzles compared to other pressure-based flowmeters [56].

#### 2.1.6.2. Mechanical Devices

Mechanical flowmeters monitor the time taken by a passing fluid to fill a compartment of known volume. Mechanical flowmeters a generally more accurate than their pressure differential counterparts. They are used in many domestic gas metering applications, and some have been historically (and still are) used as transfer standards by calibration laboratories (for example, the wet gas meter) [56]. They are also accurate within a very large range of flow rates. Turndown is used as a measure of the range over which flowmeters operate, and is defined as the ratio of the maximum to minimum flow rate that can be measured within a given uncertainty. Pressure-based flowmeters operate only within a small turndown, but rotary displacement meters maintain less than 2% uncertainty over a 10:1 turndown, while diaphragm meters maintain a less than 2% uncertainty over a 160:1 turndown [56]. However, mechanical flowmeters can be more costly to construct and maintain than pressure-based devices due to the presence of moving parts. Because of their susceptibility to wear, calibration must be performed fairly often. Leakage between moving parts is also a problem when dealing with low rotational speeds, where leakage is significant compared to the flow. In this case, additional slippage tests must be performed to measure leakage. Also, temperature and pressure changes may cause the closed compartments to expand, not only creating inaccuracy in the assumed volume of these compartments but also increasing leakage [56]. Mechanical devices include positive displacement meters, variable area meters, turbine meters, and vortex meters.

Positive displacement meters (PDMs) rely on the transfer of a moving fluid between closed compartments. Examples of PDMs include the rotary meter, which has a relatively high accuracy and is used in many domestic gas metering applications [56].

Variable area meters rely on the movement of an indicator ball that is tethered or weighed down such that its position is dependent on the balance of the drag force created by the moving fluid and the restoring force (provided by gravity or the spring tether). While the meters provide good visual indication of the flow, they are inaccurate [56].

Turbine meters translate rotary motion into flow measurement, and are used in industrial applications where high accuracy is imperative. These solutions are generally more costly [58].

Vortex meters measure eddies spun from obstacles placed in a flow path, which change characteristics based on flow rate. While the meters are robust over a wide range of flowrates and are insensitive to fluid type, they are heavily affected by upstream disturbances and are primarily designed for turbulent flow conditions.

#### 2.1.6.3. Mass Flow Devices

Coriolis, ultrasonic, and thermal mass meters comprise the main set of mass meters used in industry. Coriolis meters are widely used in the chemical industry and are increasingly replacing positive displacement flowmeters in petroleum custody transfer applications [59]. A Coriolis meter consists of a configuration of parallel bent tubes whose inlet and outlet ends vibrate at different frequencies—via the Coriolis effect—when fluid is pumped through them. The phase difference between the two frequencies is measured and directly related to mass flow rate. Coriolis meters are often considered to have accuracies near ±0.1% [60], can be used with multiple fluids, and can be used to ascertain temperature and density information as well.

Ultrasonic meters measure the difference in transit times between ultrasonic pulses transmitted in and against the direction of fluid flow. They are unobtrusive and relatively accurate (0.5% to 5% [56]) but carry a high initial cost.

Thermal mass meters use an arrangement of heating elements to measure the difference between static and dynamic heat transfer in a fluid, which can be used to ascertain flow. However, without specific heat capacity and density information, and without clean gases, thermal meters suffer from inaccuracies.

#### 2.1.6.4. Temperature Measurements

The predominant industrial temperature measurement device is the thermocouple. A thermocouple measures temperature based upon the voltage difference generated when two connected conductors are placed in a thermal gradient. Thermocouples are the preferred temperature probe because they are inexpensive, small, portable, standardized, and manufactured with interchangeable parts. They can measure a wide range of temperatures, from approximately -200 $^{o}$C to 1800 $^{o}$C [56].

In surveys to university power plant operators, no responses included information on combustion temperature. There are several factors that limit accurate measurement of this temperature. Most obviously, the air stream coming out of the combustor is very turbulent, with pockets of differing fuel:air ratios. Thus the combustor outlet temperature is best characterized as a profile or gradient, whose uniformity can affect average gas temperature and, consequently, power output and efficiency.

In addition to the fact that postcombustion temperature is an unsteady value, any metal probe placed in the air stream exiting the combustor will be affected by heat radiated by the flame/combustion. This radiation energy is proportional to the fourth power of the ($T^4$), according to the Stefan-Boltzmann law [61]. The probe will be much hotter than the air stream it is placed in. Another factor is that the upper limit of current temperature probes is ~1800$^{o}$C, while combustion temperatures typically range from 1800-1900$^{o}$C [56]. Finally, a nontechnical limitation to obtaining postcombustion temperatures is a certain element of privacy associated with these values, which could potentially be used by competitors to market the performance of one turbine over another. Attempts to locate information on combustion temperature revealed that manufacturers are protective of this data.

### 2.1.7. Material / Fluid Characteristics used in Analyses

#### 2.1.7.1. Natural Gas Properties

The thermodynamic modeling systems utilized in this research require detailed characterization of the fuel source – natural gas – in order to properly calculate the chemical reactions and heat generation / transport throughout the CHP system.

The primary fuel utilized in CHP systems is Natural Gas (NG). NG is composed of a mixture of several different hydrocarbons and other molecules, with the percentage composition of its constituents provided below [62]:

Methane ($CH_4$) – 70-90%
Ethane ($C_2H_6$) / Propane ($C_3H_8$) / Butane ($C_4H_{10}$) – 0-20%
Carbon Dioxide ($CO_2$) – 0-8%
Oxygen ($O_2$) – 0-0.2%
Nitrogen ($N_2$) – 0-5%
Trace Gases – 0-5%

This compositional breakdown of NG is present only in its natural form. Commercial NG (delivered to residential / commercial destinations) is typically cleaned and processed into a refined form composed almost entirely of methane (and minor contributions from other hydrocarbons) [62].

The properties of refined NG thus behave in a similar manner to pure methane, and can be approximated as such. The combustion (oxidation) of NG results in the stoichiometric chemical reaction:

$$CH_4[g] + 2O_2[g] \rightarrow CO_2[g] + 2H_2O[l] + 891 \text{ kJ} \qquad (2.4)$$

The properties of NG utilized in this research are provided below:

$\rho_{NG} = 0.8$ kg/m$^3$ [63]
NG Energy Content = 1.027-1.028·10$^3$ Btu/ft$^3$ = 3.826-3.830·10$^7$ J/m$^3$ [63-64]
NG Carbon Content = 0.0306 lb/ft$^3$ = 0.490 kg/m$^3$
= 14.4·10$^3$ kg/TJ = 0.490 kg/m$^3$ [64]

Data is defined for a gas at Standard Cubic Foot (SCF) conditions: 1ft$^3$ of NG at 60ºF (15.6ºC) and 14.73psi (101.325·10$^3$Pa or 1atm). Energy content is defined for higher heating values (HHV), which takes into account the condensation of combustion products expected in stationary combustion [64]. Data was acquired from [65] and [66]. These assumptions are utilized in all subsequent design / modeling calculations for the report. It should be noted that natural gas property fields modifiable in GSP included only the lower heating value. To keep the simulations consistent, all heating values used of natural gas were synchronized.

Given the economic aspect of this research, it is also important to note the costs associated with NG. In 2008, the average price of natural gas used for electric power generation was $9.41 per thousand cubic feet (MCF) at SCF conditions. This represents a $2.10 increase from the $7.31 per MCF observed in 2007 [62].

#### 2.1.7.2. Working Fluid Properties

Two primary working fluids are utilized in CHP systems: an Air / NG mixture for the turbine system and Water ($H_20$) for the HRSG system. NG parameters were defined previously. Air is composed primarily of a mixture of several different elements and other molecules, with the percentage composition of its constituents (by volume) provided below [62]:

Nitrogen ($N_2$) – 78.084%
Oxygen ($O_2$) – 20.948%
Argon ($N_2$) – 0.9340%
Carbon Dioxide ($CO_2$) – 0.0314%
Trace Gases – 0.0026%

The thermodynamic properties of these two working fluids – including enthalpy (s), entropy (u), and specific heat capacities (c) – are developed through thorough experimental measurements and provided as internal data within the modeling programs. The validity of these programs (and the accuracy of the defined fluid properties) was established previously [Section 2.1.4].

EES conducts heat generation and transfer calculations utilizing and interpolating tabulated data for the different fluids. The fluid names utilized in EES are provided in parentheses. The thermodynamic properties for air (Air_ha) as a non-ideal gas mixture use the fundamental equation of state developed by E.W. Lemmon *et. al.* [67] and property correlations are valid for temperatures between 60K - 2000K at pressures up to 2000MPa. The thermodynamic properties for NG are approximated through the use of methane ($CH_4$) as an ideal gas using the constant pressure specific heat correlation developed by G.J. Van Wylen and R.E. Sonntag [68] and are valid for temperatures of 250K - 3500K. $CH_4$ is utilized for "ideal gas properties of methane consistent with reference states used in combustion calculations" [69]. The thermodynamic properties for water substance (Water or Steam) have been implemented using the thermodynamic property correlation developed in Harr *et. al.* [70] and are valid for pressures up to 81.5MPa [69]. These properties are utilized for all thermodynamics calculations in EES.

GSP relies on equations and tabulated data modeling the behavior of air and natural gas in a similar manner to EES, but the tables of data are limited to air, specific aviation fuels, and user-defined fuel mixtures. Less flexibility is provided to the user in this situation, but GSP is far more tailored towards performing calculations with combustion engines. Air properties are defined according to the International Civil Aviation Organization's (ICAO) International Standard Atmosphere [71]. NG properties are defined according to the measured properties of turbine-specific fuels and interpolated properties for user-defined fuel mixtures (based on percent compositions of various hydrocarbons, $H_2O$, $CO_2$, $N_2$, NO, CO, etc). Combustion reactions are calculated according to gas and fuel composition data and standard chemical equilibrium equations. Water properties are included in GSP and heat exchanger operation is based on a user-defined flow and customizable fluid-specific heat transfer coefficient [72].

### 2.1.8. Correlation of Carbon Emissions to Gas Consumption

Section 2.1.7 provided details regarding the composition of natural gas (a mixture of hydrocarbon molecules dominated by methane, $CH_4$) and its combustion in air. This combustion reaction produces numerous byproducts that are known greenhouse gas contributors: $CO_2$ and $H_20$ produced as a direct result of the oxidation of $CH_4$, and the energy released also initiates the production of $NO_X$, $O_3$, and $CH_4$ (uncombusted) in various quantities. These byproducts – $CO_2$, $H_2O$, $NO_X$, $O_3$, and $CH_4$ – are all damaging to the environment as excess greenhouse gases and their production is directly related to the quantities of natural gas combusted.

Natural gas combustion produces $CO_2$ (among the different greenhouse gases) in the greatest quantities per unit of natural gas. The dominant combustion reaction for natural gas in air is provided for reference:

$$CH_4[g] + 2O_2[g] \rightarrow CO_2[g] + 2H_2O[l] + 891kJ \tag{2.5}$$

$$CH_4 = 16.04 g/mol$$
$$CO_2 = 44.01 g/mol$$

$$1.000kg\ CH_4 = 2.743kg\ CO_2$$

Thus, every 1.00 kg of natural gas ($CH_4$) that is fully combusted produces 2.743kg of $CO_2$. At the same time, increasing plant efficiency results in reduced fuel requirements to produce the same amount of electric, thermal, and mechanical power. Decreased fuel consumption thus results in the direct reduction of carbon emissions and the emissions of other pollutants [67].

## 2.2. Engineering Methodology

### 2.2.1. Research Objectives

This study's research methodology is based on two distinct but interrelated research questions:

- To what extent can a large university campus with a district heating system meet its energy needs through a CHP system while reducing carbon emissions?
- How can augmentations to CHP systems such as those at large state universities reduce carbon dioxide emissions?

The first question required consideration of the current political, entrepreneurial, and technological state of CHP systems analyzed within the basis of carbon emissions. Data from these diverse fields was collated and applied to the design of an improved CHP system for a large campus setting. The second question is answered by applying the results of the first question to the concrete example of UMD's current CHP power generation system.

Before forming and testing a hypothesis regarding how to reduce carbon emissions, it was first necessary determine the current state of campus CHP systems. This was accomplished through a survey of the general operating conditions of several campus CHP plants spread across the country, as well as more specific thermodynamic and fluid property information about select universities.

### 2.2.2. Benchmarking CHP Performance

Before developing suggestions to improve campus CHP systems, it is critical to benchmark the performance of existing university CHP systems. The first step in determining the current state of CHP across university campuses is to define a set of parameters enabling construction of a list of universities to contact. Due to the narrow focus of the project on university campuses with existing CHP systems, only universities with existing district heating systems were compiled into a list. Of specific interest for the engineering aspects of the project were those schools with simple or combined cycle gas turbines in operation. The formulation of the research question also specifies only inclusion of large university campuses; however, the number of universities that fall under this label can fluctuate greatly depending on definition. Given that the project concentrates on power generation options, a large university campus will be defined as one that uses at least five megawatts electrical and thermal power. Five megawatts was used as the cutoff for two reasons: first, below five megawatts gas turbines cease to become a major prime mover; second, at lower power levels the market for prime movers gets complicated by the increasing potential for large-scale distributed generation techniques such as micro-turbines, solar panels, and fuel cells.

Several Internet databases of universities with CHP systems were examined and cross-referenced to produce a list of possible schools to survey. A list of 222 schools with district heating systems and 68 with turbine systems was generated. Eliminating schools that produced less than five MW total electrical and thermal power reduced the list to 51 schools. Contact information for relevant personnel at each university was assembled into a single database. Once contacts were gathered, a questionnaire [Appendix 6.1.2] pertaining to the operating conditions of each facility's turbine and CHP system was developed. These questionnaires were sent out with an introductory form email [Appendix 6.1.1] introducing each contact to Gemstone and the research.

This questionnaire was initially designed with the intent to gather thermodynamic operating data of university CHP systems that would allow a relatively comprehensive consideration of current efficiency levels. Initially, a low survey response rate presented an unexpected challenge, and prolonged the survey process as further inquiries were sent to non-responsive contacts. Figure 2.13 illustrates the final response characteristics: approximately a 22% response rate and a 50% non-response rate. Ultimately, enough responses were obtained to allow for meaningful analysis and conclusions; however, the difficulties encountered during the survey process are noteworthy due to the potential implications for the state of communications in the university CHP industry.

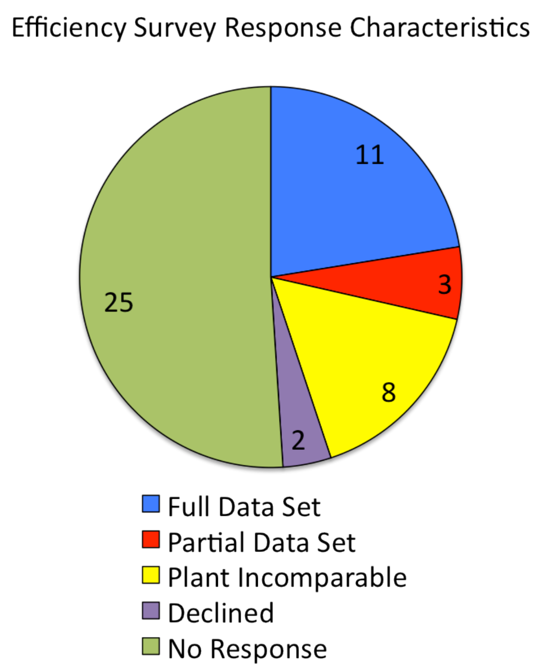



Figure 2.13. Plant Efficiency / Operational Data Survey Response Breakdown.

In addition, those schools that did provide a response to the survey often did not measure key variables that this study was looking for or had inaccurate measurements.

One such thermodynamic measurement, in particular the temperature after the combustor, is largely unmonitored (partly because of inaccuracies discussed above). Further reading about measurement techniques and fluid flow, along with conversations with turbine engineering representatives at General Electric, revealed that this measurement in particular is very hard to collect because of the very dynamic nature of the gas stream at this point in the engine cycle. Measurement techniques, discussed in detail earlier in the literature review, are thus subject to large errors due to large spatial temperature gradients, effects such as stagnation temperatures, and equal contributions (to an order of magnitude) of forced convection and radiative energy transfers. For example, according to the mass flow numbers given, the turbines at one particular university surveyed would be running at a far too rich condition with about half of the air flow expected given the physical turbine properties. The troubles encountered with this university's data raised serious questions about the accuracy of the data received from other universities.

To confront this problem and ensure uniformity of testing procedures, more generalized surveys [Section 6.1.3] were formulated. The same objective, the overall efficiency, is calculable using both methods. In the new procedure, the details of each stage of the gas turbine are ignored and the efficiency comes from a more basic energy balance of a control volume encompassing the plant including the fuel consumed, and condensate returned versus electrical and thermal energy produced. Unfortunately, this method does not allow for a detailed analysis of the operation of the gas turbines. Part of the original interest of the research was to model each turbine and compare each on an equal footing at a common ambient temperature and load condition. To do so, it would be necessary to know the thermodynamic properties of the airstream at each stage of the turbine. However, the focus of the research quickly changed course given larger inaccuracies with the data collection. The new method of data collection allows for efficient characterization of plant efficiencies and potential measurement problems.

Despite the setback, 11 complete data sets were collected. With this data, a procedure for comparing and analyzing each data point was developed.

### 2.2.3. Evaluating Present University Performance

Each data set was analyzed to extract efficiencies and identify measurement errors for both the turbine engine and the CHP system as a whole. Evaluation of the data was performed using Engineering Equation Solver (EES). Custom system models were developed in EES for individual university CHP facilities.

The models each accepted a set of uniform inputs, consisting of:

- Fuel (fuel type / mass flow rate (kg/s))
- Electricity (power out)
- Steam (temp. in/out at the HRSG / pressure in/out at the HRSG / flow rate)
- Atmospheric conditions (temperature / pressure)

Collected data was given in a range of units. All values were converted within EES into SI units [Figure 2.14]. Accommodations were made in each model to capture unique system features such as fuel division between the combustor and duct burners, the presence of boilers for added steam load, and the inclusion of make-up water to accommodate steam losses in distribution.

The models each produced a set of uniform outputs, consisting of:

- Subsystem operational efficiency (turbine / HRSG)
- Overall system efficiency

The efficiency metrics for subsystems were calculated directly from power and enthalpy values determined at specific locations in the CHP systems. Though several metrics exist for evaluating CHP systems with no consensus about which is the most accurate, this study's consideration of CHP within a holistic framework motivated the choice of the US EPA's standard methods for calculating efficiency [70]. Efficiency of the turbine was calculated from (2.6), shown below.

$$\eta_{Turbine} = (\dot{W}_{Turbine,\,Out})/(\dot{Q}_{Turbine,\,In}) \tag{2.6}$$

Electric power produced by the turbine system ($\dot{W}_{Turbine,\,Out}$) was reported by the plant operators. Heat transfer rate input into the turbine system ($\dot{Q}_{Turbine,\,In}$) via the combustion of fuel was calculated from the natural gas flow rate into the turbine and the energy content of natural gas ($39 \cdot 10^6\ J/m^3$) [63-64]. Efficiency of the HRSG and steam distribution system was calculated from (2.7), shown below.

$$\eta_{HRSG} = (\dot{Q}_{HRSG,\,Out})/(\dot{Q}_{Turbine,\,In} - \dot{W}_{Turbine,\,Out} + \dot{Q}_{Duct,\,In}) \tag{2.7}$$

Thermal power produced by the HRSG system ($\dot{Q}_{HRSG,\,Out}$) from the turbine waste airstream was calculated from the difference in enthalpy of the HRSG steam loop inflow / outflow states. Heat transfer rate input into the airstream ($\dot{Q}_{Duct,\,In}$) via duct burners after the turbine and prior to the HRSG was calculated in the same manner as $\dot{Q}_{Turbine,\,In}$. Overall system efficiency was then calculated via (2.8), shown below.

$$\eta_{System} = (\dot{W}_{Turbine,\,Out} + \dot{Q}_{HRSG,\,Out})/(\dot{Q}_{Turbine,\,In} + \dot{Q}_{Duct,\,In}) \tag{2.8}$$

CHP system efficiency is calculated as the ratio of net electrical and thermal power produced by the system ($\dot{W}_{Turbine,\,Out} + \dot{Q}_{HRSG,\,Out}$) to the net thermal power ($\dot{Q}_{Turbine,\,In} + \dot{Q}_{Duct,\,In}$) put into the system. The full model for a sample system is provided in Figure 2.14 below.

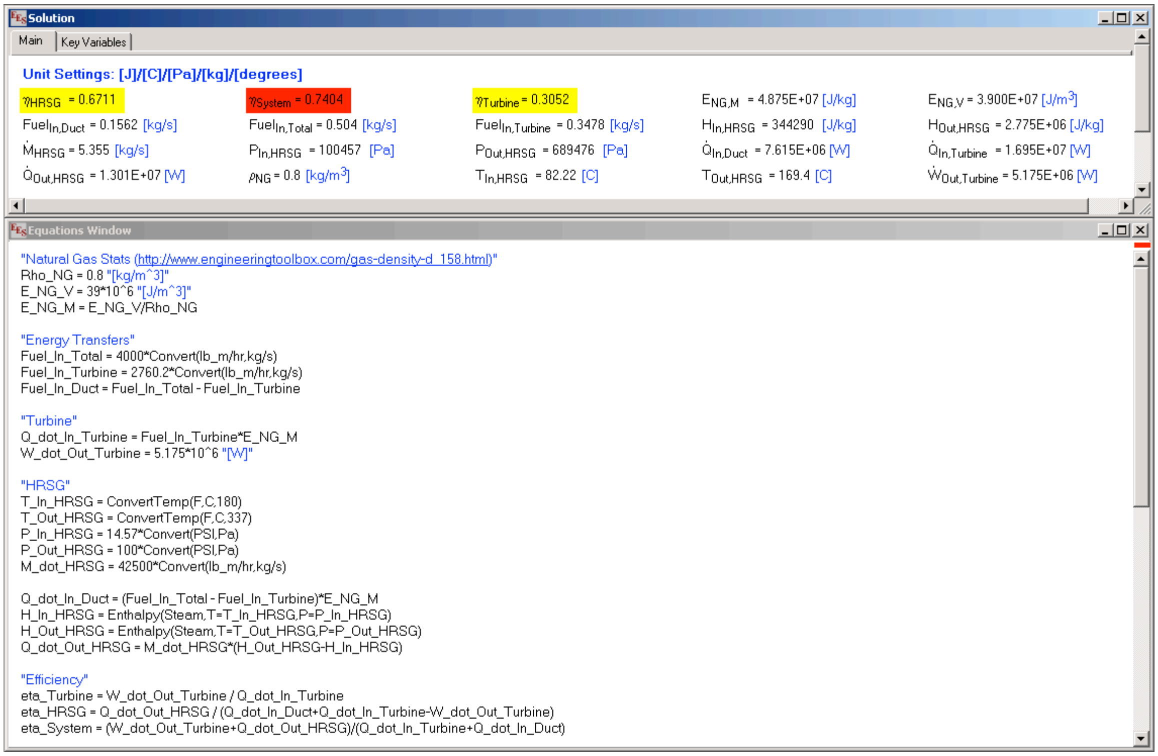



Figure 2.14. Sample CHP Simulation Developed in EES.

The team also strove to develop mechanisms for verification and trending of data acquired from the various respondents. Following the development of a university model, the results were evaluated to identify suspect data (data deviating significantly from anticipated efficiencies and energy production levels). The sources of these errors were numerous: improper measurement units, poorly calibrated sensors, and malfunctioning sensors were all cited by plant managers as acknowledged problems. In such cases the team re-contacted plants for additional information and often worked with the university contacts to fill information gaps or address problematic aspects of the data.. Tracking of plant performance on a monthly / seasonal basis (to identify weather impact on performance) was initially proposed and pursued by the team, but insufficient responses from universities precluded a full analysis at this time.

In certain situations, universities opted to provide historical data sets containing annual operational trends for the CHP plants. These data sets typically documented monthly cumulative or average values for specific data elements (electricity / steam production, fuel consumption, etc.) and indicated annual efficiency fluctuations. These compilations, however, did not track other important elements such as HRSG pressures / temperatures, which are utilized for calculating state enthalpies and system efficiency. For this reason, the team opted to analyze systems based on real-time operational data samples rather than these long-term trends.

In these simulations, efficiency calculations assessed the ability of a CHP facility to convert chemical energy into a useable electrical / thermal form. Equal weighting was given to both forms of energy production in the efficiency calculations. It is also possible to utilize a non-uniform weighting, given the different uses of the two energy types on a university campus: steam is typically limited to hot water, heating and cooling applications, while electricity is typically a flexible, more valuable source of energy. In addition, electricity can be easily utilized to produce steam, while steam is not easily converted to electrical energy. Consideration should also be given to the fact that universities often design their facilities to meet steam loads, confirmed by conversations with facility managers during the survey process. This is a potential area of future expansion for this research and would depend on input from the Business Subteam to identify an economic valuation of the two energy forms.

Preliminary analysis of non-ideal flow and component performance within generic CHP systems was also performed via EES models. These models proved challenging to tailor to real-world system inefficiencies and required significantly greater amounts of plant performance data (temperature and pressure readings, etc). As a result, the models utilizing an ideal performance assumption are sufficient for the level of detail acquired in the basic multi-university survey. Furthermore, the team opted to instead perform the non-ideal CHP system analysis using the Gas Turbine Simulation Program (GSP).

Analysis of the general and detailed university data collected led to the formation of a testable hypothesis: exotic thermodynamic cycles in a university CHP plant are feasible, but the best way to reduce carbon emissions immediately is to install a good turbine in an existing heat recovery system. The team tested this hypothesis through two different computer-modeling approaches.

### 2.2.4. The Effect of Turbine Efficiency in CHP Systems

This study's research is based on the assertion that significant reduction of carbon emissions begins with improvement of turbine efficiency. However, while CHP cycle modifications such as reheat and recuperation provide measurable improvements in system efficiency, the relationship between turbine efficiency and overall CHP efficiency may be less obvious. In an informal interview conducted with Solar Turbines, the world's leading producer of stationary turbines, it was suggested that a CHP system's thermal efficiency is improved by a less efficient turbine because a greater quantity of recoverable waste heat is produced [19].

If the flow of energy through a CHP system is considered, this assertion is not necessarily true. Figure 2.15 shows the possible paths that fuel fed to a CHP system may take: it may be converted into electrical energy, thermal energy, or waste heat through a turbine, HRSG, or boiler/duct burner.

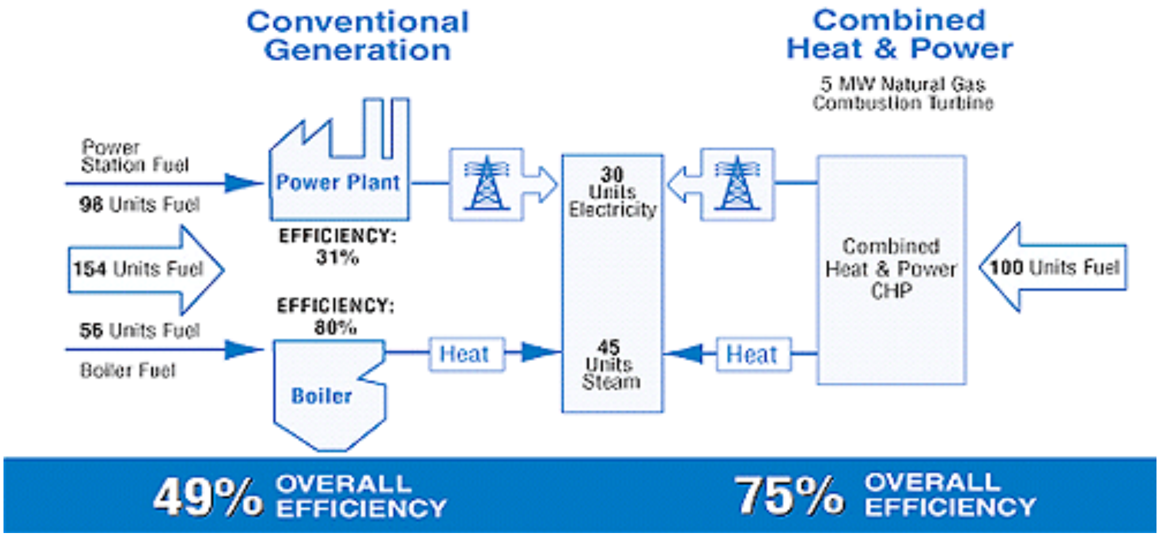



Figure 2.15. Fuel Fed to a CHP is Converted into Electrical Energy, Thermal Energy, and Waste Heat Through a Number of Paths [73].

The industry representative from Solar Turbines states that more of the fuel fed to the turbine leaves as waste heat that can be recovered by a HRSG to produce steam. However, the placement of a more efficient turbine in an existing CHP results in less fuel being required to produce a set amount of electricity. Thus, more fuel can be diverted to the boiler to meet a steam demand. The resulting relationship between turbine efficiency and overall CHP efficiency was investigated by modeling a CHP plant in the simulation software ChemCAD.

ChemCAD was used to model a simple cycle system with steam production from the exhaust heat (a basic CHP plant) with a total electrical demand of 8.51 MW and a steam demand of 43,000 lb/hr (corresponding to data from UMD's CHP plant). The process flowsheet is shown below in Figure 2.16.

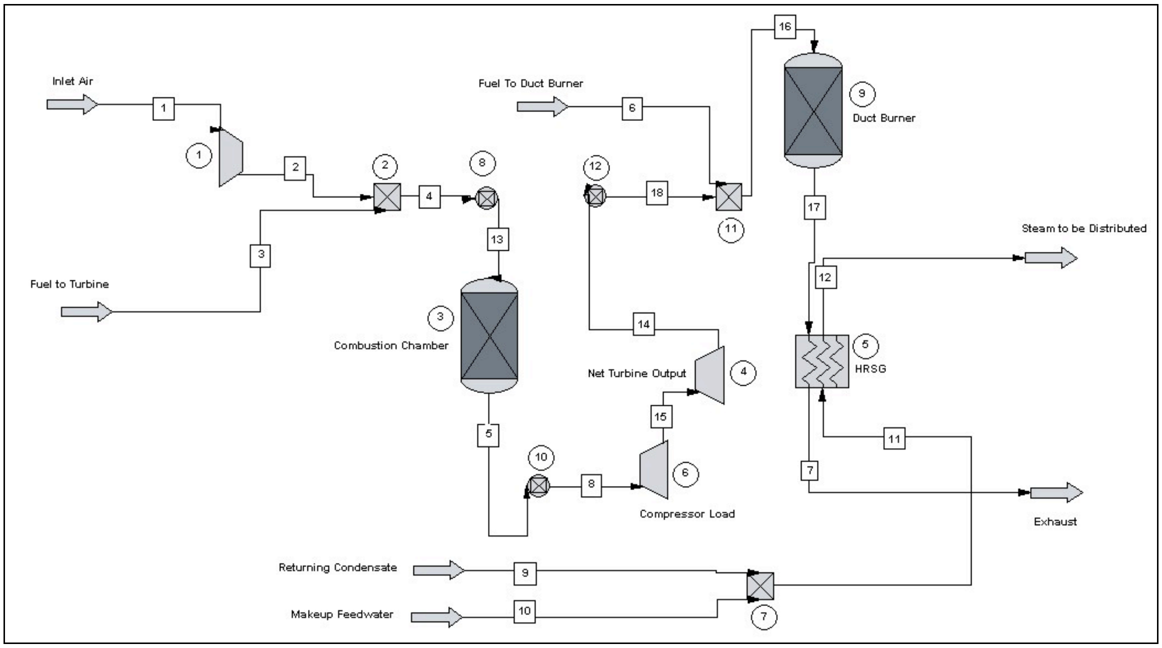



Figure 2.16. ChemCAD Model used to Simulate a Typical Combined Cycle System.

Fuel (methane) is mixed with a stoichiometric amount of air and combusted in a combustion chamber, and then expanded to generate electrical power to drive the compressor and meet the set external load. The turbine exhaust is heated in a duct burner and run through a HRSG to produce high-pressure steam (4171 kPa) from returning condensate and makeup feed water. The user defines a turbine compressor efficiency, turbine expander efficiency, and desired electrical load, and the model calculates the fuel flow rate required to meet the electrical demand. The "baseline" fuel flow rate is defined by current UMD operating efficiencies (28% turbine efficiency, 83% compressor efficiency, and 79% expander efficiency). Compressor and expander efficiencies (and thus turbine efficiency) were increased up to 90% efficiency, and the quantity of fuel "saved" as turbine efficiency was increased—i.e. the difference between the required and baseline fuel flow rates—was fed to the duct burner. The resulting effect on overall CHP efficiency was then observed. The results from this simulation are presented and discussed in detail in Section 2.3.2.

### 2.2.5. Dynamic Modeling of Turbine Performance

Detailed studies of Brayton Cycle enhancements (e.g. intercooling and recuperating) require a nuanced modeling environment, capable of handling several simultaneous thermodynamic and aerodynamic considerations. While such effects as aerodynamic drag through turbine housing, heat transfer through regenerative heat exchangers, and the relationship between shaft torque and machine power output could be manually programmed into a work environment like EES, the process would be painstaking and ultimately incomplete. While EES and ChemCAD were useful tools for verifying certain theoretical trends, they lack sufficient detail to simulate details of turbine performance as it changes with several key operational variables. The Dutch National Aerospace Laboratory's Gas Turbine Simulation Program (GSP), a component based modeling environment used primarily to simulate jet engine performance, was used to provide a more detailed perspective on terrestrial turbine operation.

#### 2.2.5.1. General Simulation Procedure

GSP provides a high degree of flexibility regarding component arrangement for the simulated gas turbine. While a number of pre-loaded component arrangements are provided with the software package, several designs had to be customized to complete the desired simulation. This was achieved by dropping components from a repository window to the current work environment. A typical simple-cycle gas turbine that comes as a default arrangement in GSP is shown in Figure 2.17. Following is the component repository window and an example of a customized layout built for the purpose of this study.

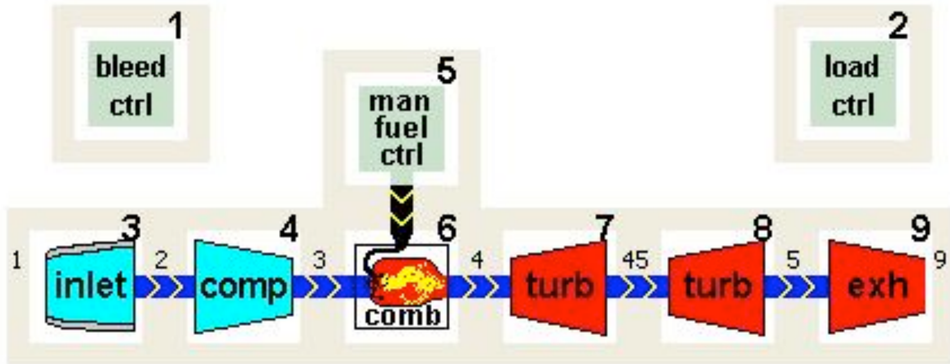



Figure 2.17. Simple Cycle Turbine Component Arrangement (Default in GSP).

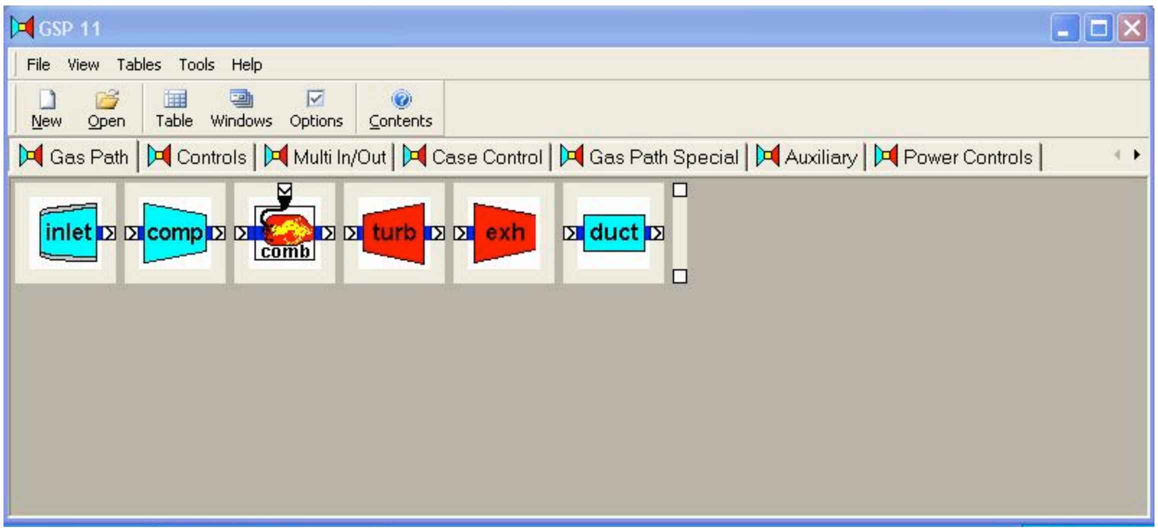



Figure 2.18. Component Repository in GSP.

Shown above in Figure 2.18 is the collection of components that can be added to a work environment. Components are grouped according to the tabs, and include both physical components (turbines, combustors, valves) and control mechanisms. These can be used to build a turbine model such as the one shown below in Figure 2.19.

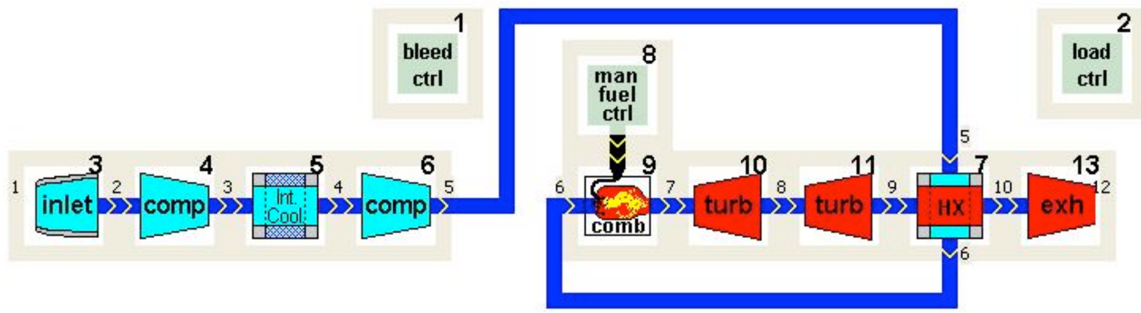



Figure 2.19. Intercooled and Recuperated Engine Model Created in GSP.

After the engine was built in the simulation environment, operational parameters were changed to achieve the desired output. The following list displays the most commonly modified variables:

- Air mass flow rate
- Compression ratio
- Intercooler inlet flow rate
- Intercooler inlet water temperature
- Recuperator heat exchanger effectiveness
- Combustion temperature
- Fuel mass flow rate
- Turbine shaft torque

Modification of these variables allowed turbine performance to be correlated against changing independent operational parameters. Data was extracted from the output table in GSP, shown below in Figure 2.20.

| ETA_b [-] | Elnox_b | Elco_b | Eluhc_b | SN_b | TT8 [K] | PT8 [bar] | W8 [kg/s] | DHW_t [kW] | Eta_t [-] | TQ_t [N m] | DHW_pt [kW] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.9850 | 0.00 | 0.00 | 0.00 | 0.00 | 865.16 | 1.48254 | 48.3147 | 27972.57 | 0.8500 | 24372.113 | 3751.58 |
| 0.9850 | 0.00 | 0.00 | 0.00 | 0.00 | 865.08 | 1.48208 | 48.3125 | 27972.57 | 0.8500 | 24372.113 | 3747.99 |
| 0.9850 | 0.00 | 0.00 | 0.00 | 0.00 | 868.51 | 1.51094 | 48.3292 | 27814.74 | 0.8500 | 24234.602 | 3946.87 |
| 0.9850 | 0.00 | 0.00 | 0.00 | 0.00 | 868.43 | 1.51048 | 48.327 | 27814.74 | 0.8500 | 24234.602 | 3943.29 |
| 0.9850 | 0.00 | 0.00 | 0.00 | 0.00 | 868.35 | 1.51002 | 48.3248 | 27814.74 | 0.8500 | 24234.602 | 3939.71 |
| 0.9850 | 0.00 | 0.00 | 0.00 | 0.00 | 868.27 | 1.50956 | 48.3226 | 27814.74 | 0.8500 | 24234.602 | 3936.13 |
| 0.9850 | 0.00 | 0.00 | 0.00 | 0.00 | 1598.44 | 3.92195 | 49.325 | 27814.74 | 0.8500 | 24234.602 | 23185.30 |

Figure 2.20. GSP Data Output Table

The above columns were output from the GSP simulation by selecting a customized mix of fields to display. Several desired measured quantities were not calculated natively by GSP, and a customized formula was plugged into the output table. The following three quantities were used most commonly:

- Approach temperature (for intercooler / regenerator): $T_{2a} - T_{2b}$, where $T_{2a}$ is the first stream exit temperature and $T_{2b}$ is the second stream exit temperature.
- Available shaft power: $\dot{W}_{T1} + \dot{W}_{T2} - \dot{W}_{C1} - \dot{W}_{C1}$ where $\dot{W}_{T1}$ is the power output from the first turbine stage, and subsequent subscripts represent the second turbine stage and the first and second compressor stages, respectively.
- Machine efficiency: $\dfrac{\text{Available Shaft Power}}{50030 \cdot \dot{m}_{fuel}}$, where 50,030 kJ/kg is the low estimate of the heating value of the natural gas used as fuel for the turbine.

#### 2.2.5.2. Program Validation

The immense flexibility GSP provides for creating and simulating gas turbine performance also brings the danger of unrealistic results. If certain selected settings were to push the simulation beyond the boundaries of physical possibility, and the program did not automatically catch the error, the data produced in that simulation could be compromised. As such, before GSP was used to run novel cycle simulations, it was used to emulate output from one existing university plant, proving it could simulate real world conditions. The exact procedure for changing operational parameters during this study can be seen in Appendix 6.1.6.

A simple cycle gas turbine was used with modified input parameters. The outputs from the simulation, along with those measured from the university plant, are shown in Table 2.1.

Table 2.1. GSP Model Output and University Data Comparison.

| Statistic | University Data | Model Output | Percent Change |
|---|---|---|---|
| $T_{amb}$ [K] | 292.6 | 292.6 | 0 |
| $T_{comp}$ [K] | 702 | 703 | 0.14 |
| $T_{comb}$ [K] | 1349 | 1343 | 0.44 |
| $T_{exp}$ [K] | 780 | 791 | 1.41 |
| $P_{amb}$ [bar] | 1.013 | 1.013 | 0 |
| $P_{comp}$ [bar] | 14.7 | 14.71 | 0.07 |
| $P_{comb}$ [bar] | 14.7 | 14.71 | 0.07 |
| $P_{exp}$ [bar] | 1.013 | 1.013 | 0 |
| $m_{air}$ [kg/s] | 46.3 | 46.3 | 0 |
| $m_{fuel}$ [kg/s] | 0.702 | 0.72 | 2.56 |
| $\eta_{comp}$ | 0.825 | 0.825 | 0 |
| $\eta_{turb}$ | 0.79 | 0.825 | 4.43 |
| $W_{net}$ [MW] | 9.037 | 9.063 | 0.29 |

As shown, the largest percent difference is between the measured and programmed isentropic efficiency of the machine (4.43%). This difference exists in an input category, and could have been changed to reflect a 0% difference, however this change would have affected total power output. The simulation was run until power output levels (often considered the most critical operating characteristic of a gas turbine) were within a 1% difference. Overall, with no category above 5% difference, the simulation program was determined to be a valid tool for novel cycle simulation.

### 2.2.5.3. Effect of Ambient Temperature

Before cycle enhancement simulations were run, GSP was used to confirm that ambient temperature has an effect on turbine performance. Colder, denser air in the heating season (October through March) yields increased mass rates in the turbines, which increases their capacity. Colder air is also denser and requires less work to bring to a certain compression ratio. While it requires slightly more fuel to heat up to a desired temperature in the combustion chamber, the decreased amount of compression work should ultimately yields increased machine efficiencies. This phenomenon has large implications for the timing of university data collection (comparison of two sites where data was taken at two different ambient temperatures) and was explored through GSP. A small study was run to change ambient temperature levels as all other operational variables remained the same. Results from this study can be seen in Section 2.3.3.

#### 2.2.5.4. Cycle Enhancement Simulations

The effects of cycle enhancements like recuperation and intercooling were explored through GSP. The first simulation run was an exploration of pressure ratio on overall machine efficiency in recuperated and non-recuperated machines. For this study, the same machine model was used for both turbines; however, in the recuperated case the recuperator was activated and in the non-recuperated case, the recuperator was set to transfer 0 kW of heat energy. For each case, the pressure ratio was gradually increased from 8 to 26, and the overall machine efficiency was measured. For the non-recuperated machine, the machine efficiency was taken directly. For the recuperated case, the recuperator heat exchange level was tweaked until the approach temperature reached between 16 and 17 Kelvin (determined to be a reasonable level for approach temperature). When that temperature was achieved, efficiency was recorded. The results from this study can be seen in Section 2.3.4.

The second simulation studied the effects of both intercooling and recuperating. A turbine model such as the one shown in Figure 2.19 was used. In this case, two independent variables were measured and their effect on overall machine efficiency was recorded. Intercooler mass flow was varied between 0-6 kg/s, with a constant temperature of 300 K. This temperature was chosen based on the expected temperature of municipal supply water in the DC area in July [74]. At each level of intercooling flow, the recuperator heat exchange level was gradually changed until an approach temperature of 16-17 K was reached. The machine efficiency was tracked throughout this process and recorded. Results can be seen in Section 2.3.4.

## 2.3. Engineering Results

### 2.3.1. State of CHP on University Campuses

The first step in testing our research questions is to determine how CHP plants on university campuses are actually operating compared to how they were designed to operate. Literature review on the topic has demonstrated that the current operation of these turbines is not very well studied and understood. In order to establish a baseline to which any improvements can be compared, 51 candidate universities situated on active district heating systems were identified as generating at least 5 MW of electricity with an on-campus CHP plant. In a survey process lasting several years, plant operators at these universities were contacted and asked to provide sufficient thermodynamic data to calculate turbine and overall efficiencies. Data from this collection process, with names omitted for anonymity, is provided in the Appendix 6.1.4.1.

#### 2.3.1.1. Ambient Temperature Effect on Turbine Performance

Ambient air temperature has a noticeable effect on turbine performance. Anecdotally, plant operators expressed that in colder weather, turbine performance and output (capacity) is increased. A brief study was conducted using the Gas Turbine Simulation Program (GSP) to evaluate the effect of temperature on turbine performance. The results of this study bear on the validity of the university data surveys. Because data sets were collected at the convenience of the plant operator, and because response times varied widely between respondents, collected data pertained to operations at different times in the year. The effect of ambient weather conditions could skew the comparison of university plants—data collected for a superior plant in mid-summer may not be very different from data collected from an inferior plant in mid-winter. Because of the collection process, these differences could not be controlled. However, using a simulation of gas turbine performance in GSP, the effect of ambient weather can be approximated, and an importance level assessed. The effect of temperature variation on simple cycle turbine machine efficiency is shown below in Figure 2.21.

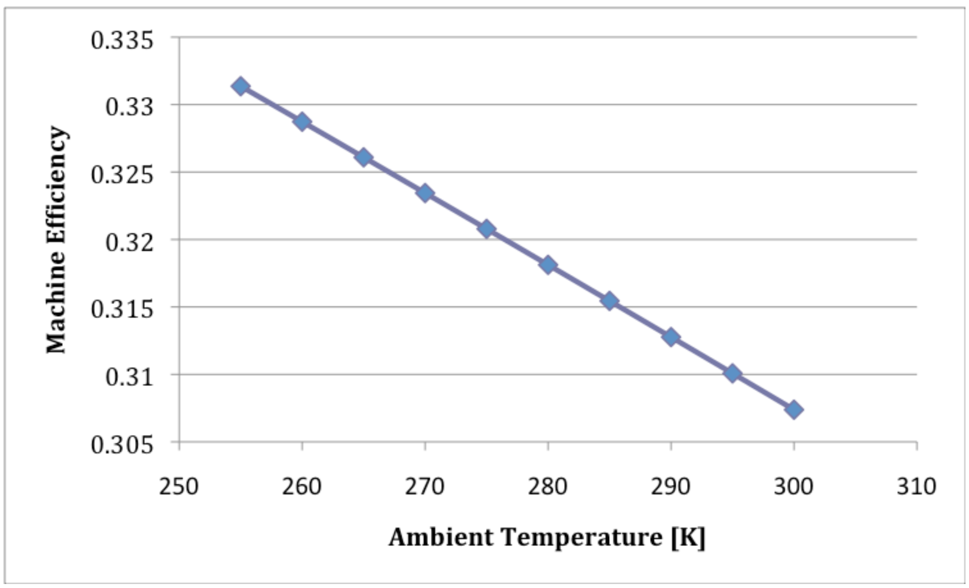



Figure 2.21. Machine Performance Efficiency Dependence on Ambient Temperature.

As shown above, an ambient temperature variation between 255 K and 300 K causes a drop in efficiency of about 2.5%. It should be noted this decrease is lower than that cited in literature published by Solar Turbines for its recuperated Mercury 50, which drops 6% in efficiency over the same temperature range. This drop in efficiency represents a decrease in available power produced by the turbine for a given level of fuel input. A decrease in available power corresponds to a decrease in the turbine output power relative to the compressor input power. This is shown in Figure 2.21.

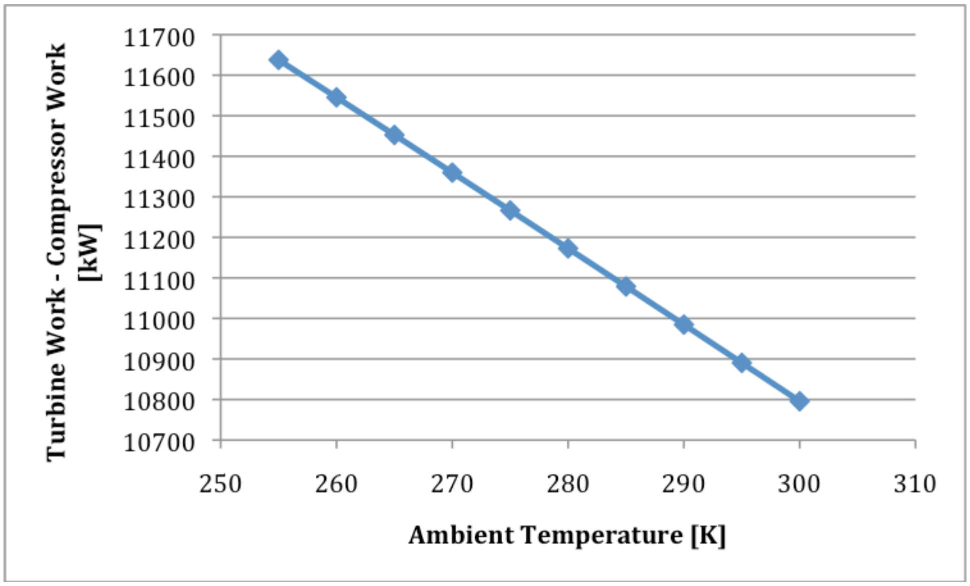



Figure 2.22. Difference Between Turbine Work Output and Compressor Work Input vs. Ambient Temperature.

While the difference between turbine work input and compressor work output decreases over the temperature increase – resulting in decreased machine efficiency for the same level of fuel input – both the individual quantities (turbine and compressor work) increase with temperature. This is shown in Figure 2.23.

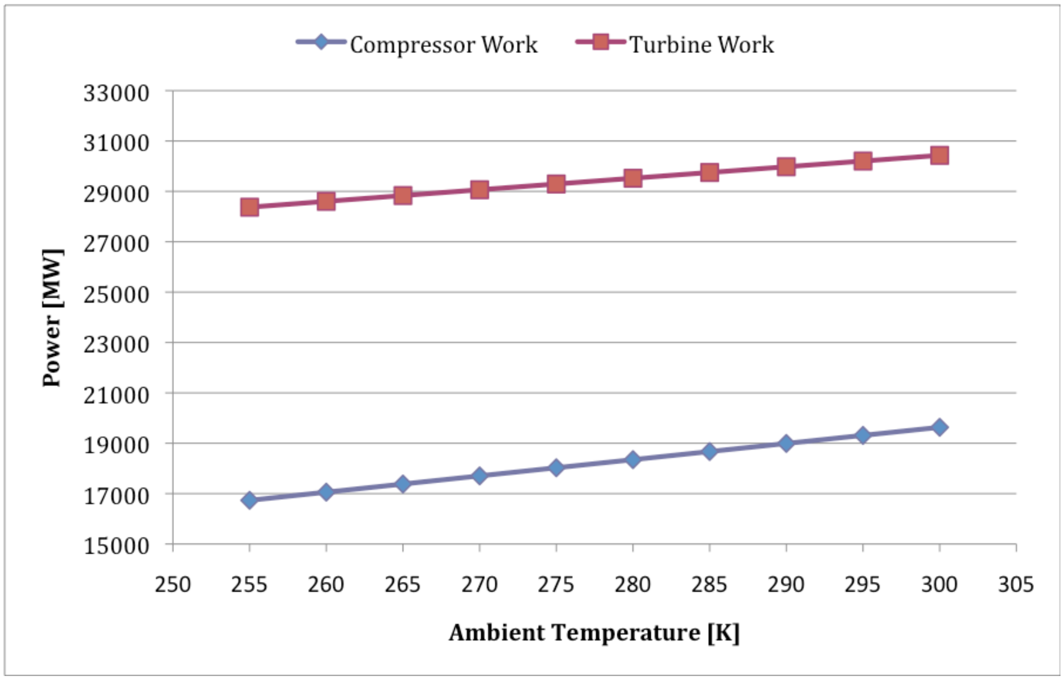



Figure 2.23. Compressor and Turbine Work over Time vs. Ambient Temperature.

Turbine work increases because the inlet temperature to the machine increases (as ambient temperature rises). This increase in inlet temperature propagates downstream, causing increases in the post-compression and post-combustion temperatures. With more heat to extract from the air stream, the turbine increases in work output. The compressor work input increases by a slightly larger amount, leading to the decrease in total machine output, as shown in Figure 2.21. Compressor work increase occurs because the density of the incoming air decreases as temperature increases. Less dense gases require more work to bring to the same compression ratio [18], and compressor input work increases accordingly.

These studies show that turbine performance is highly dependent on ambient temperature. However, in this study, very few campuses provided data for more than one point in the year, making normalization efforts difficult. A more extensive study would include a process for normalizing campus CHP data against ambient temperature.

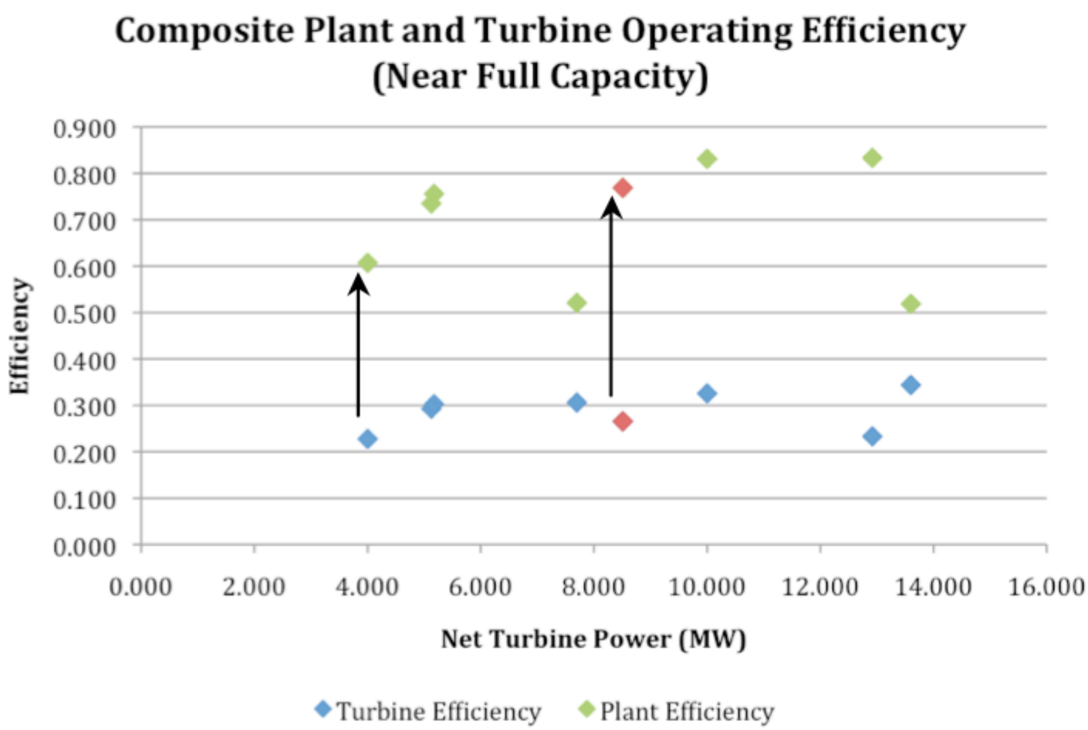



Figure 2.24. Net Plant and Turbine Operating Efficiencies vs. Turbine Power.

Following the method outlined for efficiency calculations, the thermodynamic computation software Engineering Equation Solver (EES) was used to analyze all survey data and calculate relevant quantities. Analysis of the data, shown in Figure 2.24, shows that CHP systems currently implemented on university campuses with district heating systems effectively increase the efficiency of the power generation process and subsequently reduce carbon output. Typical efficiencies seen from the data ranged from 20% - 35% for the gas turbines alone versus 50% - 85% for gas turbines existing in a CHP environment. For a typical gas turbine of this size producing 8 MW of power, an efficiency increase from 25% to 75% corresponds to a carbon savings of over 30 thousand tons of $CO_2$ yearly – assuming stoichiometric combustion, an energy content of $4.3 \cdot 10^7$ J/kg for natural gas, and $2 \cdot 10^7$ seconds (5,556 hours) of uptime over the course of a year. Clearly, CHP in a university campus setting is currently effective in reducing carbon emissions while producing an equivalent amount of power. However, there is still ample room for improvement in the utilization of this energy source on university campuses.

#### 2.3.1.2. Measurement Obstacles and Paradigm Shifts

Mentioned earlier, widespread gaps and inaccuracies in survey results – sometimes leading to operating conditions for a turbine that are thermodynamically impossible – showed an underlying lack of attention to university CHP performance. For example, the data readily available to a turbine operator is insufficient to calculate the efficiency of the turbine. In addition, this research demonstrates that the measurements available are not always accurate. To illustrate this, the airflow rate through one of the turbines at Maryland was directly measured and compared to the data available to plant operators. According to the data available to the operator of the CHP plant at Maryland, 22.1 kg/s of air was passing through the turbine when the specification for the machine was closer to 50 kg/s. To rectify this discrepancy, a pitot tube was used to directly measure the differential stagnation pressure of the air in the exhaust stream. From this raw data, shown below [Figure 2.25], the radial air velocity and subsequently the mass flow rate of air through the turbine can be determined. From the data collected, the mass flow rate was determined to be 46.3 kg/s, in agreement with the specification for the turbine, but more than double the value that was available to the operator of the turbine [Figure 2.26].

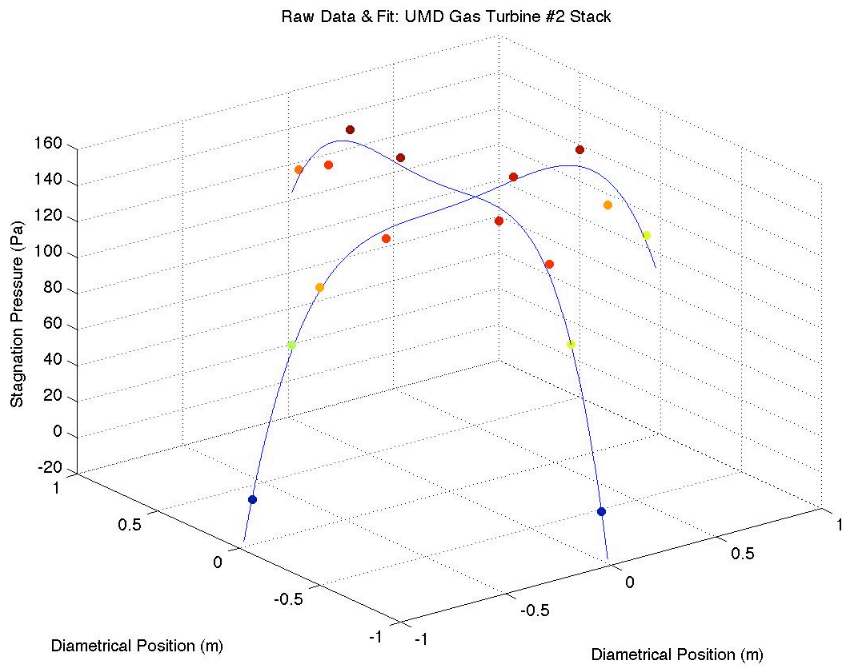



Figure 2.25. Plot of Turbine Stack Air Flow Data and Fit Functions.

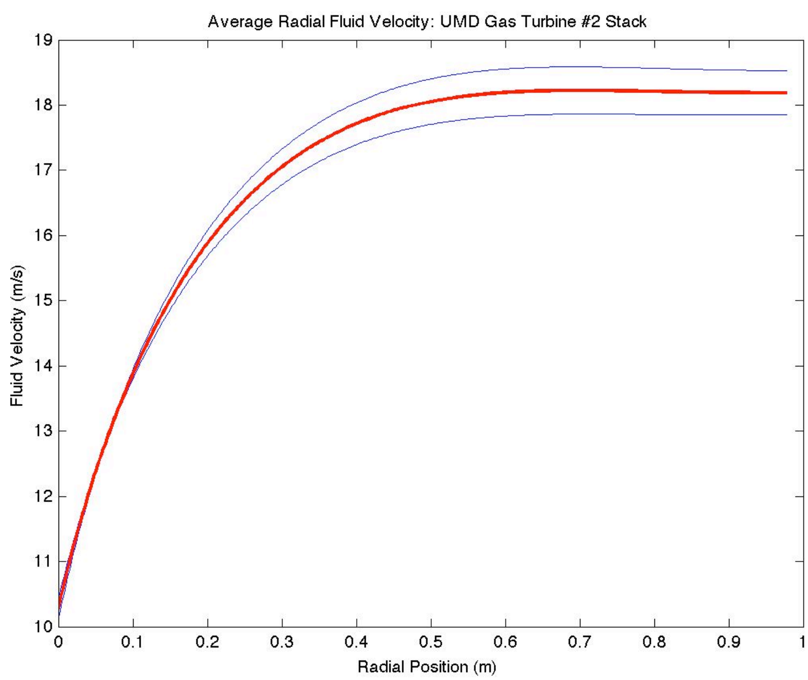



Figure 2.26. Calculation of Average Radial Fluid Velocity in Turbine Stack.

The most significant operations problem identified during the survey was that the vast majority of CHP plants have no formal calculation of net operational efficiency – simply the ratio of energy out (electricity or steam) to energy in (natural gas, etc). Operation is considered satisfactory so long as the plants are functioning within temperature and pressure specifications, producing proper electrical and steam loads at a determined level of availability, and consuming anticipated rates of fuel. For these reasons, it has become apparent that a necessary foundation for tackling the problem of reducing $CO_2$ emissions by university CHP facilities is twofold:

- Ensure functional / accurate sensors are installed in plant monitoring frameworks.
- Establish a system of monitoring, reporting, and verifying plant efficiencies.

Only once these two requirements are met can a university establish its plant efficiency and level of greenhouse gas emissions, and progress towards improving the system in these regards.

Unfortunately, this is not the only obstacle present that prevents calculation of the efficiency of a gas turbine and subsequent CHP plant. Another thermodynamic quantity that is unavailable to plant operators and researchers is the temperature of the gas after combustion and before expansion in the turbine. The unavailability of this crucial quantity is due both to proprietary concerns and difficulty in accurately measuring the temperature of a very hot, heterogeneous gas mixture (as discussed in the Literature Review). This quantity is crucial to determining the efficiency of the machine, because knowledge of the temperature at this stage allows direct calculation of the enthalpy change at each step along the turbine gas stream. Along with an accurate value for the mass flow through the system, this quantity permits calculation of the efficiency of the turbine. This is a major shortcoming in the industry, and points to an interesting direction for further research.

One more disadvantage presented by the difficulties of collecting data from a sample population of university CHP plant managers is the lack of very exhaustive statistical analysis. Given the difficulty obtaining one data set, the study was unable to generate multiple data sets for each university over a range of climate and demand conditions. For this reason, only interesting trends and general conclusions are inferred from the data and not conclusive or causal statements. A worthwhile, multi-year, research project suitable for a university or campus setting would be to collect comprehensive data on this turbine market range and analyze the total carbon saving potential of CHP implementation and advanced cycle improvements.

The university data collected provides a basis for evaluating methods of reducing carbon emissions through CHP. Improvements to CHP efficiency can be broadly divided into two categories: turbine efficiency improvements and thermodynamic cycle modifications.

### 2.3.2. Turbine Performance and CHP Performance

To disprove the idea that CHP systems benefit from the production of recoverable heat from inefficient turbines, it is first helpful to look at collected data from campus CHP plants for insight about the relationship between turbine efficiency and overall CHP system efficiency. Can a high calculated CHP plant efficiency belie inefficient operation of the turbine? Likewise, can a plant with an efficient turbine be considered a poor performer in terms of CHP? To address these questions, each surveyed campus plant's turbine efficiency and CHP system efficiency was calculated and plotted in Figure 2.27.

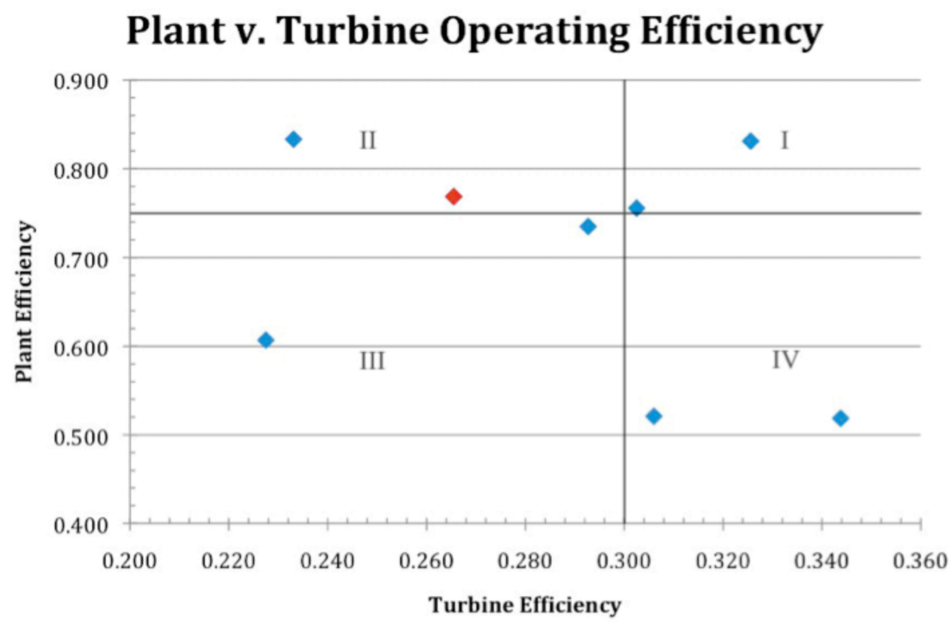



Figure 2.27. Plant vs. Turbine Operating Efficiency.

Consideration of turbine and CHP efficiency as two separate criteria is a unique perspective that necessitates development of a new metric for assessing plant performance. A quadrant system was chosen to divide campus plants into four groups:

I. Both an efficient turbine and CHP system
II. An inefficient turbine in an efficient CHP system
III. Both an inefficient turbine and CHP system
IV. An efficient turbine in an inefficient CHP system

Thresholds for "efficient" versus "inefficient" operation—75% plant efficiency and 30% turbine efficiency—were determined from midpoints of the typical efficiency ranges for industrial power generation gas turbines and CHP plants, as reported by the American Society of Mechanical Engineers (ASME) [74].

In this classification system, quadrant I represents the best-case scenario of a CHP plant operating at both a high turbine efficiency and a high CHP efficiency. Clearly, from the data gathered, a few existing campus CHP systems demonstrate efficient turbine and CHP performance, belonging in quadrant I. At the other performance extreme, quadrant

III represents the worst case scenario of poor turbine efficiency and poor plant efficiency. Several campus plants fall into this quadrant, illustrating the potential for substantial efficiency improvements and subsequent carbon reduction. Interestingly, this graphic successfully separates and identifies those systems that are only operating efficiently in one of the two areas important to efficient CHP. The next logical step to the research methodology is to address the question: are inefficient turbines beneficial in CHP applications?

To answer this question, a complete CHP plant simulation was built such that the output behavior of the turbine could be continuously controlled/varied and the behavior of the larger CHP system could be studied. The desired CHP plant was simulated as a series of unit operations in the process design software ChemCAD. The process flowsheet for the entire CHP system is displayed in Figure 2.28.

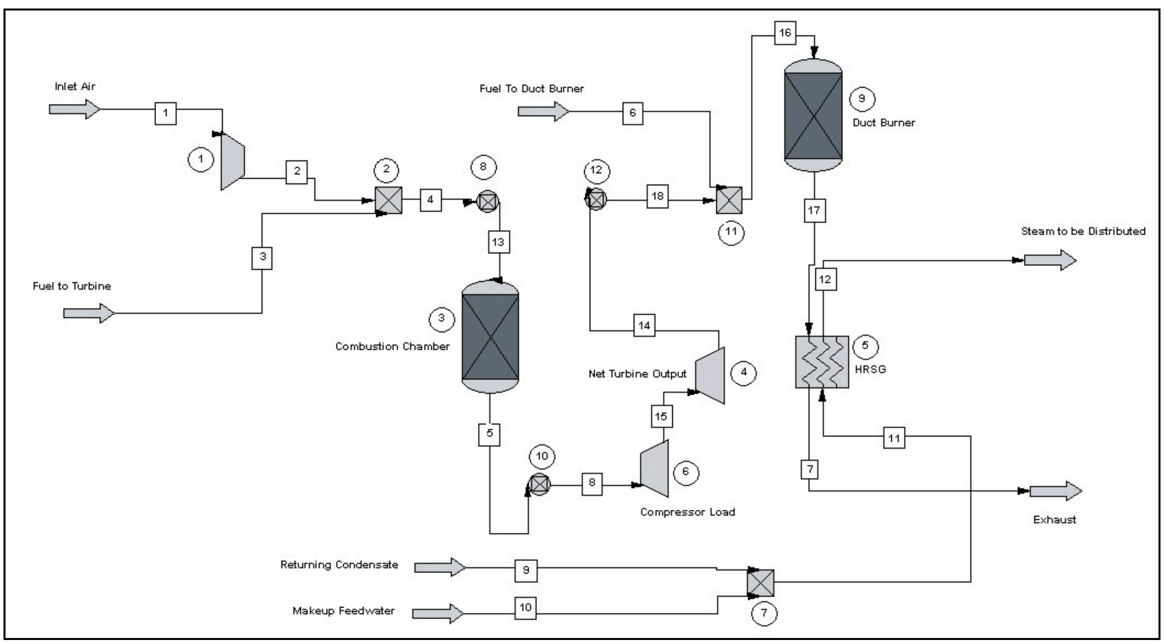



Figure 2.28. ChemCAD Process Flowsheet for a CHP System.

The ChemCAD simulation models a combined cycle system with steam production from the exhaust heat via a HRSG. In the simulation, fuel (methane) is mixed with a stoichiometric amount of air and combusted in a Gibbs equilibrium reactor. The resulting gas is expanded to generate electrical power to drive the compressor and meet the set external load. The turbine exhaust is heated in a duct burner and run through a HRSG to produce high-pressure steam from returning condensate and makeup feed water.

The unit operation-wise construction of the simulation allows the user to control turbine efficiency by adjusting the specifications of the compressor, expander, and set electrical load. From these specifications, the model adjusts the fuel flow rate to the turbine in order to meet the electrical demand.

Through this simulation, we wish to disprove the idea that an inefficient turbine benefits overall CHP efficiency. It is not beneficial to operate turbines for production of large quantities of heat—essentially using them as expensive boilers—as suggested by a Solar Turbines representative. For a set electrical demand, a more efficient turbine requires less fuel. This "saved" fuel can instead be utilized in a duct burner to generate steam. We claim that fuel is utilized more efficiently in a duct burner to track steam load than to produce heat in an inefficient turbine.

To explore this point in our ChemCAD simulation, a "baseline" fuel flow rate is defined by current UMD operating efficiencies (28% turbine efficiency, 83% compressor efficiency, and 79% expander efficiency). To investigate the effects of varying turbine efficiency on resulting system efficiency, compressor and expander efficiencies (and thus turbine efficiency) were adjusted to achieve turbine efficiencies of up to 33%The quantity of fuel "saved" by increasing turbine efficiency—i.e. the difference between the required and baseline fuel flow rates—was redirected to the duct burner. Overall CHP efficiency was calculated as:

$$\eta_{CHP} = (\dot{W}_{Electricity} + \dot{Q}_{Thermal}) / \dot{Q}_{Fuel} \tag{2.10}$$

Where $\dot{W}_{Electricity}$ is the net electrical power produced by the turbine, $\dot{Q}_{Thermal}$ is the rate of energy difference between the inlet and outlet streams of the steam cycle, and $\dot{Q}_{Fuel}$ is the rate of total energy content of the gas fed to the turbine and duct burner.

The accuracy of equally weighting thermal and electrical energy in CHP efficiency calculations must be considered. Because the two are not converted between each other with equal ease—i.e. it is a more difficult process to produce electricity from steam than vice versa—electricity is in practice a more useful form of energy. In this analysis, both energy forms are weighed equally, consistent with the reasoning in Section 2.2.3.

After all ChemCAD simulations were run, CHP efficiency was found to increase slightly with turbine efficiency in the manner shown in Figure 2.29.

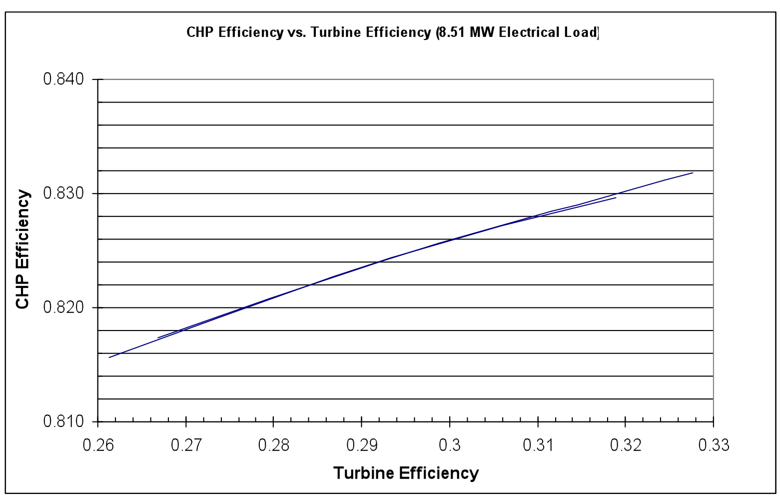



Figure 2.29. CHP Plant Net Efficiency vs. Turbine Efficiency.

Though the increase of CHP efficiency with improved turbine efficiency is not dramatic over this range, it is apparent that fuel is better utilized by a more efficient turbine coupled with a duct burner than to produce heat in an inefficient turbine. This analysis does assume that duct burners are easy to obtain and install into an existing system, which is not always the case. In addition, some campuses may have turbines that are well-matched to the university's load profile and thus do not require the presence of a duct burner. However, communication with campus CHP operators has shown that this is most often not the case and instead CHP performance could benefit significantly from improved turbine efficiency. Improvements to turbine efficiency are a necessary consideration in any effort to significantly reduce carbon emissions on university campuses. In light of the performance and efficiency observed in current CHP plants, an efficient turbine was found necessary to produce a highly efficient CHP system.

There exist two primary means to improve turbine efficiency: operational parameters for simple- cycle gas turbine systems can be optimized, and physical components—intercoolers, reheaters, and regenerators – can be integrated into simple-cycle gas turbines.

Increasing the efficiency of a CHP plant has vastly different meanings depending on the stage of development a plant is in. Once a plant is built, the potential for carbon emission improvements decreases drastically, but not entirely. However, the greatest opportunity a university campus has to reduce carbon emissions through CHP is during the planning and development stage of building a new gas turbine CHP system. As mentioned above, intercoolers, reheaters, and regenerators are the primary design changes that can be incorporated into a gas turbine to improve the efficiency; however, much research has been done on the effectiveness of these measures on large scale turbines (~100MW), but very little on small scale turbines (~10MW). The next phase of our research sought to address the question, are cycle improvements typical of large turbines always beneficial to efficiency improvements on small turbines?

### 2.3.3. Recuperation and Turbine Pressure Ratio

#### 2.3.3.1. Simple Thermodynamic Model

Utilizing the software, Engineering Equations Solver (EES), a thermodynamic model of a regenerated small turbine was constructed. The figure below presents the calculated theoretical efficiencies for turbine systems (both simple-cycle and recuperated) operating over a range of compression ratios. Note that these simulations utilize a perfectly lossless system whereas in the real world there will be losses and lower efficiencies. It is immediately apparent from Figure 2.30 that these two turbines each have ideal operating ranges: simple-cycle gas turbines have high efficiency when operated at high pressure and recuperated gas turbines have high efficiency at low pressure.

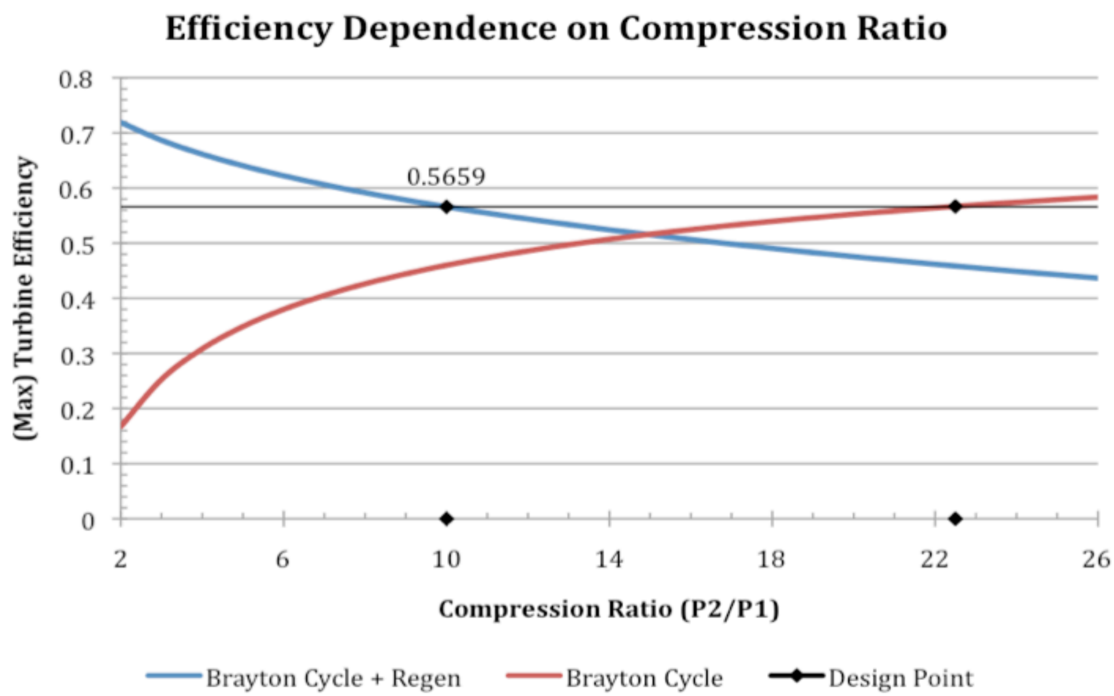



Figure 2.30. Energy Dependence on Compression Ratio (Ideal Model).

The value of this calculation lies in the ability to compare simple- cycle turbine and recuperated turbine curves and identify the compression ratios necessary for the two turbines operate at the equivalent efficiency. These pressure ratios can then be utilized as a design point for sourcing and building high-efficiency turbines. Each design presents distinct challenges: simple-cycle turbines operating at high pressures require extra reinforcing to prevent part failure, while recuperated turbines require extra equipment (the recuperator) and a larger physical turbine to maintain sufficient flow rate. The ultimate selection of a simple-cycle or recuperated turbine can thus be decided on economical considerations, while ensuring that the baseline efficiency goals are met.

#### 2.3.3.2. Recuperation / Pressure Ratio with Realistic Constraints

The theoretical curves produced from an EES simulation show non-recuperated (simple cycle) machine efficiency increasing and recuperated machine efficiency decreasing as pressure ratio increases. The point at which the two curves cross represents the coincidence of compressor exhaust temperature and turbine exhaust temperature. Both these exhaust streams are the inlets to the regenerative heat exchanger, and when both are at identical temperatures there is no added benefit from the recuperator. This point of intersection is where recuperation no loner makes sense. As the curves intersect, the recuperator should be deactivated, allowing the recuperation line to track the simple cycle line. This is shown in Figure 2.31.

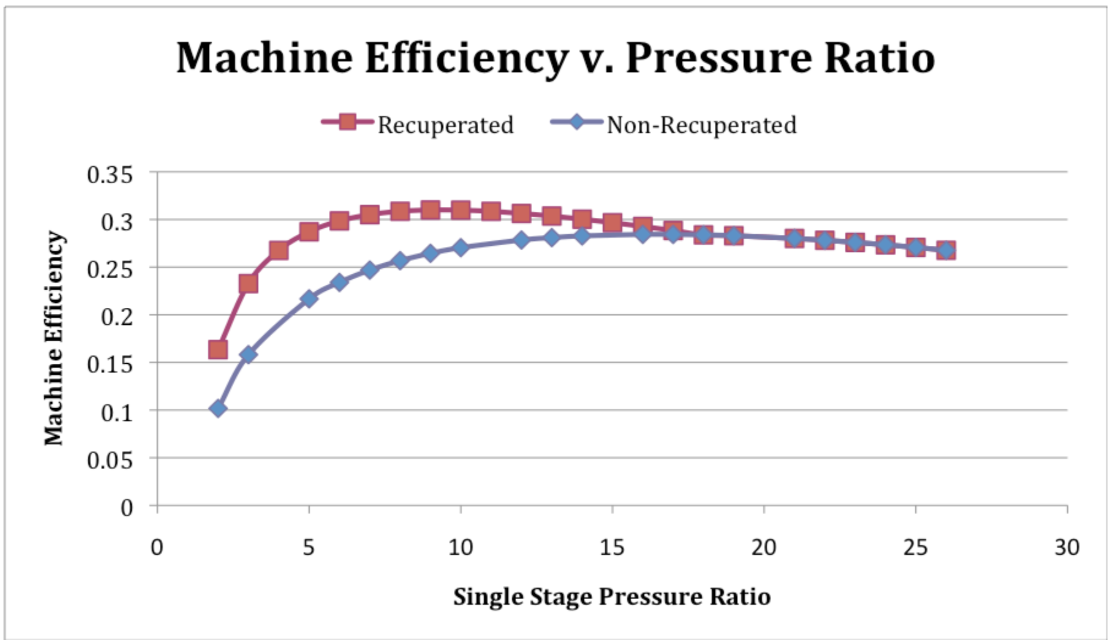



Figure 2.31. Machine Efficiency vs. Pressure Ratio (Simple Cycle and Recuperated).

There is a very clear nonlinear relationship between pressure ratio and efficiency for both machines. The simple cycle efficiency increases from about 25.7% efficiency at a pressure ratio of 7 to a peak of about 28.4% at a pressure ratio of 16. It then steadily decreases to about 26.8% efficiency at a pressure ratio of 26. While the increase in pressure ratio provides additional opportunity for power extraction through a larger expansion ratio in the turbine (increased pressure ratio yields higher machine capacity), the amount of work consumed by the compressor increases likewise. In this simulation, the amount of added benefit from the compression ratio is overtaken by the extra work required for compression at around $R_C = 16$. This simulation was conducted with a constant combustion chamber temperature of 1343 K (taken as the comfortable limit of operating temperature, based on interviews with industry experts). As the pressure ratio increases, the compressor exhaust temperature rises, and the added energy from the combustor decreases, because the gap between the exhaust temperature and 1343 K decreases. The point where the pressure ratio is about 16 (where machine efficiency begins to decline) is where the increased compressor work demand and decreasing heat addition in the combustion chamber begin to overtake the efficiency benefit of higher pressure ratios.

The recuperated machine begins at a much higher efficiency and decreases steadily until it begins to track the simple cycle curve. Recuperated efficiency decreases because the regenerative heat exchanger is exchanging less heat between the compressor exhaust stream and the combustor inlet stream. At higher compression ratios, the gas exits from the compressor at a hotter temperature. As this temperature approaches the temperature of the other stream in the recuperator (the turbine exhaust), there is a decreased potential for heat exchange and the recuperator provides decreased benefit.

Most university turbines operate with pressure ratios on the lower end of the scale tested above. Pressure ratios above 16 are common in larger (15+ MW) gas turbines, that typically don't suite campus electric load. This illustrates a critical need for turbines directed at the small-capacity campus-sized market to incorporate cycle enhancements like regeneration to increase operating efficiency. While the increased capital cost of recuperated machines can be a deterrent, there is considerable opportunity for fuel cost savings and emissions reductions. Campus power and other relevant applications where turbines with pressure ratios between 7 and 16 are appropriate should use recuperation as a method of decreasing emissions and offsetting fuel costs.

### 2.3.4. Cycle Enhancements: Recuperation and Intercooling

The interplay between recuperation and compression ratio was explored in Section 2.3.3. A second cycle enhancement, intercooling, can also be used to increase machine capacity and unlock potential for higher efficiencies. The following shows the results of multiple GSP simulations displaying the effect of intercooling and recuperating on machine efficiency [Figure 2.32].

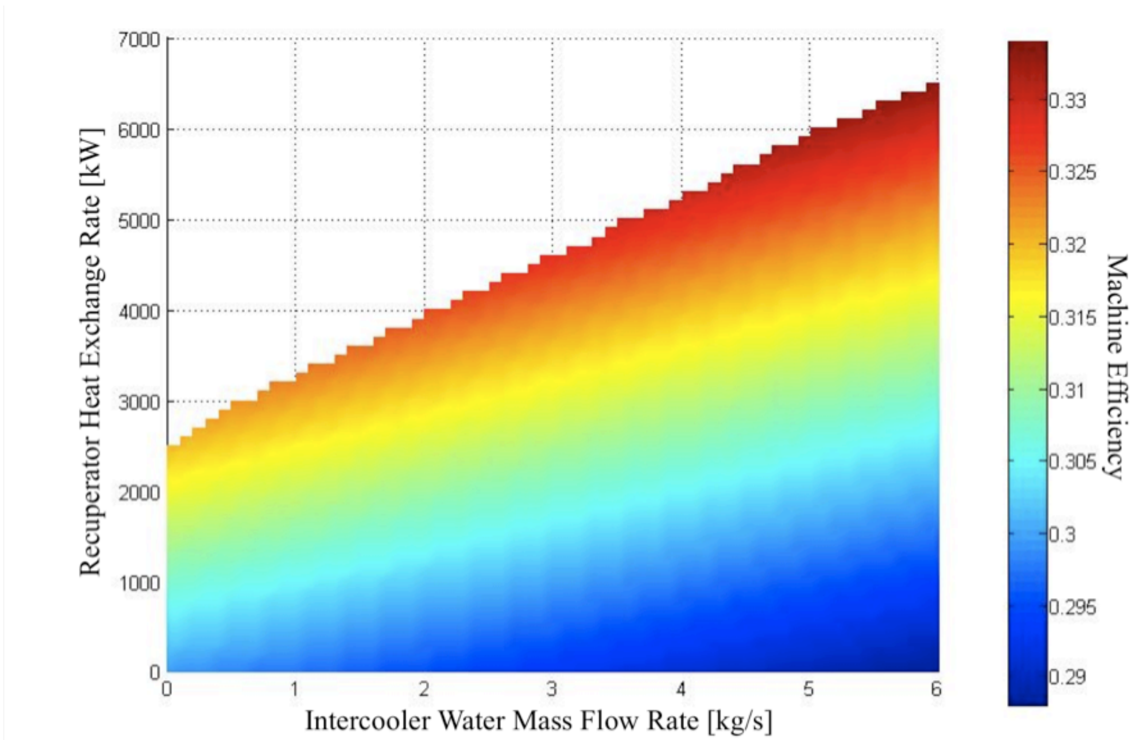



Figure 2.32. Machine Efficiency vs. Intercooler Flow and Recuperator Heat Rate.

In the figure above, the horizontal axis represents intercooler water mass flow rate in kg/s. The water inlet temperature is 300 K. The vertical axis represents heat exchange rate (between the compressor exhaust flow and the turbine exhaust flow) in the recuperator in kW. The graph is colored to represent machine efficiency, with cooler colors representing lower efficiencies and warmer colors representing higher efficiencies. The jagged diagonal boundary extending to the upper right of the graph represents the terminus of the simulation where the recuperator approach temperature reached between 16-17 ºC.

As the intercooler flow rate increased, the machine efficiency decreased along a line of constant recuperator heat rate. The intercooler is designed to remove heat from the gas stream, functioning as a parasitic loss to the engine, so this result was expected. As the recuperator heat rate increased along a line of constant intercooler flow, the machine efficiency increased. Because the recuperator is designed to add heat to the gas path by utilizing exhaust heat that would otherwise be wasted, this increase in efficiency was also expected. The more important result from this graph is the increase in efficiency unlocked by intercooling. As intercooler flow increases, the recuperator can exchange an increasing amount of heat between the gas streams before the approach temperature boundary is reached.

The intercooler and recuperator remove and add heat to the gas stream successively. If the effect of these devices were just to add and remove heat, the components would balance each other out. The lines of constant color in Figure 2.32 show where machine efficiency is constant. But intercooling also increases the density of the air stream, decreasing the amount of compression work required to achieve a certain pressure ratio. The maximum achieved efficiency with no intercooler flow is roughly 32%, and the maximum achieved efficiency with 6 kg/s of intercooler flow is roughly 34%. This 2% increase in efficiency, attributable to the presence of intercooling, is realized because of the decreased work required for compression and the decreased aerodynamic drag associated with a cooler, denser flow in the compressor housing.

Also important to mention is the increase in capacity associated with intercooling. Because cooling the stream increases its density, the mass flow rate of air increases with intercooling. This increases the total amount of power produced by the machine. As shown in Figure 2.33, for a constant recuperator heat rate of 2500 kW, the turbine capacity increases from about 11.8 MW to 13.7 MW.

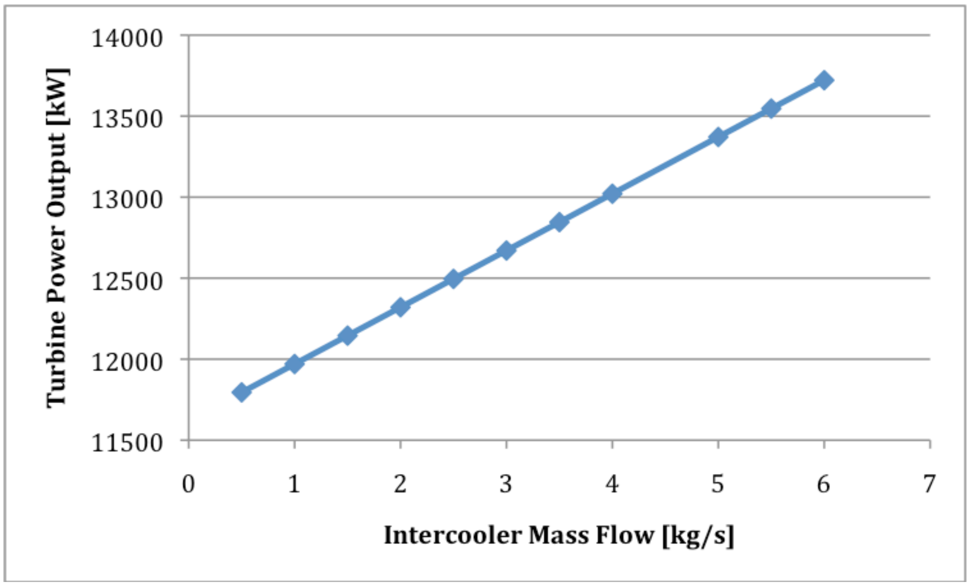



Figure 2.33. Turbine Power Output vs. Intercooler Mass Flow for Constant Recuperator Heat Rate (2500 kW).

It is also important to note that the efficiency values shown in Figure 2.32 are limited strictly to the turbine. Calculation of machine efficiency ignores the added benefit of intercooling, which is to increase the temperature of the cooling water flow. In the simulation above, temperature of the cooling water increased from 300 K to about 540 K. While this temperature obviously yields superheated steam at atmospheric pressure, a creatively designed CHP system could use a high mass flow rate through the intercooler to decrease the outlet temperature (to something closer to that of potable hot water lines).

This would allow the intercooler to be used as a water heater, in addition to a device for turbine efficiency improvement, offsetting the use of steam energy for water heating.

## 2.4. Engineering Integration with Business

The link from engineering theory to tangible physical change on college campuses will require the integration of several business concepts. Even the most efficient theoretical gas turbine will not be feasible to produce and sell if manufacturers do not perceive a demand from university purchasers and universities feel forced to purchase other, less efficient, turbines due to continuing extenuating circumstances. An analysis of gas turbine market inadequacies, quantitative numbers pointing to the economic benefits of high efficiency CHP, and concrete business recommendations for improvement would bring the aforementioned engineering findings into the real world.

# 3. CHP Business

In order to effect real change to CHP on university campuses, a greater understanding of the university turbine marketplace must be established. Effective engineering improvements can only be brought into practice if there is a legitimate market demand for the engineering findings among universities that implement CHP. Even with a defined demand for improvements, turbine suppliers must also provide adequate technology to optimally meet the findings of the engineering team. It is the intention of the CHP business portion of this research to identify the current state of the CHP market, define the greatest areas of opportunity for suppliers to maximize their engineering efforts to meet customer demand, and to validate the economic appeal of CHP as a viable form of campus energy production.

## 3.1. Business Literature Review

### 3.1.1. Economics and Profitability of CHP

Efforts to improve energy efficiency and reduce carbon emissions are not always in line with sound business plans. While solar panels are arguably the cleanest and a purely renewable form of energy, the cost per kilowatt of solar energy is well above more traditional, albeit dirtier, forms of energy generation.

> "At present, solar energy conversion technologies face cost and scalability hurdles in the technologies required for a complete energy system….low-cost, base-loadable, fossil-based electricity has always served as a formidable cost competitor for electrical power generation" [75].

CHP represents a stepping-stone between carbon-heavy turbines and carbon-neutral turbines that is both efficient and, in many cases, profitable. Available CHP technology can be installed today to immediately realize a significant reduction of carbon emissions. In a study of the trigeneration (cogeneration integrated with cooling) system in place at one of Slovenia's largest hospitals, researchers compared installation, operation, and depreciation costs to the energy savings imparted by increased efficiency and reduced fuel use. Conclusions suggested that the increased efficiency in meeting power, heating, and cooling needs offset the more expensive gas turbine technology. Further economic analysis of cogeneration and trigeneration systems demonstrate that the payback period is low, profitability index is high, and the net present value of these projects is positive [76].

The potentially positive economic value of a CHP system makes it an attractive choice for universities. With the addition of the environmental cost of carbon, universities are given further incentive to explore and pursue cogeneration. This cost will be derived from a series of existing valuations made by several researchers.

### 3.1.2. Social Cost of Carbon

A number of studies on the social cost of carbon emissions have been conducted. Each employed a different cost determination methods and obtained drastically different results [77]. Several efforts, including The Stern Review, have cited high social costs of carbon emissions—up to $312 per ton [78]. Such interpretations have endured criticism that they overemphasize the damages caused by carbon emissions in order to encourage action [77]. Due to apparent variability in assessing the cost of carbon, this study will assume a more conservative value of $30 per ton of carbon emissions, a value estimated by Professor William Nordhaus, a Yale University economist [79]. Dr. Nordhaus, who is considered to be one of, if not the, "leading economist in the climate change field," determined this value through usage of a computer modeling system. The value is relatively aligned with current carbon credit costs and will adequately serve the purposes of this study [80].

Historically, there has been significant controversy concerning the need for an immediate response to climate change indicators. The Stern Review puts the significance of reducing carbon emissions in a global context and demonstrates the need for immediate changes to avoid drastic, irreversible damage to the Earth [78]. The Stern Review quantifies the severity of potential environmental effects of current emission levels by utilizing economic modeling systems that take into account ecological, social, and economic effects. The review indicates that a 20% reduction in international Gross Domestic Product (GDP) will result from carbon emissions within the next couple decades, if current emission rates continue [78]. Critics of the report, however, note that this 20% reduction in GDP was calculated using a near-zero social discount rate, meaning that this value incorporates distant future expenses [81]. In addition, Dr. Nordhaus argues that with this near-zero discount rate, an immediate cost of seven trillion dollars would have to be spent today in order to offset a .01% drop in output in the year 2200 caused by carbon emissions [82]. In contrast to the drastic changes called upon by the Stern Review, Dr. Nordhaus and several other leading environmental economists argue that a better solution to the carbon crisis is to slowly introduce long-term carbon reduction measures [83]. Regardless of which economic theory one subscribes to, the fact remains that carbon emissions must be reduced to avoid catastrophic future costs.

### 3.1.3. Gas Turbine Industry

The gas turbine manufacturing industry is a subset of the engine, turbine, and power transmission manufacturing industry in the United States. Product and service segmentation shows that gas turbines and accessories make up 11.7% of this general industry, making it the fourth largest segment. This market share is set to increase over the next five years, “due to the refurbishment of archaic power stations with cleaner burning gas turbines” [84].

Like any industry, the gas turbine manufacturing industry has many unique characteristics. These characteristics include nuances in industry competition, growth risk, structural risk, sensitivity risk, market segmentation, life cycle, all of which create the framework that influences how the industry behaves and how the gas turbine market is served.

The gas turbine industry can best be characterized as an oligopoly; the market is dominated by a small number of sellers. This, coupled with the amount of growth in this industry, produces a steady, low to medium level of competition in the industry. While the growth forces manufacturers to develop new technologies to capture market share, the low number of competitors puts a disproportionate amount of power into the seller’s hands and away from the purchaser. Without competition from peers and the constant threat of new entrants, gas turbine manufacturers do not have to resort to price cutting strategies to increase market share [84]. Thus, prices remain high and pricing power remains with the seller. Furthermore, manufacturers are effectively free to develop products and target consumers at their discretion, without any economic pressure or pressure from buyers.

The gas turbine industry tends to be difficult to enter. Although the IBIS World Industry Report suggests that, “there are no licensing requirements, government regulations, or resource constraints that are significant enough to prevent firms from entering this industry," there is an incredible amount of capital investment required to become a turbine producer [84]. Designing a turbine requires major research and development investments as well as the employment of industry experts with experience in the field. Additionally, turbines are such large investments that purchasers are often unwilling to take a chance on a company that has not proven itself through products with past demonstration of a high percentage of successful operating hours [84].

In terms of acquiring the newest technology or gas turbines designed for specific situations, many purchasers are at the mercy of just one seller [85]. This increases prices and often forces purchasers to buy turbines that are priced more reasonably but are ill fit for their needs. The structure and nature of the gas turbine industry lends itself to serving commercial, industrial, and government clients. High research and development costs force gas turbine manufacturers to focus on clients who can feasibly commit to purchasing large turbines in large quantities and thus recoup their initial investments. Thus, large-scale commercial and industrial gas turbines are more widely available at various sizes and higher efficiencies. The most valuable clients for most gas turbine manufacturers include aerospace corporations, members of the gas and oil extraction industry, and the military [84].

### 3.1.4. Gas Turbine Market

Overall, the market for gas turbines has been steadily growing over the past decades. Driven by increases in demand, sales of gas turbines have experienced a relatively positive trend. Figure 3.1, taken from Turbine and Gas Worldwide's Power Generation Order Survey, displays this upward trend in sales from 1978 to 2009.

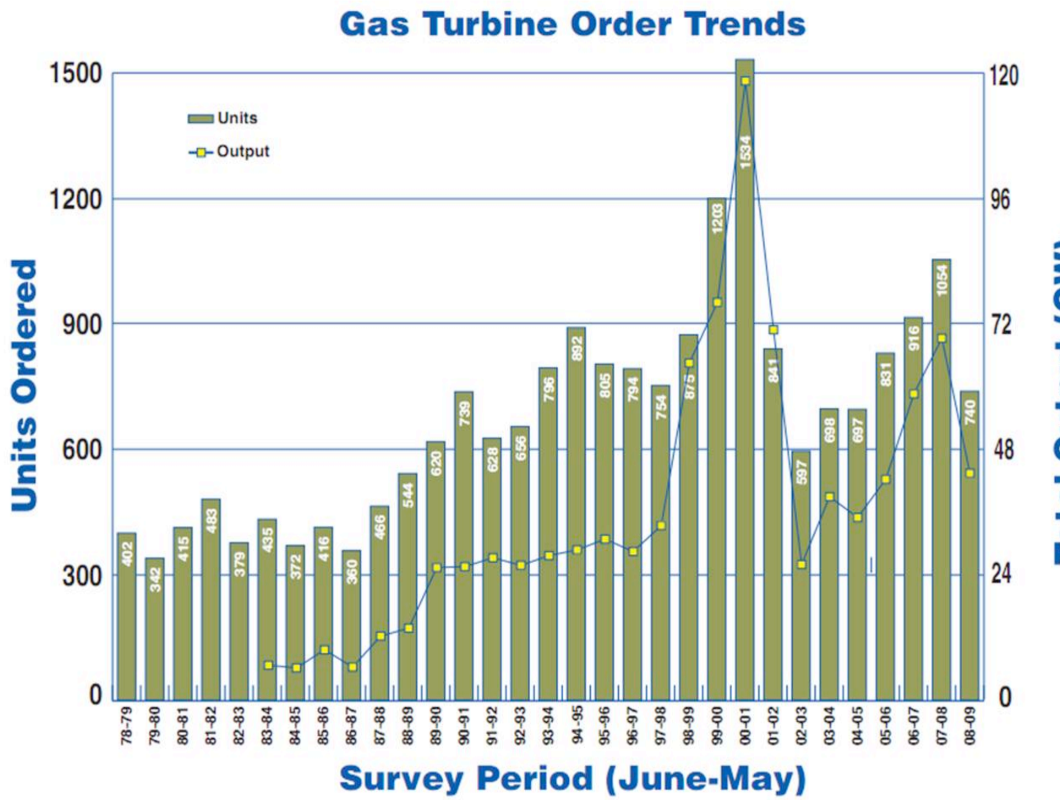



Figure 3.1. Gas Turbine Order Trends.

Worldwide, gas turbine sales dropped from 2008 to 2009 from 1054 to 740, a 30% decline over one year [86]. However, this decline is most likely attributable to a downturn in the economy, not a long-term decline in turbine sales. As the economy picks up and the recession ends, turbine sales are expected to once again grow [86].

A gas turbine sales breakdown reveals a slight majority of sales in smaller turbines. Figure 3.2 shows gas turbine sales from 2007 to 2009, distributed by turbine size [87]. While worldwide sales declined, the percentage of sales in the 1-2 MW range experienced a significant increase in percentage of sales.

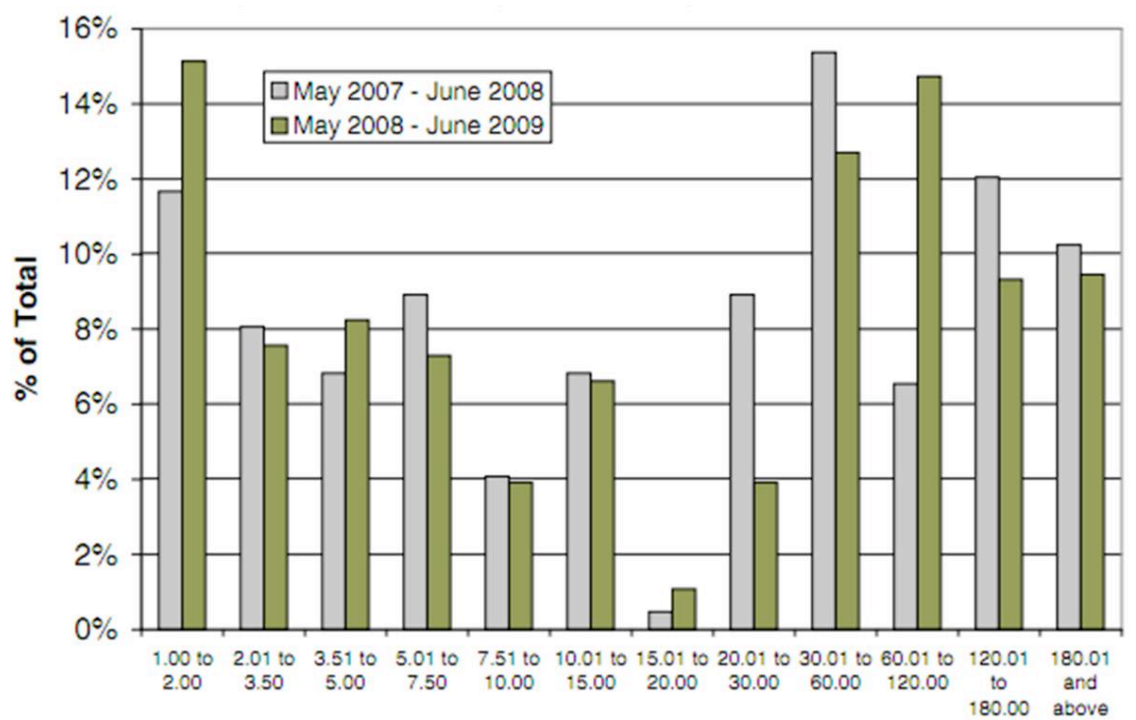



Figure 3.2. Comparison of Gas Turbines by Power Range (MW).

Within the United States, 99 turbines were sold from June 2008 to May 2009, a slight decrease from the 125 turbines sold in the previous year [87]. However, sales in the 3.51 to 5.00 MW range more than doubled from the previous year, increasing from 10 to 21. This increase reflects the potential for turbine manufacturers to increase their sales in the small turbine market, the segment in which most universities fall.

According to the International District Energy Association, 330 universities in America have district heating, an infrastructural requirement for CHP implementation [88]. This effectively means that all of these universities are potential purchasers of a new CHP system. While the 330 universities vary considerably in size, the fact that they already have district heating systems in place makes them viable potential customers. In comparison, only 85 downtown utilities and 123 hospitals have district energy systems, making universities the largest potential purchasers for small-scale turbines.

### 3.1.5. Purchasing Consortiums

One of the main concerns for purchasers in the gas turbine market is price. Consumers in similar industries have adopted the practice of forming purchasing consortiums to control prices by buying products and services in groups. Consortiums achieve this by following one main objective:

> "Suppliers' total costs for the goods and services supplied to the consortium members truly are reduced through this increased volume, which clearly justifies lower selling prices, higher quality, better services, and their investment in new technology to add more value to their products and services" [87].

Consortiums employ a variety of structures. However, the most successful consortiums typically display certain characteristics. 73% of the most successful are structured formally and managed by participant members. There is no formal written agreement in 65%, and 72% consist of members that are considered non-profit organizations. In 96% of the most successful consortiums, there are no penalties for leaving organization. Finally, in 92%, there is no minimum level of purchase required of members [87].

Consortiums also differ based on what types of products they purchase. Most consortiums aim to bring down the prices of commodities (54%); services (46%); and direct materials used in production (42%). Approximately 35% of consortiums purchase capital goods [87]. The dynamics among the participants of consortiums are also key to their success in accomplishing price reductions. Two of the most important factors for achieving success include a high degree of trust among participants and similar buyer-supplier relationship philosophies [87]. The purchasing consortium method is not currently observed as being operational in the gas turbine industry.

### 3.1.6. Levelized Cost of Energy Analysis

A Levelized Cost of Energy analysis (LCOE) is designed to allow for "rapid comparison of technology cost and performance characteristics, not for project or location specific analyses" [89]. This comparative analysis does not include policy or regulatory costs or incentives related to differing production methods. When identifying an average price per unit of energy, only variables relating to operation and maintenance, fuel, and capital costs for production are considered [90]. Furthermore, costs associated with particular circumstances, such as the cost to transport fuel, are not included.

Several LCOEs have been conducted in a number of cases to serve as comparisons for differing forms of energy production. The National Renewable Energy Laboratory outlines several of the calculations performed by different entities regarding similar forms of energy production. These institutions include the Energy Information Administration, National Renewable Energy Laboratory, ICF International, Electric Power Research Institute, and Pacific Northwest National Laboratory. Within all of these calculations is a degree of variability, stemming from the different methods, scope, and weight of variables [89]. For the purposes of this research, the average LCOE values were found by calculating the mean cost per MWh for various forms of energy production as determined by the aforementioned institutions Table 3.1.

Table 3.1. Range of LCOE Calculations for Electricity Production when Considering Methods of Carbon Zero Energy Production.

| Form of Production | LCOE of Electricity | Average Plant Output (MW) |
|---|---|---|
| Nuclear | $69 | 1290 |
| Biomass | $75 | 83 |
| Offshore Wind | $101 | 100 |
| Solar Thermal | $181 | 120 |
| Solar PV | $270 | 23 |

It should be noted that the cost of fuel transportation was not included in these calculations. This is particularly notable for biomass electricity production, which requires a substantial volume of input to produce energy [87]. Furthermore, the average plant output should be noted because larger plants generally trend towards a lower cost per MW due to the distribution of costs over a higher amount of plant production.

## 3.2. Business Methodology

To properly analyze the strengths and weaknesses of the gas turbine industry and its relationship with universities, this research considered both supply and demand. First, a study of the supply side—gas turbine manufacturers involved in university CHP—was conducted. The nature of gas turbine manufacturing operations and development inadequacies were exposed. Second, a study of the demand side—gas turbine purchasers at universities and colleges—was conducted. Two quantitative analyses, a house of quality and a levelized cost of energy, were also performed to provide a demonstrated quantitative basis for our business recommendations.

### 3.2.1. Supply

The initial step of this research was to compile a comprehensive database of all gas turbine products offered by the major gas turbine manufacturing companies: General Electric, Solar, and Rolls Royce. This database catalogued general information along with specifics including product capacity and intended use. A simple analysis of products from the database that fit the specifications for university CHP would determine if gas turbine manufacturing companies are at all focused on providing universities with the products they need. The next step of the supply side research was to conduct interviews with executives and directors of gas turbine manufacturing companies to determine the company’s perspective in terms of research and development, marketing, and most notably, serving universities as clients.

### 3.2.2. Demand

A study of the demand side followed. The demand side is defined as universities that are currently operating or are potential candidates for installing a CHP system. The initial phase of this research was to examine sources of existing and potential demand by creating a comprehensive database of schools with existing CHP systems and district energy systems.

The next step was to survey 95 directors of CHP at college campuses. The universities surveyed were based on several lists of nationwide CHP systems on college campus settings. The pie chart below represents the response rates observed during the administration of our buyer preference survey to 95 universities [Figure 3.3]. The green section shows the non-response rate, which was about 80%. The red section titled “Data Incomparable” represents universities that responded but provided data that was unfit to be analyzed, because the questions were improperly answered. Ultimately, 16 full data sets were obtained during the survey process, reflecting a 17% response rate.

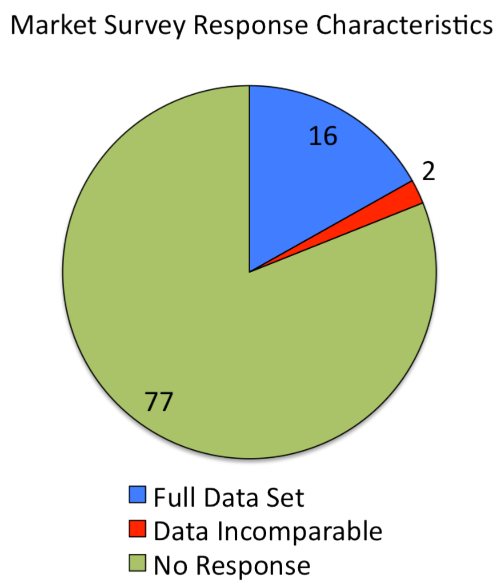



Figure 3.3. Turbine Market Survey Response Characteristics.

The survey included both qualitative and quantitative questions designed to identify the priorities for a typical university's gas turbine purchases. The survey asked the respondent to rank ten turbine specifications in terms of priority. These requirements were fuel efficiency, reliability, alignment to steam demand, alignment to electricity demand, price, product reputation, physical size, cost of maintenance, service and support, and longevity. These requirements were selected for inclusion in the survey based on preliminary research, discussions with industry experts, and collaboration with the engineering sub-team. The survey also included questions regarding the availability of products that meet purchasers' specific needs and cooperation with other universities during the process of selecting and purchasing gas turbines. These questions were designed to help reveal universities' purchasing behavior. By studying demand dynamics, the research aimed to determine areas of weakness that prohibit suppliers from providing relevant, efficient, and price-competitive products to those who demand them.

### 3.2.3. House of Quality

The quantitative results from our surveys were totaled and summarized in a House of Quality. Existing, reliable templates for a House of Quality exist from numerous sources. The first aspect of the House of Quality is the analysis of consumer demand. To fulfill this aspect of the House of Quality, the results from our survey were sorted and assigned weights, based on the responses to our survey. These consumer desires help ensure that the House of Quality is relevant to current demand in the market.

The next aspect of the House of Quality is the identification of the engineering characteristics that affect the consumer requirements. A preliminary list of these characteristics was crafted based on initial research, meetings with industry experts, and review of relevant literature. This initial list was reviewed and corrected by the engineering subgroup and subsequently reviewed by an industry expert.

Next, following the House of Quality guidelines, tradeoffs and relationships among the different engineering characteristics were analyzed and entered into the House of Quality template. These relationships were developed by the business team, examined and corrected by the engineering team, and corroborated by an industry expert.

The central relationship matrix portion of the House of Quality was then completed. This portion analyzes the relationships between consumer requirements and engineering characteristics, determining which engineering characteristics have positive or negative effects on each consumer requirement. This portion of the House of Quality is critical in determining accurate results, and each relationship was extensively researched.

The final portion of the House of Quality is the results section. In this portion, the template uses the weighted consumer requirements, the tradeoffs among the engineering characteristics, and the central relationship matrix to determine which changes in engineering characteristics have the greatest effect on creating a product that best meets the consumer demands.

The House of Quality is able to effectively combine the external market demands with the capabilities of a firm to help ensure they are producing a product that consumers in the marketplace will purchase. The House of Quality points to a direction for the most effective research while taking into account the goal of meeting the needs of customers.

### 3.2.4. Levelized Cost of Energy

A levelized cost of energy (LCOE) is used to compare the average cost per unit of a standard measurement of energy between various energy sources. In order to complete a LCOE comparison between CHP and alternative forms of campus energy production, both the investment and operational costs of a CHP plant were considered. Due to the high variability in the operation and function of different plants, and in order to place this analysis within a realistic context, the University of Maryland College Park was selected to be the subject of this portion of the study. The following data points were required for the LCOE analysis:

$LCOE_{CHP}$ = Levelized cost of electrical energy for CHP
$C_c$ = Capital Cost of Installation in dollars
$C_o$ = Monthly Operating Expense in dollars
$C_f$ = Cost of Fuel in dollars
$Y$ = Years Operational in years
$p$ = Megawatts produced
$\dot{m}$ = kg/s of natural gas fuel intake per second
$E$ = Total carbon emissions in metric tons
$C_C$ = Cost per metric ton of carbon dioxide in dollars

The LCOE was then calculated after incorporating the following calculated fields.

$O_t$ = Lifetime Operating Expenses $= (C_o \cdot 12) \cdot Y$
$F_t$ = Lifetime Fuel Usage (MMBtu) $= ((46.206 \cdot \dot{m}) \cdot 60) \cdot 5.256 \cdot 10^5) \cdot Y$
$C_{LC}$ = Lifetime Cost of Carbon $= E \cdot C_C \cdot Y$
$T_{mw}$ = Lifetime MW produced $= p \cdot (8.760 \cdot 10^3) \cdot Y$

The final LCOE was then found using the following calculation.

$$LCOE_{CHP} = (C_c + O_t + F_t + C_{LC}) / T_{mw} \quad (3.1)$$

The lifetime of the UMD plant, as well as the capital cost of installation and MWs produced per hour, were identified through a University of Maryland case study produced by the Mid-Atlantic CHP Application Center [90]. The monthly operating expense included in the LCOE, which included maintenance and facility operations, was calculated by combining all CHP operational costs accounted for in the 2010 University of Maryland detailed budget. The 2010 operational costs were then used to represent the estimated operational costs for the full 20 years of a system. The cost per MMBTU of natural gas fuel was based on the average projected cost of natural gas between 2010 and 2030 in 2009 dollars identified by the U.S. Energy Information Administration [91]. This cost was then multiplied by the system's average intake per second, 0.7 kg/s, and an average cost of fuel per second was found. This number was then extrapolated to find an estimated total cost of fuel for the lifespan of the system. After factoring all of the lifetime systems costs together, this sum was then divided by the total MWh produced by the system over its twenty-year lifetime. This final calculation produced a final LCOE per MWh of electricity production for the University of Maryland College Park CHP plant.

After identifying the tangible average cost per MWh of electricity, the additional cost of carbon dioxide was also included in the LCOE calculations, primarily as a result of university interest in achieving carbon neutrality. It was the intent of this additional calculation to identify if it would be more economical for a university to reduce its carbon emissions by purchasing a more expensive, carbon neutral form of energy production or to purchase a less expensive, carbon positive form of energy production and offset the associated costs of their emissions with an alternate method. In sum, this calculation is intended to identify if selecting a carbon neutral form of energy production over CHP is an economical way for universities to reduce their carbon emissions.

In order to produce this calculation, an average economic cost per ton of carbon dioxide was identified. In this study, the estimated cost of $30 per ton of carbon dioxide was selected. This value was produced through an economic analysis produced by William F. Nordhaus who identified the environmental cost of a ton of carbon dioxide is $30 between the years of 2010 and 2050 [79]. This cost was then multiplied by the annual carbon emissions created through the electricity production process at the UMD CHP plant and expanded to reflect the full lifetime emissions of the system. The total cost of the system's lifetime carbon emissions was then divided by the system's lifetime MWh energy production to find the added cost of carbon per MWh of energy production. This value was then entered into the tangible average cost per MWh of electricity production to find a LCOE for CHP electricity production with the quantitative inclusion of environmental impact.

## 3.3. Business Results

### 3.3.1. Supply

Research on the supply side of the gas turbine industry determined that the key producers in the gas turbine market are GE, Rolls Royce, Solar, though other producers certainly exist. From these three manufacturers, 78 turbines were catalogued in a product differentiation database and examined. A simple breakdown based on MW produced by these turbines showed that only one-third (26 turbines) were of a practical size for university campus use (<20MW). Turbines with specialized tasks such as marine propulsion and petrochemical applications eliminate an additional seven options, leaving 19 turbines of appropriate size and function for university campus use.

Not only does a product diversity gap exist between large and small turbine markets, a performance gap is also present. An average of mean efficiencies within each subgroup of turbines sizes (small, mid, and large) clearly shows significant differences in the rated efficiencies of various small, middle, and large capacity turbines. From these results it becomes evident that the technologies that are available to large-scale CHP turbines are not translated as the turbine sizes are scaled down [Table 3.2]. The small-size subgroup, which includes turbines suitable to meet the energy demands of college campuses, has a significantly lower mean efficiency than the large-size turbine subgroup meant mostly for commercial and industrial use.

Table 3.2. Average Efficiency Levels of Turbines Available to Consumers.

| Turbine Size | MW | Mean Efficiency |
|---|---|---|
| Small Size Efficiency Average | (1-20) | 32.206 |
| Mid-Size Efficiency Average | (20-50) | 37.567 |
| Large Size Efficiency Average | (>50) | 52.083 |

The repeated sentiments of several campus energy officials reveal that at this time only one gas turbine is being produced that meets the size and efficiency requirements of most universities: the Mercury 50, manufactured by Solar Turbines. Unfortunately, the purchase and operation of college campus CHP are driven by various factors that oftentimes force universities to purchase less appropriate turbines from other manufacturers.

These results indicated that the small-scale CHP turbine market is broken. From the industry's perspective, there is little perceived demand for a high-efficiency gas turbine suitable for college campus use and very little progress is being made towards the development of such a product.

### 3.3.2. Demand

Unlike commercial and government clients, most universities buy turbines independently, in smaller sizes, and in fewer quantities. Thus, the purchasing power of universities is extremely low and the selection of gas turbines available to universities is severely diminished. However, the research suggests that a significant potential market exists.

The 677 signatories of the President's Climate Commitment, an initiative designed to achieve carbon neutrality on university campuses, is the broadest representation of potential demand for CHP on college campuses. The signatories pledge to "initiate the development of a comprehensive plan to achieve climate neutrality as soon as possible." [1] Although this call to action is vague and open to interpretation, it certainly presents a desire to works towards carbon neutrality in the immediate future and CHP is undoubtedly a viable option for many of these schools.

Creating a more focused database of 330 schools with either district heating or CHP reveals several sources of potential demand [Figure 3.4]. This database revealed that 135 universities have existing CHP systems. The 135 schools with existing CHP represent the most obvious source of demand for CHP specific high-efficiency gas turbines developed with a college campus's needs in mind. These schools will need to upgrade and update their gas turbines in the future and the availability of high-efficiency and relevant products will be well received by this group. However, the 194 schools discovered to have district energy systems only also represent a meaningful source of demand. District energy systems are oftentimes precursors to CHP systems since the latter cannot exist without the former. These 194 schools already have the basic infrastructure necessary to install new CHP systems and realize cost and energy savings.

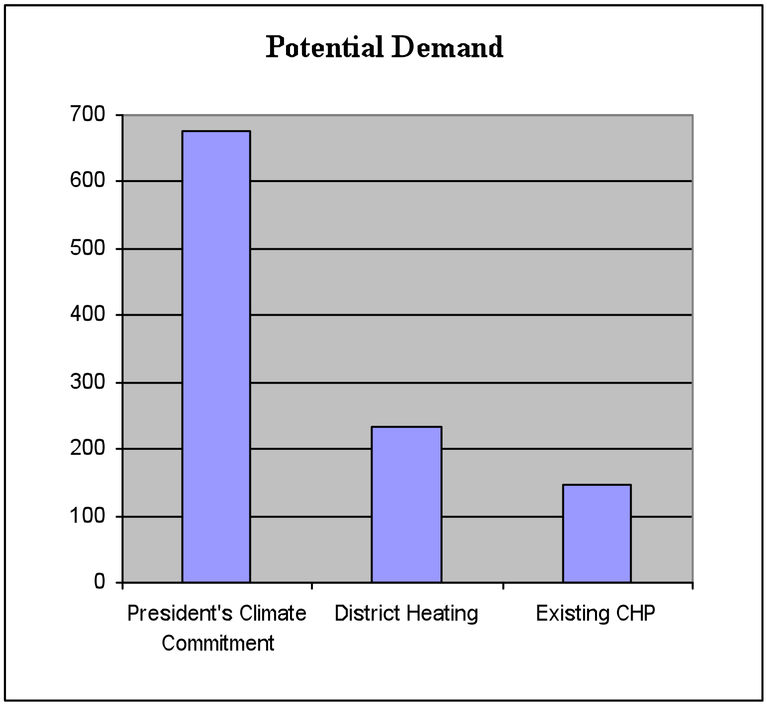



Figure 3.4. Potential Demand for CHP Systems when Considering Demand and University Capability for Implementation.

After collecting surveys and conducting several interviews it was determined that a common impediment to both consortium purchasing (which would increase buying power) and product development geared towards college campus CHP is the uniqueness of each school's situation both in terms of energy demands and environment. However, the geographic distribution of university district energy [Figure 3.5] and existing CHP [Figure 3.6], reveals several key regions in the United States where the climate and energy demand at comparably sized schools would be extremely similar.

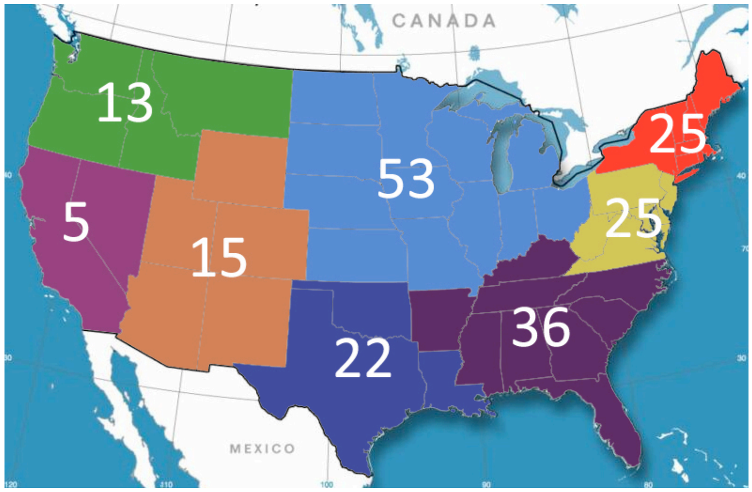


Figure 3.5. District Energy Systems at College Campuses (By DOE CHP Application Regions).

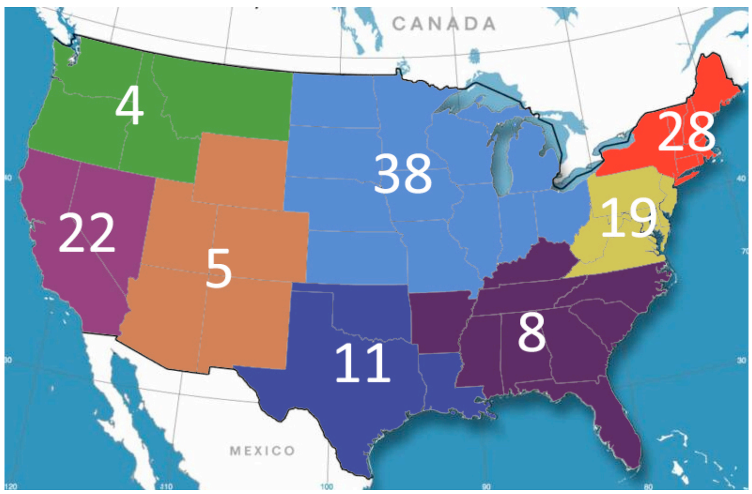


Figure 3.6. CHP Systems at College Campuses (By DOE CHP Application Regions).

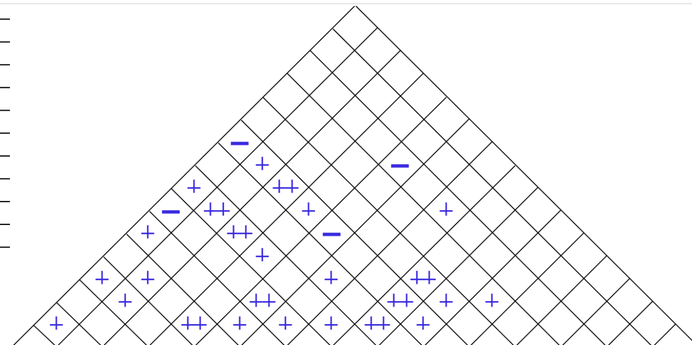
A brief geographical analysis of potential demand by region reveals several areas with particularly high concentrations of demand. In terms of existing CHP systems, New England, the Mid-Atlantic, and California regions have particularly high densities of schools. In terms of district energy systems, the highest density of such schools exists in the eastern half of the United States. The regional breakdown is particularly relevant for manufacturers to conceptualize the demand in areas where climate and other environmental factors is relatively uniform. For these regions, standardized products can be created that will satisfy both electricity and steam demand.

Consortium purchasing within these regions would be an effective method of consolidating demand and articulating the common needs of schools seeking high-efficiency gas turbines. The formation of a consortium would increase the buyer power to bring down the cost of purchasing gas turbines, but more importantly, it would capture the attention of the manufacturers to research and develop high-efficiency gas turbines that are suitable for college campuses within the region.

### 3.3.1. House of Quality

The results of the consumer survey are displayed in the House of Quality, a statistical and symbolic representation that matches the desires of consumers with the capabilities of engineers to determine the ideal product to sell in a market. As previously explained, the demand for turbines from universities is potentially very high. However, the products that engineers produce do not always reflect the characteristics that consumers (in this case universities) desire. If manufacturers' turbines do not effectively address the preferences of university officials, universities will not be interested in purchasing the turbines. The goal of the House of Quality is to conclusively determine the aspects that engineers need to focus on to ensure their products will sell in the marketplace [Figure 3.7].

**Title:** Turbine Market House of Quality
**Author:** Team COGEN
**Date:** 2/14/11
**Notes:** Copyright Kenny Voshell 2011



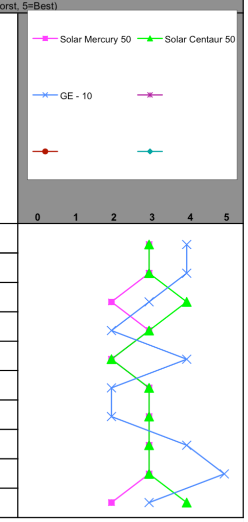
| Legend | | |
|---|---|---|
| Θ | Strong Relationship | 9 |
| O | Moderate Relationship | 3 |
| ▲ | Weak Relationship | 1 |
| ++ | Strong Positive Correlation | |
| + | Positive Correlation | |
| — | Negative Correlation | |
| ▼ | Strong Negative Correlation | |
| ▼ | Objective Is To Minimize | |
| ▲ | Objective Is To Maximize | |
| x | Objective Is To Hit Target | |

Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")

Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)

Competitive Analysis (0=Worst, 5=Best)

| Row # | Max Relationship Value in Row | Relative Weight | Weight / Importance | Demanded Quality (a.k.a. "Customer Requirements" or "Whats") | 1 Compressor or Pressure Ratio | 2 Aerodynamics (Blades/Stators) | 3 Bearing Quality | 4 Blade Metallurgy | 5 Combustion Temperature | 6 Turbine Generator Nominal Size | 7 Recuperation | 8 Manufacturing Quality | 9 Gear Box Design | 10 MTBF | 11 Generator Efficiency | 12 Air Filtering | 13 HRSG Ductburner | 14 | 15 | Solar Mercury 50 | Solar Centaur 50 | GE - 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Direction of Improvement | ▲ | ▲ | ▲ | ▲ | ▲ | x | ▲ | ▲ | x | ▲ | ▲ | ▲ | x | | | | | |
| 1 | 9 | 17.4 | 7.3 | Reliability | | | Θ | Θ | | | | Θ | | | | Θ | | | | 3 | 3 | 4 |
| 2 | 9 | 15.1 | 6.3 | Alignment to Steam Demand | | | | | | | | | | | | | Θ | | | 3 | 3 | 4 |
| 3 | 9 | 14.1 | 5.9 | Fuel Efficiency | Θ | Θ | O | Θ | Θ | | Θ | | Θ | | Θ | | | | | 2 | 4 | 3 |
| 4 | 9 | 12.2 | 5.1 | Price | Θ | | | Θ | Θ | Θ | | Θ | | | | | Θ | | | 3 | 3 | 2 |
| 5 | 9 | 10.8 | 4.5 | Alignment to Electricity Demand | | | | | | Θ | | | | | | | | | | 2 | 2 | 4 |
| 6 | 9 | 10.5 | 4.4 | Maintenance | | | | | | | | | | Θ | | | | | | 3 | 3 | 2 |
| 7 | 9 | 8.9 | 3.7 | Service/Support | | | | | | | | | | Θ | | | | | | 3 | 3 | 2 |
| 8 | 9 | 6.7 | 2.8 | Longevity | | | Θ | | | | | Θ | | | | Θ | | | | 3 | 3 | 4 |
| 9 | 9 | 3.1 | 1.3 | Product Reputation | | | | | | | | | | Θ | | | | | | 3 | 3 | 5 |
| 10 | 9 | 1.2 | 0.5 | Physical Size | | | | | | Θ | | | | | | | | | | 2 | 4 | 3 |




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Target or Limit Value | | | | | | | | | | | | | | | |
| Difficulty (0=Easy to Accomplish, 10=Extremely Difficult) | | | | | | | | | | | | | | | |
| Max Relationship Value in Column | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | | |
| Weight / Importance | 237.0 | 127.1 | 259.3 | 393.6 | 237.0 | 217.6 | 127.1 | 326.8 | 127.1 | 202.6 | 127.1 | 216.9 | 245.7 | | |
| Relative Weight | 8.3 | 4.5 | 9.1 | 13.8 | 8.3 | 7.6 | 4.5 | 11.5 | 4.5 | 7.1 | 4.5 | 7.6 | 8.6 | | |

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Figure 3.7. House of Quality for the University Turbine Market.

The first result displayed in the House of Quality, shown in Figure 3.8 below, reveals that university officials in charge of purchasing turbines are interested in reliability, alignment to steam demand, fuel efficiency, price, and alignment to electricity demand, in order of decreasing importance. The remaining customer desires that are less important are cost of maintenance, service and support, longevity, product reputation, and physical size, also in order of decreasing importance [Figure 3.8].

| Row # | Max Relationship Value in Row | Relative Weight | Weight / Importance | Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats") |
|---|---|---|---|---|
| 1 | 9 | 17.4 | 7.3 | Reliability |
| 2 | 9 | 15.1 | 6.3 | Alignment to Steam Demand |
| 3 | 9 | 14.1 | 5.9 | Fuel Efficiency |
| 4 | 9 | 12.2 | 5.1 | Price |
| 5 | 9 | 10.8 | 4.5 | Alignment to Electricity Demand |
| 6 | 9 | 10.5 | 4.4 | Maintenance |
| 7 | 9 | 8.9 | 3.7 | Service/Support |
| 8 | 9 | 6.7 | 2.8 | Longevity |
| 9 | 9 | 3.1 | 1.3 | Product Reputation |
| 10 | 9 | 1.2 | 0.5 | Physical Size |

Figure 3.8. House of Quality – Room 1.

These results reveal what university officials consider to be high priorities when purchasing turbines. First and foremost, customers are looking for turbines that are reliable. In fact, eight of the 16 university officials who completed our survey in full ranked reliability as the most important characteristic. If engineers are not able to produce a turbine with proven reliability, universities will not be willing to purchase it. Alignment to steam demand, the second most important characteristic, must also be met for the majority of consumers. 10 of the 16 respondents ranked the alignment to steam demand as among the three most important characteristics. Finally, consumers place a strong emphasis on fuel efficiency, with eight of ten respondents ranking this characteristic as among the three most important. According to our survey, turbine producers must produce turbines with high reliability, appropriate alignment to steam demand, and high fuel efficiency to sell to most universities.

Important conclusions can also be drawn from the characteristics that university representatives ranked as the least important. Nine of the 16 respondents ranked physical size as the lease important characteristic for a turbine purchase. Knowing this, engineers can proceed with designing a turbine with little regard to physical size. 13 of the 16 respondents ranked product reputation as among the three least important characteristics. This reveals that purchasers are not very concerned with the brand name of the product they are purchasing. Smaller companies that produce turbines that are not as well known do not suffer a huge disadvantage, since consumers place little importance on the reputation of the product. Similarly, longevity of the turbine was ranked very low, with an overall ranking as the third least important characteristic. This indicates that turbine producers do not have to focus their efforts on physical size, product reputation, and longevity of turbines.

The second result derived from the House of Quality is the engineering attributes that can be changed to improve the quality of a turbine. While ideally each of these attributes would be maximized (those with an up arrow above them) or hit an exact target (for those with an X above them), there are tradeoffs in altering certain engineering characteristics that affect each other. These tradeoffs are symbolized in the "Top of the House" by the relationships displayed in the legend, representing strong positive, positive, negative, or strong negative relationships [Figure 3.9]. These relationships were developed by the research of our engineering team and confirmed with an industry expert.

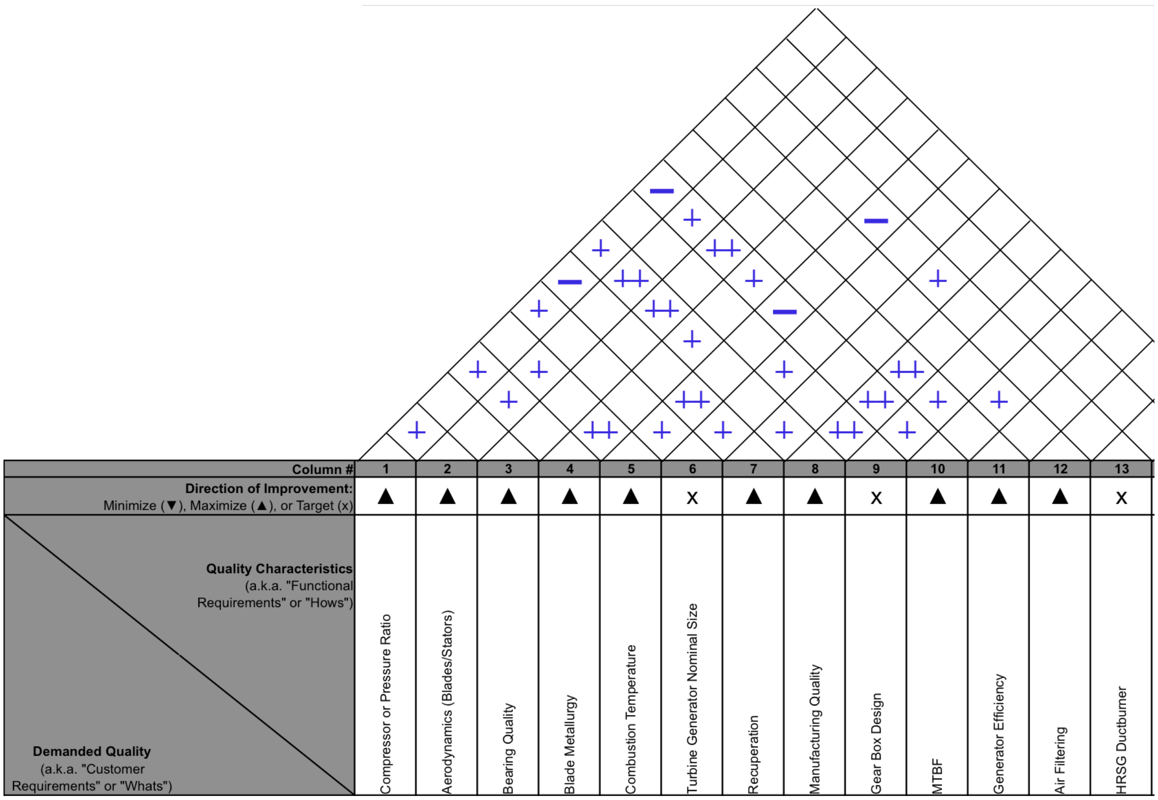


Figure 3.9. House of Quality – Room 3.

Figure 3.9 displays the relationships among the 13 engineering aspects, as determined by the survey responses and subsequently constructed House of Quality. Based on this relationship analysis, manufacturing quality has the greatest impact on the other engineering attributes, as it has a strong positive relationship with five other engineering attributes and positive relationships the three other attributes. Therefore, improving the manufacturing quality will also increase the quality of eight of the other engineering attributes.

However, increasing some engineering characteristics will negatively affect other engineering characteristics. For example, increasing the combustion temperature will lower the Mean Time Between Failure and the HRSG Duct burner. Because of this, combustion temperature should not necessarily be increased as high as possible, but has to be weighted with the negative effects it can have.

The key to the House of Quality is the relationship matrix in the middle of the house. Here, relationships are displayed between the consumer characteristics and the attributes that engineers can change [Figure 3.10].

| | | | | Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x) | ▲ | ▲ | ▲ | ▲ | ▲ | x | ▲ | ▲ | x | ▲ | ▲ | ▲ | x | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Row # | Max Relationship Value in Row | Relative Weight | Weight / Importance | Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats") | Compressor or Pressure Ratio | Aerodynamics (Blades/Stators) | Bearing Quality | Blade Metallurgy | Combustion Temperature | Turbine Generator Nominal Size | Recuperation | Manufacturing Quality | Gear Box Design | MTBF | Generator Efficiency | Air Filtering | HRSG Ductburner | | |
| 1 | 9 | 17.4 | 7.3 | Reliability | | | Θ | Θ | | | | Θ | | | | Θ | | | |
| 2 | 9 | 15.1 | 6.3 | Alignment to Steam Demand | | | | | | | | | | | | | Θ | | |
| 3 | 9 | 14.1 | 5.9 | Fuel Efficiency | Θ | Θ | O | Θ | Θ | | Θ | | Θ | | Θ | | | | |
| 4 | 9 | 12.2 | 5.1 | Price | Θ | | | Θ | Θ | Θ | | Θ | | | | | Θ | | |
| 5 | 9 | 10.8 | 4.5 | Alignment to Electricity Demand | | | | | | Θ | | | | | | | | | |
| 6 | 9 | 10.5 | 4.4 | Maintenance | | | | | | | | | | Θ | | | | | |
| 7 | 9 | 8.9 | 3.7 | Service/Support | | | | | | | | | | Θ | | | | | |
| 8 | 9 | 6.7 | 2.8 | Longevity | | | Θ | | | | | Θ | | | | Θ | | | |
| 9 | 9 | 3.1 | 1.3 | Product Reputation | | | | | | | | | | Θ | | | | | |
| 10 | 9 | 1.2 | 0.5 | Physical Size | | | | | | Θ | | | | | | | | | |

Figure 3.10. House of Quality – Room 2.

This relationship matrix reveals which engineering attributes can positively affect each of the consumer characteristics. While each engineering characteristic has a strong relationship with at least one consumer attribute, there are several engineering characteristics that affect more than one consumer attributes. Blade Metallurgy, Turbine Generator Nominal Size, and MTBF each have three strong relationships with the consumer attributes. However, the relative importance of each consumer attribute, listed in descending importance, must also be considered. Blade Metallurgy has a strong positive relationship with three of the four most important consumer attributes, making it relatively more important for creating a turbine that consumer will want to purchase. Manufacturing quality also has a strong positive relationship with two of the four most important attributes for consumers, including reliability, the most important attribute.

The bottom portion of the House of Quality displays the relative importance of each engineering characteristic and is ultimately the most important portion of the House for turbine producers [Figure 3.11].

| Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Direction of Improvement:** Minimize (▼), Maximize (▲), or Target (x) | ▲ | ▲ | ▲ | ▲ | ▲ | x | ▲ | ▲ | x | ▲ | ▲ | ▲ | x | | |
| **Quality Characteristics** (a.k.a. "Functional Requirements" or "Hows") / **Demanded Quality** (a.k.a. "Customer Requirements" or "Whats") | Compressor or Pressure Ratio | Aerodynamics (Blades/Stators) | Bearing Quality | Blade Metallurgy | Combustion Temperature | Turbine Generator Nominal Size | Recuperation | Manufacturing Quality | Gear Box Design | MTBF | Generator Efficiency | Air Filtering | HRSG Ductburner | | |
| ••• | | | | | | | | | | | | | | | |
| **Max Relationship Value in Column** | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | | |
| **Weight / Importance** | 237.0 | 127.1 | 259.3 | 393.6 | 237.0 | 217.6 | 127.1 | 326.8 | 127.1 | 202.6 | 127.1 | 216.9 | 245.7 | | |
| **Relative Weight** | 8.3 | 4.5 | 9.1 | 13.8 | 8.3 | 7.6 | 4.5 | 11.5 | 4.5 | 7.1 | 4.5 | 7.6 | 8.6 | | |

Figure 3.11. House of Quality – House 9.

This final portion of the House of Quality weighs in all the other information in the House, including the relative importance of the consumer attributes, the relationships between the engineering characteristics, and the central relationship matrix between the consumer attributes and the engineering characteristics. By weighing all these relationships, the House of Quality ranks the importance of research into improving each engineering characteristic with regard to its effect on the consumer attributes. The engineering characteristics rank as follows in order from most important to least important: Blade Metallurgy, Manufacturing Quality, Bearing Quality, HRSG

Ductburner, Compressor Pressure Ratio, Combustion Temperature, Air Filtering, Turbine Generator Nominal Size, Mean Time Between Failure, Generator Efficiency, Gear Box Design, Recuperation, and Aerodynamics. The results of the House of Quality indicate that by focusing on these most important engineering characteristics, turbine producers can effectively sell their turbines in the market and meet the demand from universities.

Within turbine-producing firms, engineers should focus on developing blade metallurgy. This characteristic is important because it has a strong relationship with reliability, fuel efficiency, and price, three of the top four consumer characteristics. Improving blade metallurgy will improve these attributes and make turbines move valuable for potential consumers. Engineers should also focus on improving manufacturing quality, which has a strong relationship with reliability and price, both important attributes for consumers.

The House of Quality provides characteristics for turbines producers to focus on that will provide additional value to consumers. It also indicates which characteristics are less important to consumers and should have fewer resources devoted to developing them. By concentrating resources on the characteristics that consumers value most, particuarly research and development of blade metallurgy and manufacturing quality, producers will be able to better meet the needs that exist in the turbine market and ultimately increase their sales.

### 3.3.2. Levelized Cost of Energy

A final value of $67.53 per MWh was determined in tangible system costs, and a LCOE of $84.72 per MWh was calculated after factoring in the cost of carbon dioxide emissions for CHP at UMD. To substantiate the legitimacy of this estimation, the identified LCOE for the UMD CHP system was found to be consistent with the range for general natural gas energy production provided by the PEW Research institute [91]. These identified values were found to be cost competitive with varying forms of carbon zero energy production methods [Figure 3.12].

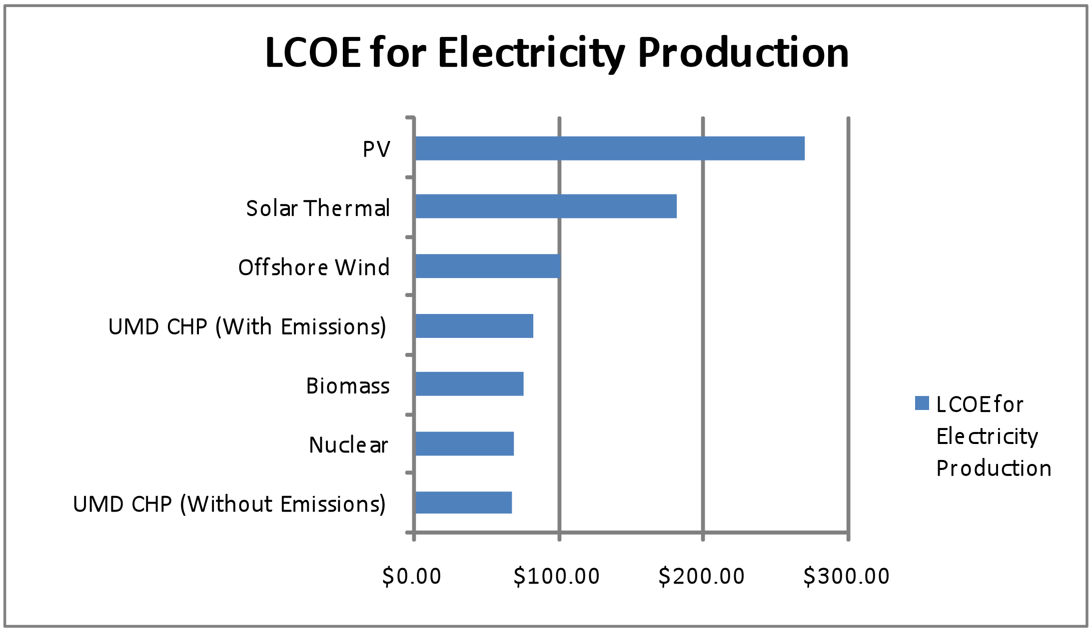


Figure 3.12. Levelized Cost of Energy for UMD's CHP Electricity Production.

When compared to forms of renewable energy production methods, CHP is the most cost effective form of substantial electrical energy production (when disregarding the environmental costs of carbon dioxide at a price of $67.53 per MWh). The nearest form of energy production to CHP is nuclear with a cost difference of slightly under $1.47 per MWh. When factoring in the environmental damages associated with carbon dioxide emissions, CHP does become a slightly less attractive method of energy production for university campuses. In this case CHP has a cost of $82.26 per MWh. This amount is $18.74 less than offshore wind electricity production but $7.26 greater than biomass energy production.

It should be noted that the LCOE for nuclear energy production is based off of a 1,290 MW power plant, which is 1,265 MW greater than the production levels of the UMD CHP plant. Although the purchase of nuclear energy for university use is feasible, the potential for a university owned power plant of this projected capacity is an economically improbable course of action. In addition, the viability of biomass depends heavily upon available resources within a given geographic area. While in some areas biomass fuel is readily available, access in others is significantly less, resulting in unfavorable transportation costs.

The economic value of operating a CHP system in close proximity of a campus is also increased through the production of high quantities of steam. In addition to producing electricity at a competitive level, a CHP plant provides a high quantity of steam with minimal added cost to the operator. This added benefit only strengthens the economic benefits of operating a CHP plant on a university campus.

These calculations confirm the economic viability of CHP for university campuses. In an environment in which a power plant can provide both thermal and electrical energy to a geographically concentrated area, the economic favorability of this form of energy production exceeds other, renewable forms of production. Even when factoring in the environmental costs of carbon these calculations suggest that in the short-term future it would be more economically favorable for a university to produce energy in a method that produces carbon dioxide and offset the effects of these emissions through alternative measures.

## 3.4. Business Integration with Policy

While it is important to consider engineering specifications and market conditions during the design process of a CHP plant, it is equally as critical to consider all relevant policies and regulations. The proposed design of a CHP plant may have optimal engineering specifications but if it does not conform to federal, state and local regulations the work will be immediately rendered impractical. This is why it is important to have an understanding of the implications of all relevant past and present, and potentially future, federal, state, and local policies that will affect a future CHP plant on a university campus in the United States.

# 4. CHP Policy

Energy policy can be extremely complicated and prohibitive, and it also has a history of being contentious. The policy challenges faced by university CHP users reflect these larger themes. The obstacles became even greater when considering plant operation with the goal of carbon reduction. This portion of the research focused on policy impacts on carbon emissions of CHP plants. To examine this issue, a thorough review of existing relevant state and federal regulations was undertaken.

## 4.1. Policy Literature Review

### 4.1.1. PURPA

Although it may seem counterintuitive to reference a policy more than 30 years old, given the ever-changing nature of American politics, a historical context is immensely helpful when examining CHP policy. The first major policy initiative that directly affected cogeneration was the Public Utilities Regulatory Policies Act (PURPA) of 1978, and many subsequent relevant laws are revisions or updates to this law. PURPA was one of the most prominent of a significant number of conservationist bills passed by Congress in response to the 230% increase in oil prices during the 1970s [92]. PURPA required utility companies to purchase power from designated “qualifying facilities” (QF) at the utility's avoided cost of producing power. To be named a qualifying facility a cogeneration plant was required to meet selected criteria, as stated in Section 201 of PURPA and enforced by the Federal Energy Regulatory Committee (FERC). The primary point of consideration for a plant attempting to become a QF was the production of electric energy and steam, heat, or another form of energy from the same primary fuel.

In addition, the QF was required to meet other specified standards that regulated ownership of the plant, its operating policies, and minimum efficiency levels [93].

The primary purpose of PURPA was to alleviate some of the issues that had previously been detrimental to facilities experimenting with cogeneration, a technology in the infancy of its commercial viability. By requiring utilities to buy power from a CHP plant, even if only under certain conditions, PURPA helped QFs immensely by allowing them to profit from the sale of their power [94]. In addition, other clauses within PURPA allowed cogenerators to more easily interconnect to the grid, purchase backup power at reasonable rates, and to exempt themselves from certain federal and state utility regulations [93]. Without the enactment of PURPA to make its endeavors profitable, cogeneration would have struggled unsuccessfully against powerful utility companies and the trajectory of the technology may have been very different.

### 4.1.2. Energy Policy Act of 1992

For several decades, PURPA "set the institutional and economic framework for the encouragement of cogeneration as a means of conserving energy" [95]. Various criticisms existed, but an assessment in 1989 argued, "cogeneration policy is basically sound, although improvements are needed regarding price signals and institution building" [95].

In 1992, the introduction of the Renewable Energy Production Incentive (REPI) program by Energy Policy Act of that year provided financial incentives for renewable energy electricity produced and sold by qualified renewable energy generation facilities, in the form of annual payments up to 2.0 cents/kWh. Cogeneration was excluded from these provisions (with the exception of biomass-burning systems). This omission prevented many CHP plants from obtaining this additional financial incentive, and further issues arose just a few years later, with the Energy Policy Act of 2005 [96].

### 4.1.3. Energy Policy Act

The Energy Policy Act of 2005, the first major energy law enacted in more than a decade, amended PURPA with the stated purpose of securing the environmental integrity of future cogeneration plants. The actual outcome was the removal of QF statuses and the associated power purchasing agreements in several areas around the country. The Energy Policy Act had three central goals: to increase competition in wholesale power markets; increase FERC's regulatory power to ensure this competition succeeded; and develop a stronger energy infrastructure. These goals resulted in a policy that increased FERC oversight and regulations of power producers nationwide, and significantly altered the policy landscape for QF cogenerators in many parts of the country.

The law increased the thermal efficiency requirements for QFs, stating an intent to limit the "potential for abuse under PURPA, curtail sham transactions, and prevent new PURPA 'machines' " [97]. These regulations were designed to foster the development of new cogeneration facilities that emphasized energy conservation by ensuring that QFs "use thermal output in a productive and beneficial manner, and that the electrical, thermal, chemical or mechanical output of new qualifying cogeneration facilities is used fundamentally for industrial, commercial or institutional purposes" [97]. In addition, ownership restrictions on qualifying cogeneration and small power production facilities were eliminated [97]. The Energy Policy Act also authorized the Department of Energy to issue loan guarantees to eligible projects that "avoid, reduce, or sequester air pollutants or anthropogenic emissions of greenhouse gases" and use "new or significantly improved technologies when compared to technologies in service in the United States at the time the guarantee is issued" [96]

The Energy Policy Act introduced a new section to the IRS code, Section 54, which detailed a new type of tax credit bond, the clean renewable energy bonds (CREB) [98]. Rather than paying the bondholder interest, CREBs pay the bondholders by providing federal income tax credits. Effectively, CREBs provide "interest-free financing for clean energy projects" [99].

In addition, FERC was tasked with conducting a joint study with the Department of Energy (DOE) and submitting a report to Congress on the benefits of small power production and distributed generation [97]. This report, completed in February 2007, discussed the many potential benefits of distributed generation and CHP that are well-known: a reduction of peak load, an increase in reliability, and maintenance of power during outages. Environmental concerns were not listed as a major consideration in the study, and the potential for reduction of harmful emissions was not discussed. The need for an expansion of research on this additional benefit is illuminated by its absence in this important government research document [100].

A final ruling released by FERC in early 2006 cemented the Energy Policy Act's importance in the history of CHP. It was a partial repeal of PURPA in certain regions of the country. The policy's stated objectives and request for a study on distributed generation indicated support for CHP, but in actuality, the Energy Policy Act reduced support for CHP plants by removing QF status and eliminating the PURPA mandatory purchase agreements in certain parts of the country with organized markets.

The ruling eliminated certain exemptions from regulations that were previously granted to QFs, and most importantly, allowed utilities to leave their purchase deals with CHP QFs. The law accomplished this by establishing a rebuttable presumption that utilities in certain areas of the U.S., including the Midwest Independent Transmission System Operator, the PJM Interconnection, and the New York Independent System Operator, among others, could prove that wholesale markets in those areas provided an outlet for QF owners to sell their power [101]. However, this tenet provoked controversy: it was reported in a testimony before Congress in 2009 that "utilities are not required to demonstrate that their markets were functionally competitive before being relieved of their PURPA mandatory purchase obligation" [102].

Effectively, utilities were allowed to stop purchasing power from local CHP plants, if they chose to do so, under the premise that there were adequate viable wholesale markets for these plants to engage in. FERC argued that the ruling supported QFs by claiming that, "by ensuring that where the newly revised requirements of PURPA have been met, market forces will stimulate QF deals, and where the requirements are not met QF development will continue to be stimulated through the mandatory purchase obligation" [103]. These rollbacks were lessened for QFs of 20MW and below, which were classified under a rebuttable presumption that PURPA purchasing rules remain in effect for such facilities. The utility would have to prove that a small QF had adequate access to the market in order to remove their purchasing agreement. In effect, the FERC ruling allowed utilities to leave their PURPA-mandated power purchasing agreements with local cogenerators if they could prove that there were adequate markets available in that region. While FERC argued that their support for CHP had not wavered, this was a serious shift in federal CHP policy that had important implications for many power producers.

#### 4.1.4. EISA

Although the drastic revisions to PURPA in 2006 heavily impacted CHP policy, federal lawmakers shortly thereafter produced other, more beneficial initiatives. In 2007, Congress passed the Energy Independence and Security Act (EISA), in which the definition of energy savings reduction was extended to include "increased use of an existing energy source by cogeneration or heat recovery, use of excess electrical or thermal energy generated from onsite renewable sources or cogeneration, and increased energy-efficient use of water resources" [104].

In addition, EISA required the Environmental Protection Agency (EPA) to create a Registry of Recoverable Waste Energy Sources. The goals of this registry were to determine the number of economically feasible waste energy recovery opportunities in the U.S.; calculate totals of these opportunities and the potential pollutant and emissions reductions that could result if these opportunities were utilized; and help monitor what outlets were feasible opportunities when financial and regulatory incentives were considered and implemented [105]. This registry was crafted using responses to a voluntary ongoing survey of major industrial and commercial sources of energy production. Each source was reviewed to determine "the quantity and quality of potential waste energy produced" [105]. Waste energy recovery was being considered an important aspect of U.S. energy production and finally, cogeneration was being considered in the same realm of emissions reductions. EISA was not solely dedicated to cogeneration, but it helped bring the technology back into political interests after the difficult blow of the 2006 FERC ruling.

### 4.1.5. EIEA and ARRA

Shortly after the passage of EISA, two key federal bills, the Energy Improvement and Extension Act of 2008 (EIEA) and American Recovery and Reinvestment Act of 2009 (ARRA) were passed that significantly increased federal financial support for CHP. The EIEA expanded federal energy tax incentives for renewable energy initiatives, including CHP, and introduced a new provision, the CHP investment tax credit (ITC). The ARRA further expanded and revised those tax incentives and promised to provide billions of dollars in funding opportunities for CHP and waste energy recovery [99]. A brief description of these financial incentives provides insight into the workings of energy incentives and their complexities.

#### 4.1.5.1. Tax Provisions

EIEA created an ITC designed to directly support increased CHP plant efficiency. The ITC was a 10% credit for the costs of the first 15 megawatts of CHP Property [99]. For a plant to receive the ITC, it must 1) have a capacity of less than 50 megawatts, 2) achieve 60% efficiency on a lower heating value basis (excluding biomass plants), 3) be tax-dollar funded, 4) produce at least 20% of its useful energy as electricity and 20% as thermal energy, and 5) begin running between October 3, 2001 and January 1, 2017 [99]. ARRA expands this benefit by allowing plants eligible for the CHP ITC to opt to receive a grant from the U.S. Treasury Department instead of accepting the ITC for new installations. These grants are issued in amounts equal to 10% of the system cost and provide an alternative cost-saving mechanism for plant owners.

The EIEA also extended the renewable energy production tax credit (PTC) through 2010 for renewable energy producers, including some waste-to-energy providers. The renewable energy PTC is a per kilowatt-hour (kWh) federal tax credit for electricity generated by qualified energy resources. ARRA extended the PTC through 2013 and increased flexibility for eligible recipients by allowing them to choose between the PTC or the federal business energy investment tax credit (ITC), or a grant from the Treasury Department. CHP plants were excluded from the PTC provision, however, and are unable to qualify for this tax credit [106].

#### 4.1.5.2. Bonus Depreciation

The Modified Accelerated Cost-Recovery System (MACRS) of the IRS provides depreciation deductions for various types of property. ARRA extended the five-year bonus depreciation schedule through 2010 and included CHP, which means 50% of the depreciation value of CHP properties may be taken in the first year, and the remainder over four more years [99].

#### 4.1.5.3. Bonds

The EIEA allocated an additional $800 million for the CREBs created by the Energy Policy Act of 2005, and ARRA added $1.6 billion more to this fund. The EIEA also changed several of the required qualifications for the issuance of a CREB. In March 2010, Congress passed H.R. 2487 (Sec. 301) allowing new CREB issuers to elect to receive a direct payment in the form of a refundable tax credit instead of the non-refundable tax credit that would otherwise be provided to the bondholder [99].

In addition to extending these government-issued bonds, the EIEA created the qualified energy conservation bonds (QECBs), which also allow the bondholder to receive tax credit rather than interest payments. State and local governments were tasked with issuing these bonds to qualified energy conservation projects. The EIEA provided $800 million and ARRA gave an additional $2.4 billion to this endeavor. Holders of bonds issued after March 2010 can receive a direct payment rather than a tax credit, if they so choose. The requirements to qualify as an energy saving project are broad enough to encompass CHP. Bonds are allocated to each state based on its percentage of the U.S. population as of July 2008. States are required to allocate a portion of its share to 'large local governments', based on the local government's percentage of the state's population [99].

#### 4.1.5.4. Grants and Incentives

$156 million of the ARRA funds were reserved by the Department of Energy (DOE) to distribute grants to support projects utilizing efficient technologies in the areas of CHP, district energy, industrial waste energy recovery, and industrial equipment. These grants were awarded to 41 industrial energy efficiency projects in 2009. Nine of the largest projects received $150 million, a sum supplemented by $634 million in private industry support. These projects were designed to "promote the use of CHP, district energy systems, waste energy recovery systems, and energy efficiency initiatives" [99]. This show of support by the DOE was important in promoting CHP; however, it was disappointing to learn the $1.1 billion that was allocated for this initiative in the original bill was cut to $156 million. The funds were oversubscribed by 25:1, indicating a vast number of CHP projects interested in and eligible for federal grant money that were unable to be funded with this limited amount.

#### 4.1.5.5. EECBG

ARRA allotted $3.2 billion to a block grant incentive initially signed into law in EISA, entitled the Energy Efficiency and Conservation Block Grant Program (EECBG) and modeled after the Community Development Block Grant program crafted by the Department of Housing and Urban Development (HUD). The EECBG initiative distributed $3.2 billion in grant money to local, tribal, state and territorial governments to implement projects designed to reduce energy use and fossil fuel emissions through energy efficiency improvements. The funds were distributed the funds to both retrofit and new construction projects through grants. “Installation of distributed energy technologies including combined heat and power and district heating and cooling systems” constitutes a project qualified to receive funding [107]. Adhering to ARRA’s core objective, one of the listed goals of the EECBG program is job creation and retention.

#### 4.1.5.6. Loan Guarantee

Finally, ARRA expanded the loan guarantee program of the Energy Policy Act of 2005 by $6 billion. The program provided loan guarantees to projects designed to avoid, reduce, or sequester air pollutants or anthropogenic emissions of greenhouse gases, while implementing new or significantly improved technologies. The program, designed to support larger scale projects, was accompanied by an $8.5 billion solicitation by the DOE for projects employing “innovated energy efficiency, renewable energy, and advanced transmission and distribution technologies” [99]. The emphasis on increased efficiency and decreased emissions was an encouraging aspect of ARRA, and led the New York Times to point out that the approximately $80 billion allotted to clean energy initiatives made the unprecedented stimulus bill “the biggest energy bill ever” [108].

### 4.1.6. Current Initiatives

#### 4.1.6.1. TREEA Bill

The Thermal Renewable Energy and Efficiency Act of 2010 (TREEA) supported an expansion of the district energy and combined heat and power market by extending the tax credit for renewable electricity production to thermal energy production [109]. This bill garnered support from industry groups and has been slightly altered and renamed the Clean Local Energy Efficiency and Renewables Act (CLEER) [110]. At the time of this writing, the language is being finalized before the bill can be reintroduced.

#### 4.1.6.2. Comprehensive Climate Legislation

Recently, federal regulation of greenhouse gas emissions has become the center of heated debate. A particularly well-known cap and trade bill, the American Clean Energy and Security Act of 2009 or the Waxman-Markey Bill, passed the House of Representatives by a narrow margin in June 2009 but ground to a halt on the Senate floor during heated debate over healthcare reform [111]. At the time of this writing, the potential for comprehensive climate change legislation seems low, with widespread conservative opposition in a Republican-controlled House. Alternative legislation using a more limited cap and trade program has been discussed, since the more extensive and complex system put forth by the House bill did not have the support it needed to pass the Senate [112]. However, the issue seems to have fallen off of the media radar and will likely remain at an impasse until the political climate changes.

### 4.1.7. Emissions Regulation

Environmental Protection Agency (EPA) regulation of greenhouse gas emissions is, at the time of this writing, suffering from criticism for what is being called its excessive regulatory constrictions. CHP plants are required to monitor and report emissions levels to regulatory federal agencies, under Title V requirements of the Clean Air Act [113]. Main pollutants from gas turbines in addition to NOx are carbon monoxide (CO), unburned hydrocarbons (UHC), sulfur oxides, and particulate matter; however, NOx and possibly CO have been widely considered the only "emissions of significance" from gas turbine combustion [114].

Nitrogen oxides (NOx), the pollutants that contribute most heavily to smog, were the primary target of emissions regulations introduced in the 1970s. Industry response to this issue came in the form of water or steam injection to reduce NOx levels [115]. Reduction requirements increased in the 1980s, and it was discovered that increased water or steam injection caused "detrimental effects to the gas turbine cycle performance" and "other exhaust emissions began to rise to measurable levels of concern" [115]. There is a "design dichotomy" that exists, in which "increasing firing temperature to increase the efficiency of the combustion process…produces more NOx, requiring more injection, which lowers the thermodynamic efficiency, producing more CO" [114]. The outdated elevated requirements to meet lower NOx levels have been shown to have a negligible effect on NOx, and a detrimental effect on other aspects of gas turbine operation. Researchers concluded that the overall impacts of requiring lower levels of NOx, with a gas turbine combustion system that is already capable of achieving single digit NOx reach the point of diminishing return: "the cost of add-on emission controls to achieve a lower NOx level becomes excessive, the heat rate increases, and the overall environmental impacts are actually worsened" [114]. It was recommended that the regulatory process is amended to consider "environmental, energy, and economic impacts" in cases where add-on emission controls will result in only a small reduction in emissions [114].

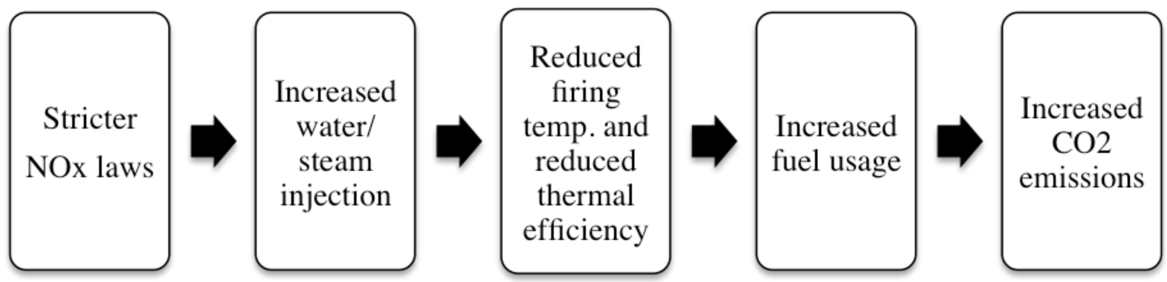


Figure 4.1. Negative Impact of NOx Laws on Carbon Emissions.

### 4.1.8. State Initiatives

State bodies also play important roles in CHP governance. In order to regulate emissions levels, operating permits for air pollution sources are required under Title V of the Clean Air Act (1990). State and local permitting authorities issue most of these Title V permits, although the EPA is responsible for certain areas of the country [113].

In addition to emissions permitting administration, state governments are responsible for establishing renewable portfolio standards (RPS). An RPS is a state policy that requires electricity providers to obtain a minimum percentage of their power from renewable energy sources by a certain date [116]. As of 2009, 24 states plus the District of Columbia had RPS policies in place, accounting for more than half of U.S. electricity sales. Maryland's RPS requires the state to obtain 20% of its power from renewable energy sources by 2022. As of 2009, 13 states list CHP as a source designated as eligible for RPS renewable energy credits—this list does not include Maryland [117].

### 4.1.9. Interconnect Agreements

Interconnection rules incorporate processes and technical requirements that bind distributed generators, including CHP plants, seeking to connect distributed generation systems to the electric utility grid. An interconnect agreement is a document that outlines the rules governing a generator's interconnection to the grid and is a central part of the application process to obtain interconnection. Effective interconnect agreements give utility consumers the benefits of CHP power without sacrificing safety or reliability [118]. The application process, which can be lengthy and complicated, includes "technical interconnection requirements, such as technical protocols and standards that dictate how generators must interconnect with the electric grid" [118].

Standardizing interconnect agreements encourages CHP by establishing a set of simplified and standardized rules that dictate the conditions under which clean energy systems can connect to the grid. Standardized interconnection rules, which are usually designed and administered by a state's public utility commission, play an important role in improving the market conditions for CHP. A facility connected to the grid can purchase power from the grid as supplemental power when needed, sell excess power to the utility, and maintain grid frequency and voltage stability [118-119].

Interconnection standards are helpful when CHP project developers want to understand the technical requirements for interconnection. The standardized rules dictate the application process as well as the technical requirements for interconnecting plants of a certain type and size with the electric grid.

## 4.2. Policy Methodology

### 4.2.1. Overview

To understand the policy-related challenges facing CHP plant owners and operators, a qualitative modified case study approach was used. A careful examination of the literature, notably a thorough review of relevant texts of national energy laws, played an important role in determining the methodology. An examination of the political dynamics affecting university CHP systems revealed the importance of using local examples to build a more comprehensive dialogue about national trends, and revealed several policies that warranted deeper investigation.

A historical consideration of energy legislation and regulation in the United States indicated discrepancies between the motivations and rhetoric behind a law and the actual consequences it produced. To test this hypothesis several cases were examined. The benefit of such a specific approach is an in-depth understanding of the policy forces at work in a particular plant's design, construction, and operation. As such, close comparison of the intentions of a law and the consequences it actually produced were used to observe instances of efficacy of energy policy in America, as it pertains to CHP.

Plant managers from three universities included in the thermal efficiency surveys mentioned above were interviewed. Each hour-long interview contained questions about plant-specific policy influences as well as any follow-up questions and discussions on subjects that came up in the interview. The questions were intentionally kept open-ended and yielded a variety of responses that prompted further study of and validation by the literature. All interviews were conducted in confidentiality, and the names of interviewees are withheld by mutual agreement. Combining the preliminary policy studies with the interview results and subsequent additional policy studies demonstrated the breadth of influence that a single policy or type of policy can have.

### 4.2.2. Research Design

The policy section of this research was prompted by an unexpected response to a data collection request for plant operation data. When asked for operating data, a subject responded that the university plant he worked at had ceased to operate several years earlier, due to policy issues. His brief explanation of the issue that had forced the university's CHP plant to close indefinitely prompted further examination and it was decided that additional research into policy impact on CHP was warranted.

In order to determine the impact of federal, state, and local policies on the planning, development, and daily operation of CHP plants, it was necessary to study these processes at several universities that have (or had) CHP plants supplying their campus demand. Rather than considering a large number of plants, it was decided to consider just a few carefully selected subjects, so as to get a detailed and comprehensive understanding of a small number of policy implications as possible. Attempting to study all of the potential policy issues affecting CHP plants was determined to be impossible given the scope of this project. With these considerations in mind, three universities were selected for study.

### 4.2.3. Subject Selection

The three university power plants we studied for the policy research wish to remain anonymous. For that reason, they will be referred to as University A or Plant A, University B or Plant B, and University C or Plant C. The plant managers will be referred to in similar fashion: Plant Manager A, Plant Manager B, and Plant Manager C.

The three universities selected for study are all large (>25,000 students) institutions that have constructed a CHP plant to meet some or all of their power generation needs. University A is in the Western part of the United States, University B is in the Midwest, and University C is on the East Coast. University A was selected because of its role as the subject that prompted this portion of the research design and its clear ability to contribute valuable policy information. Universities B and C were also surveyed in the engineering data collection process and were selected based on plant manager willingness to participate in an additional portion of our study.

### 4.2.4. IRB Approval

Before conducting the interviews, approval from the University of Maryland Institutional Review Board (IRB) was needed, because our research involved interaction with human subjects, the power plant managers at the three universities. The application for IRB approval detailed the selection of subject process, the interview process, the questions to be asked in the interview, and the larger implications of the research. The application also required consent forms for each of the interview subjects to be submitted for approval. The script is available in Appendix 6.3.1.

Once IRB approval was obtained, interviews began. Phone interviews were scheduled for two of the contacts and an in-person interview could only be used for the third, due to geographical constraints. The subjects were given a copy of the questions and a consent form and consent was obtained before interviewing began. They consented to be interviewed as well as to be recorded, and were informed that their recordings and related materials would be kept confidential, per IRB requirements.

### 4.2.5. Interview Proceedings

The questions detailed on the IRB form were designed with the primary goal of prompting conversations with the subjects on their experiences with CHP policy. The questions were not designed to be presented in any strict order, because the goal of the research was to gain a qualitative sense of the state of CHP policy for actors at different plants in different parts of the country. A free-flowing conversation was necessary and encouraged to allow subjects to raise and discuss topics that were of particular interest to this study but may not have been anticipated in the prepared question list. This was simply due to the huge breadth of issues that exist and an inability to ask about every single one of those. The power plants at each of the universities have different characteristics, different situations in which they were established, different levels of requirements to serve their campus demand, and different state and local legislation to adhere to—it was highly unlikely that we could design a wholly comprehensive question list on all the related policy issues.

Although the questions were designed to be very open-ended, it was important that background research was conducted on each of the universities and their plants prior to the interview. This gave the interviewers the ability to establish rapport with the subject and conduct a worthwhile interview. This background research consisted of secondary review of newspaper articles and publications by the subject universities on their plant construction, in addition to the general policy research already conducted as part of the literature review.

The interviews each lasted about 45 minutes and, as expected, varied greatly in their content. A digital voice recorder was used to record the interviews and a formal transcription was typed for each. Subjects were first asked background information about their professional history and the history of the plant at their current employing university. General questions about the impact of CHP policy, per their experience as plant manager, were then used to initiate conversations, which in all three cases provided important insight.

### 4.2.6. Analysis

After the interview process was complete, an analysis of the results directed further review of legislation text and secondary sources. Each of the plant managers emphasized different policy concerns related to constructing and operating a CHP plant on university campuses and as a result, there were a wide variety of topics to further research. The findings of this additional research are incorporated in the analysis of the interviews that appears below.

## 4.3. Policy Results

### 4.3.1. Overview

Policy reviews quickly indicated the sheer volume of related policy, and confirmed that it is imperative to consider policy issues when contemplating the construction of a plant. Myriad federal and state energy policies require that necessary steps be taken for a plant to remain in compliance during its construction and operation. Particularly important considerations include permitting issues, emissions compliance and related costs, and federally mandated power purchasing agreements. An examination of three large universities across the country reveals these issues to be particularly pressing and greatly influential on the costs and day-to-day operations of the plants.

To further explore these issues and discuss the implications of various policies for CHP plants and emissions reductions efforts, the results of the three case study interviews will be related and analyzed.

### 4.3.2. Case Study Findings

The actual effects of many policies vary considerably from their stated purposes, and CHP legislation is no exception. The case studies revealed several policy areas that are particularly challenging to plant owners and operators, and in some cases, directly prohibit plants from operating at maximum efficiency. The case studies yielded a breadth of experiences that speaks to the wide range of potential impact that policies can have. For confidentiality purposes, the subject schools and plant managers will be referred to as Universities A, B, and C and Plant Mangers A, B, and C. A brief description of the findings from each subject university provides the basic framework for our general conclusions about CHP policy and its effect on carbon emissions reductions efforts.

#### 4.3.2.1. University A

Federal policy provides the basis of the very existence of some CHP plants in the U.S. As discussed previously, the implementation of PURPA in the late 1970s resulted in increased economic feasibility for many plants due to its mandate that utility companies purchase power from designated “qualifying facilities” (QF), at the utility's avoided cost of producing power. The FERC ruling in 2006 that repealed portions of PURPA, however, including key elements of the QF initiative, changed the nature of cogenerating for plants around the country.

Plant A, located on the campus of a well-known large university in the Western part of the U.S., was directly adversely affected by the partial repeal of PURPA. As a result of the 2006 changes, the university's local utility, which had been purchasing University A's excess power since its construction in the early 1990s, was able to apply to exit its federally mandated power purchasing agreement. The power purchasing agreement had been supported by PURPA and its Qualifying Facility (QF) provision since the plant's design and construction. As a designated QF, University A was designed to be able to justify its CHP plant economically through its sale of excess power to the utility company. The utility company only purchased the university's power, however, because it was federally required to do so. As a general rule, the utility is able to acquire and produce power at a cheaper rate due to its reliability on coal, and so under market forces, it was no longer interested in purchasing Plant A's power after 2006. When PURPA was partially repealed in 2006, with the stated purpose of allowing market forces to govern the CHP industry, University A was forced to close its plant. It was no longer economically feasible to run the plant, and the University is currently purchasing electrical power from the utility grid while its plant sits idle for most of the year.

The closure of University A's plant had adverse implications for their campus carbon dioxide emissions levels. The local utility is a coal-fired operation and extremely emissions-heavy. The president of University A is a signatory of the ACUPCC, which requires University A and its peer signatories to commit to significant carbon emissions reductions in the near future. If the campus plant were still serving the campus' electrical power needs, the University would have a significantly smaller carbon footprint and be closer to reaching its commitments. The federal policies in place, however, are severely hindering University A's ability to meet its carbon reduction goals. The disconnect between ideological statements on and actual obstacles to carbon neutrality demonstrates the overarching disconnect between normative political statements and goals and actual policy realities.

#### 4.3.2.2. University B

University C faced a second unique obstacle. When its plant was designed, the exact emissions levels of its gas turbines were unknown because they were new models from the manufacturer. In order to ensure the plant remained in compliance with emissions standards, University B officials applied for a permit dictating their carbon emissions would be a certain, rather high, level. Once the turbines were installed, their efficiency levels were better than anticipated, which is an advantage, in the context of carbon reduction and reduced fuel costs for University B. However, the nature of the permit required the plant to produce at or very near its permitted level, and so additional equipment had to be installed to actually *increase* emissions to that level. The permit in this case cannot be reopened because emissions standards today are stricter than they were when the original permit went into effect, and as Plant Manager B explained, the university would have to take additional costly actions to reduce emissions in other areas to meet overall requirements, if the permit were reopened. Once again, a plant was shown to experience unnecessarily high emissions levels due to ineffective policy initiatives.

Emissions testing and compliance create another costly issue for university plants, and Plant Manager B estimated the cost of twice-annually testing at $20,000 per test. Plant Manager B emphasized the extensive nature of operating costs and cited them as a significant barrier. As this case study demonstrated, minor permitting issues at the time of construction can cost hundreds of thousands of dollars in lost fuel efficiency and substantially increase fuel emissions over the plant's lifetime.

#### 4.3.2.3. University C

University C has two 10.5 MW gas turbines housed in a plant of approximately 27 MW total operating capacity. The plant has been operating since 2003 and replaced an oil-fired system that had previously replaced a coal-fired system. University C has encountered difficulties maximizing its on-campus CHP plant's efficiency due to an ineffective interconnect agreement. As a result of an interconnect agreement negotiated with the local utility company at the time of construction in a regulated energy market, University C is not allowed to sell excess power to the local utility and thus is not able to produce more power than it can consume at any given time. In the past, the plant has had to reduce the speed of its turbines so it did not violate its interconnect agreement. This reduced turbine efficiency levels and the efficiency levels of the plant as a whole. Reduced efficiency levels correspond with higher carbon emissions and are directly antagonistic to the University's goals of carbon reduction, as a signatory of the President's Climate Commitment.

Plant Manager C cited capital funding as the greatest obstacle to plant implementation, and explained that the state in which University C is located was unable to help the university finance the plant's construction and operation. A third party company was contracted to issue bonds on behalf of the university to finance the construction. This company's reluctance to be perceived as a utility or a utility-providing entity is the main reason the interconnect agreement was crafted to prohibit any sell-back.

University C is anticipating significant campus expansion in the coming years and it is highly likely that there will be an increase in demand. The interconnect agreement may have to be reopened if this construction falls under the same utility meter, and this could potentially present some additional considerations and challenges for the university.

### 4.3.3. $NO_X$

As previously discussed, research has demonstrated that NOx emissions regulations reach a point of diminishing return, when the effects of increasing the stringency of permitted NOx emissions become negligible and even potentially harmful. Considering this notion in the context of carbon dioxide emissions applies well to this project. To reduce carbon emissions, efficiency must increase, and NOx-dictated actions (injection methods designed to decrease NOx emissions) have an adverse effect on this course of action. The relationship between efficiency and combustion temperature demonstrates that to achieve higher efficiency levels, higher temperatures must be allowed—increasing NOx, a serious issue under current emissions laws [Figure 4.2]. However, emissions laws that carefully consider carbon emissions as well will take into consideration the need for a compromise between the two emissions, a compromise that is a combustion temperature that allows the maximum NOx levels deemed safe, and the minimum carbon dioxide levels possible. A carefully-constructed balance is needed to allow for increased combustion temperatures, increased efficiency, and an immediate realization of lower carbon emissions, while still maintaining a safe level of NOx emissions.

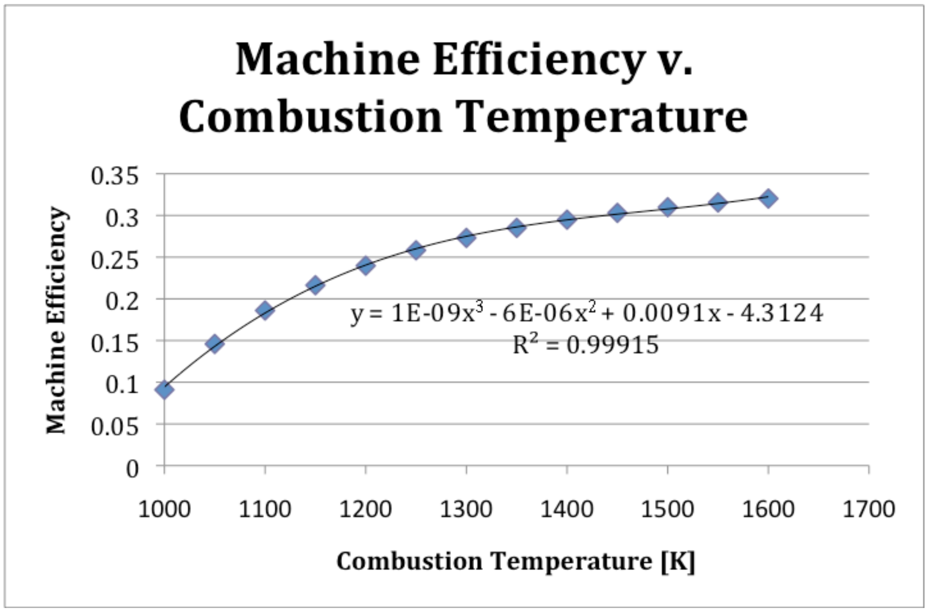


Figure 4.2. Machine Efficiency vs. Combustion Temperature.

## 4.4. Recommendations

The interviews and research conducted during the completion of three miniature case studies revealed a number of areas in which policy obstacles result in obstacles for university CHP plant operations that may increase carbon emissions. Taking these issues into consideration, a number of recommendations for minimizing policy barriers and maximizing incentives have been developed. Some of these recommendations are broad and would likely be difficult to implement for a variety reasons, ranging from the logistical to the political. However, rather than focus on the obstacles to effective policy, these recommendations take a more holistic view and discuss the potential for what ideal CHP policy may look like.

### 4.4.1. Greater Accountability of Federal Initiatives

Federal rhetoric on controlling greenhouse gas emissions has been characterized by partisanship and turbulence during recent years. The effect of this disarray on daily CHP operation and attempts to increase efficiency and decrease emissions should be minimized whenever possible. This requires a greater assurance that actual outcomes of policy initiatives match anticipated and desired outcomes. Specifically, this broad issue manifests in such cases as that of University A. A far-reaching, general policy decision handed down by the Energy Policy Act and a FERC ruling in 2005-06 had a drastic adverse effect on Plant A's operations and the university's total carbon emissions. There must be a way to ensure situations such as this do not occur. This redress could occur in two potential ways: first, the university could have some mechanism by which they can present an appeal or request a reconsideration of their particular individual situation, or second, an accountability or monitoring scheme could be developed. Both options will likely require additional funding and time, but the emissions reductions potential of a system in which university plants were able and encouraged to operate and lower emissions would be highly beneficial to emissions reductions goals—a goal that the current administration claims to support wholeheartedly.

### 4.4.2. Nationwide Inclusion of CHP in Eligible RPS Technologies

As discussed in the literature review, 13 states currently include CHP on their lists of technologies eligible for RPS incentives. Maryland is not one of these states, and neither is the state in which University C operates. In the interview with Plant Manager C, it was suggested that CHP should be eligible for renewable energy credits (RECs). Perhaps if it is not entirely eligible (i.e. 1 MWH of CHP may not be eligible for 1MWH of a REC) then it could receive partial qualification (i.e. 1 MWH of CHP may qualify for .5 or .25 of an REC). If adopted, this policy could encourage CHP construction at universities seeking to reduce carbon emissions and would provide financial assistance to plants already in operation [117-121].

### 4.4.3. Widespread Standardization of Interconnect Agreements

The issues that can arise when creating interconnect agreements are numerous: “terms, conditions, demands for redundancy, interconnection rules, back-up service charges and everything that's in the restructuring tariffs”, all of which are “keeping distributed generation projects from going forward” [122]. These obstacles were evidenced by the case study of University C and are currently being improved in many states in various ways. Notably, a standardization of these rules is utilized as a way to make the process simpler. 34 states currently have standardized interconnect agreements in place [123]. (This list includes the state in which University C operates. However, the standardized agreement was not put into place until after the plant was constructed.) For states that lack such standardized agreements, it is recommended that a system similar to that of Texas be adopted. Texas has an extremely simple interconnection process often referred to as a “plug and play” system, under which “pre-certification exempts units from further review of the system design”—i.e., once the system is approved to connect to the grid, the process is complete. No negotiation of an agreement happens, because it is already designed and agreed upon beforehand, when a producer decides to integrate into the grid [124].

### 4.4.4. Consider Efficiency when Constructing and Operating Plants

During the design and construction of a new CHP plant, administrators craft a number of agreements that dictate various aspects of the plant’s operations. A particular type of agreement that was found to have a direct adverse effect on carbon emissions was the interconnect agreement. Efficiency levels were not carefully considered during the creation of University C’s interconnect agreement and as a result, its plant’s carbon emissions are unnecessarily high. Cost, logistical concerns, and technical specifications are clearly very important considerations during the construction and implementation of a new university CHP plant, but these findings indicate that for the carbon-conscientious operator, efficiency is equally important.

### 4.4.5. Streamline Emissions Testing Process

Universities are required to comply with a number of emissions requirements, and these regulations are an important part of ensuring air quality. However, a study of University B's plant revealed that regular emissions testing can be time-consuming, convoluted, and extremely costly. To attempt to alleviate this potentially detrimental and prohibitive issue, regulatory agencies could conduct a detailed study of the emissions testing requirements that CHP plants must comply with and identify areas that overlap or appear redundant. These could then be condensed and streamlined so as to decrease cost and hassle for plant operators—potentially providing additional time and money to be spent on tasks and upgrades designed to increase efficiency and reduce emissions.

In addition, allowing increased flexibility in emissions permitting processes would be beneficial, as shown by University B's experience with an incorrectly-designed emissions permit, to which compliance ultimately forced increased emissions. To combat this counter-productivity, perhaps university plants (likely attempting to install CHP for carbon reduction reasons more than profit-making ones anyway) could enjoy some increased flexibility during permitting processes. For example, this plant, attempting new, groundbreaking, emissions-reducing turbines, could be given an extension on permit applications so that proper operating standards—specifically, ones that maximize efficiency—could be determined before they were legally cemented into existence.

### 4.4.6. Update Emissions Laws to Emphasize $CO_2$

Current emissions laws governing CHP plants focus primarily on levels of NOx produced by these plants. These outdated laws should be updated to reflect a greater emphasis on $CO_2$ emissions, as its contribution to climate change has been widely accepted in the scientific community. Accepting past research on diminishing returns on ever-increasing NOx requirements, this issue can be addressed through a carefully designed lessening of NOx requirements. If properly crafted, this balance between the two types of emissions will allow greater turbine combustion temperatures, which will increase efficiency, and reduce carbon emissions.

## 4.5. Policy Conclusions

There is a literal maze of costly obstacles to overcome during the design and construction of a plant that does not disappear once operation is underway. Policies arising from goals to regulate energy markets, control emissions, and maintain legal contractual agreements often result in unforeseen consequences and obstacles for plant managers and others in the field. These consequences often remain unaddressed. In the struggle to reduce carbon emissions, CHP must remain an immediate viable alternative to currently unrealistic renewable alternatives, and more streamlined permitting and emissions testing requirements and careful monitoring of ineffective purchasing agreements would significantly aid in this task.

# 5. Conclusions

This research took three tacks toward a common goal – to reduce carbon emissions on university campuses. A community-wide lack of understanding of the operating efficiencies of existing turbines was exposed in the findings. There are shortcomings in existing CHP systems' measurements of operating efficiencies due to the lack of real-time efficiency calculations and measurement fidelity. This also demonstrates that a more efficient turbine is more ideal for a CHP system and that higher efficiency is achievable with current technology (recuperators and intercoolers) affixed to current machines. Despite the favorability of more efficient turbines, and the strong existing and potential market for CHP systems, there remains a very low supply of highly efficient turbines in the existing marketplace. Combined with the lack of market competition in this field, it was concluded that the small turbine market was thus a broken one. However, along with any increase in viable products that capitalize upon engineering considerations, the only way in which these solutions can become a reality are if there are increased accountability in federal CHP policy, streamlined permitting processes, and simplified interconnection rules. Overall, improvements in existing power generation practices like CHP technology hold a vast and yet untapped potential for carbon footprint reductions in the immediate future – one that will come to fruition as more sophisticated power generation techniques are being developed.

# 6. Appendices

## 6.1. Engineering Materials

### 6.1.1. Engineering Introduction Letter

Dear [Plant Operator],

My name is [Researcher], and I am pursuing my undergraduate degree in [Major] at the University of Maryland - College Park. I am simultaneously participating in the Gemstone Program, which is a four-year research program designed to allow undergraduates to conduct graduate-style team research projects. I am currently a member of a team consisting of 10 students and a mentor from interdisciplinary backgrounds with a focus on improving cogeneration technology integration in university campuses. Our proposed research objective is twofold: 1) to develop a model CHP system that best meets the energy needs of a generic university campus while minimizing carbon emissions, and 2) to apply the model to existing universities to provide recommendations of specific improvements to their cogeneration systems.

In order to achieve these goals, we are attempting to compile data from a number of different university cogeneration systems for use in our CHP simulations. Our initial research has identified [University] as having a well-established CHP system that we believe could be highly beneficial in our study. We were hoping that you (or a contact of yours) would be able to provide us with some specific operational figures for your CHP system. If you are willing and able to provide us with this information then we can forward you a list of the variables that we are attempting to measure. Any information would help us immensely with our research. Thank you in advance for your assistance.

Best Regards,
- [Researcher]

Phone: [Phone]
E-mail: [E-mail]

### 6.1.2. Engineering Survey (Detailed)

| Cogen Survey Data | | | | | |
|---|---|---|---|---|---|
| **General System Design** | | | | | |
| Fuel Type | | | | | |
| Fuel Energy Density | | | | | |
| | Present (Y/N) | Manfacturer | Quantity | Efficiency | |
| Compressor (Gas / Steam / Other) | | | | | |
| Multi-Stage (1) | | | | | |
| Multi-Stage (2) | | | | | |
| Intercooler | | | | | |
| Combustor (Gas / Other) | | | | | |
| Boiler (Steam) | | | | | |
| Turbine (Gas / Steam / Other) | | | | | |
| Multi-Stage (1) | | | | | |
| Multi-Stage (2) | | | | | |
| Reheater (Duct Burners) | | | | | |
| Recuperator (Heat Exchange) | | | | | |
| HRSG (Heat-Recovery Steam Generator) | | | | | |
| Boiler (Back-Up Steam Generator) | | | | | |
| **Alternate System Peripherals** | | | | | |
| Absorption Chillers | | | | | |
| Duct Burners | | | | | |
| **System Operating Conditions** | | | | | |
| | Single-Stage | Multi-Stage | Multi-Stage | | |
| Ambient $T_{Dry\ Bulb}$ | | | | | |
| Ambient $T_{Wet\ Bulb}$ | | | | | |
| Air Flow Rate | | | | | |
| Fuel/Air Ratio | | | | | |
| $T_{Air}$ (After Compressor) | | | | | |
| $P_{Air}$ (After Compressor) | | | | | |
| $T_{Air}$ (After Intercooler) | | | | | |
| $P_{Air}$ (After Intercooler) | | | | | |
| $T_{Air}$ (After Combustor) | | | | | |
| $P_{Air}$ (After Combustor) | | | | | |
| $T_{Air}$ (After Turbine) | | | | | |
| $P_{Air}$ (After Turbine) | | | | | |
| $T_{Air}$ (After Reheater/Duct Burner) | | | | | |
| $P_{Air}$ (After Reheater/Duct Burner) | | | | | |
| $T_{Air}$ (After HRSG) | | | | | |
| $P_{Air}$ (After HRSG) | | | | | |
| **Fuel Usage** | | | | | |
| Fuel/Air Ratio | | | | | |
| Fuel Firing Rate (Combustor) | | | | | |
| Fuel Firing Rate (Reheater/Duct Burner) | | | | | |
| **Turbine Output** | | | | | |
| Turbine RPM | | | | | |
| **Generator Output** | | | | | |
| Nominal Power Output (MW) | | | | | |
| Average Power Output (MW) | | | | | |
| Peak Power Output (MW) | | | | | |
| Generator Eff | | | | | |
| Generator Voltage | | | | | |
| Transformer Voltage | | | | | |
| **HRSG Input / Output** | | | | | |
| Feedwater Temperature | | | | | |
| Steam Production Rate | | | | | |
| $T_{Steam}$ (Produced) | | | | | |
| $P_{Steam}$ (Produced) | | | | | |
| Steam Recovery Rate (%) | | | | | |
| $T_{Steam}$ (Return) | | | | | |
| $P_{Steam}$ (Return) | | | | | |
| Quality (Return) | | | | | |

### 6.1.3. Engineering Survey (Simple)

| Cogen Survey Data | | | | |
|---|---|---|---|---|
| | | | | |
| | | | | |
| Variable | Data | Unit | Standard Unit | Conversion |
| Ambient temperature | | | C | |
| Ambient pressure | | | kPa | |
| Total fuel mass rate | | | kg/s | |
| Fuel mass rate into the turbine | | | kg/s | |
| Total electrical MW out | | | kg/s | |
| Temperature of steam (when exiting plant to be distributed) | | | C | |
| Pressure of steam (when exiting plant to distributed) | | | kPa | |
| Mass rate of steam (when exiting plant to be distributed) | | | kg/s | |
| Temperaure of incoming condensate | | | C | |
| Pressure of incoming condensate | | | kPa | |
| Mass flow / % return of incoming condensate | | | % | |
| | | | | |
| | | | | |

### 6.1.4. EES Simulations

#### 6.1.4.1. University Simulations

Sample code for the university simulations is provided below.

```
"Natural Gas Stats"
Rho_NG = 0.8 "[kg/m^3]"
E_NG_V = 39*10^6 "[J/m^3]"
E_NG_M = E_NG_V/Rho_NG

"Energy Transfers"
Fuel_In_Total = (0.588+0.727)/2
Fuel_In_Turbine = (0.588+0.727)/2
Fuel_In_Duct = Fuel_In_Total - Fuel_In_Turbine

"Turbine"
Q_dot_In_Turbine = Fuel_In_Turbine*E_NG_M
W_dot_Out_Turbine = (8.51)*10^6 "[W]"

"HRSG"
T_Room = ConvertTemp(F,C,70)
T_In_HRSG = ConvertTemp(F,C,246)
T_Out_HRSG = ConvertTemp(F,C,744)

P_In_HRSG = (14.70+605)*Convert(PSI,Pa)
P_Out_HRSG = (14.70+616)*Convert(PSI,Pa)

M_dot_HRSG = (43000+52000)/2*Convert(lb_m/hr,kg/s)
Pct_Return = 0.675

Q_dot_In_Duct = (Fuel_In_Duct)*E_NG_M
H_In_HRSG = Enthalpy(Steam,T=T_In_HRSG,P=P_In_HRSG)
H_Out_HRSG = Enthalpy(Steam,T=T_Out_HRSG,P=P_Out_HRSG)
Q_dot_Out_HRSG = M_dot_HRSG*(H_Out_HRSG-H_In_HRSG)

"Efficiency"
eta_Turbine = W_dot_Out_Turbine / Q_dot_In_Turbine
eta_HRSG = Q_dot_Out_HRSG / (Q_dot_In_Duct+Q_dot_In_Turbine-
    W_dot_Out_Turbine)
eta_System = (W_dot_Out_Turbine+Q_dot_Out_HRSG)/(Q_dot_In_Turbine+
    Q_dot_In_Duct)
```

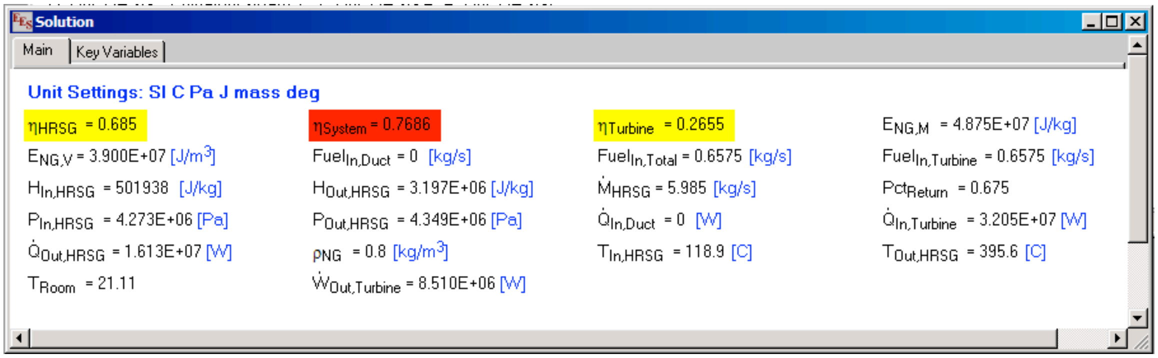


Figure 6.1. University 1 – Results.

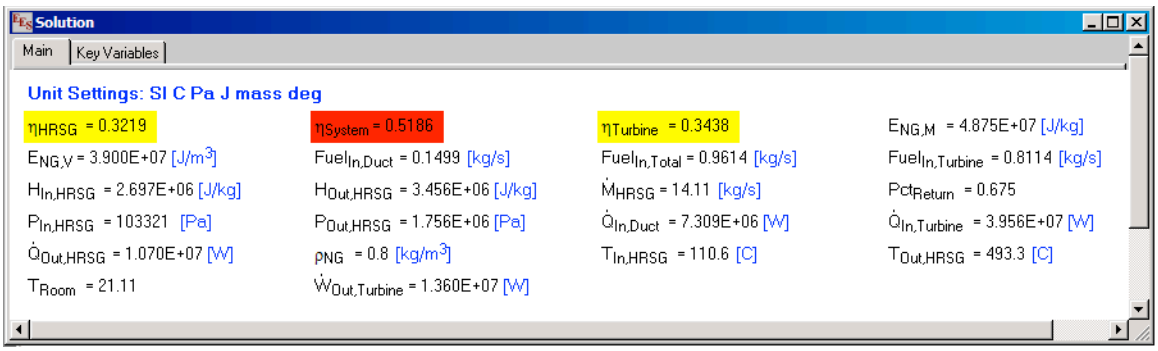


Figure 6.2. University 2 – Results.

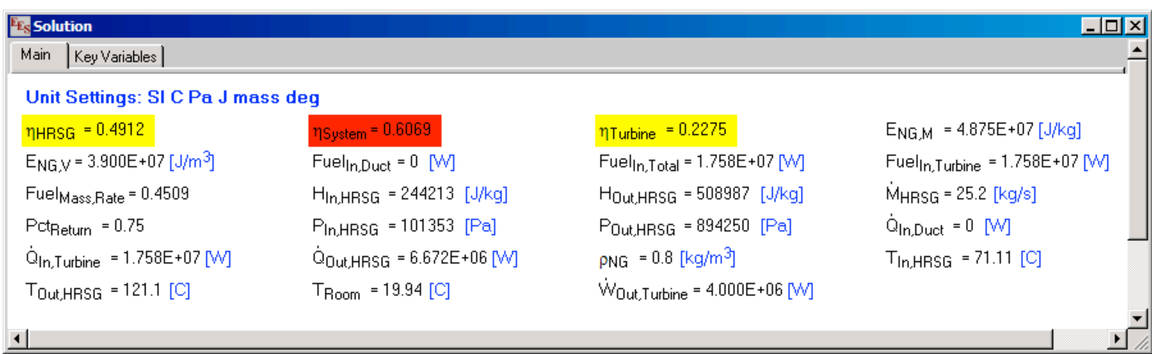


Figure 6.3. University 3 – Results.

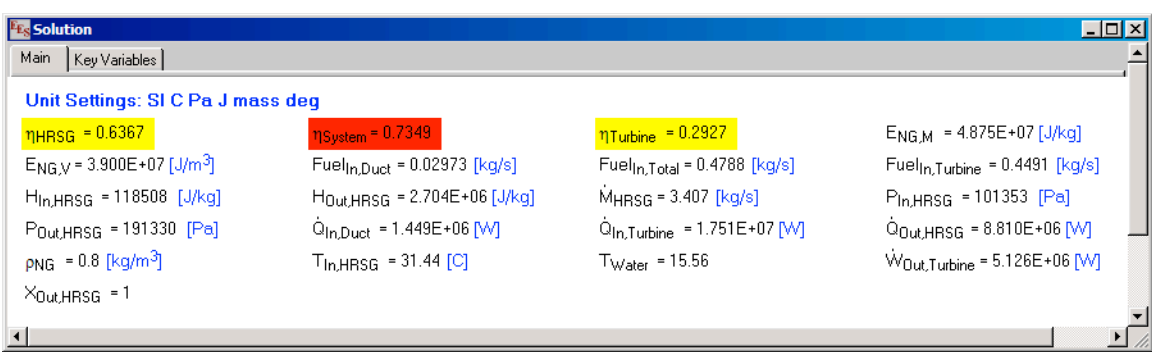


Figure 6.4. University 4 – Results.

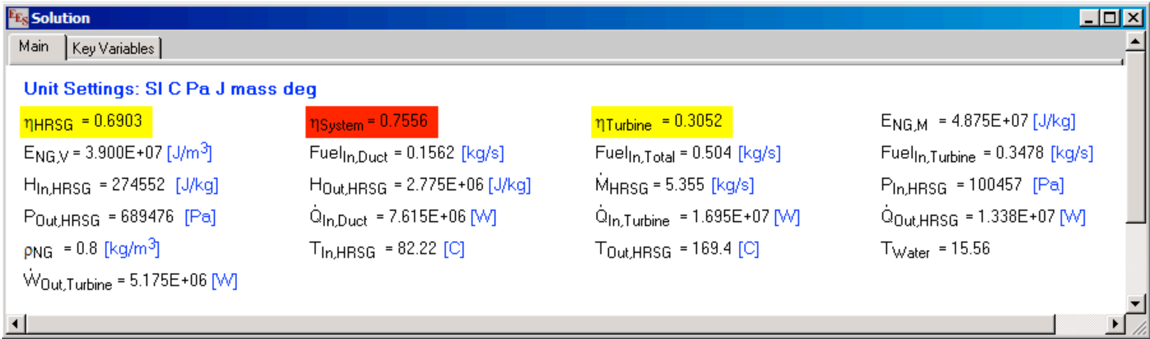


Figure 6.5. University 5 – Results.

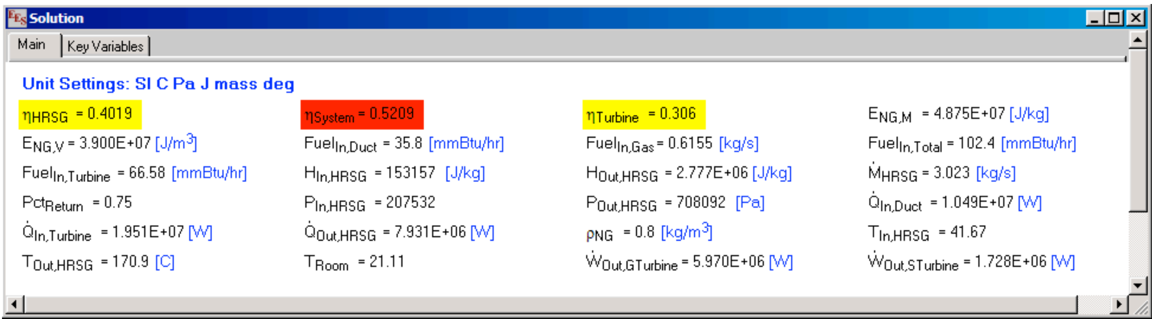


Figure 6.6. University 6 – Results.

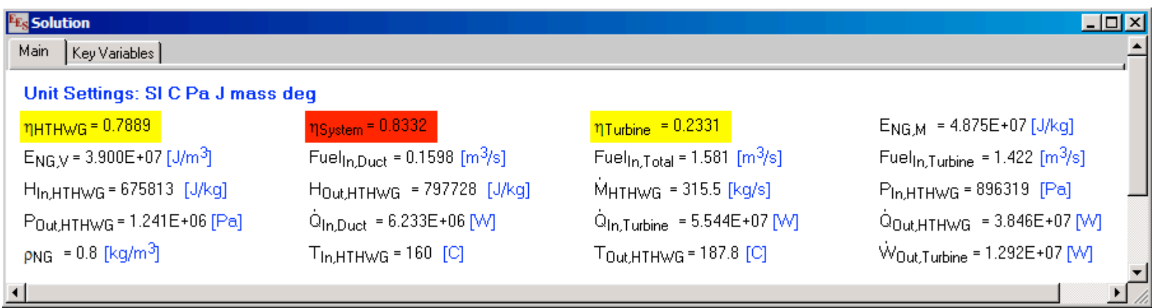


Figure 6.7. University 7 – Results.

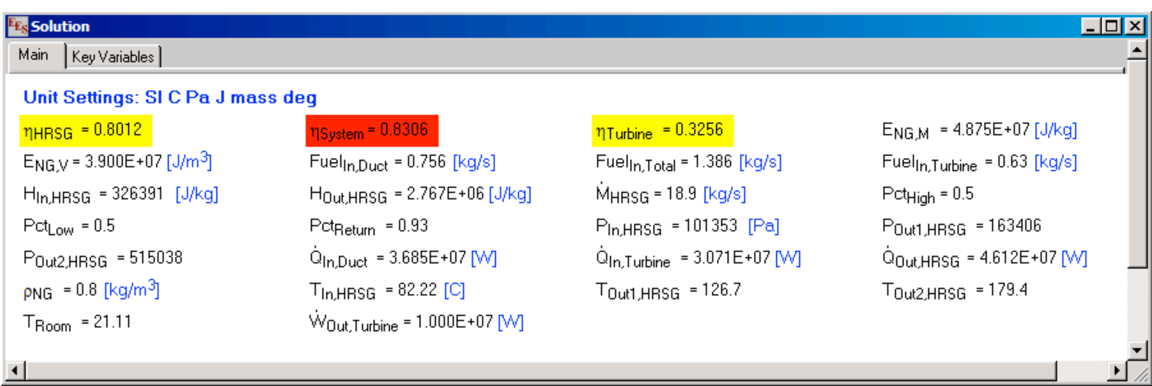


Figure 6.8. University 8 – Results.

### 6.1.4.1. Generic Plant Simulations

Brayton Gas Cycle with No Modifications

```
Rho_NG = 0.8 [kg/m^3]
E_NG_V = 39*10^6 [J/m^3]
E_NG_M = E_NG_V/Rho_NG

T_Min = 25[C]
T_Max = 1000[C]

M_dot = 10[kg/s]
"P_Ratio=1"

eta_Turbine=1.0
eta_Compressor=1.0

"State 1 - Intake"
T_1=25[C]
P_1=101325[Pa]
S_1=Entropy(Air_ha,T=T_1,P=P_1)
H_1=Enthalpy(Air_ha,T=T_1,P=P_1)

"State 2  - Compressor / Combustor"
P_2=P_Ratio*P_1
S_2=S_1
T_2=Temperature(Air_ha,P=P_2,S=S_2)
H_2=Enthalpy(Air_ha,S=S_2,P=P_2)

"State 3 - Combustor / Turbine"
T_3=1000
P_3=P_2
S_3=Entropy(Air_ha,T=T_3,P=P_3)
H_3=Enthalpy(Air_ha,T=T_3,P=P_3)

"State 6 - Outlet"
S_4=S_3
P_4=101325[Pa]        "Ambient"
T_4=Temperature(Air_ha,P=P_4,S=S_4)
H_4=Enthalpy(Air_ha,S=S_4,P=P_4)


W_In = M_dot*(H_2-H_1)/eta_Compressor
W_Out = M_dot*(H_3-H_4)*eta_Turbine
Q_In = M_dot*(H_3-H_2)
Q_Waste = M_dot*(H_4-H_1)
```

```
Fuel_In = (Q_In)/E_NG_M

W_Net = W_Out - W_In
eta_Net = (W_Net)/(Q_In)

WorkFuel_Ratio = W_Net / Fuel_In
```

Brayton Gas Cycle with Recuperation

```
Rho_NG = 0.8 [kg/m^3]
E_NG_V = 39*10^6 [J/m^3]
E_NG_M = E_NG_V/Rho_NG

T_Min = 25[C]
T_Max = 1000[C]

M_dot = 10[kg/s]
"P_Ratio=9.9"


"State 1 - Intake"
T_1=25[C]
P_1=101325[Pa]
S_1=Entropy(Air_ha,T=T_1,P=P_1)
H_1=Enthalpy(Air_ha,T=T_1,P=P_1)

"State 2  - Compressor / Regeneration"
P_2=P_Ratio*P_1
S_2=S_1
T_2=Temperature(Air_ha,P=P_2,S=S_2)
H_2=Enthalpy(Air_ha,S=S_2,P=P_2)

"State 3 - Regeneration / Combustor"
T_3=T_5
P_3=P_2
S_3=Entropy(Air_ha,T=T_3,P=P_3)
H_3=Enthalpy(Air_ha,T=T_3,P=P_3)

"State 4 - Combustor / Turbine"
T_4=1000
P_4=P_3
S_4=Entropy(Air_ha,T=T_4,P=P_4)
H_4=Enthalpy(Air_ha,T=T_4,P=P_4)

"State 5 - Turbine / Regenerator"
```

```
S_5=S_4
P_5=P_6
T_5=Temperature(Air_ha,S=S_5,P=P_5)
H_5=Enthalpy(Air_ha,S=S_5,P=P_5)

"State 6 - Outlet"
T_6=T_2
P_6=101325[Pa]        "Ambient"
S_6=Entropy(Air_ha,T=T_6,P=P_6)
H_6=Enthalpy(Air_ha,T=T_6,P=P_6)


W_In = M_dot*(H_2-H_1)
W_Out = M_dot*(H_4-H_5)
Q_Regen = M_dot*(H_3-H_2)
Q_In = M_dot*(H_4-H_3)
Q_Waste = M_dot*(H_6-H_1)

Fuel_In = (Q_in)/E_NG_M

W_Net = W_out - W_in
eta_Net = (W_Net)/(Q_in)

WorkFuel_Ratio = W_Net / Fuel_In
```

### 6.1.5. ChemCAD Simulations

In the flowsheet, each stream and unit operation is identified by a number.

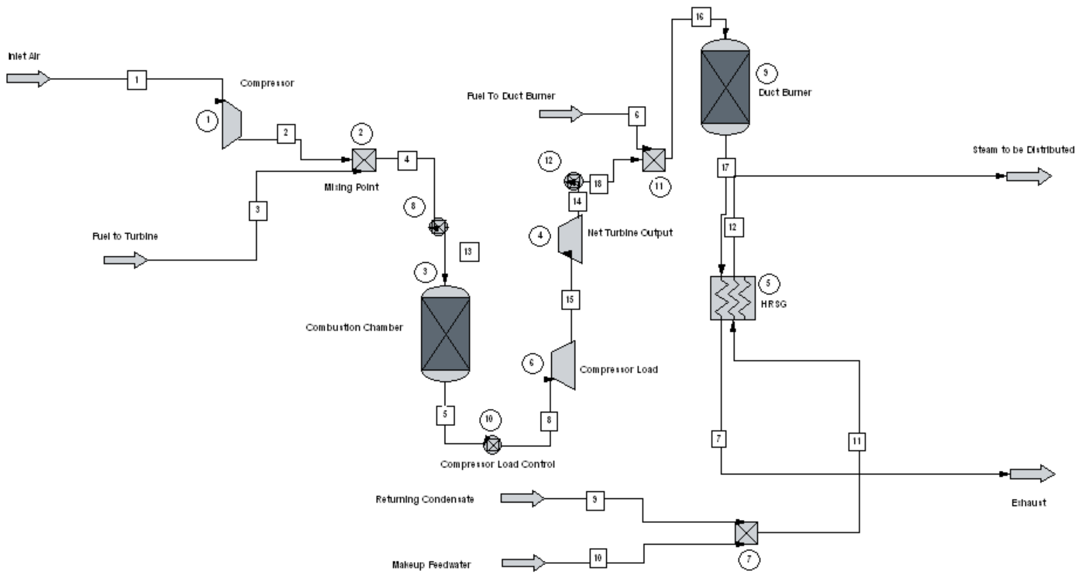


Figure 6.9. Overall Process Flowsheet for a CHP Plant.

The specifications for the combustion chamber (modeled as a Gibbs equilibrium reactor) are shown below. The only item set by the user is the Thermal Mode.

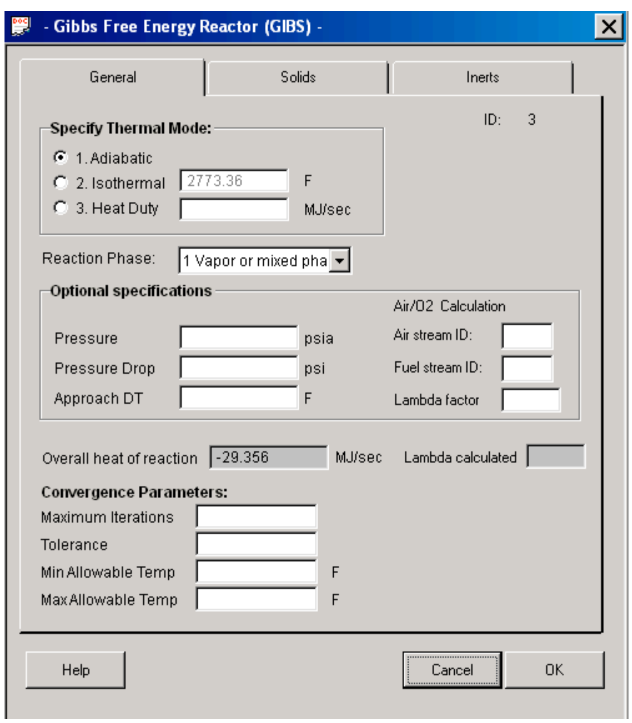


Figure 6.10. Combustion Specifications (Unit Operation 3).

Figure 6.11 displays the specifications for controller 8, located downstream of the compressor, which ensures through a feed-backward mechanism that a stoichiometric amount of air is mixed with the fuel.

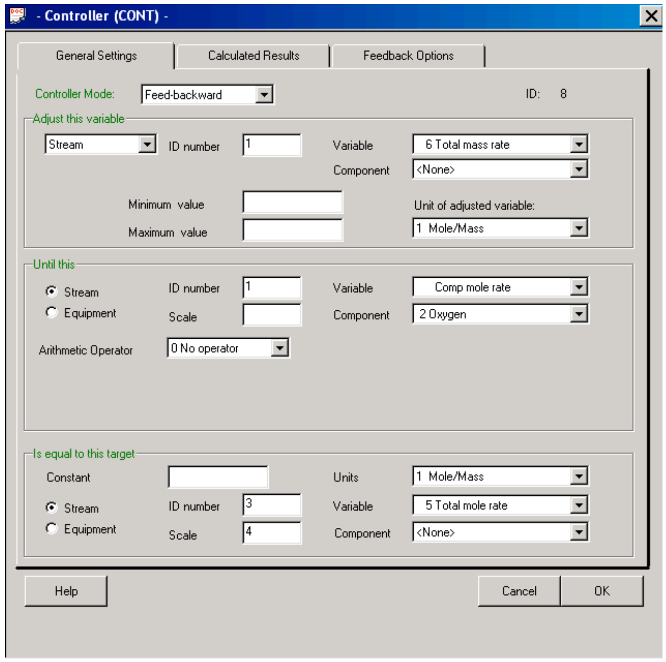


Figure 6.11. Specifications for Air/Fuel Mixing Proportions (Controller 8).

Controller 10 specifies the redirection of some work produced by the turbine to power the compressor. Figure 6.12 shows the details of controller 10.

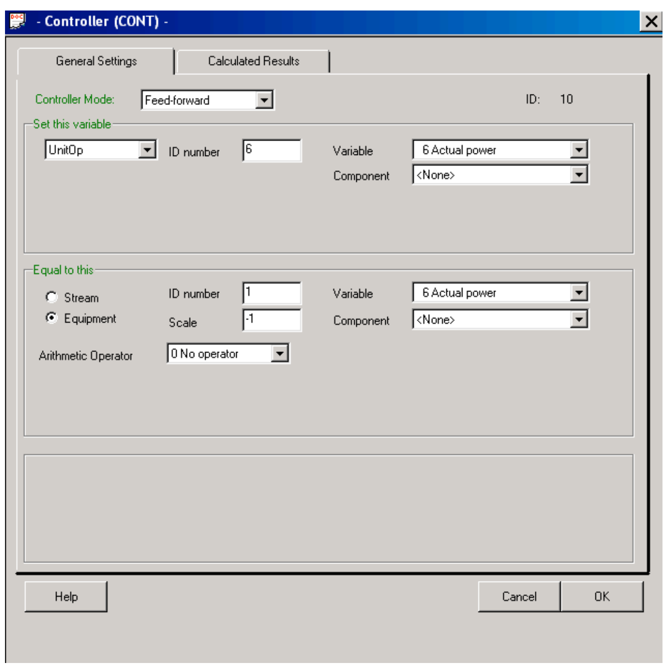


Figure 6.12. Specifications for work used to power the compressor (controller 10).

Figure 6.13 displays the specifications for controller 12, located downstream of the turbine, which controls the amount of fuel fed to the duct burner according to the amount of fuel needed in the turbine to produce a set electrical demand.

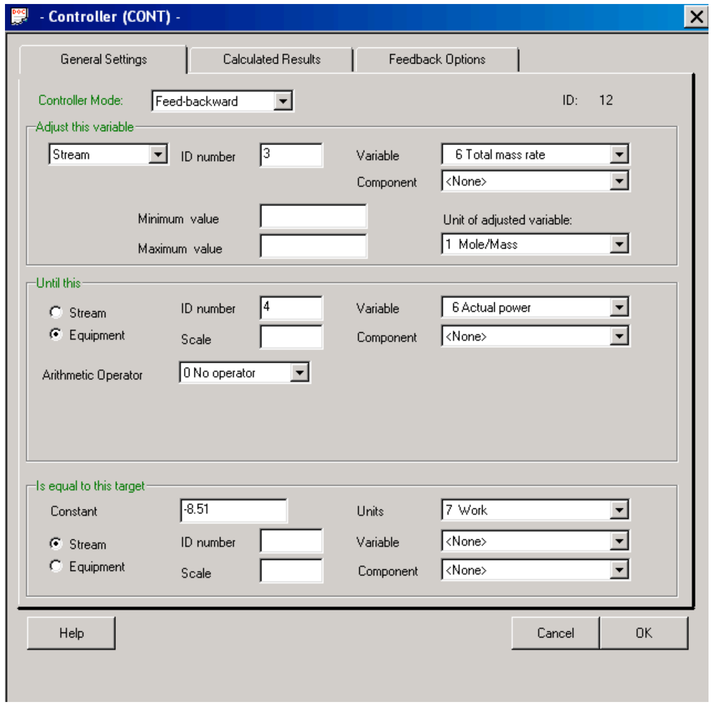


Figure 6.13. Specifications for Fuel Fed to Turbine and Duct Burner (Controller 12).

### 6.1.6. GSP Simulations

The following is a detailed procedure on generating the simulation / inputs necessary for modeling a gas turbine.

1. Open TSHAFT.mxl in GSP11.
2. Beneath the reference model [1], we will be using three different configurations:
   - [1.1] Manual_fuel_control as a main configuration
   - [1.1.1] PW_as_input as a sub configuration
   - [1.1.1] Case_1 as the case
3. The following things are to be set in [1.1] Manual_fuel_control

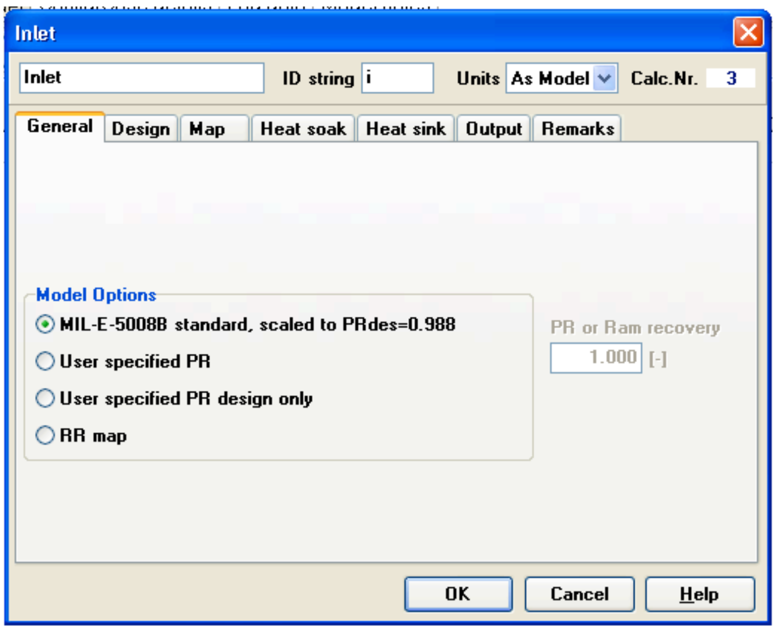


Figure 6.14. Inlet – General.

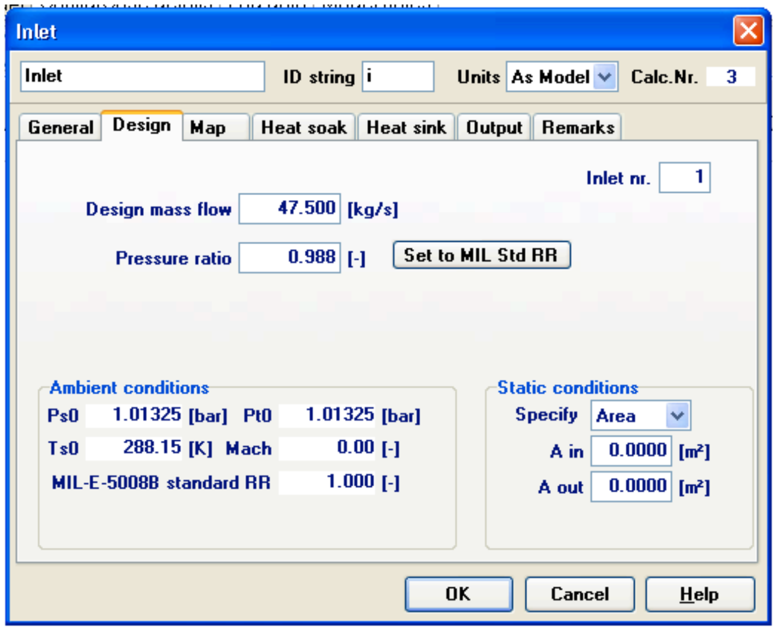


Figure 6.15. Inlet – Design.

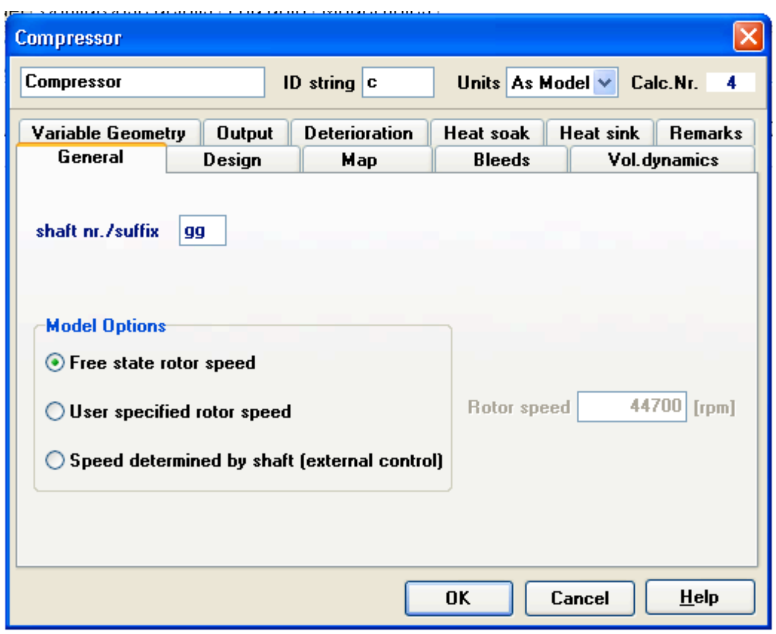


Figure 6.16. Compressor – General.

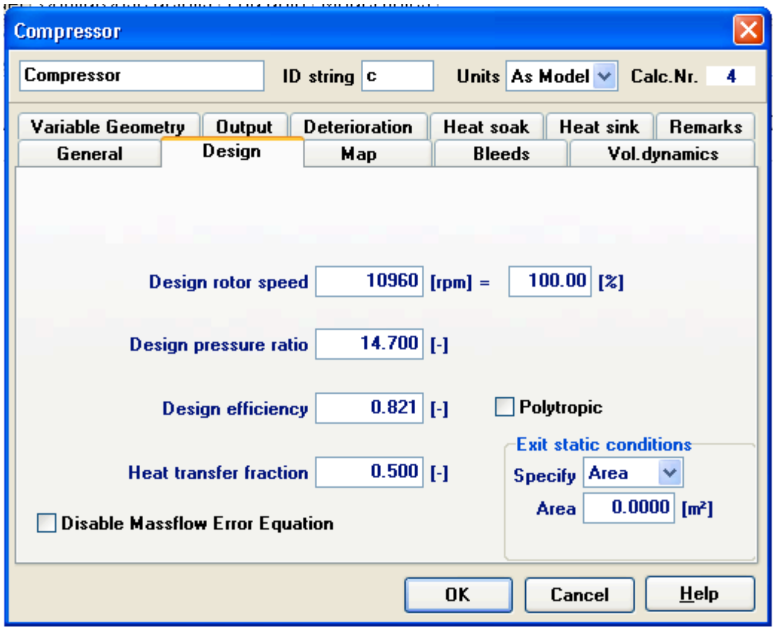


Figure 6.17. Compressor – Design.

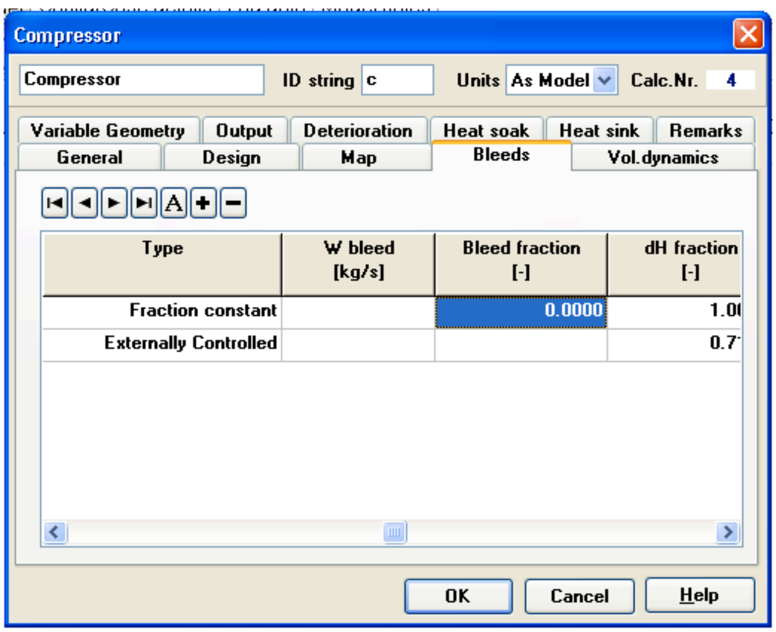


Figure 6.18. Compressor – Bleeds.

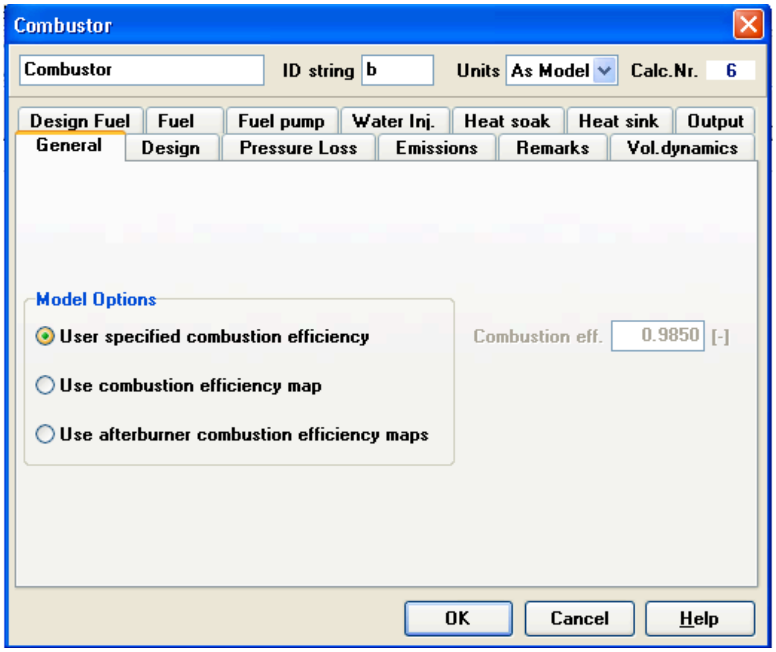


Figure 6.19. Combustor – General.

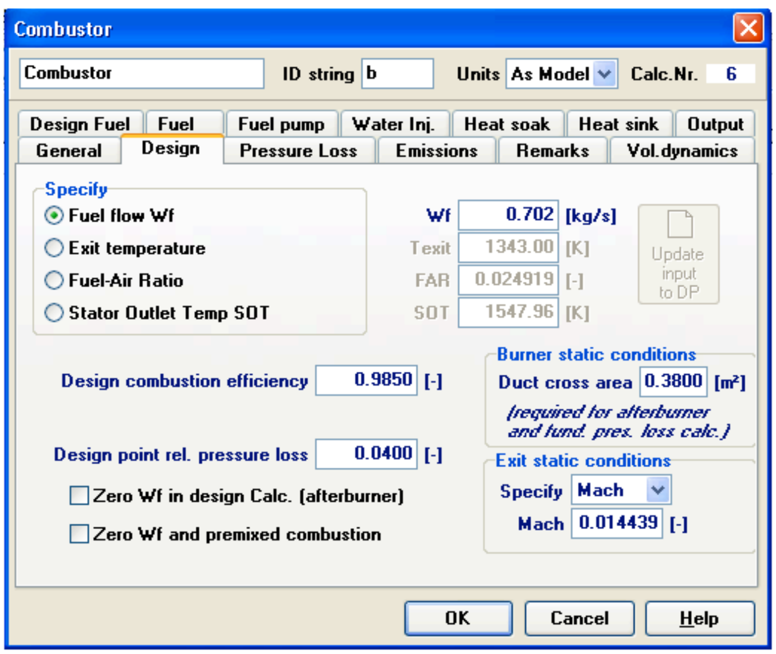


Figure 6.20. Combustor – Design.

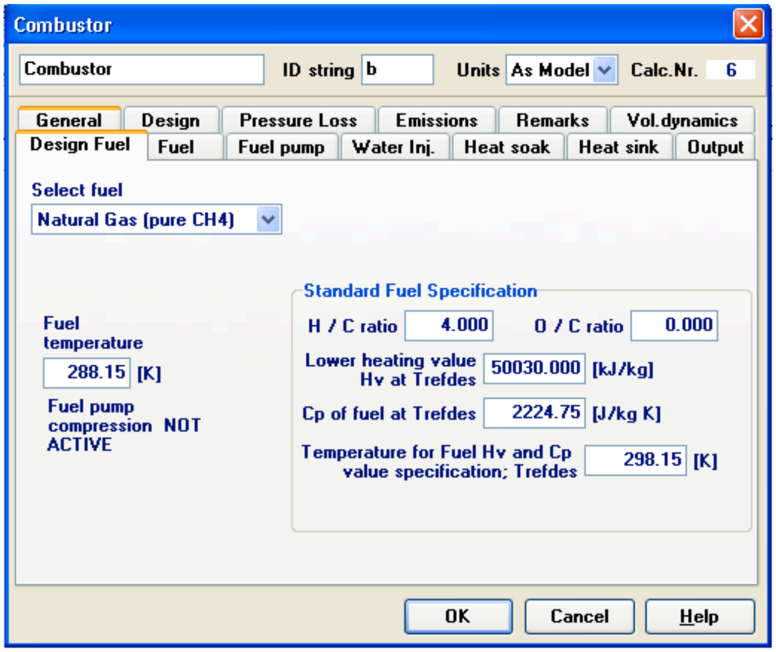


Figure 6.21. Combustor – Design Fuel.

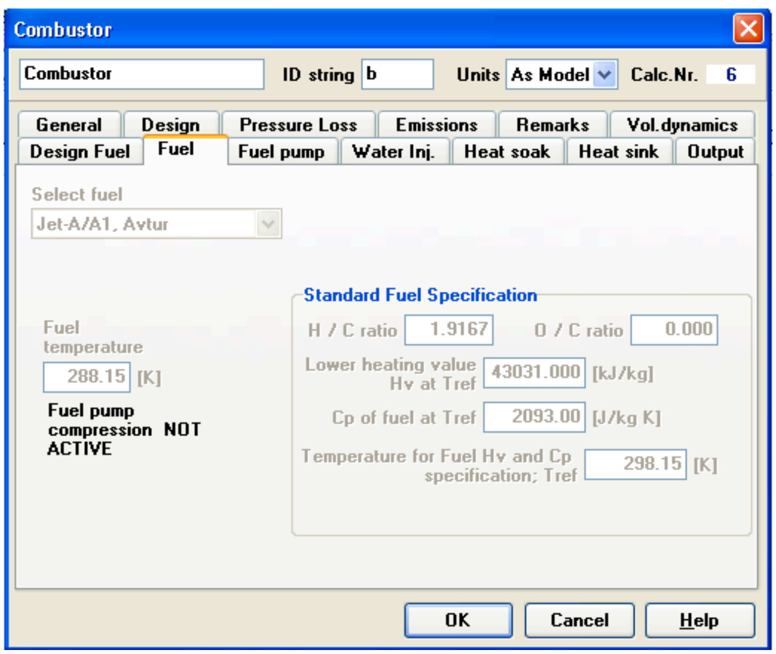


Figure 6.22. Combustor – Fuel.

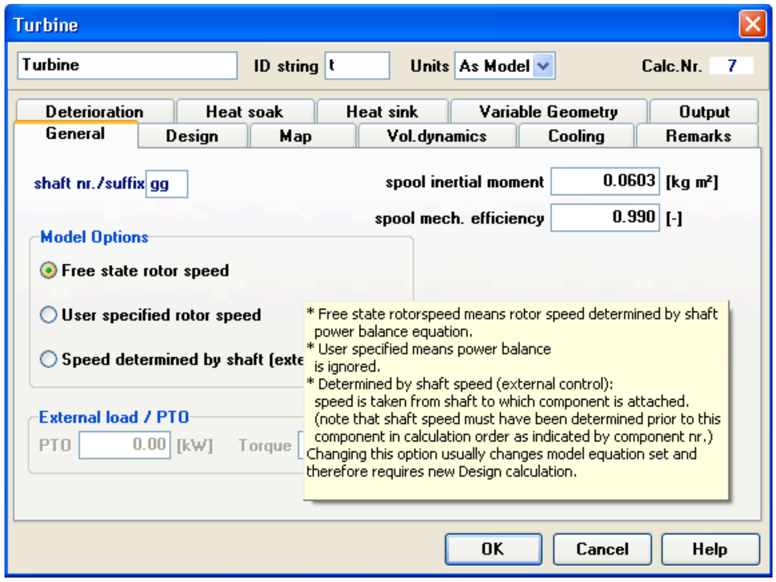


Figure 6.23. Turbine 1 – General.

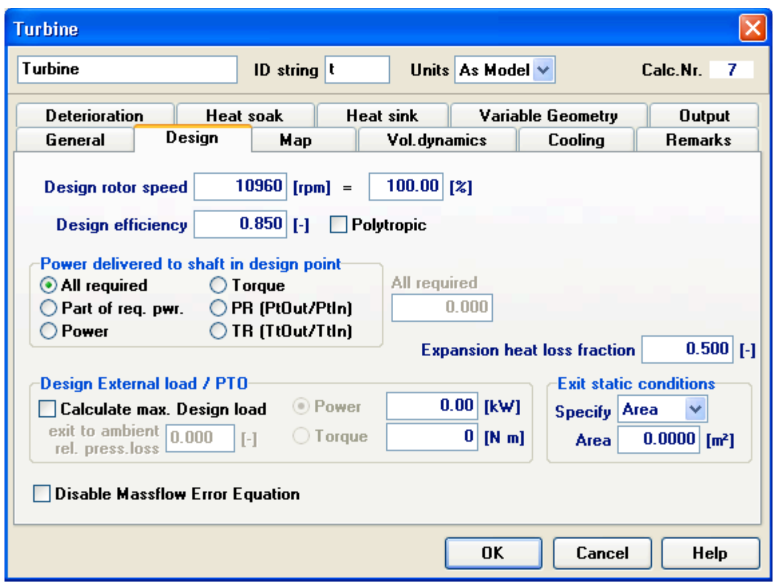


Figure 6.24. Turbine 1 – Design.

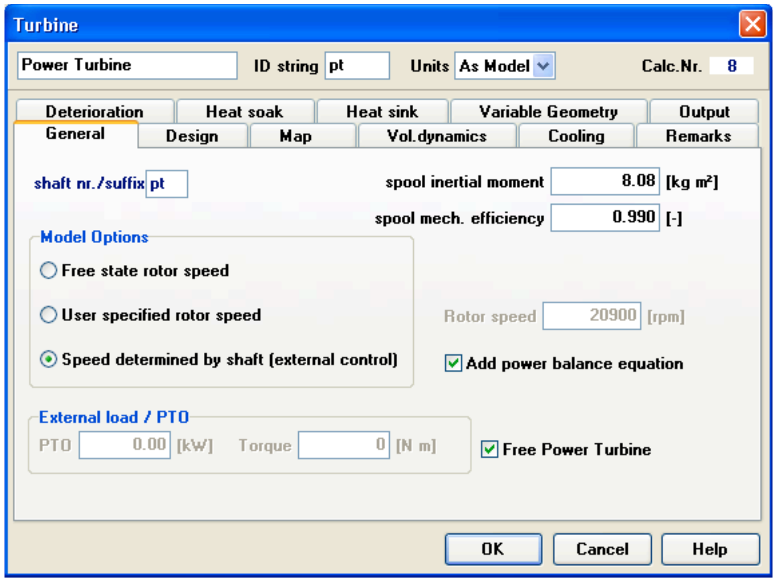


Figure 6.25. Turbine 2 – General.

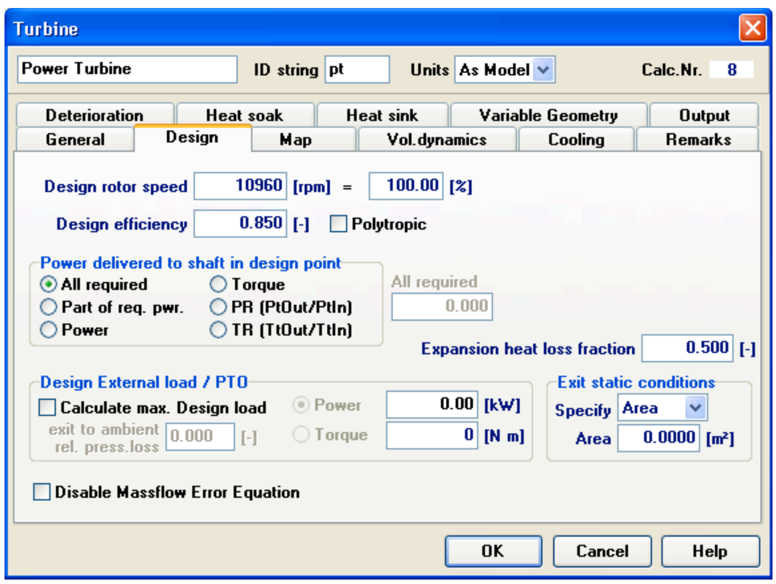


Figure 6.26. Turbine 2 – Design.

4. The following parameters are to be set in [1.1.1] PW_as_input

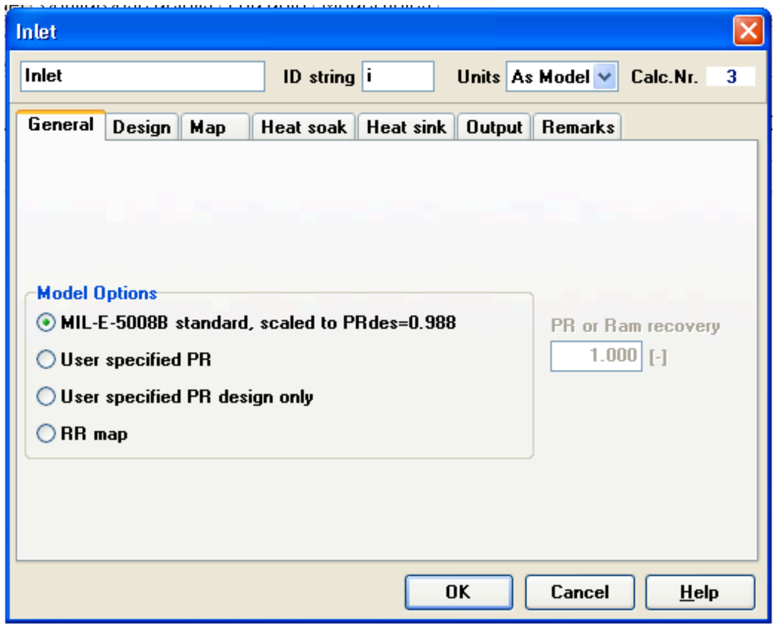


Figure 6.27. Inlet – General.

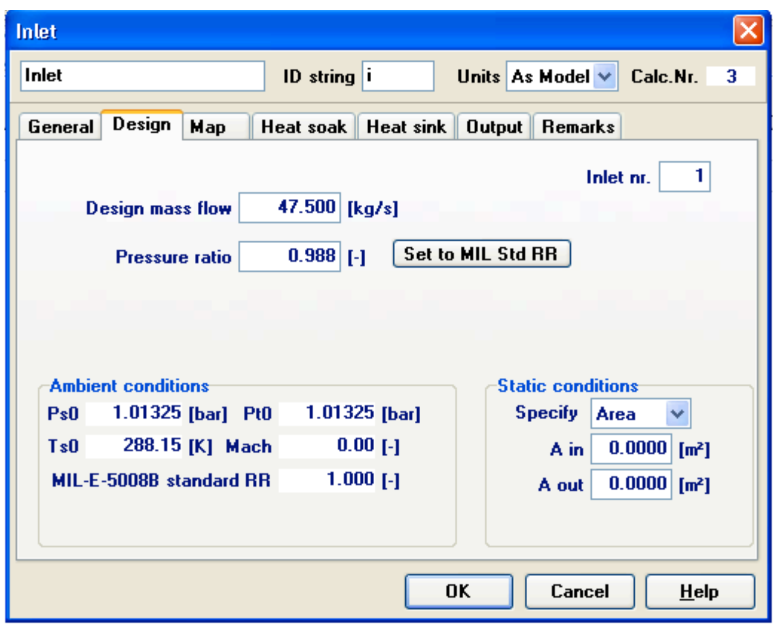


Figure 6.28. Inlet – Design.

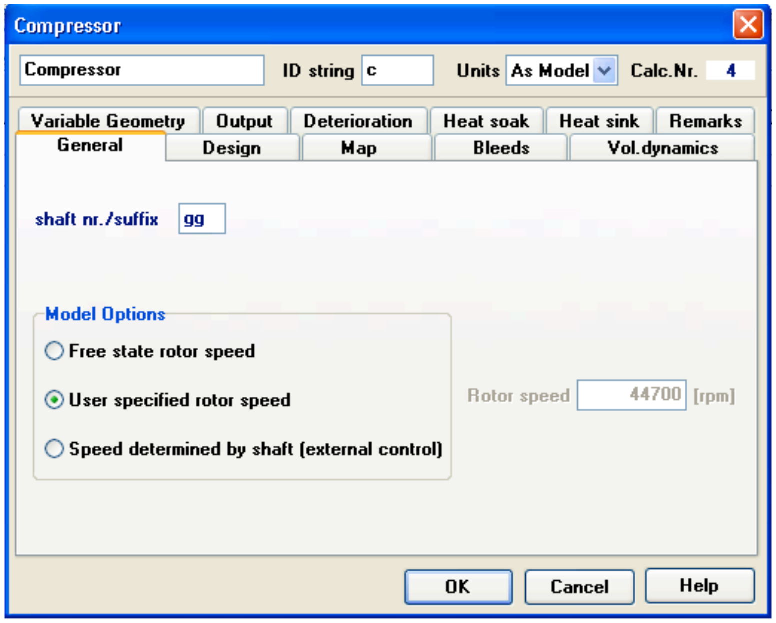


Figure 6.29. Compressor – General.

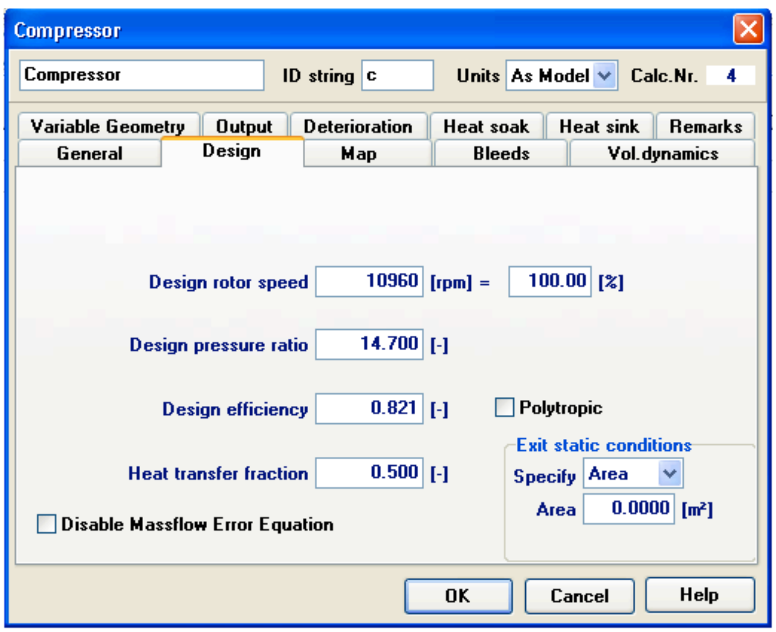


Figure 6.30. Compressor – Design.

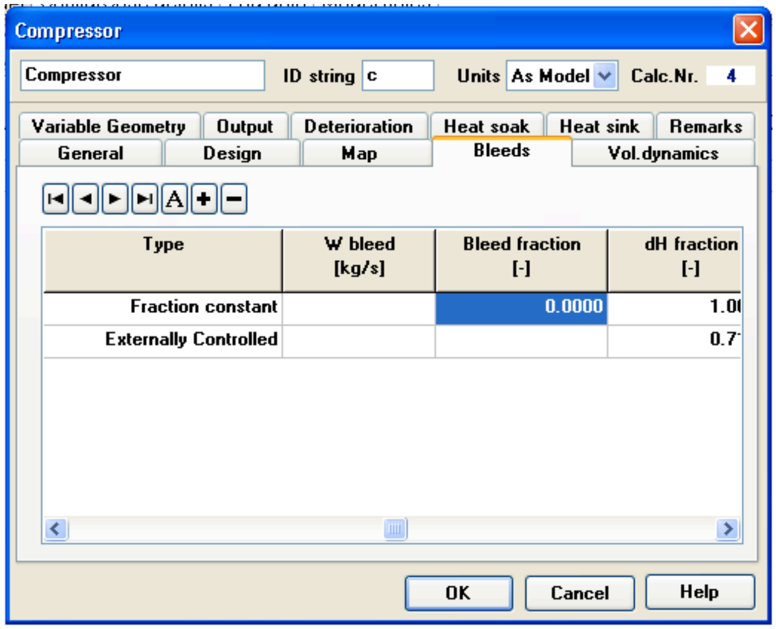


Figure 6.31. Compressor – Bleeds.

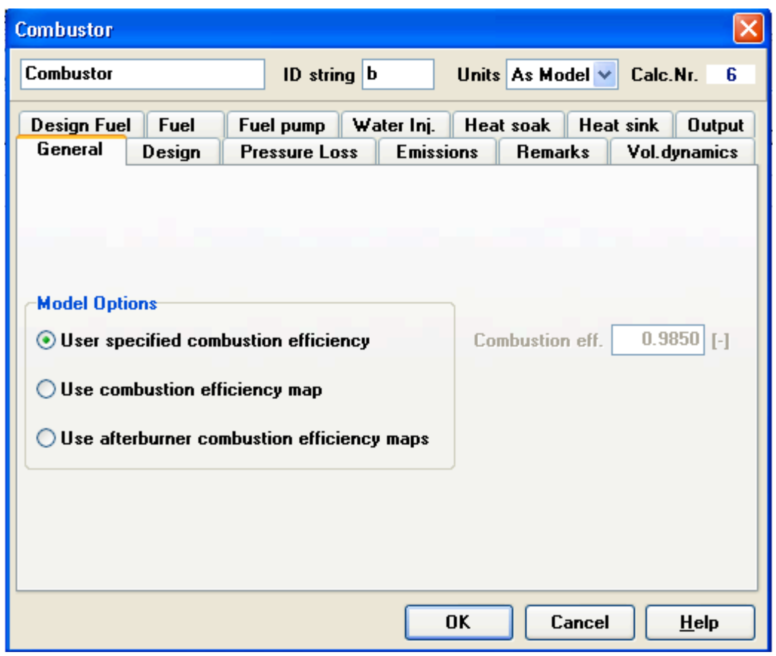


Figure 6.32. Combustor – General.

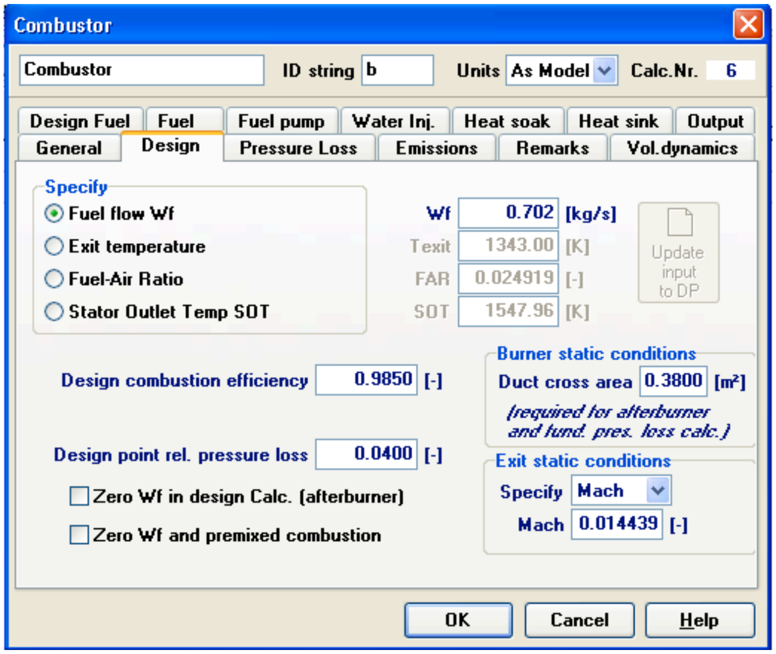


Figure 6.33. Combustor – Design.

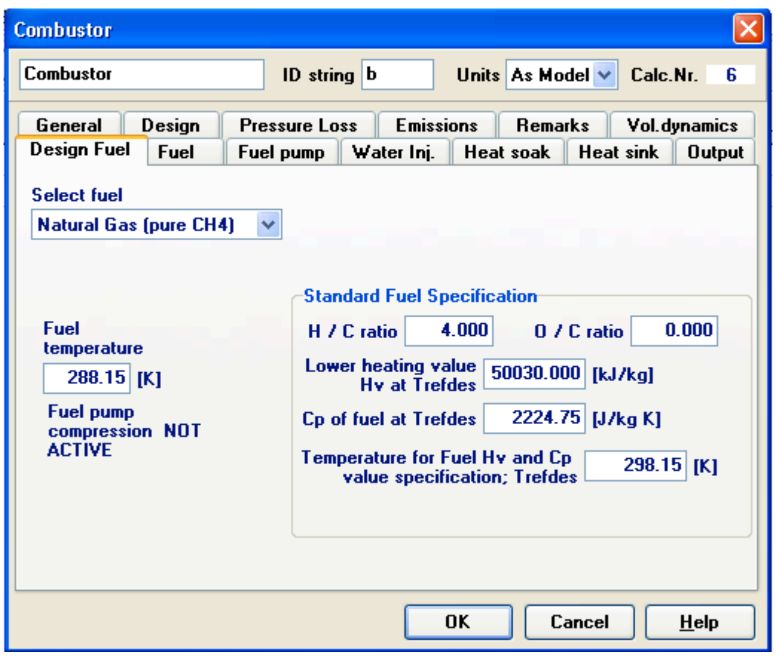


Figure 6.34. Combustor – Design Fuel.

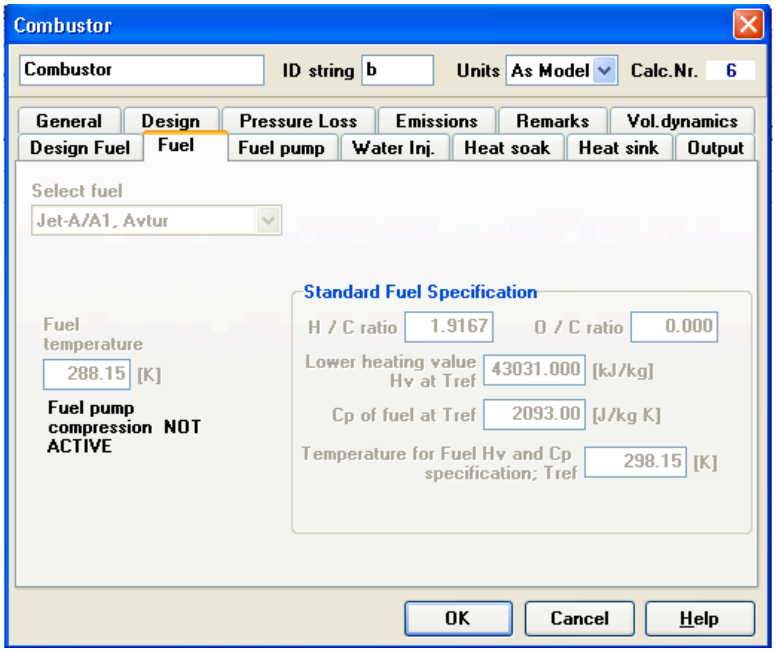


Figure 6.35. Combustor – Fuel.

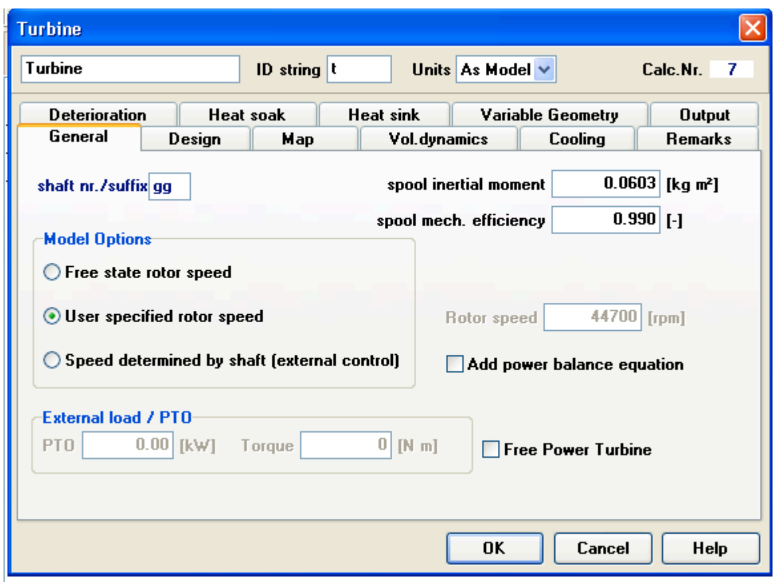


Figure 6.36. Turbine 1 – General.

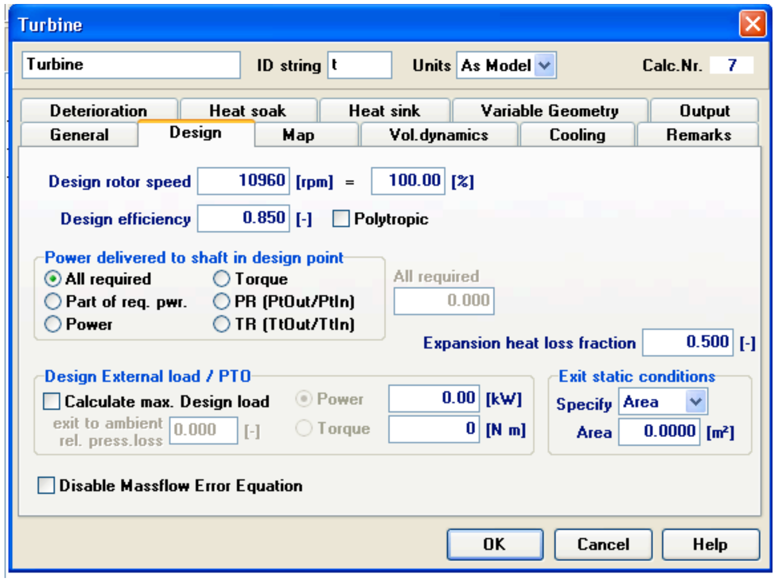


Figure 6.37. Turbine 1 – Design.

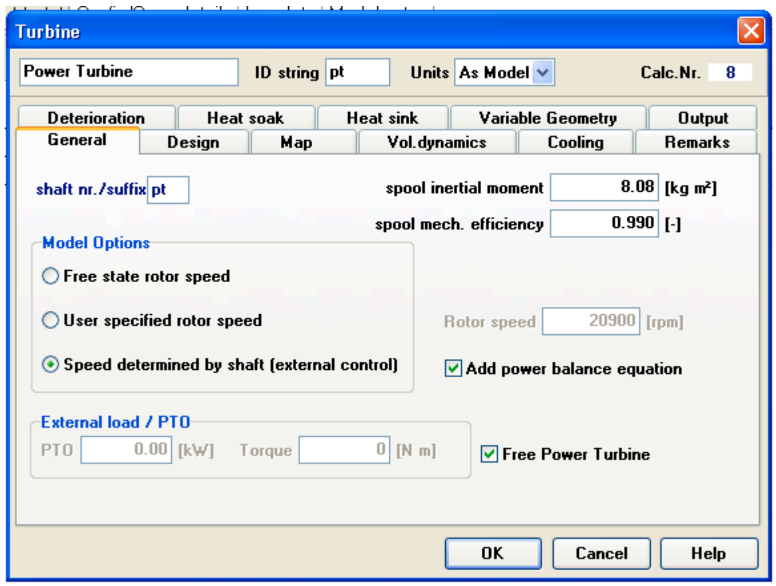


Figure 6.38. Turbine 2 – General.

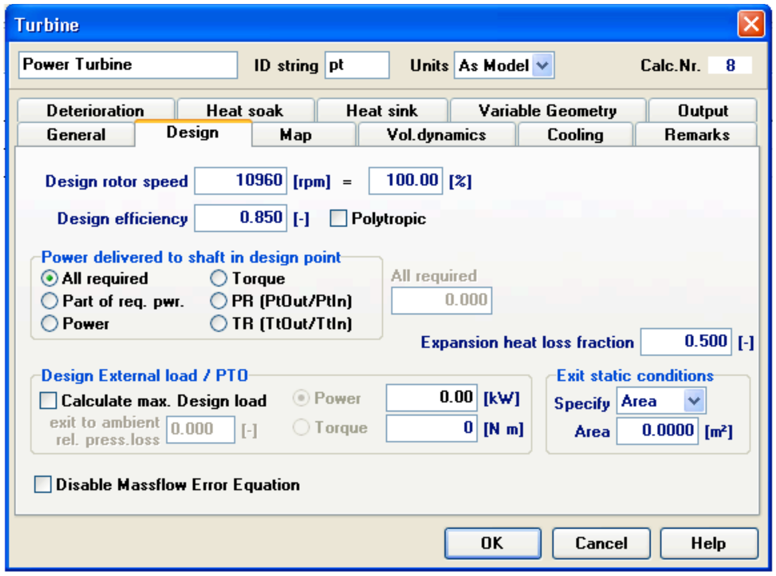


Figure 6.39. Turbine 2 – Design.

5. The following parameters are to be set in [1.1.1.1] Case_1

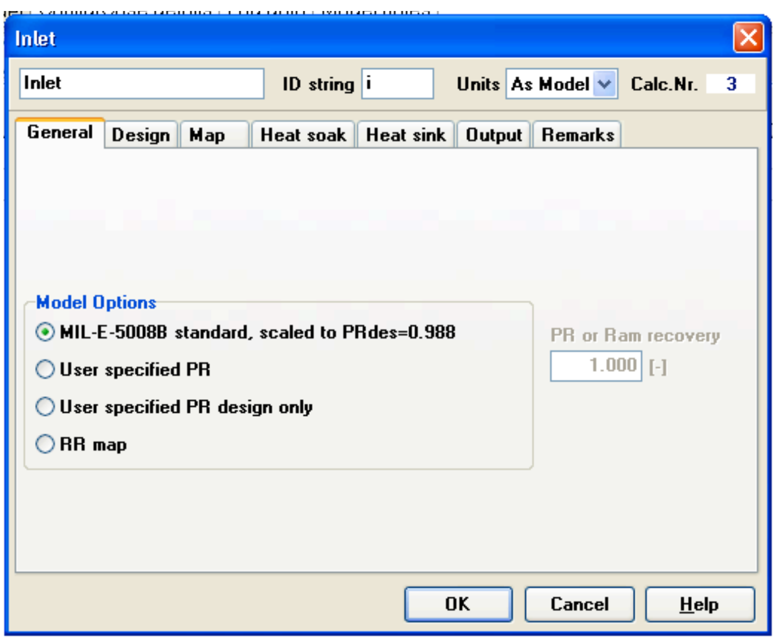


Figure 6.40. Inlet – General.

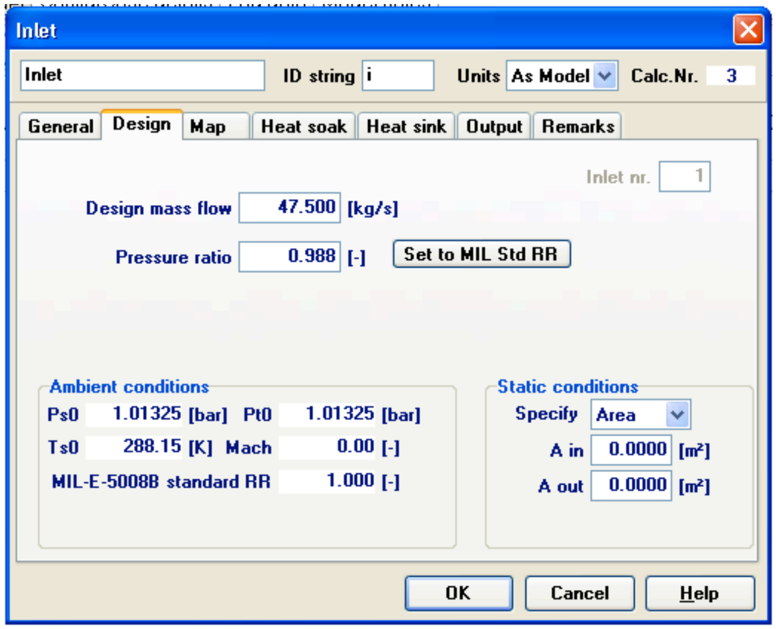


Figure 6.41. Inlet – Design.

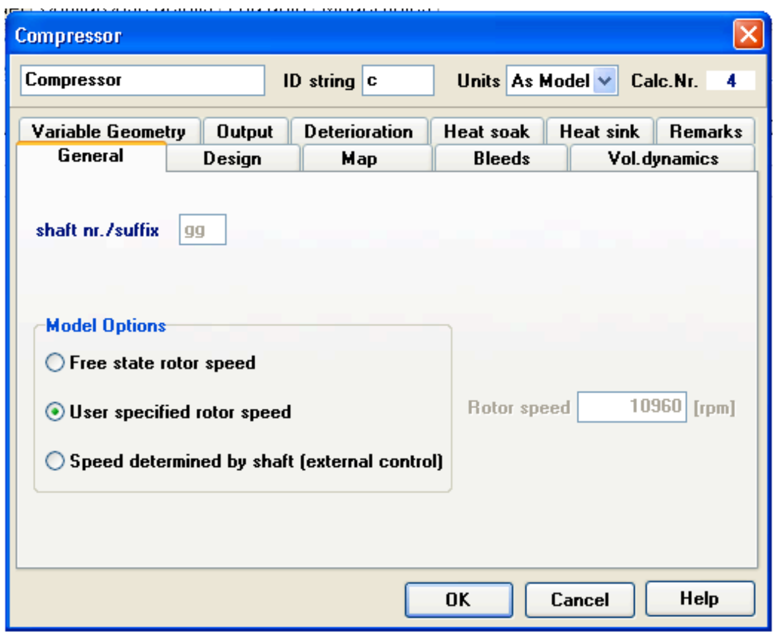


Figure 6.42. Compressor – General.

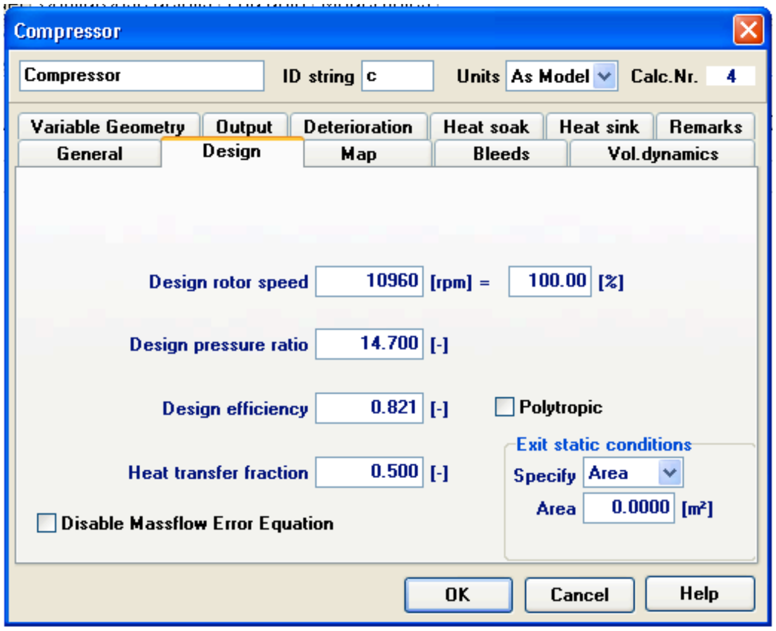


Figure 6.43. Compressor – Design.

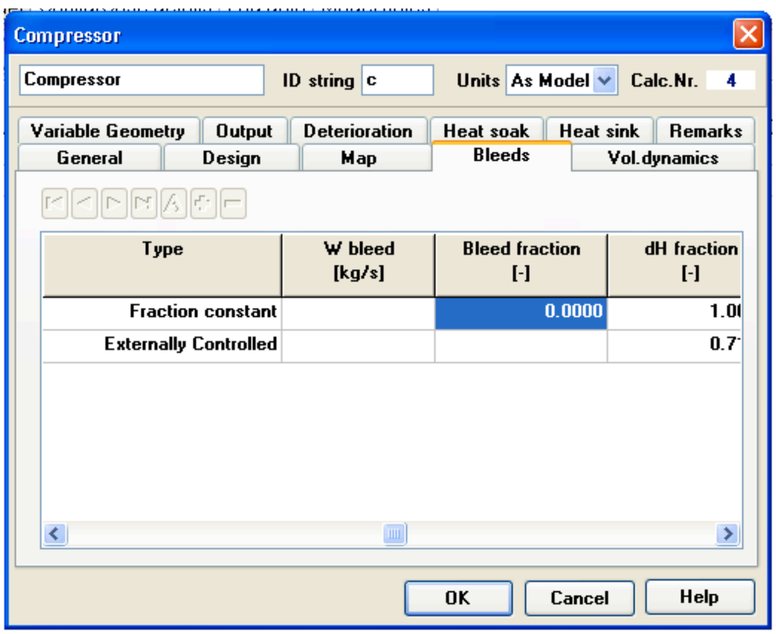


Figure 6.44. Compressor – Bleeds.

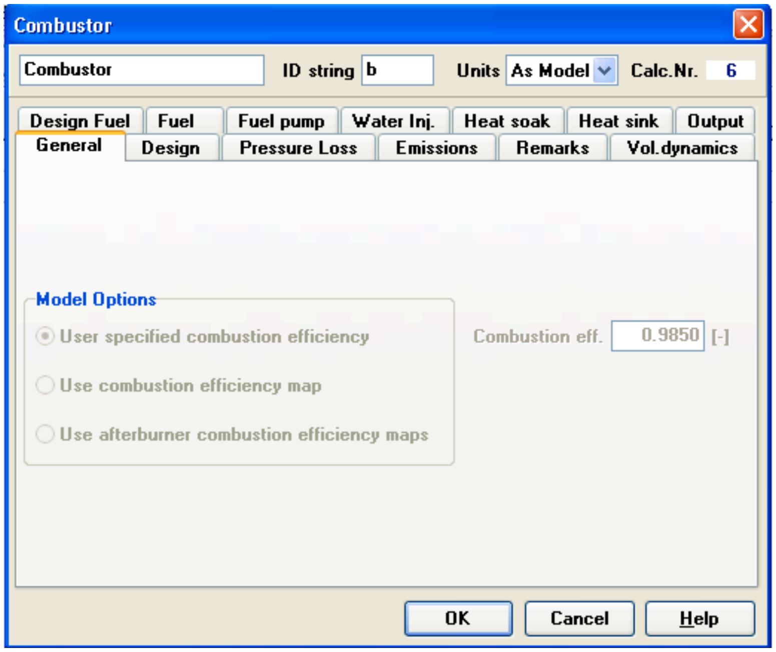


Figure 6.45. Combustor – General.

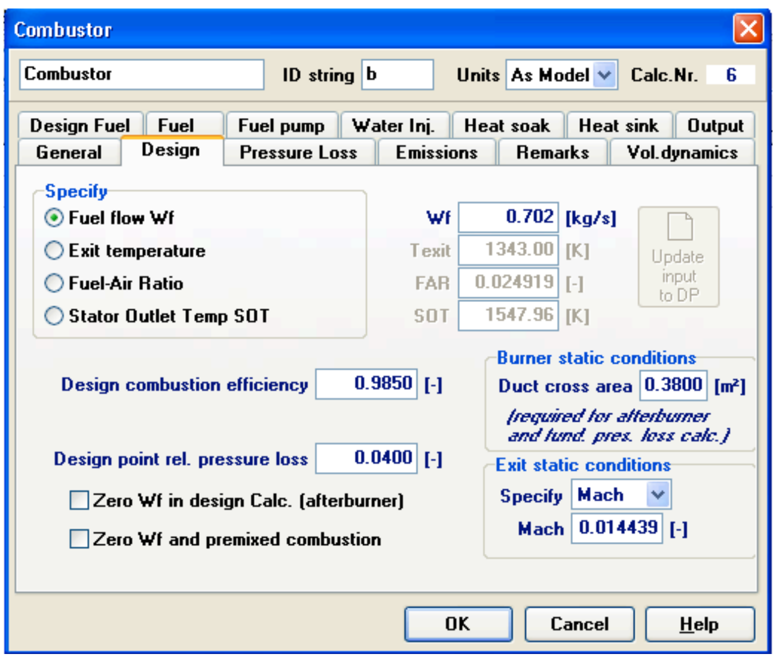


Figure 6.46. Combustor – Design.

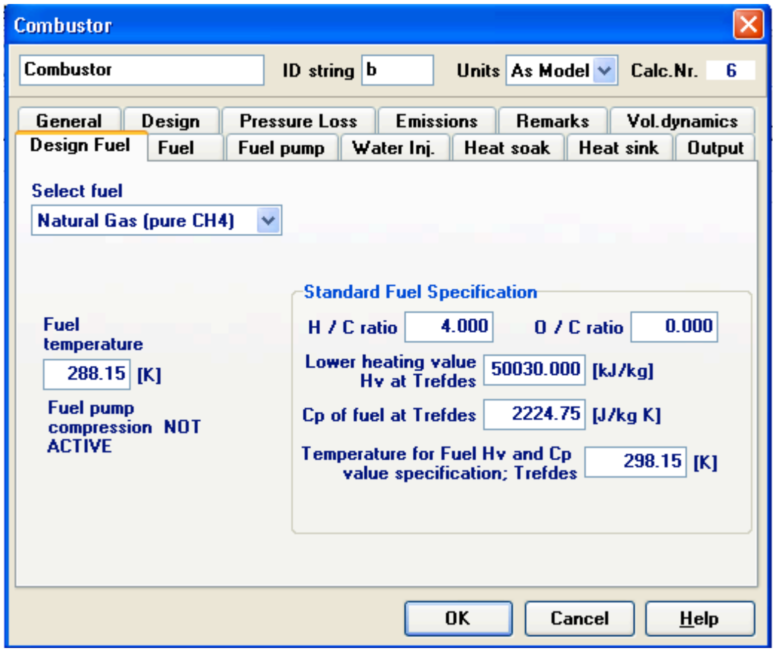


Figure 6.47. Combustor – Design Fuel.

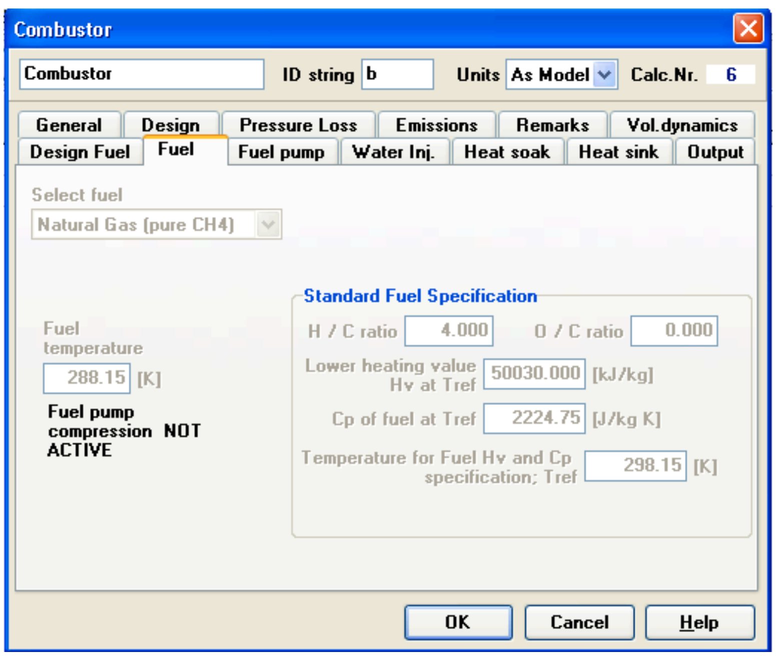


Figure 6.48. Combustor – Fuel.

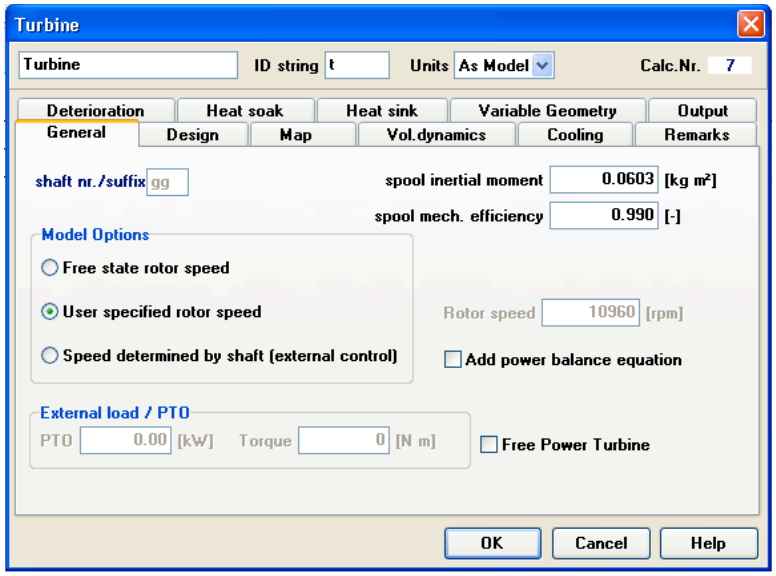


Figure 6.49. Turbine 1 – General.

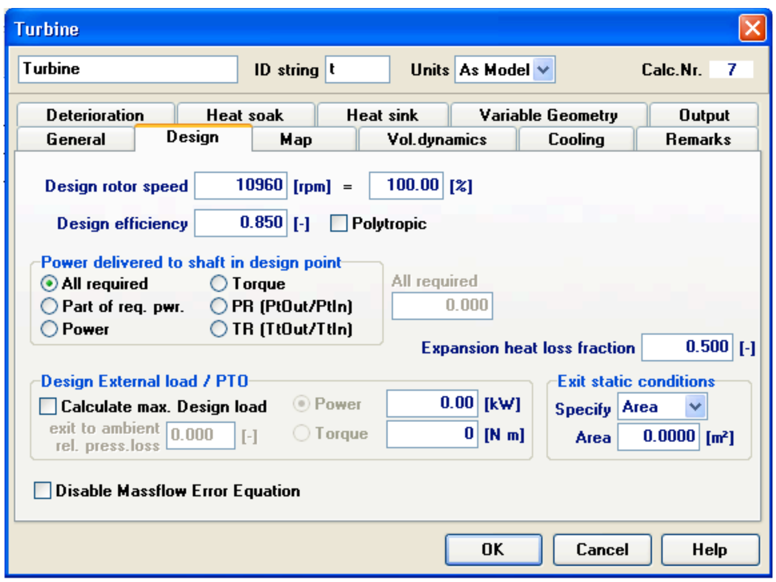


Figure 6.50. Turbine 2 – Design.

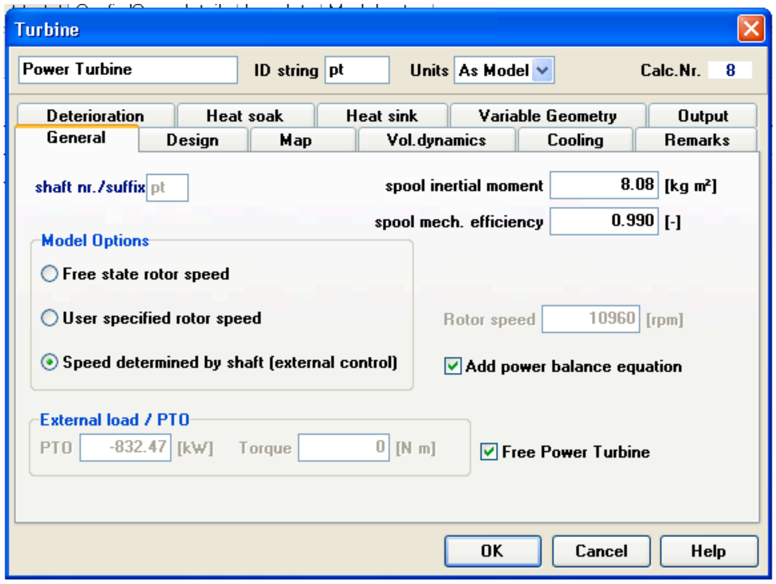


Figure 6.51. Turbine 2 – General.

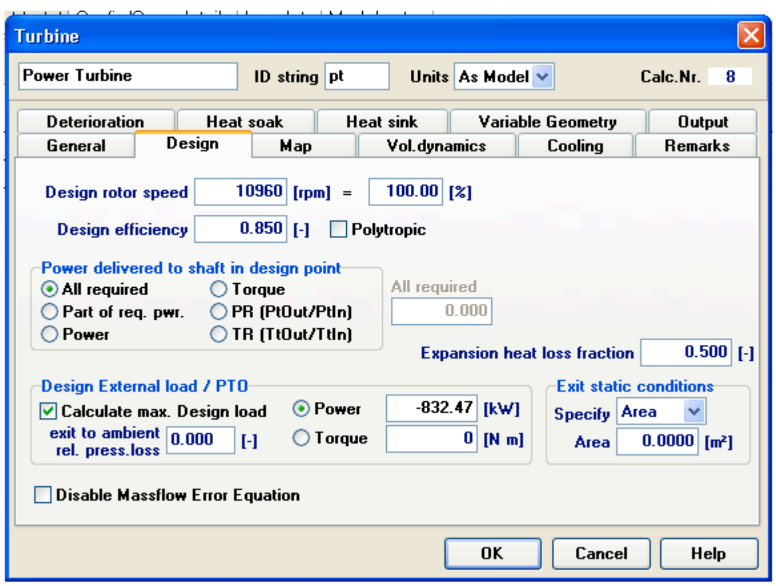


Figure 6.52. Turbine 2 – Design.

Table 6.1. Design Point Data Output from a Run for a Model Simple Cycle Gas Turbine (Utilizing UMD Data).

| Comment | Design Point |
|---|---|
| TRQ_total_lc | 10000 |
| TT1 | 288.15 |
| PT1 | 1.01325 |
| W1 | 49 |
| TT2 | 288.15 |
| PT2 | 1.001091 |
| W2 | 49 |
| WC2 | 49.59514443 |
| TT3 | 682.0590604 |
| PT3 | 14.7160377 |
| W3 | 49 |
| PR_c | 14.7 |
| Wbld1_c | 0 |
| Wbld2_c | 0 |
| Ngg | 10960 |
| Nc_c | 100 |
| DHW_c | 19888.14003 |
| Eta_c | 0.821 |
| TQ_c | 17328.26165 |
| TT4 | 1258.553865 |
| PT4 | 14.12739619 |
| W4 | 49.702 |
| Wf_b | 0.702 |
| Tfueltank_b | 288.15 |
| Tfuelin_b | 288.15 |
| PWfuelcomp_b | 0 |
| RHFAR_b | 0.014326531 |
| SN_b | |
| WC4 | 7.750457601 |
| TT45 | 922.0721372 |
| PT45 | 2.965338108 |
| W45 | 49.702 |
| PR_t | 4.764177196 |
| Wcompc_t | 7.750457601 |
| WC45 | 31.33393191 |
| TT5 | 735.0544779 |
| PT5 | 1.01325 |
| W5 | 49.702 |
| PR_pt | 2.926561172 |
| Npt | 10960 |
| N%pt | 100 |
| DHW_pt | 10635.75519 |
| TQ_pt | 9266.786565 |
| Wcompc_pt | 31.33393191 |
| TS9 | 735.0544671 |
| PS9 | 1.01325 |
| PWshaft | 10529.38907 |
| SFCshaft | 0.240013925 |

### 6.1.7. MATLAB Calculations

```
% M1 = input('Input 8x1 column vector from measurement one - ');
% M2 = input('Input 8x1 column vector from measurement two - ');
% Stack diameter is 77"
% Mn => Measurement #n
% Rn => Position #n, 0 is absolute, 1 is with the zero at center
close all
clear all

M10 = [.02; .34; .45; .52; .58; .60; .46; .37];
M20 = [.03; .37; .525; .57; .61; .62; .52; .48];
M1 = M10*250;
M2 = M20*250;

R0 = [1.617; 9.009; 14.168; 26.565; 50.435; 62.832; 67.991; 75.306]*.0254;
R1 = R0 - 38.5*.0254;
% R3 & R4 is the grid of (x,y) points
R3 = [R1;zeros(8,1)];
R4 = [zeros(8,1);R1];

% Fitting Mx to a nth order polynomial with coefficients Pn
d = 4;
%d = input('Fit to a polynomial of degree - ');
[P1, f1] = polyfit(R1,M1,d);
[P2, f2] = polyfit(R1,M2,d);

%Creating two lines of best fit
syms x
syms y
X1 = x.^([d:-1:0]');
Y2 = y.^([d:-1:0]');
Z1 = P1*X1;
Z2 = P2*Y2;

%Plotting Zn
close all
figure
scatter3([R1;zeros(8,1)],[zeros(8,1);R1],[M1;M2],25,[M1;M2],'filled')
hold on
R5 = [-38.5:.1:38.5]'*.0254;
Z3 = subs(Z1,x,R5);
Z4 = subs(Z2,y,R5);
g1 = plot3(R5,zeros(771,1),Z3);
plot3(zeros(771,1),R5,Z4)
xlabel('Diametrical Position (m)')
```

```
ylabel('Diametrical Position (m)')
zlabel('Stagnation Pressure (Pa)')
title('Raw Data & Fit: UMD Gas Turbine #2 Stack')

% name = input('Input file name for data and fit with single quotes - ');
saveas(g1, 'test3d', 'jpg')
hold off

%Error analysis
[T1,sigma1] = polyval(P1,R1,f1);
[T2,sigma2] = polyval(P2,R1,f2);

%fit1 = input('Input name for 1D fit with single quotes - ');
figure
g2 = errorbar(R1,T1,sigma1,'ko');
hold on
plot(R1,M1,'rX')
plot(R5,Z3,'k')
xlabel('Diametrical Position (m)')
ylabel('Stagnation Pressure (Pa)')
title('Raw Data, Fit & Errors: UMD Gas Turbine #2 Stack')
hold off
saveas(g2,'fit1','jpg')

%fit2 = input('Input name for 1D fit with single quotes - ');
figure
g3 = errorbar(R1,T2,sigma2,'ko');
hold on
plot(R1,M2,'rX')
plot(R5,Z4,'k')
xlabel('Diametrical Position (m)')
ylabel('Stagnation Pressure (Pa)')
title('Raw Data, Fit & Errors: UMD Gas Turbine #2 Stack')
hold off
saveas(g3,'fit2','jpg')

%Flow Averaging
R6 = abs(R5);
R7 = [0:.1:38.5]*.0254;
n = 1;
   while n<386.5
   ave1(n) = (Z3(n)+Z3(722-n))/2;
   n = n+1;
   end
m = 1;
   while m<386.5
```

```
    ave2(m) = (Z4(m)+Z4(772-m))/2;
    m = m+1;
    end

%Mass density of air
r = .863;

%Flow calculation
v1 = (2*ave1/r).^.5;
P3 = polyfit(R7,v1,d);
v2 = (2*ave2/r).^.5;
P4 = polyfit(R7,v2,d);
Z4 = P3*X1;
Z5 = P4*X1;
figure
g5 = plot(R7,v1);
hold on
plot(R7,v2)
plot(R7,(v1+v2)/2,'r','Linewidth',2)
xlabel('Radial Position (m)')
ylabel('Fluid Velocity (m/s)')
title('Average Radial Fluid Velocity: UMD Gas Turbine #2 Stack')
saveas(g5,'Fluid Velocity','jpg');
hold off
m1_dot = double(r*2*pi()*int(x*Z4,x,0,38.5*.0254));
m2_dot = double(r*2*pi()*int(x*Z5,x,0,38.5*.0254));
m_dot = (m1_dot+m2_dot)/2
s = sqrt(.5*((m_dot - m1_dot)^2+(m_dot - m2_dot)^2))
```

## 6.2. Business Materials

### 6.2.1. Business Introduction Letter

Dear [Plant Manager],

Hello my name is [Researcher] and I am student at the University of Maryland College Park. I am a member of an honors undergraduate research team working to better understand CHP on university campuses.

We were hoping that you could fill out this quick, one page survey to help us better understand the wants and buyer habits of individuals involved with CHP systems.

All the information we receive from this survey is kept anonymous and we will keep you up to date on our research as we finalize our thesis. Should you want to find out more about our current work please visit our website at http://teams.gemstone.umd.edu/classof2011/cogen/.

Thank you so much for your time and I look forward to hearing from you.

Regards,
- [Researcher]

### 6.2.2. Business Survey

UMD COGENERATION TECHNOLOGY
BUSINESS SURVEY

In what university does your CHP system operate?

______________________________________

Are you an employee of the university or an employee of a company in charge of operating the CHP system?

______________________________________

Rank these turbine requirements in terms of priority.

| | |
|---|---|
| | Fuel efficiency |
| | Reliability |
| | Alignment to steam demand |
| | Alignment to electricity demand |
| | Price |
| | Maintenance cost |
| | Longevity |
| | Service/support |
| | Physical size |
| | Product reputation |

Was there any collaboration with another university(ies) in informing the purchase decision for your turbine? Explain.

Was there any collaboration with another university(ies) in the actual purchase of your turbine? Explain.

How many turbine manufacturers were considered when making your purchase decision? To your knowledge, how many turbine manufacturers carried a product that was relevant to your needs?

## 6.3. Policy Materials

### 6.3.1. Policy Survey

UMD COGENERATION TECHNOLOGY
POLICY SURVEY

1. Did you read over the consent form that was attached as a document to the email you received? *If yes, proceed to next question. If no, read consent form aloud to subject and then proceed to next question.*
2. Do you consent to be interviewed? *If yes, proceed to next question. If no, thank him or her for their time and conclude interview.*
3. Please state your name.
4. What is your place of employment and what is your job title?
5. What are your position's responsibilities?
6. How long have you held this position?
7. How long have you been in the field?
8. How long has the University of ____ had a CHP Plant?
9. How big is the plant?
10. In your experience, have federal and/or state legislation had an effect on the following of your plant:
    a. Original establishment/implementation of the plant
    b. Daily operation of the plant
    c. Profitability of the plant
    d. Future viability of the plant
11. What additional information would you be able to share with us regarding your experience with the impact of policy on CHP success on university campuses?

*Note: These questions are meant to prompt an extended conversation with the interview subject. Follow-up questions that will be specifically modified to individual interviews are likely and necessary in order to fully understand all information the subject provides.*

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