Guideline

Gas Engine-Driven Chillers

Southern California Gas Company

New Buildings Institute

Advanced Design Guideline Series

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CHAPTER 1: PREFACE

These Advanced Design Guidelines have been developed by the New Buildings Institute in cooperation with Southern California Gas Company to assist designers, program planners, and evaluators to make informed decisions on the application and cost-effectiveness of gas engine-driven cooling. There are two basic types of gas chillers: engine-driven systems and absorption systems. This Guideline deals specifically with gas engine-driven systems. These Guidelines are intended to be a step toward a comprehensive approach to design specifications, which encompasses the full range of efficiency options for a building.

This Advanced Design Guideline is based on careful evaluation and analysis of gas engine-driven cooling to determine when it is appropriate, how it is best implemented, how cost effective it is, and how its energy savings are described. These Guidelines describe efficiency measures that are more advanced than standard practice, yet still cost effective in appropriate applications. Design Guidelines are used by individuals and organizations interested in making buildings more energy efficient. They provide the technical basis for defining efficiency measures used in individual building projects, in voluntary energy efficiency programs, and in market transformation programs.

It should be remembered that this Guideline document deals primarily with the comparison of a single efficiency measure and its baseline. This means that the analysis assumes that all other features of the building are fixed. This is done primarily for clarity of the analysis, and allows one to focus on the advantages and economics of the single measure.

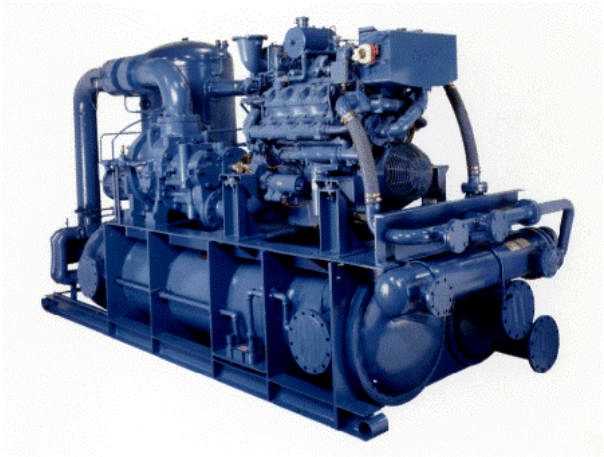
In reality, most new building design situations involve multiple energy efficiency options. The cost effectiveness of one measure is often influenced by other measures. For example, increases in building envelope insulation can often reduce HVAC loads enough to reduce the sizing requirements for the heating and cooling equipment. It is not uncommon for the cost savings from smaller equipment to offset increased insulation costs.

It is beyond the scope of this Guideline to attempt to address the interactions between measures, especially because these interactions can cover a huge range of options depending on the climate, the local energy costs, the building, and its systems. Nevertheless, the New Buildings Institute recommends that building designers give careful consideration to measure interactions and to integrated systems design. This Guideline can provide the starting point by providing insight into the performance of one measure.

CHAPTER 2: DESCRIPTION

Gas engine-driven chillers offer a unique and very attractive opportunity for commercial building owners to shave electric demand charges and reduce operating expenses. Engine-driven systems have several potential advantages over electric motor-driven units. Among them are variable speed operation, high part load efficiency, high temperature waste heat recovery from the engine, and reduced annual operating costs.

Gas engine-driven systems use the same refrigerant compression cooling process as conventional electric-powered systems. The only difference is that the compressor is powered by a natural gas engine rather than an electric motor. Gas engine-driven chillers are available with reciprocating, screw and centrifugal compressors. A Tecogen gas engine-driven chiller is shown in Figure 1.



Source: AGCC

Figure 1 - Gas Engine-Driven Chiller

Although gas engine-driven chillers have been in use since the 1960s, current research is resulting in better performance, lower maintenance requirements, and longer operating lifetimes. Research and development efforts have also resulted in improved serviceability due to the use of microprocessor controls, which facilitate preventive maintenance, and allow remote monitoring and troubleshooting, and on-board diagnostics.

Gas engine-driven chillers are more expensive to purchase than comparable electric motor-driven chillers, but they typically cost less to operate. Operating cost savings are primarily driven by electric demand charges. Operating costs are dominated by fuel costs, but also include maintenance costs. The reliability of gas cooling equipment has improved in the last few years and maintenance requirements have decreased.

A very important feature of engine-driven chillers is variable speed control of chiller output. Engines are designed to operate over a wide range of speeds. Reducing the capacity of a compressor by slowing the shaft speed is the most efficient way to retain a high coefficient of performance. By varying engine speed alone, partial cooling load capacities, down to approximately 35%-65%, can be achieved efficiently without resorting to less efficient compressor capacity control mechanisms.

A. Applications

Gas engine-driven chillers are used for space conditioning for a variety of building types, including

- hospitals,
- schools, universities and colleges,
- office,
- retail,
- manufacturing, and
- hotels.

Gas engine-driven chillers can also be used for other applications such as process cooling, commercial and industrial refrigeration and ice making. Government buildings have been the top market segment for engine chillers. They typically have high energy costs and are more willing to accept longer payback periods and life cycle cost arguments than other building types. They also often have internal staff familiar with and able to maintain and service the equipment.

The primary variable that drives the economics of gas engine-driven chillers is the electric demand charge. Ideal candidates for engine chiller applications are those where the peak demand charge is high. Since cooling is generally the primary cause of sharp spikes in a building's electric load profile, it is advantageous to investigate alternatives that can reduce this peak. Gas cooling minimizes or flattens the electric peaks in a building's electric load.

The gas engine-driven chiller should be operated to maximize electric peak-shaving in areas with high demand charges or extended ratchet electricity rates. Base-loading the gas chiller is an attractive option in regions with high electric costs. This can be achieved

with a hybrid system, which uses an electric chiller for base load, and the gas engine-driven chiller for peak loads.

Engine-driven chillers can be economically installed simply as a chiller or as part of an integrated cooling and heating facility. In many parts of the country, the cost difference between electricity and natural gas is sufficient to justify engine-driven chillers. Additional cost savings can be realized through the use of heat recovery, since engine-driven chillers represent an excellent opportunity to more fully utilize the energy content of the fuel. Energy utilization efficiencies can exceed 75% by recovering heat from the engine as well as generating chilled water.

In summary, good applications for engine chillers have the following characteristics:

- High demand charges
- Coincident need for air conditioning and heating
- Maintenance and service requirements are acceptable to building owner
- Payback period of 2 to 5 years is acceptable

Other system design considerations include natural gas engine technology, heat recovery options, part-load operation and integration of engine-driven chillers to optimize the energy efficiency of a facility's cooling and heating plant.

B. Sizes

Gas engine-driven chillers are available for reciprocating, screw and centrifugal compressors. Reciprocating chillers, both air-cooled and water-cooled, are available up to 200 tons. Air-cooled screw chillers are available in the 100 to 400 ton size range, while water-cooled screw chillers are available up to 1,000 tons. Water-cooled centrifugal chillers are available in sizes from 400 tons up to 6,000 tons. Further detail of available equipment is provided in Chapter 4, Section D, *Equipment Manufacturers*.

C. Benefits

The ability to vary engine speed to control chiller output is the predominant advantage when considering the part load operation of the engine-driven chiller. From an efficiency perspective, reducing engine speed to achieve better part load performance is advantageous both for the engine and the compressor. Engine efficiency increases as shaft speed decreases, which positively affects the COP.

Gas engine-driven chillers have the following additional features:

- high temperature exhaust valves and seats
- water cooled exhaust manifolds
- low pressure natural gas fuel system
- optimum compression ratio design
- electronic ignition systems
- low emission package
- Microprocessor controls
- COPs up to 2.0

They have considerably higher COPs than comparable gas-fired absorption cooling systems. The electricity use of the condenser water pumping and cooling tower fans is not as high, allowing them to be more competitive with electric chillers. Due to the higher gas COPs of engine-driven chillers, they are generally the best gas cooling alternative in areas with high natural gas rates ($0.70 to $1.00 per therm) such as the Northeast.

The COP metric is also applied to electric chillers. However, since COP is based on site energy, it is not appropriate for comparing gas and electric chiller efficiencies.

A better metric is the Resource COP, which accounts for the source to site efficiency of the fuel, accounting for electricity generation and transmission losses. Figure 2 shows typical values for both electric chillers and absorption chillers.

Chiller	Site COP	Source -to-Site Factor	Resource COP
Electric	2.0 - 6.1	0.27	0.54 - 1.65
Engine	1.3 - 2.2	0.91	1.2 - 2.0

Figure 2 - Site vs. Resource COP

An advantage of engine-driven cooling equipment over electric motor-driven is the ability to use the heat rejected from the engine during operation. During heating operation, the recovered heat can be used to supplement the refrigeration cycle or to supply other space heating or process loads. The use of the engine waste heat results in greater operating efficiency compared to similar electric motor-driven units.

D. Limitations

Despite the many benefits of gas engine-driven systems, there are some limitations and drawbacks.

Gas engine-driven equipment requires more frequent maintenance by knowledgeable technicians than conventional electric motor-driven equipment. However, if properly serviced, engine-driven chillers have extremely high reliability. The key to widespread commercialization of these systems will be the development of a maintenance infrastructure to provide low-cost service and retain high availability. Maintenance issues are discussed in further detail in the following section.

Additionally, gas systems can use significant amounts of electricity. For all central systems, both gas and electric, there is auxiliary energy use by the cooling towers, condenser water pumps and chilled-water pumps. Although the electricity use of these components in a gas system is no different from an electric system, the electric energy consumption must be included in the analysis of the system.

E. Maintenance

Maintenance of the refrigeration subsystem of an engine-driven chiller is the same as for electric chillers. The gas engine that drives the compressor requires daily checks of engine oil and coolant levels. Long-term maintenance includes oil and filter changes, replacing coolant and spark plugs, testing batteries, checking timing, and making valve adjustments.

Improvements in engine construction and reduced operating speeds have reduced maintenance requirements. Improvements include longer-lasting materials for spark plugs, valve and valve seat materials, and improved oils and bearing materials.

Many manufacturers provide maintenance contracts that include routine maintenance and major overhauls performed by trained mechanics. Other than major overhauls, engine service is comprised of routine inspections/adjustments and periodic replacement of engine oil, coolant and spark plugs. To ensure that maintenance is performed in timely manner, detailed operating records should be kept.

Figure 3 indicates typical recommended service intervals for natural gas engines including lubrication, cooling, ignition/electrical and fuel systems. These service intervals assume that the chiller is installed in a relatively clean, dry environment, typical of most applications.

	SERVICE AT CALENDAR OR HOUR INTERVAL**				
	Daily	Monthly or 750 hr*	6 Months or 4,000 hr*	12,000 - 15,000 hr*	24,000 - 30,000 hr*
Engine Lubrication System					
Oil (engine/auxiliary)	check level	test	replace	-	-
Oil filter	check P	-	replace	-	-
Crankcase breather	-	check		-	-
Oil Cooler	-	-	-	clean	-
Engine Cooling System					
Coolant	check level	check additives	-	replace	-
Coolant pump	-	-	check	-	-
Thermostats	-	-	-	replace	-
Ignition/Electrical System					
Batteries	-	check level	-	-	-
Spark plugs	-	check gap	replace	-	-
Timing	-	check	-	-	-
Alternator	-	-	check	-	-
Starting motor	-	-	check	-	-
Fuel System					
Air cleaner	check	-	replace	-	-
Air-fuel ratio	-	check	-	-	-
Control linkages	-	check	-	-	-
Gas regulator	-	check	-	-	-
Aftercooler	-	check	-	clean	-
Carburetor	-	-	check	rebuild	-
Turbocharger	-	-	check	rebuild	-
Engine Mechanical					
Valve lash	-	check	-	-	-
Exhaust valve blow-by	-	check	-	-	-
Vibration damper	-	check	-	-	-
Crankshaft/camshaft	-	-	-	check	-
Cylinder heads	-	-	-	rebuild	rebuild
Crankshaft bearings/seals	-	-	-	-	replace
Piston rings/cylinder liners	-	-	-	-	replace
Engine mounts	-	check	-	-	-
Engine Auxiliaries					
Belts and hoses	-	check	-	-	-
Safety controls	-	check	-	-	-
Driven equipment	-	-	check	-	-
** Whichever comes first					
* Full load hours					

Source: ACCC Applications Engineering Manual for Engine-Driven Chillers

Figure 3 - Typical Gas Engine Service Schedule

F. Installation Issues

The following issues need to be considered when installing gas cooling equipment:

- engine room ventilation
- fuel supply system, and
- exhaust system

Engine Room Ventilation

Ventilation air must be supplied to the engine-driven chiller for proper combustion and to remove heat radiated from the engine and exhaust piping surfaces. Approximately 3% to 6% of the energy input to the engine is lost to the surroundings from the engine surface. The heat lost from piping and other sources can double the amount of heat loss to the engine room. Because engine power is adversely affected by high inlet air temperatures, sufficient air flow must be provided to the engine so that the temperature rise in the engine room does not exceed 15 - 20°F. The engine room temperature should be less than 110°F. Engine room ventilation is also required to protect electrical components and equipment from excessive temperatures that could negatively impact performance.

Engine room ventilation must meet ASHRAE Standard 1, *Safety Code for Mechanical Refrigeration*. Additionally, ventilation air must flow properly through the mechanical room to provide effective cooling of the engine-driven chiller. To do so, the air should flow so that it does not bypass the chiller, as shown in *Figure 4*.

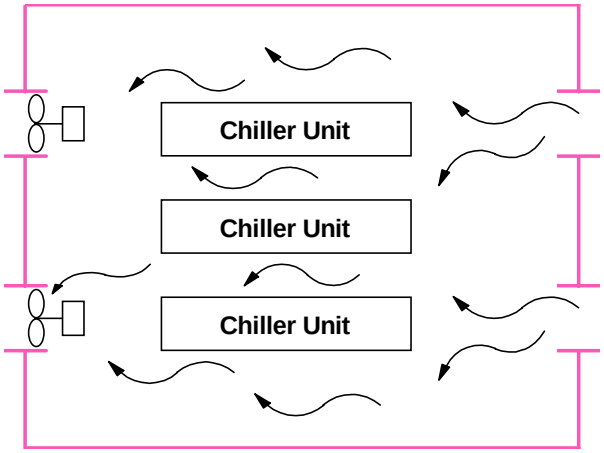


Figure 4 - Good Engine Room Design

Consideration must be given to the fuel supply piping system. Gas piping to the building should be black iron. A flexible connector should be installed between the gas engine and the gas supply line.

As part of the safety features built into the fuel supply system, a fuel shut-off valve should be installed that automatically ensures that the fuel flow to the engine is stopped when the engine is shut down either normally or in an emergency.

Exhaust System

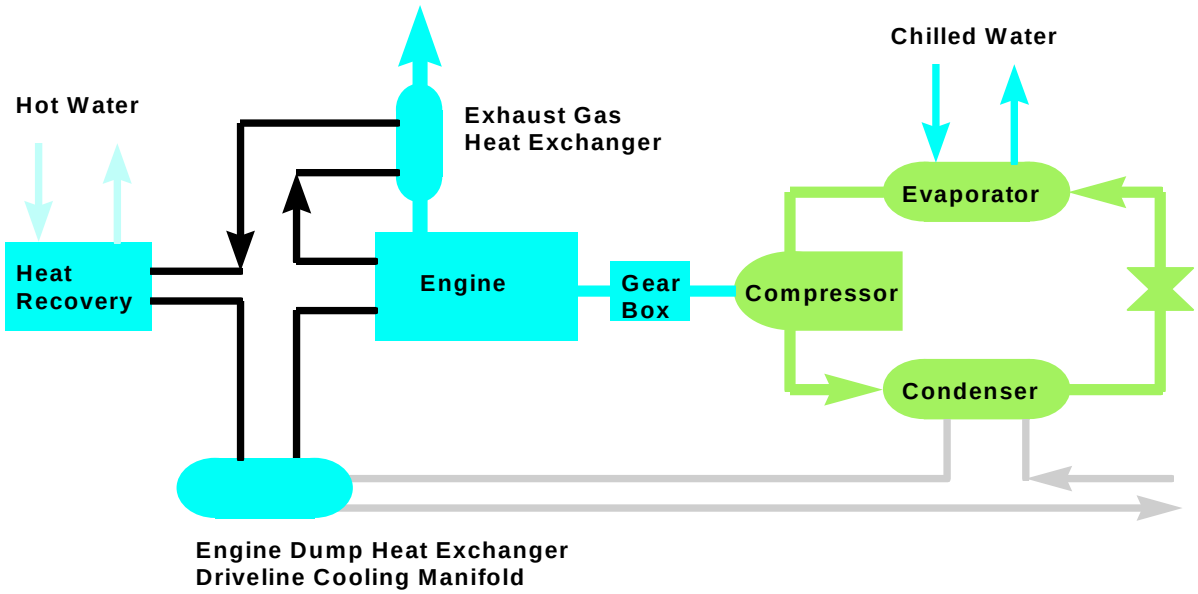
The primary function of the exhaust system is to remove products of combustion from the engine. The exhaust system is also designed to reduce engine exhaust noise through the use of mufflers and silencers. Proper exhaust system sizing and layout is crucial to minimize pressure drop in the piping. Excessive back pressure causes engine power loss, poor fuel economy and high exhaust valve temperatures. Allowable back pressure typically ranges from 12 to 27 inches of water column, depending on design engine speed, engine type and exhaust heat recovery options. The exhaust system must vent to an appropriate outdoor location, away from air intakes, windows, or outdoor use areas.

G. Heat Recovery

The gas engine produces a substantial amount of thermal energy that can easily be recovered from the engine cooling jacket and the engine exhaust. Effective recovery of this heat is an important consideration in fully utilizing the fuel input energy to the engine. By recovering heat in the jacket water and exhaust, approximately 75-80% of the fuel's energy can be effectively utilized. The schematic in Figure 5 illustrates the engine-driven chiller heat recovery system.

As shown in Figure 6, heat recovered from the engine jacket accounts for up to 30% of the energy input and is capable of producing 200ºF hot water. Almost all of the heat transferred to the engine coolant can be recovered, limited only by the efficiency of the heat exchange, and assuming that there is a demand for the heat.

The other major source of heat is the engine exhaust. Exhaust temperatures of 850ºF - 1200ºF are typical. Only a portion of the exhaust heat can be recovered since exhaust gas temperatures are generally kept above condensation thresholds. Most heat recovery units are designed for a 300ºF - 350ºF exhaust outlet temperature to avoid the corrosive effects of condensation in the exhaust piping. Exhaust gas can generate hot water to about 230ºF or low-pressure steam (15 psig). There is



Source: AGCC

Figure 5 - Engine Heat Recovery Schematic

up to 21% non-recoverable exhaust heat, assuming an exhaust stack temperature of approximately 300ºF - 350ºF. For applications using condensing heat recovery systems, additional heat can be recovered.

Closed-loop systems are the most common configuration for removing engine heat. They are designed to cool the engine by circulating coolant through engine passages with an engine coolant pump. Most engine-driven chillers are provided with an excess heat exchanger that transfers engine heat to a cooling tower or radiator (air cooled). In heat recovery configurations, the excess heat exchanger is used to provide a secondary heat sink in the event that demand for hot water is reduced while the chiller is operating.

Another type of cooling system is the ebullient cooling system. An ebullient cooling system is designed to cool the engine by natural circulation of the coolant without a jacket water pump. It is typically used in conjunction with exhaust heat recovery for production of low-pressure steam. Cooling water is introduced at the bottom of the engine where the transferred heat begins to boil the coolant generating two-phase flow. The formation of bubbles lowers the density of the coolant, causing a natural circulation to the top of the engine. The coolant at the engine outlet is maintained at saturated steam conditions and is usually limited to 250°F and a maximum of 15psig. Inlet cooling water is also near saturation condition and is generally 2° - 3°F below the outlet temperature. Uniform temperature throughout the coolant circuit helps to extend engine life. The uniform temperature also contributes to improved combustion efficiencies and reduced friction in the engine.

The recovered heat can be used to generate steam or hot water, or it can be used directly in certain industrial applications. Recovered heat is typically used for space heating, reheat, domestic hot water and absorption chilling. The thermal energy can be used for domestic hot water heating or steam generation without additional fuel consumption.

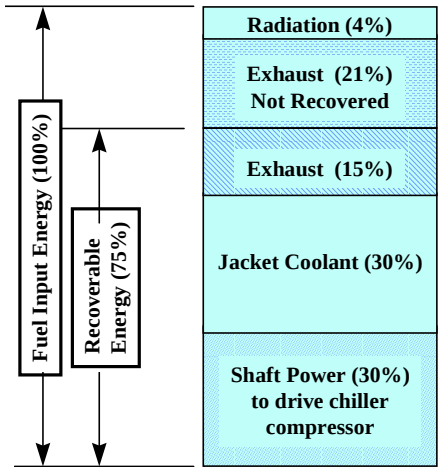


Figure 6 - Engine Heat Balance and Recovery

H. Hybrid Systems

A hybrid system includes a gas chiller and an electric chiller. A hybrid system allows for preferential loading of either the gas or electric chiller. Typically, the gas chiller is used during peak electric demand periods, when the cost of electricity is high. The control of a hybrid system allows the operator to select the most cost-effective and appropriate fuel source based on both cost and availability.

The restructuring of the utility industry adds significant complexity and uncertainty to the economics of chiller system design and operation. It is expected that there will be greater variety in electric rates including seasonal and time-of-use rates, and real-time pricing. The key is operational flexibility. The use of gas engine-driven chillers eliminates the high incremental cost of electricity, while a hybrid systems maximizes the flexibility of an “all-energy ” plant.

With restructuring of the electric utility industry, demand for hybrid gas/electric cooling systems will likely increase. According to Gary Nowakowski, of the Gas Research Institute (GRI), a hybrid system allows the user to hedge against future energy rate uncertainties and choose the most economical energy source from hour to hour. The move toward real-time pricing will favor those customers, both gas and electric, that have relatively flat energy load profiles. Gas cooling represents an efficient way to level the energy profiles and gain leverage when purchasing energy.

CHAPTER 3: HISTORY AND STATUS

A. History

During the 1930s and 1940s, gas engine-driven cooling systems dominated the U.S. market. In the 1950s and 1960s electric equipment began competing with gas equipment due to increased electric chiller efficiencies and the growing electric utility infrastructure.

Engine-driven chillers still were successfully marketed by the gas utilities and manufacturers in the 1960s. The gas companies used promotional rates and subsidies programs to entice buyers. The outstanding operating economics were sufficient to place nearly 2,000 units in the field between 1962 and 1970. The majority of these were located in Texas, presumably due to higher cooling loads and the availability of cheap gas. Counteracting this, innovations in compressors, electric motors, and controls increased the performance and decreased the cost of electric cooling systems.

In the 1970s, price controls and other government restrictions helped push electric chiller sales ahead of gas chillers. The gas crunch of the seventies curtailed gas cooling promotion and forced prospective buyers to select conventional electric systems.

The Gas Research Institute (GRI) initiated a program in 1984 to develop commercial chillers using the engine-driven concept. GRI is a not-for-profit organization that manages R&D programs for the benefit of gas consumers and the natural gas industry. As part of the program, an extensive study was conducted to evaluate the problems of past systems, the potential impact of engine-driven chillers on the HVAC market, and the design considerations, which would lead to favorable economics and commercialization potential.

B. Current Market Share

The potential for the gas engine-driven chiller is attractive in regions with high electric demand charges. The gas engine chiller's capability to operate efficiently at part load makes it an ideal peaking unit.

According to GRI, sales of natural gas engine-driven chillers in the commercial market quadrupled between 1994 and 1995, from about 7,000 tons of cooling to more than 30,000 tons per year. By the end of 1996, sales were almost 50,000 tons per year. During 1997, engine chiller sales increased by about 20%, to an estimated 60,000 tons from 1996's 50,000-ton record. The fast growth rate is due to the market entry of major HVAC manufacturers, a growing awareness of gas cooling benefits, and a relentless business trend toward reducing costs, including energy bills. At current energy rates, about 50% of all U.S. commercial energy users could realize more than a 20% return on investment with a gas-powered chiller.

Natural gas equipment including both absorption and engine-driven units accounts for 8 to 10 percent of the market for larger chillers. Gas engine-driven chillers represent about 2% of the total market. This number is expected to grow, however, as a result of increased efficiency, reliability, and accessibility of gas equipment. Figure 7 shows gas engine-driven chiller sales for 1994 through 1997. The y-axis is the number of units sold in rated tons times 1,000. For example, in 1994 approximately 7,000 tons were sold. In 1997, approximately 70,000 tons were sold. This indicates a tenfold increase in sales.

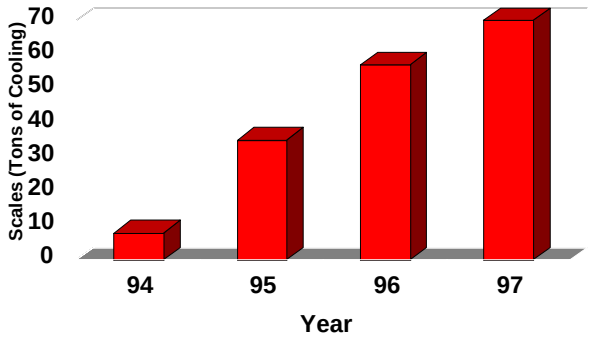


Figure 7 - Gas Engine-Driven Sales

C. Standards and Ratings

Currently there are no state or federal standards that regulate gas engine-driven cooling systems. However, there are several metrics that are used to define engine-driven chiller efficiency, including:

- COP
- IPLV
- APLV

Coefficient of Performance (COP)

The performance of gas cooling equipment is usually rated in terms of COP, defined as cooling output, or

refrigeration effect, in Btu, divided by energy input, in Btu. This same metric is applied to electric chillers, but since it is based on site energy, it is not appropriate for comparing gas and electric chiller efficiencies.

Engine-driven chillers have the highest coefficient of performance of any gas cooling product. This performance advantage enables engine-driven chillers to compete very effectively with electric chillers in many parts of the country.

Engine-driven chillers, as well as electric chillers, are rated to Air Conditioning and Refrigeration Institute ARI-550-92 conditions as listed below:

Chilled Water Conditions:

- 44ºF chilled water supply temperature
- 54ºF chilled water return temperature
- 2.4 gpm/ton chilled water flow

Water Cooled Condensers:

- 85ºF condenser water supply temperature
- 95ºF condenser water return temperature
- 3.0 gpm/ton condenser water flow

Air Cooled Condensers:

- 95ºF air supply temperature
- 20ºF temperature differential between air supply and condensing refrigerant
- 2ºF refrigeration system loss to the condenser

Figure 8 provides a typical range of engine-driven chiller COP's with and without heat recovery.

Heat Recovery Option	COP at Full Load
No Heat Recovery	1.2-2.0
Jacket Water Heat Recovery	1.5-2.25
Jacket Water and Exhaust Heat Recovery	1.7-2.4

Figure 8 - COP of Gas Engine-driven Chiller

Heat recovery from the jacket coolant and exhaust gas will boost overall energy utilization. The COP of an engine-driven chiller can reflect this heat recovery benefit as shown in the following equation:

$$COP = \frac{\text{System Cooling Load + Recovered Heat}}{\text{Engine Fuel Input}}$$

The heat recovered is added to the cooling load produced by the engine-driven chiller, thereby increasing useful thermal output and the COP.

There is no industry standard on how to calculate the COP of an engine-driven chiller when considering heat recovery partly because the economic value of the recovered heat is so variable. Some manufacturers calculate COP assuming that the recovered heat is fully utilized for domestic hot water, space heat or process needs. Others assume that the recoverable heat is used to produce additional cooling in a single-effect absorber. The former definition is generally preferred and provides a higher calculated COP since the efficiency of the absorber does not deduct from the value of the recovered energy.

Integrated Part Load Value (IPLV)

Another measurement of chiller efficiency is Integrated Part Load Value, IPLV. IPLV is an industry standard for calculating an annual COP based on a typical load profile and the part load characteristics of chillers. It was originally conceived as part of ANSI/ASHRAE Standard 90.1 (*Standard for Energy Efficient Design of New Nonresidential and High-Rise Residential Buildings*) in response to a need for directly comparing manufacturers' part load data. The method assumes that the chiller operates at a specific part load for a specific number of hours during the year, according to the following equation:

$$IPLV = \frac{1}{\underset{A}{\frac{0.17}{}} + \underset{B}{\frac{0.39}{}} + \underset{C}{\frac{0.33}{}} + \underset{D}{\frac{0.11}{}}}$$

Figure 9 provides the assumption and appropriate values for the equation.

Chiller Load (%)	Chilled Water Return Temp (ºF)	Mfgr. Rated COP	Part Load Hours (%)
100	85	A	17
75	78.75	B	39
50	72.5	C	33
25	66.25	D	11

Figure 9 - IPVL Calculation Assumptions

COP ratings A, B, C and D at each part load condition are obtained from the chiller manufacturer and should be derived from actual chiller tests. Note that the calculation allows for a 2.5ºF reduction in the entering cooling water temperature for every 10% drop in cooling load. A lower entering cooling water temperature corresponds to part load (reduced) cooling demand, which results from a drop in ambient temperature.

Engine driven chillers have excellent IPLV ratings. Part load operation of an engine driven chiller means that engine speed is reduced to slow the compressor speed in response to a reduced cooling load. Reducing engine speed means that the engine is operating at greater efficiency which contributes to a higher IPLV. For this reason, engine driven chillers have better part load performance gains than constant speed electric motor driven chillers (hermetic or open drive).

Although IPLV is a useful way to compare different manufacturers' chiller models, it probably doesn't represent actual operating conditions. For applications where cooling load is not significantly affected by ambient temperature conditions, (e.g., cooling load is dominated by internal gains) this estimate of part load performance may not provide accurate results. Chiller performance should be modeled to actual building load profiles tailored to site-specific ambient conditions.

Applied Part Load Value (APLV)

The Applied Part Load Value, APLV is calculated using the same IPLV formula, except that actual chilled and condenser water temperatures and flow rates are used. The advantage of using the APLV over the IPLV, is that this rating more closely approximates actual operating conditions imposed on the chiller. The disadvantage is the additional performance data that needs to be collected.

D. Economics/Cost Effectiveness

The economics of gas-fueled cooling systems vs. electric chillers are driven by the additional investment cost and several factors influencing operating cost, including:

- relative costs of the electricity and gas, and their billing structures,
- relative performance characteristics,
- operating characteristics, and
- relative maintenance costs.

The first three factors are discussed in the following sections and combined to produce estimates of Annual Energy Savings. Annual operating savings include an energy component and a comparison of O&M costs.

Energy Rates and Billing Structure

Energy rates and billing structure have a major impact on economic evaluations of gas versus electric cooling equipment. Energy rates include:

- Electric demand, $/kW
- Electric energy, ¢/kWh
- Gas energy rate, $/MMBtu (or therms)

It is essential that the complete utility rates and rate structures are used for an accurate economic analysis. Utility rate structures may include one or more of the following:

Block Rates - The electric block rates maybe in terms of kWh, with different rates for various levels of energy consumption. It may also be stated in kWh per kW of demand. In this case the kWh rate is a function of demand. A lower demand typically results in a large amount of kWh at a lower rate. A high demand results in a small amount of kWh at a lower rate. Typically, although not always, the unit price per kWh increases as demand increases.

Time-of Use Rates - the electric rate may vary depending on the time of day. The time-of-use rate is typically described in terms of on-peak and off-peak, and sometimes partial peak.

Ratchets - the electric rate may include a demand ratchet, which allows for a variation on how the demand kW is defined.

Seasons - some utilities have different summer and winter rates.

Taxes - applicable taxes and franchise fees, which can be over 10% in many areas.

Special Rates - for gas cooling equipment or special load-management electric rates are sometimes available.

Using average electric and gas costs is rarely adequate to capture the cost of operating cooling equipment, especially when the rate structure includes demand charges or declining blocks. The marginal electric price for cooling has a larger demand component relative to usage, which drives up the unit price. The details of the actual electric rates must be considered in the total analysis of chiller system operating costs.

Performance Characteristics

When comparing gas and electric cooling options there are several equipment performance characteristics that must be considered:

- Electric chiller seasonal COP and peak load COP,
- Gas cooling equipment seasonal COP,
- Gas and electric differential auxiliary power requirements, seasonal and peak, and
- Gas and electric differential O&M cost requirements, $/ton hour.

Miscellaneous electric loads, such as the engine coolant and oil pumps, should be included in the calculation of annual savings. The energy required to reject excess engine heat to a radiator or a cooling tower should also be included. In practice, however, these parasitic losses are a small percentage (typically less than 3%) of the savings achieved by the gas engine-driven chiller.

Operating Characteristics

Operating schedules for building types vary. For example, HVAC equipment for office buildings generally are operated approximately 10 –12 hours per day, five days per week. Equipment in hospitals will operate near full load for much of the day and at reduced, but still significant load for the remainder of the day. The descriptions of the building types used in the analysis, provided in the appendix, include the assumed operating schedules.

Annual energy savings need to be large enough to overcome higher initial costs and potentially higher maintenance costs for gas-engine driven chillers to be cost-effective. Annual energy savings will be a function of the operating schedule. An operating schedule that has a significant number of hours where the equipment runs at part load, favors gas engine-driven chillers because of their excellent part load performance. However, operating schedules that require equipment to run at full load for relatively few hours and not at all for most hours will result in too little annual energy savings to realize an acceptable payback for most business' requirements.

Estimating Annual Energy Savings

To estimate annual energy savings, the performance characteristics of each chiller alternative must be carefully compared. Part load performance characteristics are essential for predicting energy savings adequately. It is part load operation that distinguishes engine-driven chiller performance, significantly contributing to energy efficiency.

The customary approach to analyzing chiller economics has been to employ "equivalent full load hour" methodology. Equivalent Full Load Hours (EFLH) are defined as the total cooling load supplied over the cooling load (ton/hours) divided by the cooling equipment capacity (tons). Part load operation is modified to obtain the equivalent of running at full load. While this method does not reflect the efficiency of part load operation, it does simplify economic comparison. Because the engine chiller has superior part load performance, it does not benefit from this approach and the results are consequently conservative. Longer hours of operation at part load conditions will increase the energy savings benefit of engine-driven chillers.

Since the economics of gas cooling are highly dependent on operating hours, accurate analysis requires a detailed building simulation. A comprehensive analysis should be done with an hourly simulation model, such as DOE-2, HAP, or TRACE, which predicts when, where and how much cooling is required for the building.

The current publicly available version of DOE-2.1E contains performance simulation modules for:

- direct-fired absorption chillers,
- natural gas engine-driven chillers, and
- gas engine-driven air conditioners and heat pumps.

These models accurately adjust for the part load performance and variable speed operation of gas cooling equipment as well as electric options.

E. Equipment Manufacturers

There are several manufacturers and packagers of engine-driven chillers.

- Caterpillar and Waukesha actively promote the use of their engines in cooling configurations with Carrier, York, Trane, Vilter, Bell & Gossett, Ingersoll Rand, Frick, and Dunham Bush compressor packages.
- Napps Technology offers split system units in the 15 to 25 ton range.
- Cummins Southwest offers built-up gas chiller systems from 55 to 200 tons.
- Tecogen makes air-cooled units in the 50-120 ton size range, water-cooled units in the 125-350 ton range and industrial engines between 500 and 1,000 tons
- York International makes engine chillers ranging from 400 tons up to 2,100 tons.
- Alturdyne Energy Systems offers an extensive product line of engine chillers ranging from 25 tons up to 3,500 tons.
- The Trane gas Powered CentraTraVac GPC is composed of centrifugal chiller driven by a Waukesha engine.
- Industrial Heat Recovery Equipment (IHRE), make 100 to 1,100 ton engine chillers.

Tecogen and York Intl. currently have the largest market share for gas engine-driven chillers.

F. Equipment Installations

Installations of gas engine-driven chillers include a variety of building types including, hotels, hospitals, schools, office buildings, shopping centers, apartment buildings, industrial plants, and ice rinks. Following are several examples of gas engine-driven chiller installations:

A.M. Best Company, Oldwick, New Jersey

In the spring of 1995, three new Alturdyne engine-driven chillers were installed in the A.M. Best Company's 105,000 sq. ft. office. Two 100-ton and one 130-ton engine-driven chillers replaced two existing 150-ton electric centrifugal chillers. The company realizes a net energy cost savings during the cooling season, from April to October, of approximately $42,800.

"We knew it was time to replace the aging chillers," explains C. Burton Kellogg, II, senior vice president for A.M. Best. "After learning about all the environmental and economic advantages of the Alturdyne chillers, we decided to go the natural gas route."

J.C. Penny Department Store, Atlanta, GA

The installation at the 16,500 sq. ft. Cumberland Mall J.C.Penney store in December 1994, consisted of a 250 ton engine-driven chiller. The store saves nearly $55,000 in energy costs annually.

Carpenter's Home Church, Lakeland, Florida

The 167,000 sq. ft. church, completed in January 1985, includes a bookstore, child care center, wedding chapel, offices, and a radio station. In July 1987, two 150-ton Tecochill chillers were installed in an old boiler room.

"When we were building the church, the electric utility gave us an estimate on what we could expect to pay for cooling the facility," says Church Comptroller Joe Perez, "They quoted figures around $22,000 per month. Our highest bill with the Tecochill chillers has been $12,000.

"We've always performed our own maintenance on the chillers," says Facilities Engineer Jack Collins. " One engine has run for 24,000 hours and the other unit for 22,000 hours." The life span is supposed to be 20,000 hours before a complete overhaul is required.

Peachtree Tower, Atlanta, GA

Three 150 ton engine-driven chillers were installed in the 418,000 sq. ft. high rise condominium complex in 1993, replacing an aging electric chiller. The complex, which has 335 units, saves around $65,000 annually through reduced demand charges and an additional $5,000 from engine heat recovery which is used for domestic hot water heating.

Boston YMCA, Residential/Hotel Facility

The 106,000 sq. ft. YMCA building, built in 1992, has a pool, exercise room, saunas, basketball court, and 140 living quarters, some with kitchenettes. The 150 ton engine chiller operates 12 months per year. Waste heat is used to heat the swimming pool, and to provide hot water for the laundry. Savings are estimated at $25,000 per year over an electric chiller.

The system is tied by modem back to the manufacturer. “The technicians are constantly monitoring our system. They’re able to see any potential difficulty before it ever has a chance to happen,” says Lou Falzarano, Maintenance Director at the YMCA.

CHAPTER 4: ANALYSIS

A. Overview

Gas engine-driven chillers were compared to the following chiller options:

- Standard efficiency electric screw or centrifugal
- High efficiency electric screw or centrifugal
- Indirect-fired single effect absorption

The analysis is structured to provide "typical" values that can be used as a screening tool during schematic design of a building or as guidance on equipment efficiency issues for voluntary programs or energy code bodies. The results of a detailed energy and rates analysis, for seven building types in ten cities, have been distilled down to a series of graphs.

The cities and buildings are representative of the range of climates and building occupancies where gas cooling options would be used. The list of cities, sorted by Cooling Degree Day (CDD) is provided in Figure 10. Information on building type and size are provided in Figure 11. The economic analysis is of course dependent upon gas and electric rates. Building descriptions and city specific utility rates are provided in the Appendix.

The results are graphed for various gas rates and various electric rates. Due to the complexities of the interactions between fuel type usage and utility rates, it was not possible to develop "typical" gas-to-electric cost results. These graphs can be used, as will be shown by example in the following chapter, to determine relative increase in gas consumption and relative decrease in electric consumption, when comparing a gas chiller to an electric chiller. The results of separate fuel type analysis can then be combined to provide a complete picture of the savings opportunities.

City	CDD_{50}
San Francisco	2,883
Chicago	2,941
Washington DC	3,734
Los Angeles	4,777
Atlanta	5,038
San Diego	5,223
Riverside	5,295
Fort Worth	6,557
Phoenix	8,425
Miami	9,474

Figure 10 - Cities used for Cooling Analysis

Figure 11 shows the building types included in the analysis, along with the building size in square feet, and the cooling equipment size in tons. The range of equipment sizes represents the variation in cooling load for the cities analyzed. The sizing of the cooling plant follows ASHRAE 90.1R ECB guidelines with a 20 % oversizing margin.

Type	Size (Sq Ft)	Cooling (tons)*
Medium Office	49,000	100 - 143
Large Office	160,000	408 - 573
Hospital	272,000	384 - 519
Hotel	315,000	645 - 891
Out-Patient Clinic	49,000	90 - 111
Secondary School	50,000	90 - 205
Large Retail	164,000	165 - 393

*Cooling plant capacity includes 20% additional oversizing

Figure 11 - Building Type and Size

As shown in Figure 12, the type of electric equipment, either screw or centrifugal, used as a comparison, was dependent on the size. Figure 13 shows the standard and high efficiencies assumed for the various types of chillers.

Size (tons)	Type
100 - 300	Screw
>300 - 600	Screw
>600	Centrifugal

Figure 12 - Cooling Equipment Type Based on Size

Because of the complexities and "individual" nature of hybrid systems, results of any hybrid systems analysis cannot be generalized. They were therefore intentionally not included in this analysis. However, if the results indicate that a gas engine-driven chiller is cost-effective, or even marginally not cost-effective, a hybrid system under the same conditions, will typically be cost-effective.

B. Energy Savings

Energy savings were calculated using detailed DOE-2.1E building simulation models. The models provide comprehensive data on energy use and savings. The modeling included a complete comparison of system components, including auxiliary equipment such as cooling towers, fans and pumps.

The graphs in the following chapter present the energy savings for each of the cities for a range of marginal gas and electrical prices. The graphs present the annual energy cost savings, in dollars per year, versus the marginal cost of gas, in dollars per therm, or the marginal cost of electricity in dollars per kWh. The marginal energy cost, gas or electric, is calculated as energy cost savings, in dollars, divided by energy savings in therms or kWh. The marginal cost accounts for varying rates that may apply based on total usage.

C. Cost Effectiveness

Cost effectiveness is based on the calculation of the Savings to Investment Ratio (SIR). SIR is defined as the Life Cycle Cost (LCC) savings, in dollars, divided by the incremental measure cost per unit capacity, in dollars per ton capacity, as shown in the following equation:

$$SIR = \frac{LCC\ Savings}{Incremental\ Cost}$$

The SIR uses an investment model over the life of the equipment rather than the simplistic and short range perspective of simple payback.

The LCC savings describe the present worth of the energy cost savings over the life of the investment. If the LCC savings are greater than the incremental cost, then the SIR will be greater than one and the measure is assumed to be cost effective.

Savings to Investment Ratios (SIR's) indicate the cost effectiveness of the equipment selection depending upon several factors including:

- building type,
- equipment,
- climate,
- utility rate, and
- scalar ratio.

Specific equipment cost information is provided in the Appendix. Additional first cost and maintenance costs were applied to the cost-effectiveness model, including:

- additional cooling tower capacity for engine-driven chiller adds $15-$20/ton to first cost.
- additional boiler capacity for single effect absorption adds $50-$150/ton to first cost.
- the maintenance cost premium for engine-driven versus electric chiller reduces operating cost savings by $10-$20/ton/yr. This number will be higher for buildings with long run hours, which require maintenance at shorter time intervals.

Another element of the cost for gas engine-driven chillers is the potential savings from interactions with other building elements. For example, installing a gas engine-driven chiller may reduce the building's electric load enough to allow for downsizing of the electric service drop and load center. These savings could be significant but are not included due to the variability between installations.

The scalar ratio is a single term that combines discount rate, period of analysis, and fuel escalation. A scalar ratio is a mathematical simplification of life cycle costing (LCC) analysis. The first year savings are multiplied by the scalar to arrive at the life cycle savings. In technical terms, the scalar ratio represents the series present worth multiplier. A more detailed description of the scalar ratio is provided in the Appendix.

Different scalars have been used to evaluate the cost-effectiveness based on different economic assumptions. Typical values of the scalar are in the 8 to 16 range. This approach has the virtue that different life cycle costing criteria, and different scalars may be applied to the results.

Equipment Type & Size	Standard Efficiency		High Efficiency	
	COP	kW/ton	COP	kW/ton
Electric Screw, <150 tons	3.8	0.93	4.45	0.79
Electric Screw, =>150 to 300	4.2	0.84	4.90	0.72
Electric Centrifugal, >300	5.2	0.68	6.01	0.58
Single Effect Absorption	-	-	0.60	5.86
Engine-Driven Screw	-	-	1.30	2.70
Engine-Driven Centrifugal	-	-	1.85	1.90

Reference: ASHRAE 90.1R "Minimum Efficiency" and "Efficiency as of Jan, 2000"

Figure 13 - Cooling Equipment Efficiencies

CHAPTER 5: DESIGN ANALYSIS GRAPHS

A. Using the Graphs

The following pages contain families of graphs that describe the performance of gas engine-driven chillers in a variety of cities and building types. As described in Chapter 4, these graphs were developed from DOE-2.1E runs done for representative prototype buildings using the actual utility rate structures currently published for each of the cities. The graphs can save the reader a great deal of analysis work, and can provide good information about when and where of gas engine-driven chillers can be cost effective.

Each of the lines on the graphs represents the energy savings potential of the prototype building in one of the ten cities studied. Markers on each line indicate current local gas and electric rates for each city. By following the line on the graph, the results can be extrapolated to different utility rates.

Annual Energy Cost Savings Graphs

Two sets of energy cost savings are calculated for each building type. One is for a range of marginal gas costs and a fixed marginal electric cost. The other is for a range of marginal electric costs based on a fixed marginal gas cost.

The top graph in Figure 14 is typical of the annual energy cost savings vs. marginal gas cost graphs. The bottom graph is for the same conditions showing the energy cost savings vs. marginal electric costs. These particular results are for the medium office building prototype. The comparison is between a gas engine-driven chiller and a standard efficiency electric screw chiller.

The horizontal x-axis of these graphs is the marginal cost of gas, in dollars per therm, or the marginal cost of electricity, in dollars per kWh. Marginal cost is the cost charged, under the local utility rate structure, for those kilo-Watt/hours that are saved by the use of the gas chiller. For the case of gas rates, marginal cost represents the costs charged per therm for the increase in gas consumption. The marginal cost does not include the utility basic service charges or other charges that are common to both equipment scenarios.

The vertical y-axis shows the annual energy cost savings, in dollars per year, between the base equipment and the gas engine-driven chiller.

As shown on the top graph, as gas prices increase, the energy savings associated with an engine-driven chiller decrease. Conversely, as electric prices increase, savings from the gas chiller increase, as shown in the bottom graph.

For example, as shown in Figure 22, Chicago is represented by a solid diamond marker. In this example, the prototype large office building in Chicago has a marginal gas cost of approximately $0.37 per therm, and a marginal electric cost of approximately $0.11 kWh. The gas engine-driven chiller would save approximately $14,000/year compared to a high efficiency screw chiller.

The slope of the line represents the rate of change in annual energy cost savings for each increment or decrement in the marginal cost of energy. In the Chicago example, if gas were to increase to $0.45 per therm, a 20% increase, the energy cost savings would decrease to approximately $12,000 per year. Conversely, if the electric rate increased to $0.20, the savings would increase to $32,000 per year.

The cases shown on this graph can also be used to estimate savings for other cities with comparable climates. For example, the Chicago line would also be reasonably representative of Milwaukee or Detroit or Omaha. The gas costs in these other locations may be different than Chicago, but by entering the graph at the x-axis value that represents the costs in the other location, an estimate of the savings can be obtained.

Cost Effectiveness Graphs

This section presents the cost effectiveness graphs developed for various utility rates and locations.

The SIR is used as the figure of merit for cost effectiveness, as described in Chapter 4. It is the ratio of the life cycle cost (LCC) savings to the incremental first cost, as shown in the following equation:

$$SIR = \frac{LCC\ Savings}{Incremental\ Cost}$$

If the LCC savings are greater than the incremental cost, then the SIR will be greater than one and the investment is a sound one. Thus, any point on the graph that is above the 1.00 point on the vertical axis is a good investment.

Calculating the LCC savings can seem complicated to anybody unfamiliar with present worth analysis principles. It involves several variables, including the lifetime of the investment, the rate of increase in energy costs, and the rate of economic inflation. These factors have been combined into a single numeric parameter called the scalar ratio, or "scalar," as described in Chapter 4.

The graphs in Figure 36 are typical of the "savings-to-investment ratio (SIR) as a function of marginal gas costs" graphs for scalars of 8, 12, and 16. Figure 37 is an example of the "SIR as a function of marginal electric costs" graphs. For each of the SIR graphs, particular scalar and incremental equipment values are used. The top graph in Figure 36 is for a scalar of 8, and the incremental equipment cost is $369/ton of chiller capacity. There are different sets of graphs for each of the different building types studied.

Each graph enables one to quickly determine the cities where the gas engine-driven chiller is currently cost effective. If the marker for the city is above the 1.00 SIR line, it's cost effective. If the marker is not quite over the 1.00 line, then one can see how much of an increase in marginal gas cost would be needed to bring it over the line.

For example, if one were comparing a gas engine-driven chiller to a high efficiency chiller for a large office for a scalar of 8, in Miami (marked with an X in Figure 53), the SIR would be 0.80, which is not cost effective. However, if the marginal gas rate were approximately $0.55, the gas cooling option would be cost-effective.

As with the previous graphs, one can also apply these graphs to other cities by selecting one of the ten cities whose climate conditions are most similar and moving to the point on that line, which corresponds to the gas or electric costs in the other city.

These graphs can be adjusted for different incremental equipment costs. For example, the SIR for a scalar of 8 for Miami, shown in the graph in Figure 54, is based on an incremental cost of $369/ton. This value is the denominator of the SIR values plotted on this graph. If the incremental cost for a particular installation was instead $450/ton, then the SIR value from the graph would be adjusted to reflect the new cost. In this case, an SIR value of 0.80 from the graph would be multiplied by 369/450 to arrive at an adjusted SIR of 0.66. If, instead, the incremental cost was $225/ton, the adjustment factor would be 369/225, for an adjusted SIR of 1.31, which makes the gas option cost effective. The adjustment factor will always have a numerator of 369 and a denominator of the new incremental equipment cost, in dollars per ton capacity, as shown in the following equation:

$$SIR_{Actual} = SIR_{graph} \times \frac{Cost_{graph}}{Cost_{Actual}}$$

Further review of the Cost-Effectiveness, or SIR graphs, shows that for a large office, Figure 53, an engine-driven chiller compared to a high efficiency electric chiller is cost-effective based on a scalar of 8 for all cities except Miami. Using a scalar of 12, gas cooling also becomes cost-effective in Miami. The cost-effectiveness results can be obtained from either the gas or the electric based graphs.

The following pages contain the full set of graphs comparing gas engine-driven chillers to other cooling options. For each comparison there are different energy and equipment costs, and different economic criteria.

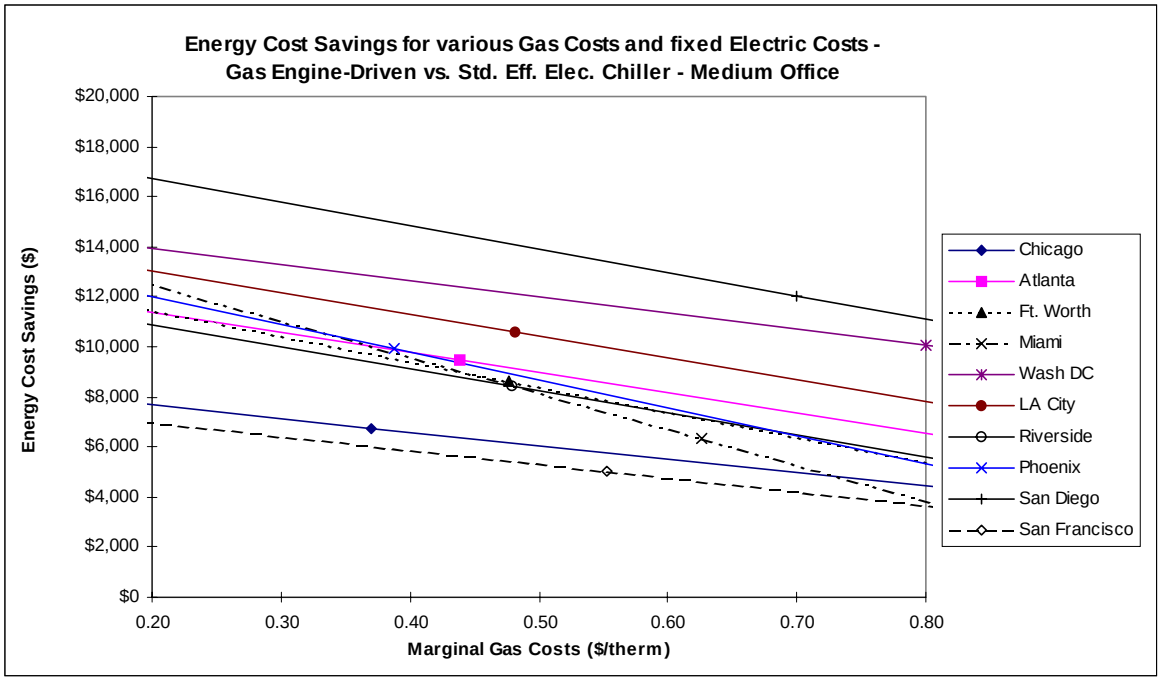
Some of the graphs have no or almost no savings curves on them, while others are apparently missing curves for one or two cities. In these cases the energy savings are so great that the curves are literally off the scale. For example, in Figure 37, the graph for SIR comparing gas engine driven chillers against standard efficiency chillers with a scalar of 12, shows curves for only four cities, and only one of them, Miami, has the marker showing (above 1.0). This technology can be assumed to be cost effective for these conditions.

A singular exception to the above discussion is the graph showing gas driven chillers versus high efficiency chillers in hospitals (Figure 55). In this case, gas rates are high enough and electric rates low enough in Miami that there are no energy savings for the technology. Savings/Incremental Equipment Cost is a negative number, and the marker for Miami is below the x-axis of the graph.

In any case where the marker for a city does not appear on the line, you can simply estimate where the market would be based on the local marginal cost of gas and an extension of the city's SIR curve.

B. Energy Savings Graphs

Gas Engine-Driven Chiller vs. Standard Efficiency Electric Chiller



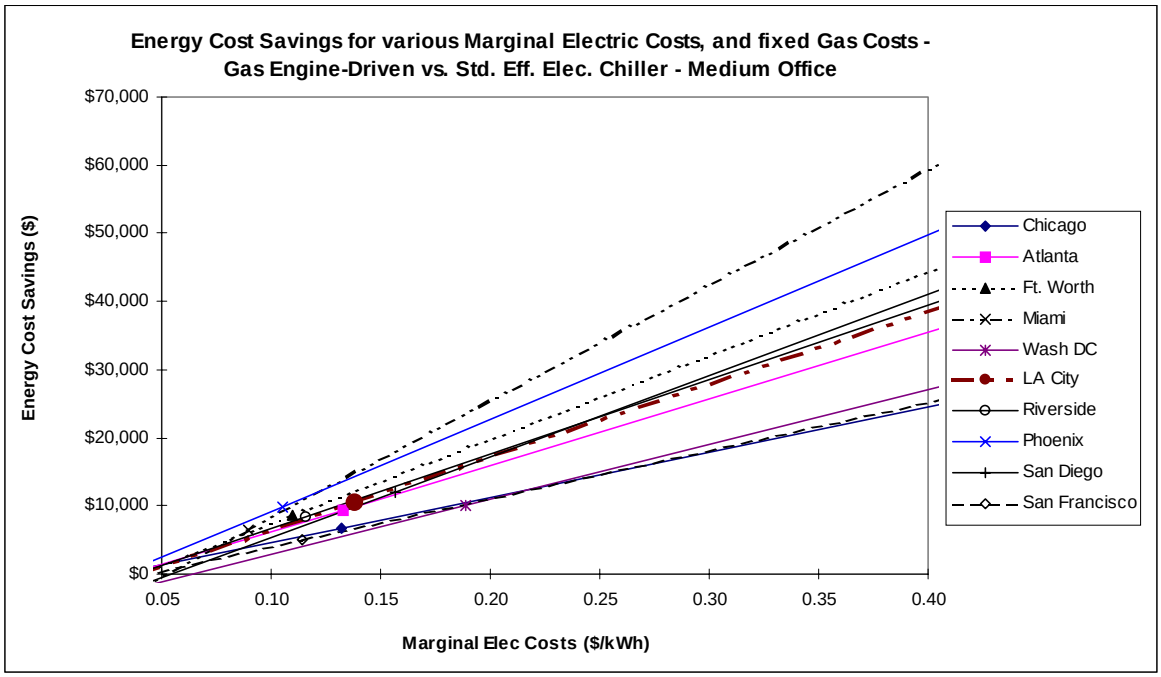
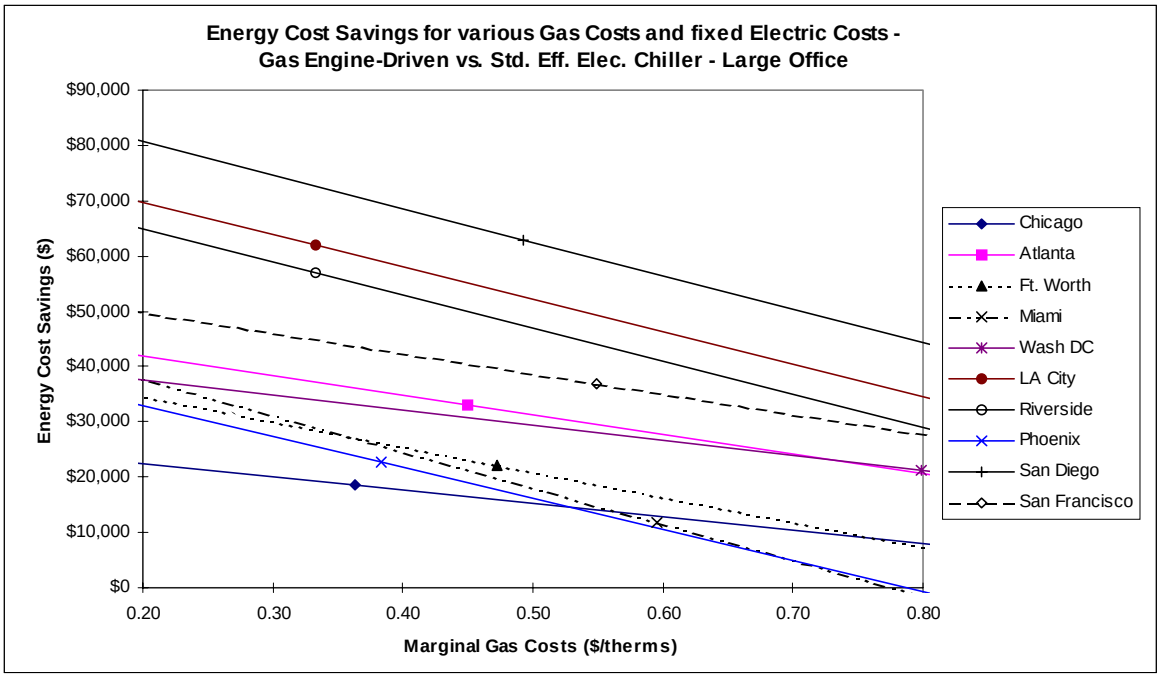


Figure 14 - Energy Cost Savings for Gas Engine-Driven vs. Standard Efficiency Chiller for Medium Office



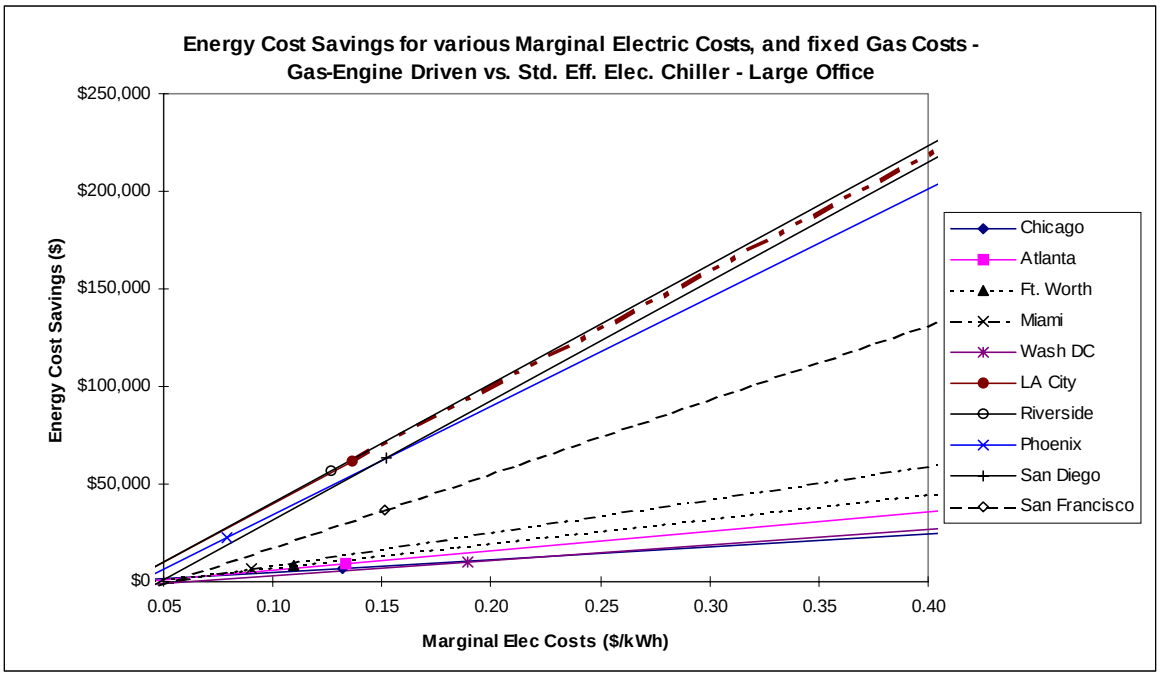
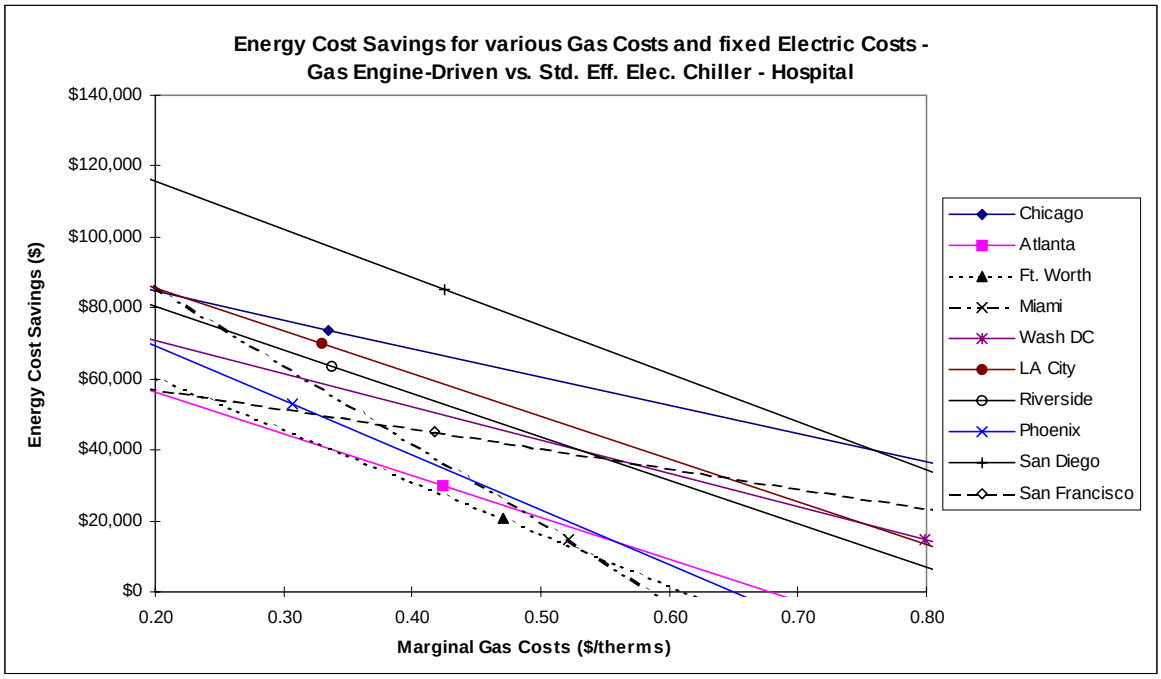


Figure 15 - Energy Cost Savings for Gas Engine-Driven vs. Standard Efficiency Chiller for Large Office



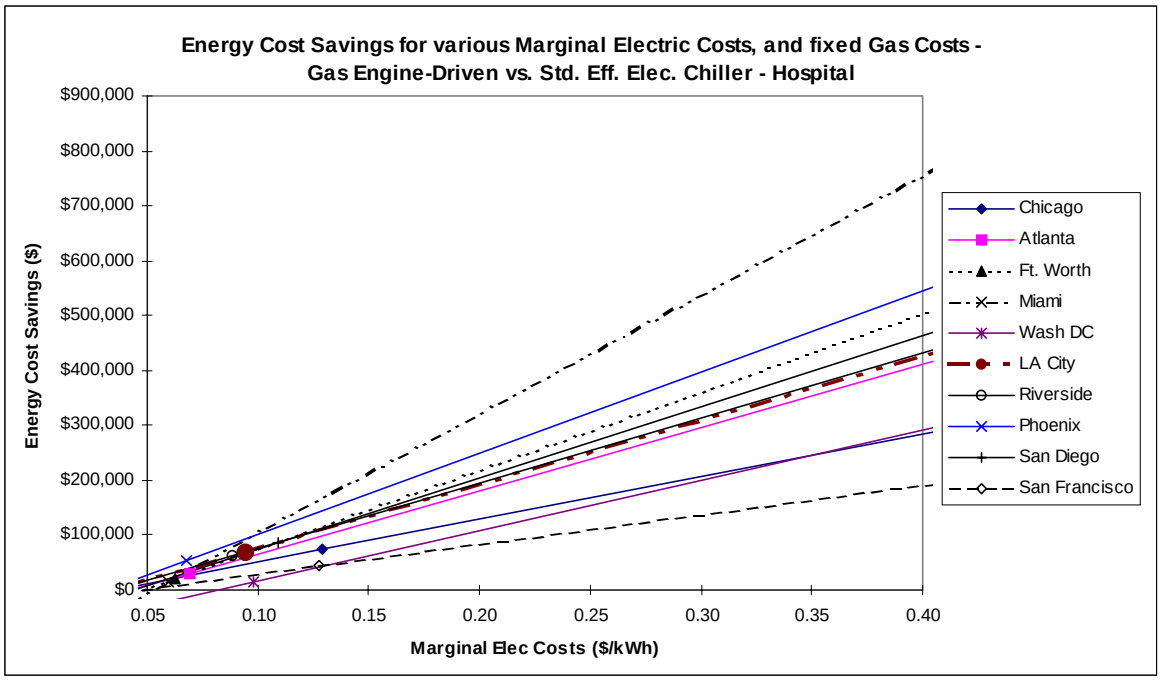
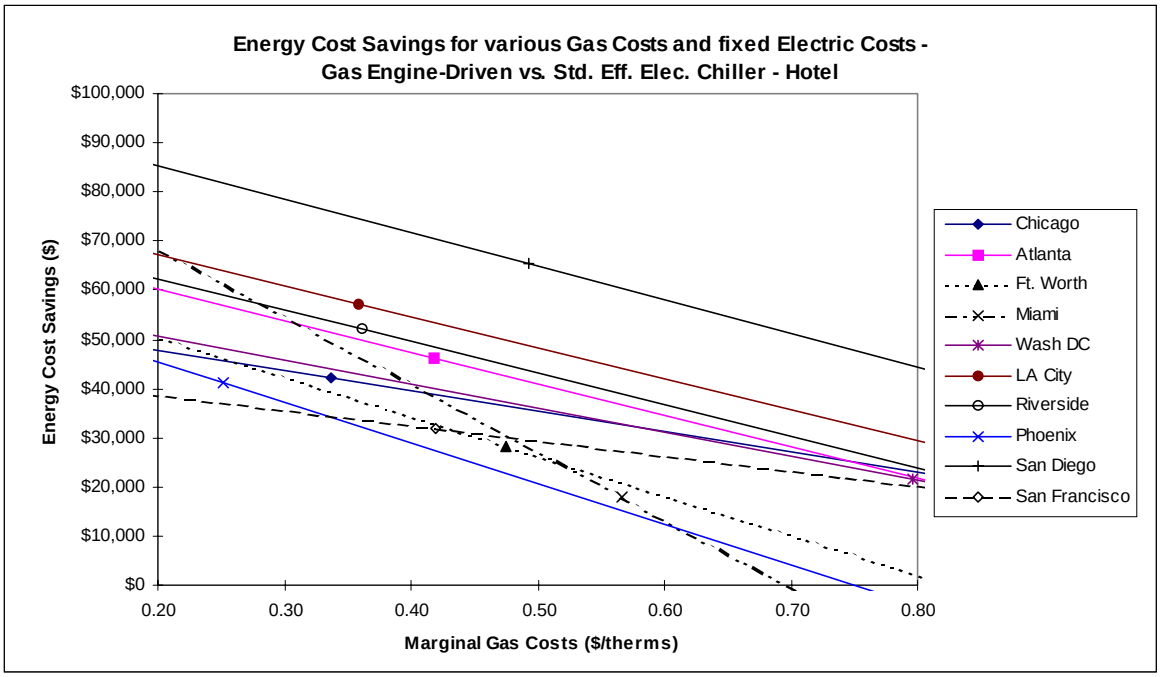


Figure 16 - Energy Cost Savings for Gas Engine-Driven vs. Standard Efficiency Chiller for Hospital



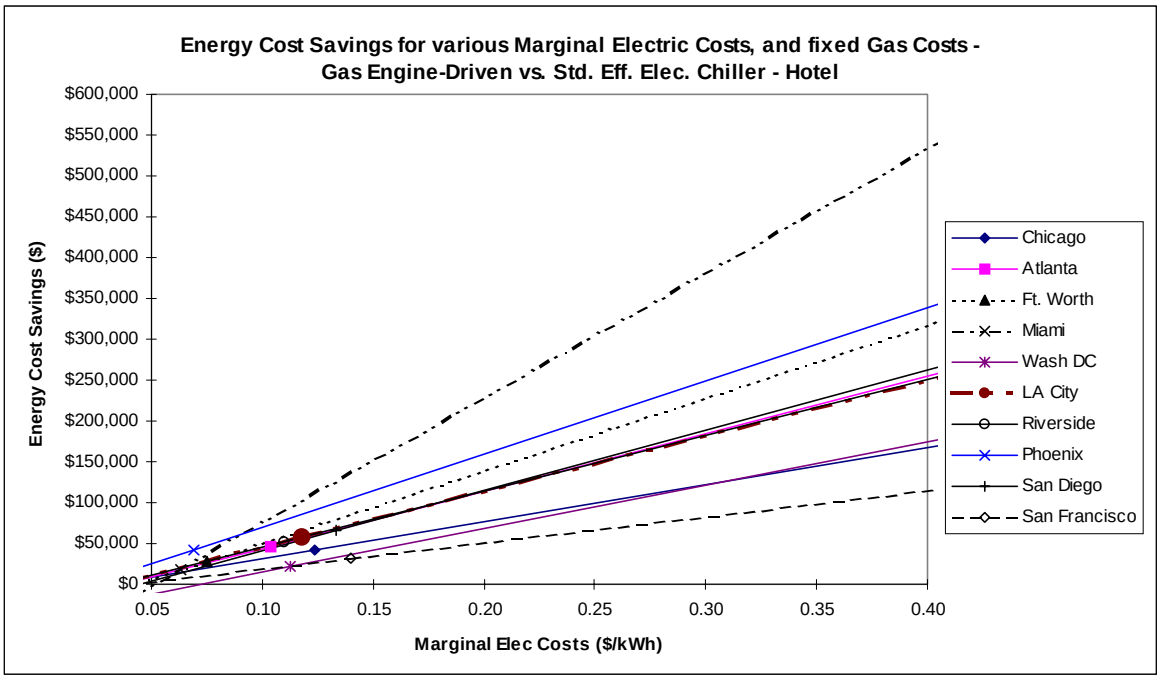
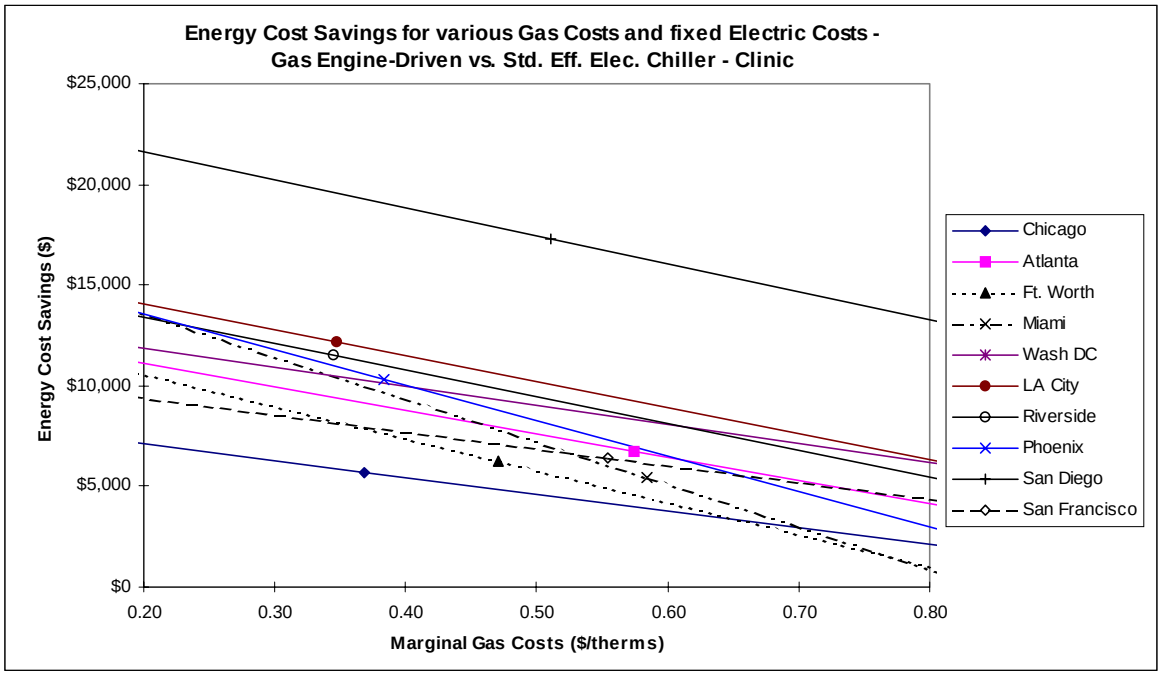


Figure 17 - Energy Cost Savings for Gas Engine-Driven vs. Standard Efficiency Chiller for Hotel



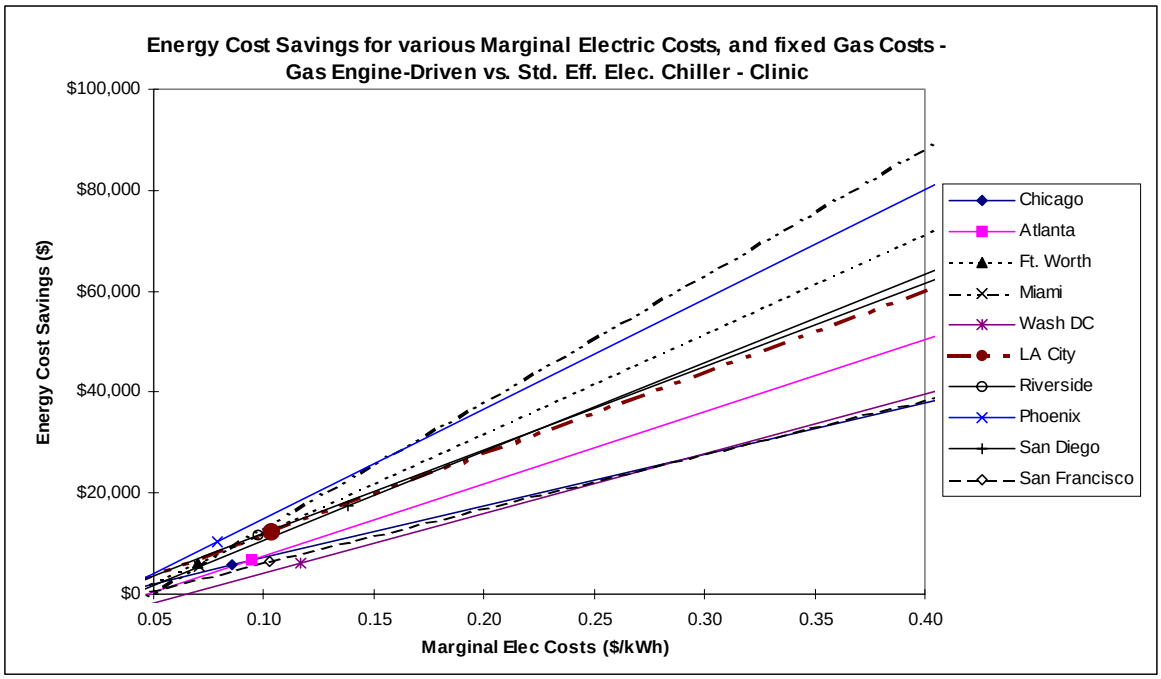
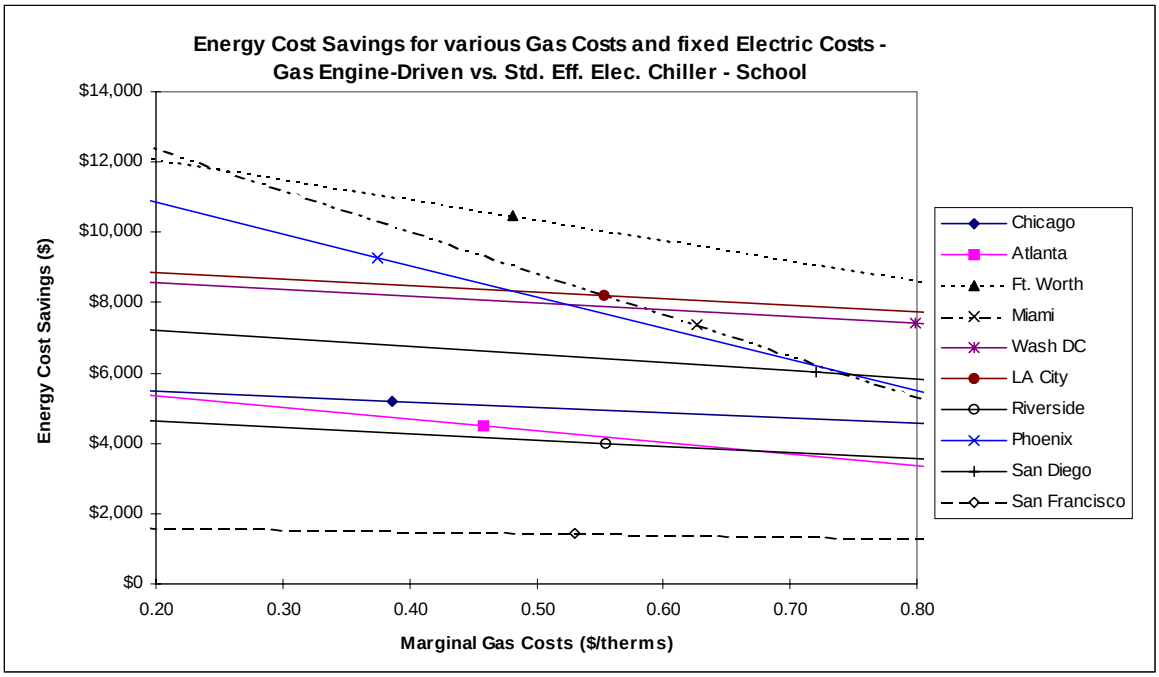


Figure 18 - Energy Cost Savings for Gas Engine-Driven vs. Standard Efficiency Chiller for Clinic



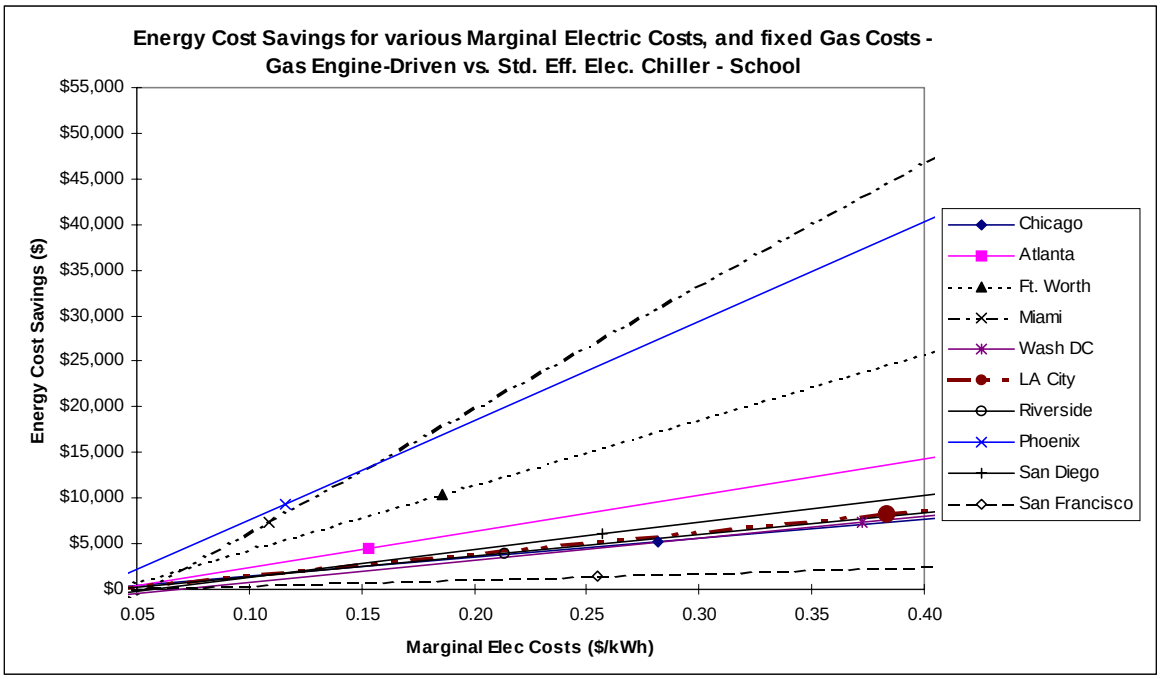
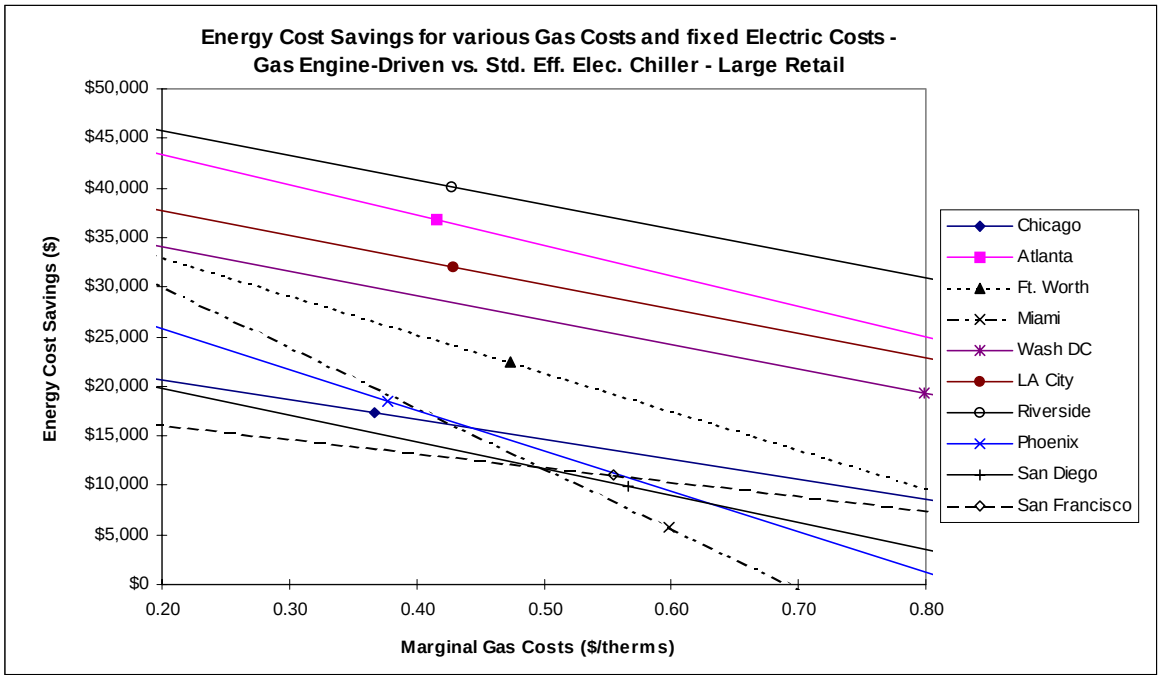


Figure 19 - Energy Cost Savings for Gas Engine-Driven vs. Standard Efficiency Chiller for School



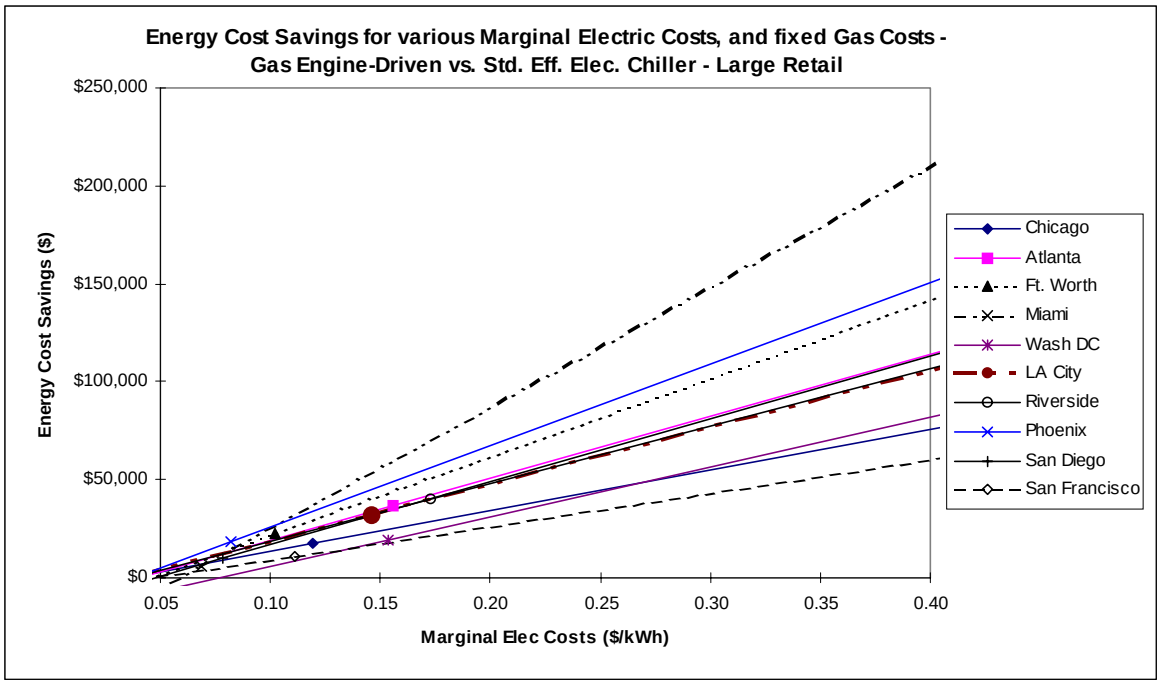
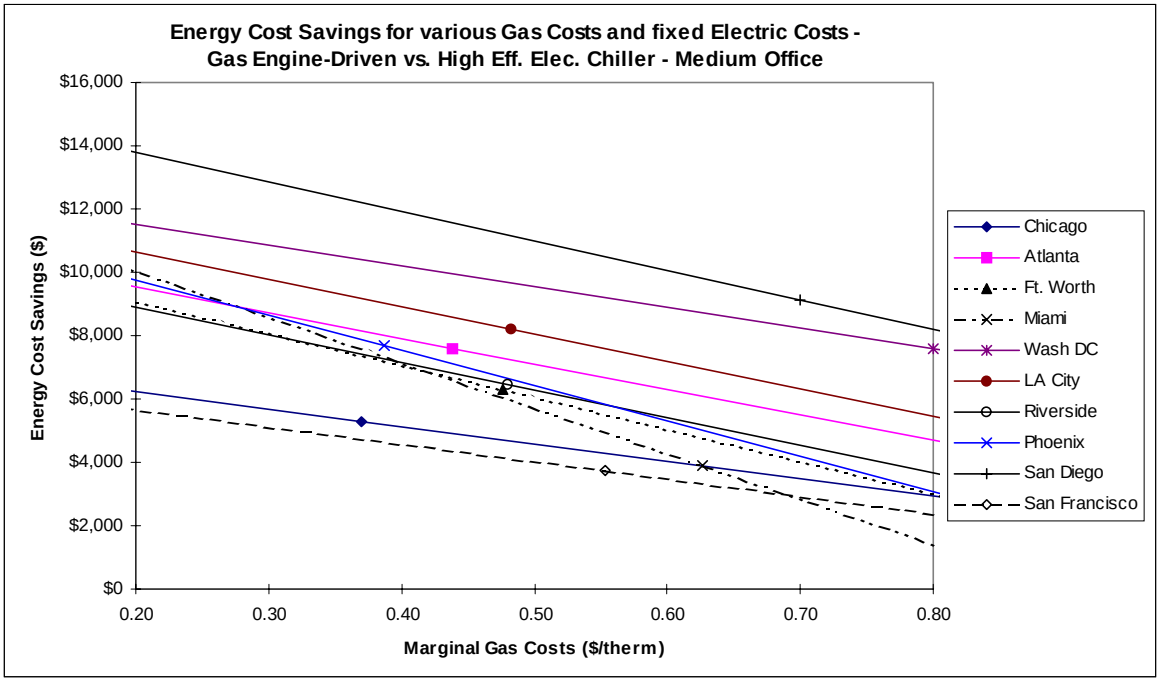


Figure 20 - Energy Cost Savings for Gas Engine-Driven vs. Standard Efficiency Chiller for Large Retail

Gas Engine-Driven Chiller vs. High Efficiency Electric Chiller



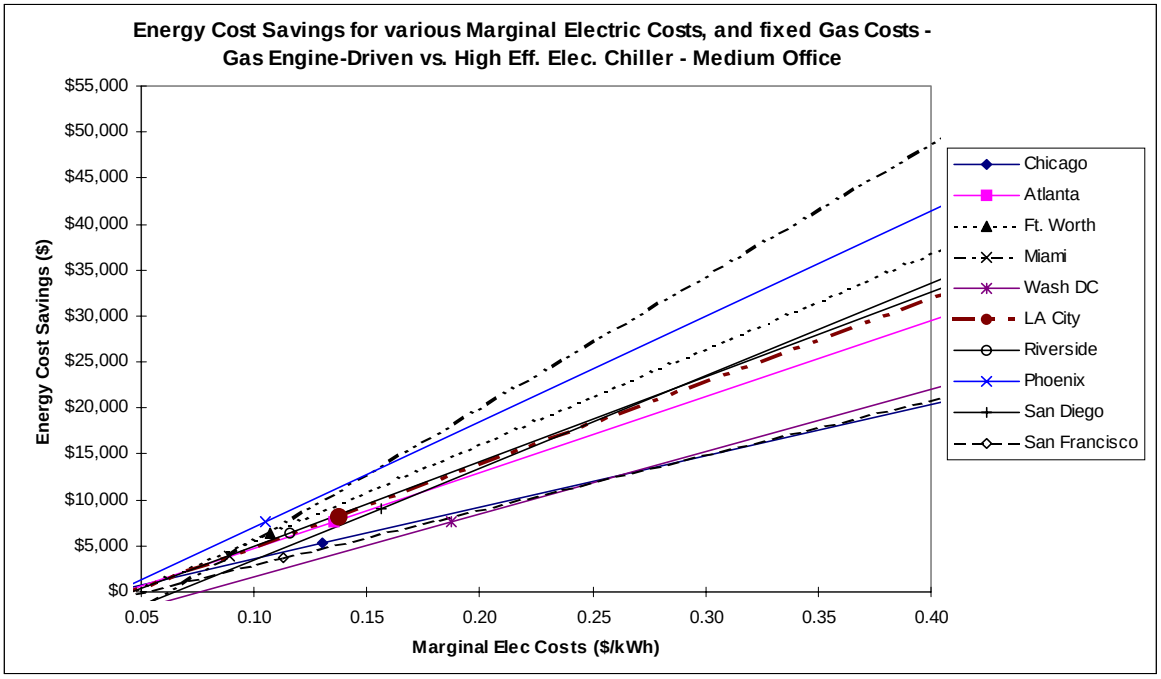
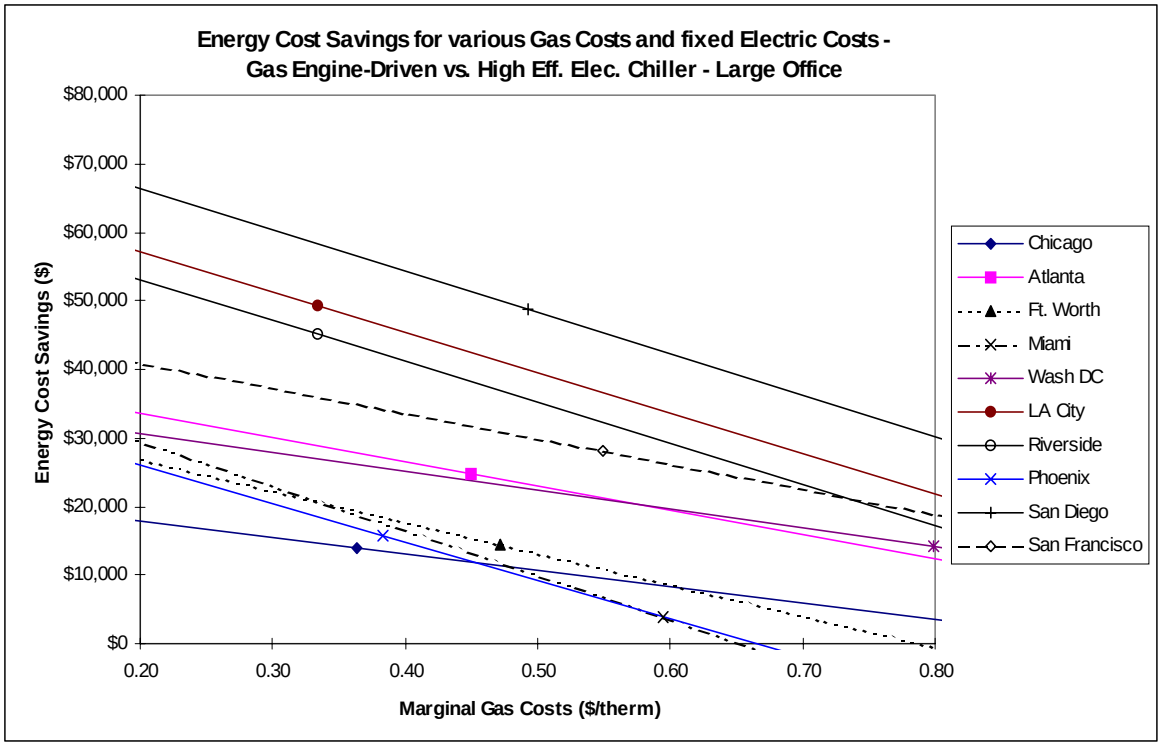


Figure 21 - Energy Cost Savings for Gas Engine-Driven vs. High Efficiency Chiller for Medium Office



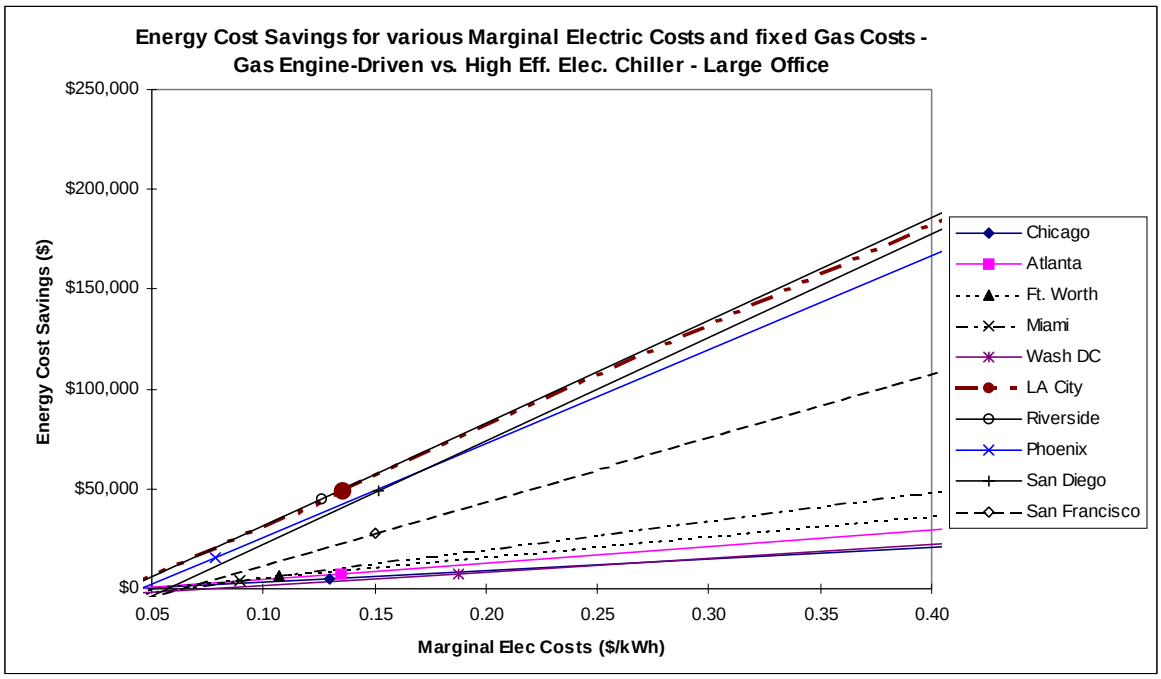
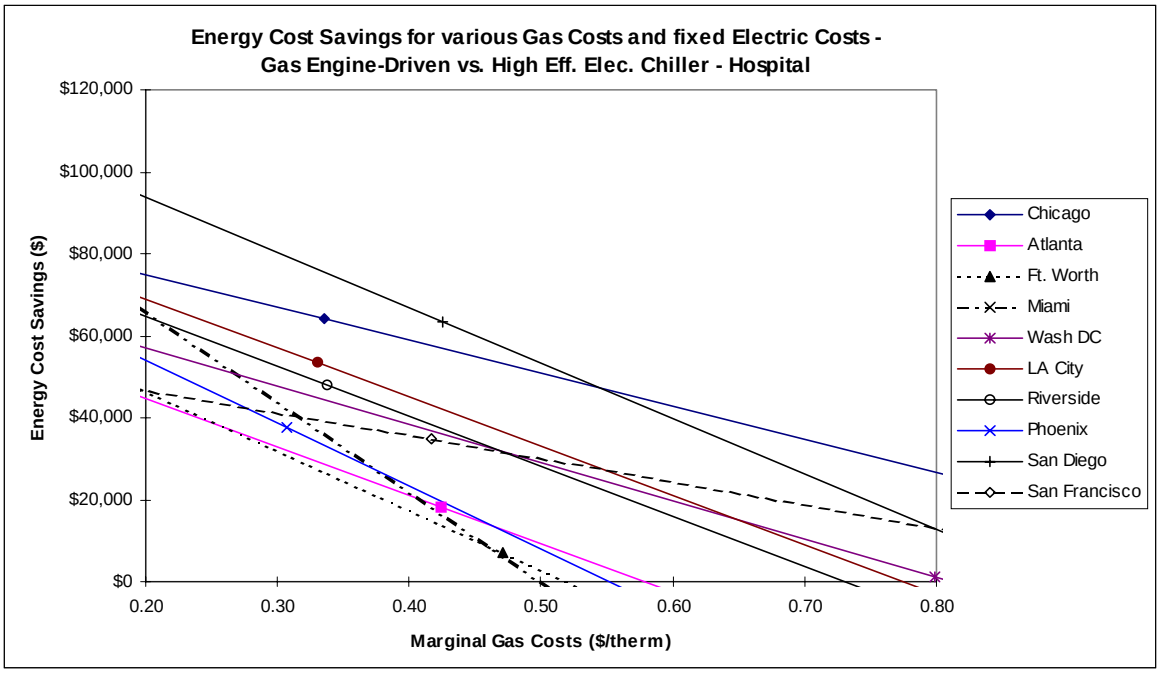


Figure 22 - Energy Cost Savings for Gas Engine-Driven vs. High Efficiency Chiller for Large Office



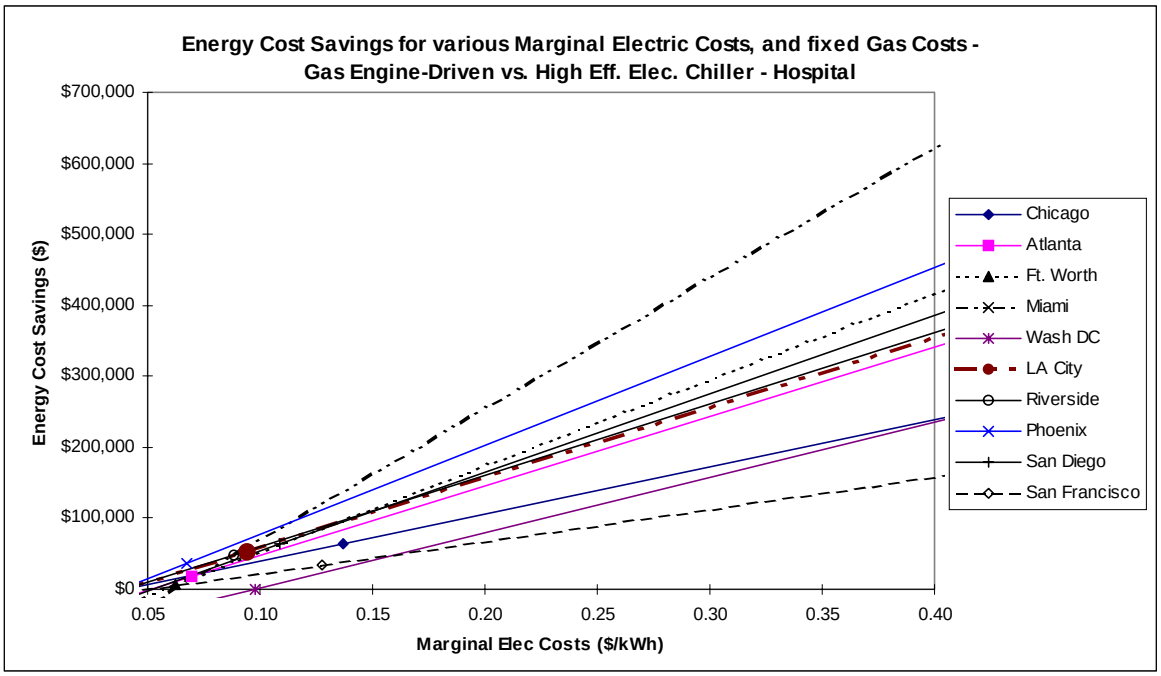
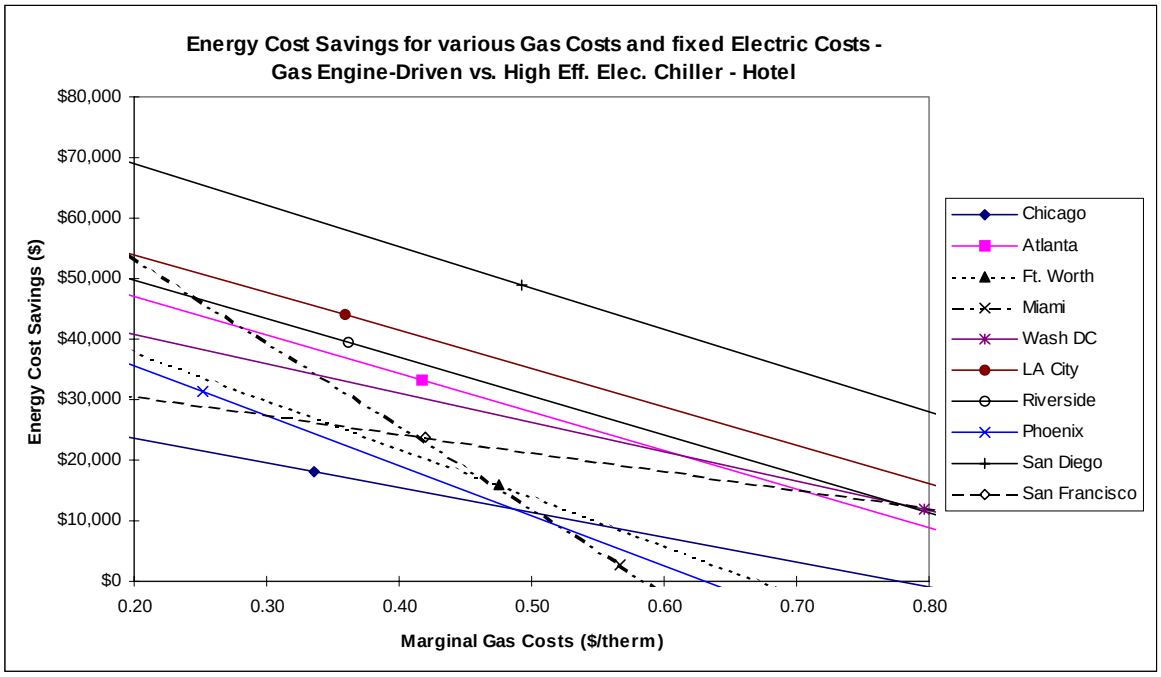


Figure 23 - Energy Cost Savings for Gas Engine-Driven vs. High Efficiency Chiller for Hospital



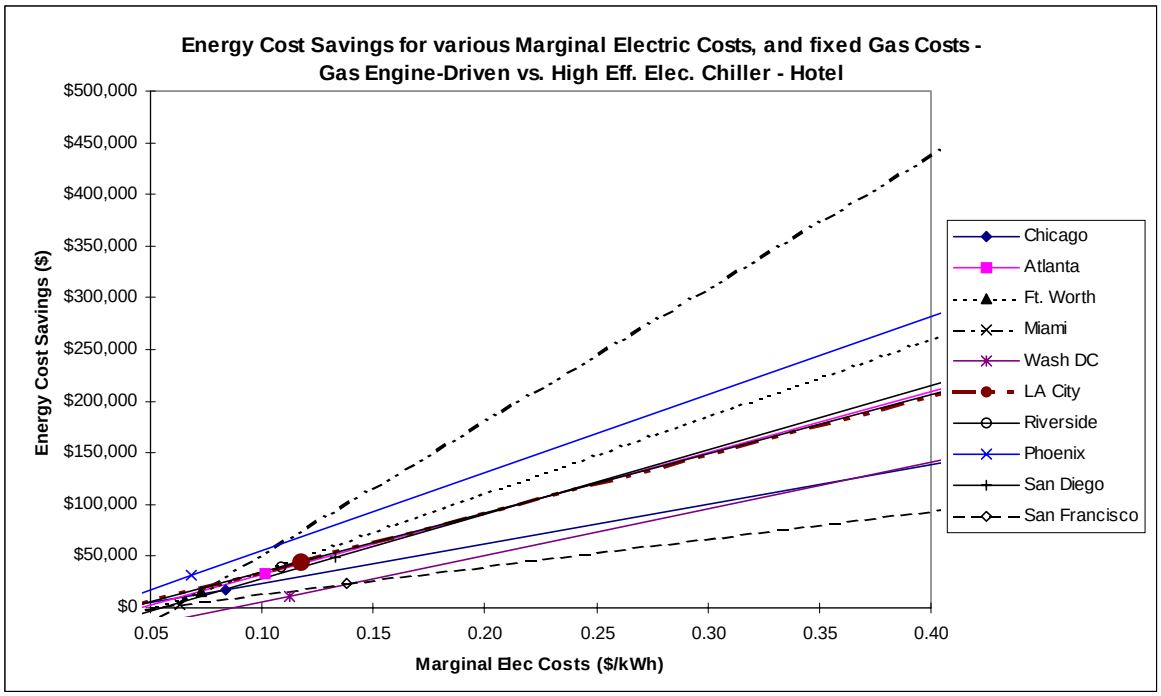
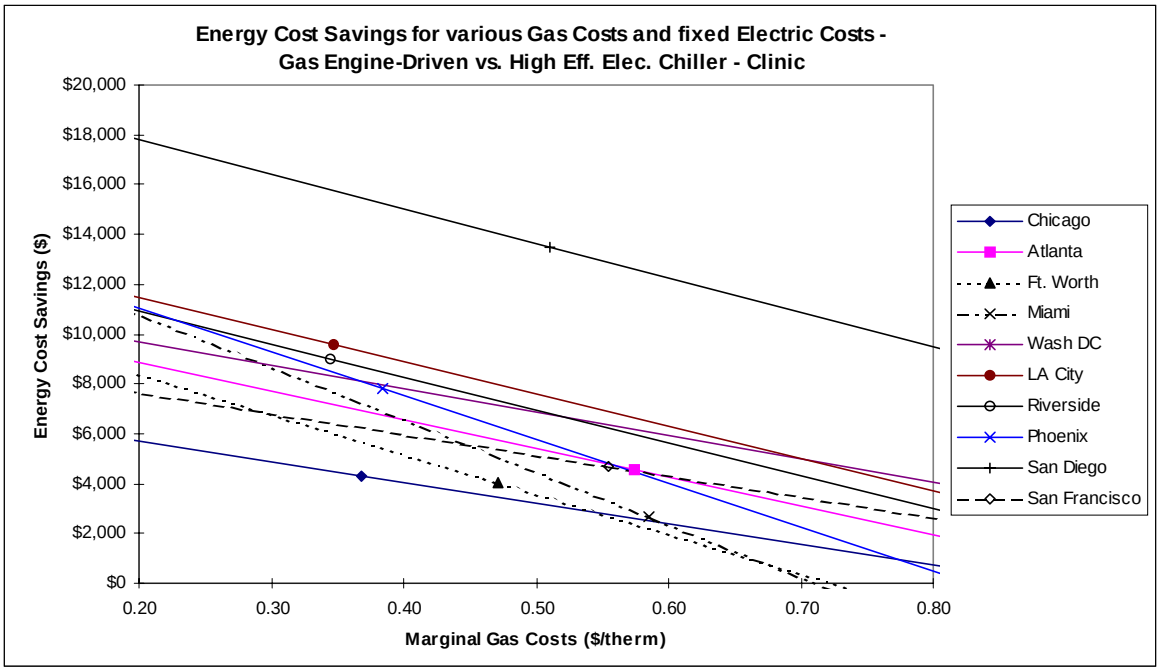


Figure 24 - Energy Cost Savings for Gas Engine-Driven vs. High Efficiency Chiller for Hotel



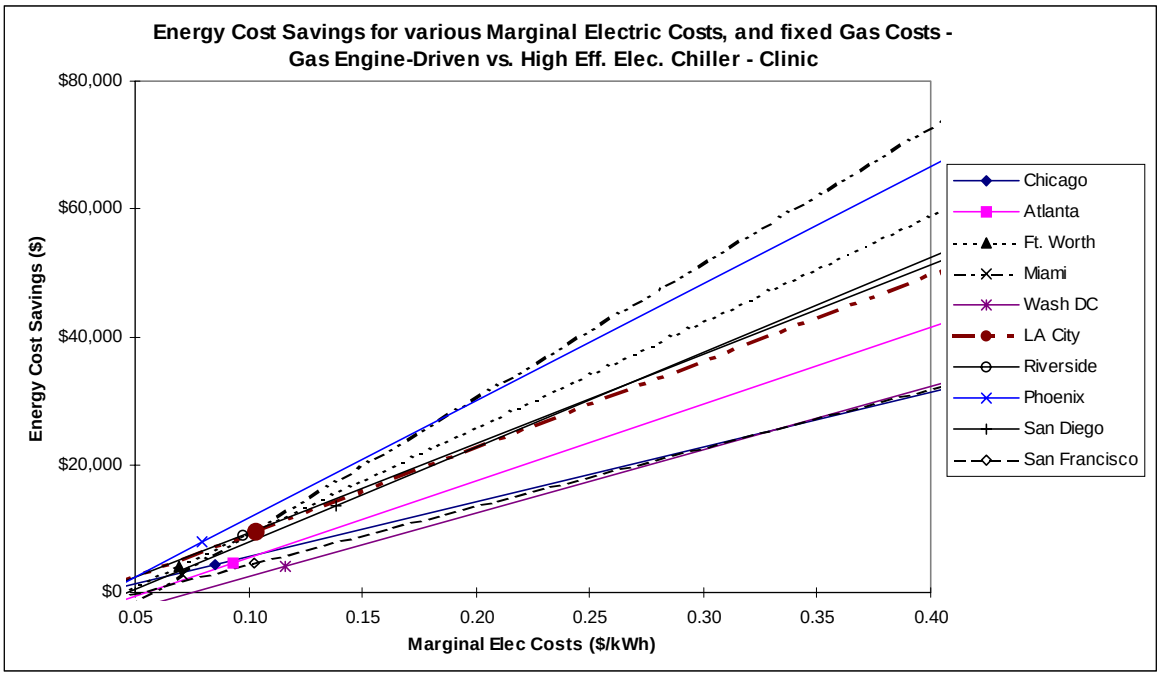
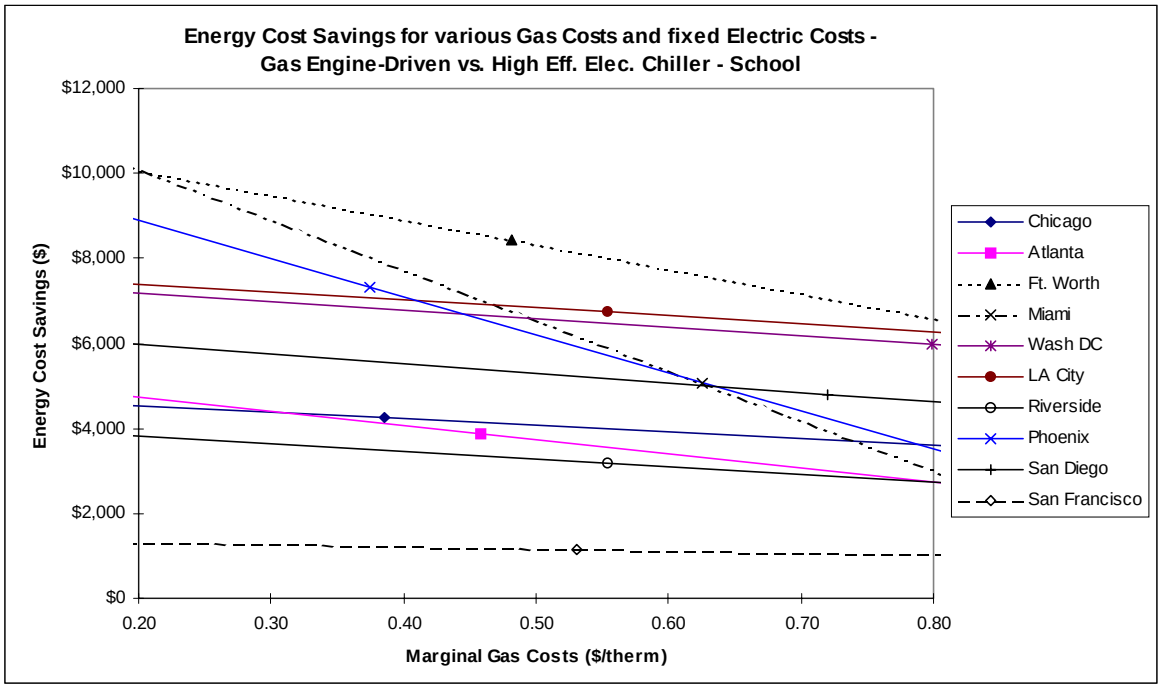


Figure 25 - Energy Cost Savings for Gas Engine-Driven vs. High Efficiency Chiller for Clinic



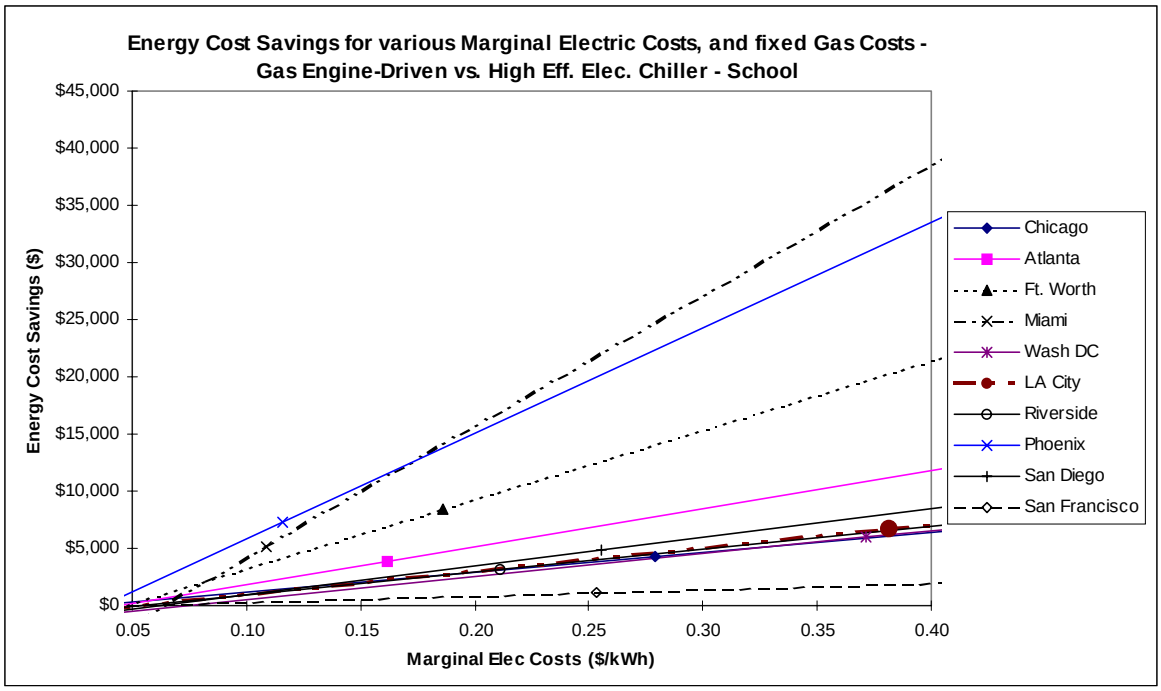
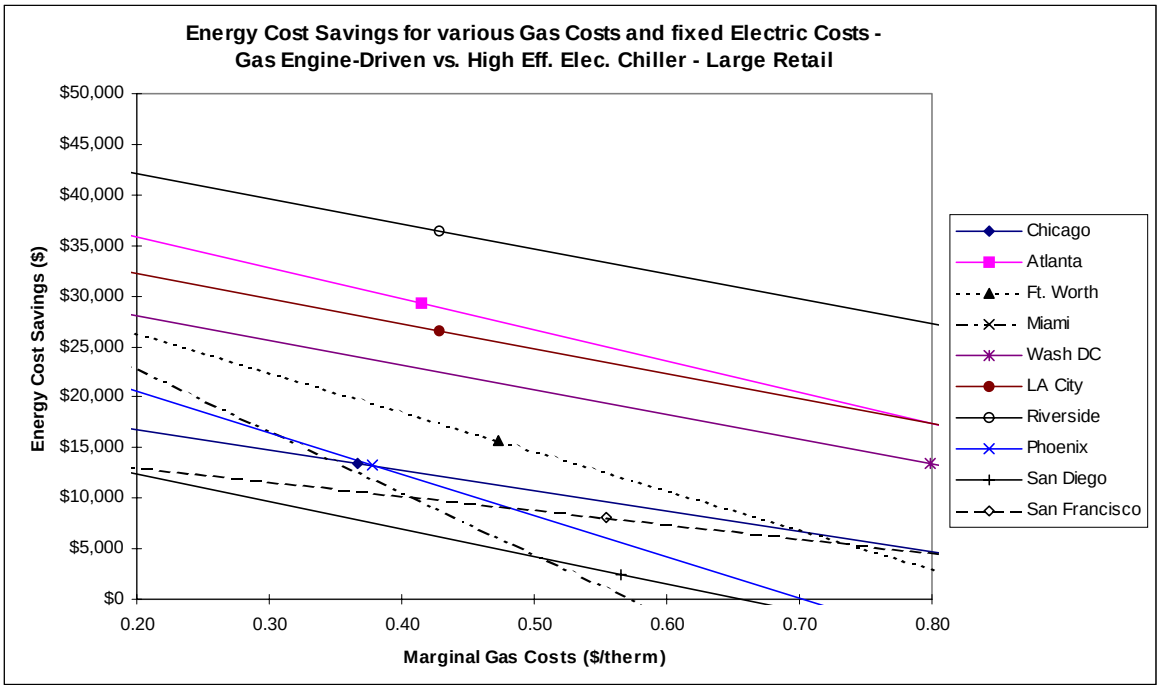


Figure 26 - Energy Cost Savings for Gas Engine-Driven vs. High Efficiency Chiller for School



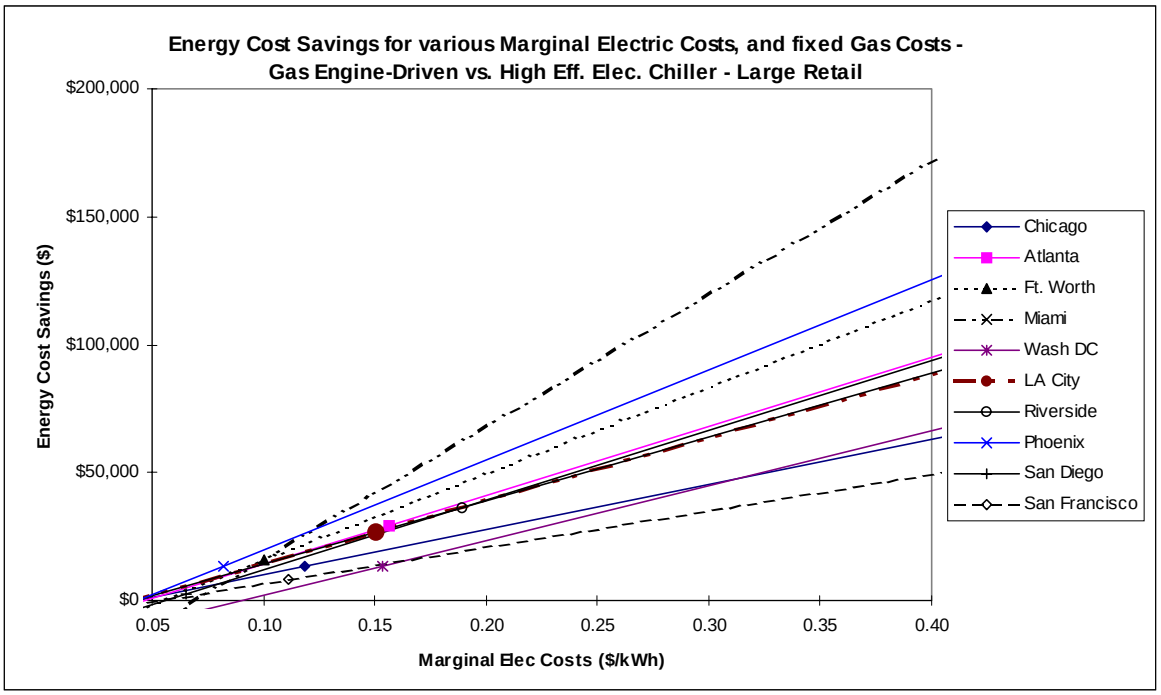


Figure 27 - Energy Cost Savings for Gas Engine-Driven vs. High Efficiency Chiller for Large Retail

Gas Engine-Driven Chiller vs. Single Effect Absorption Chiller

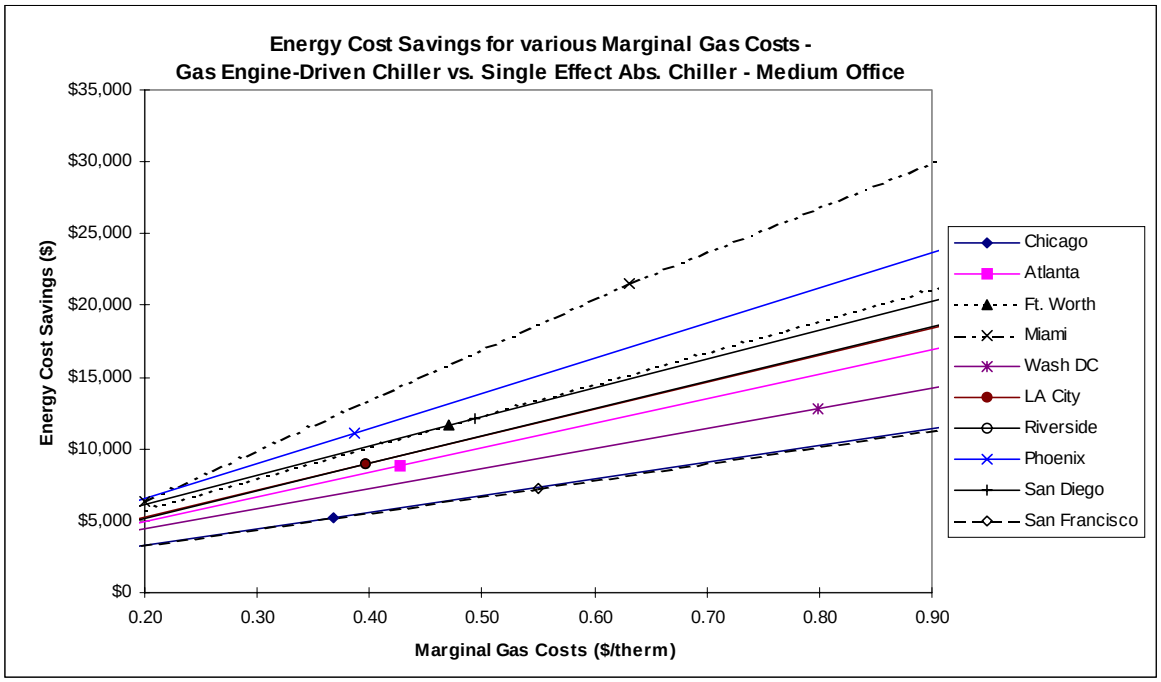


Figure 28-– Energy Cost Savings for Gas Engine-Driven vs Absorption Chiller for Medium Office

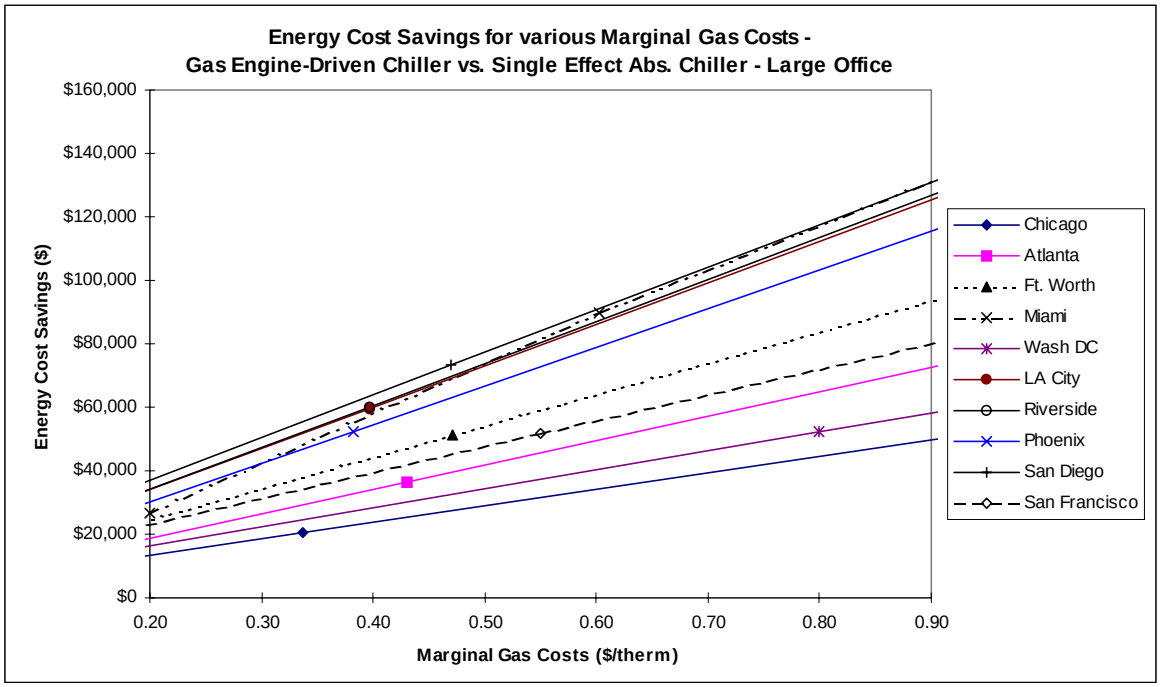


Figure 29 - Energy Cost Savings for Gas Engine-Driven vs Absorption Chiller for Large Office

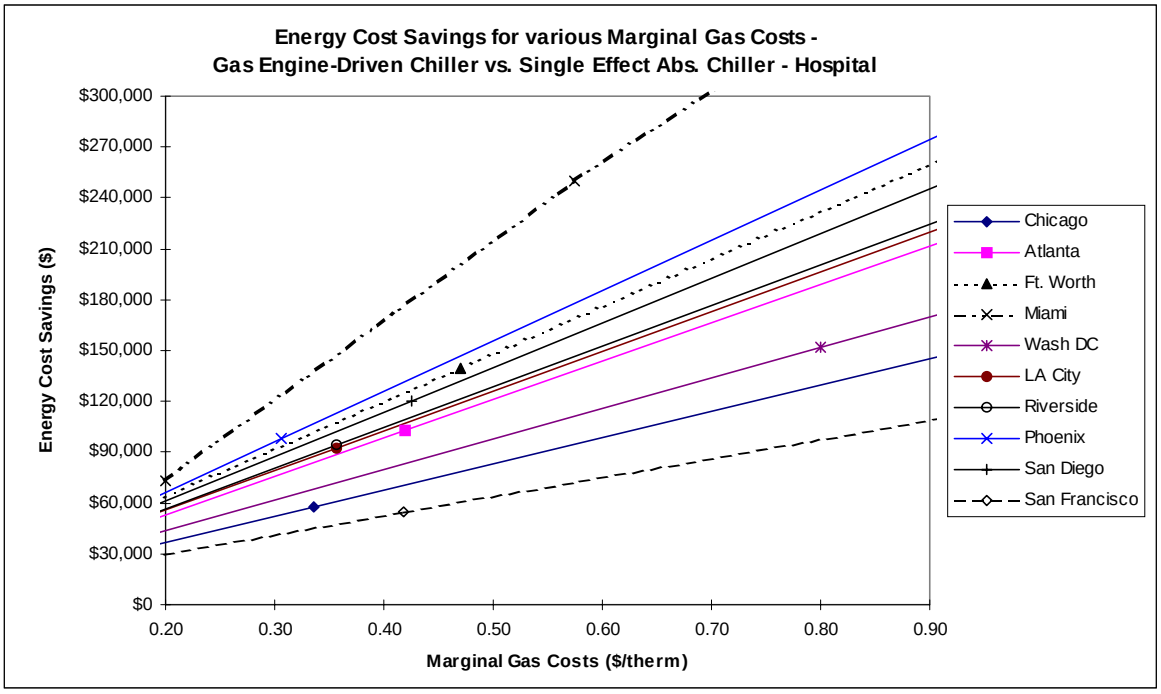


Figure 30 - Energy Cost Savings for Gas Engine-Driven vs. Absorption Chiller for Hospital

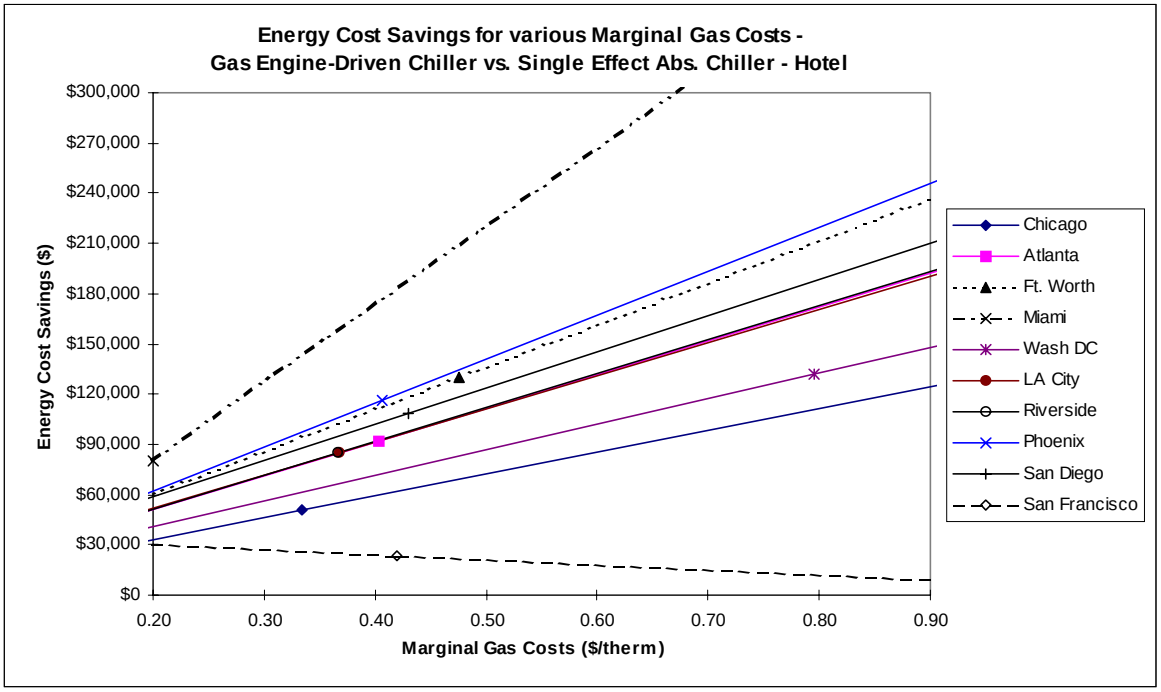


Figure 31 - Energy Cost Savings for Gas Engine-Driven vs. Absorption Chiller for Hotel

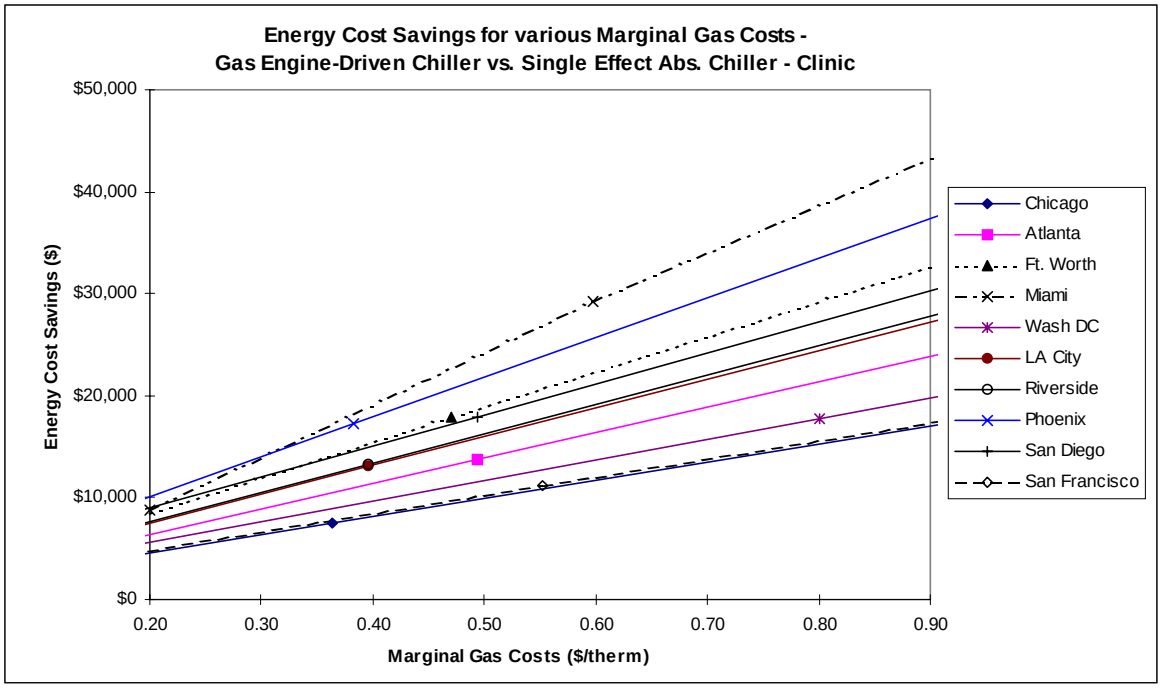


Figure 32 - Energy Cost Savings for Gas Engine-Driven vs. Absorption Chiller for Clinic

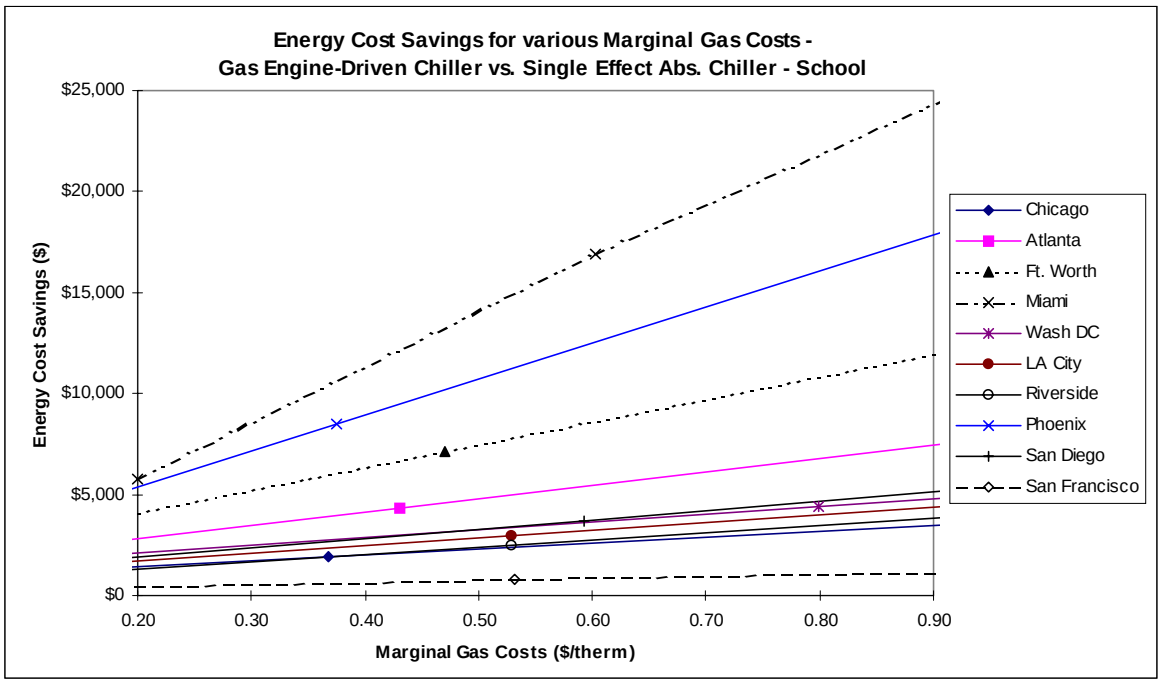


Figure 33 - Energy Cost Savings for Gas Engine-Driven vs. Absorption Chiller for School

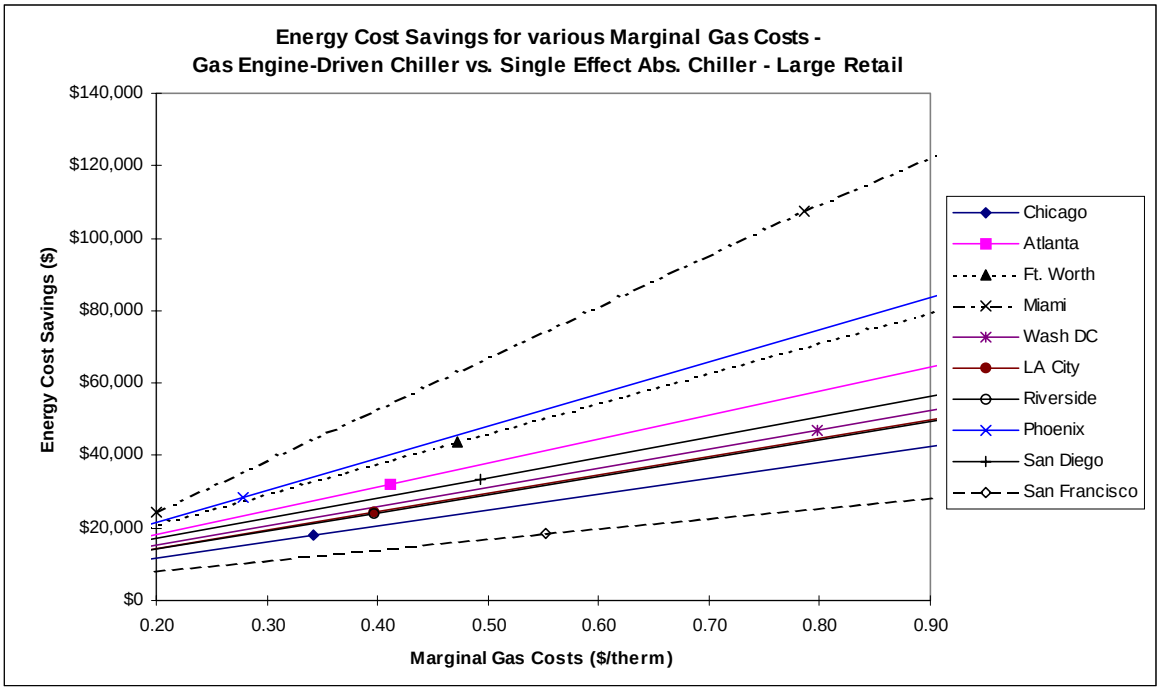


Figure 34 - Energy Cost Savings for Gas Engine-Driven vs. Absorption Chiller for Large Retail

C. Cost Effectiveness Graphs

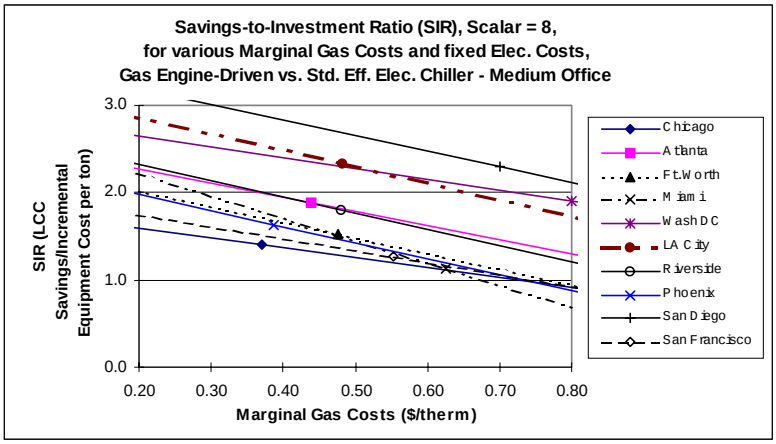
Gas Engine-Driven Chiller vs. Standard Efficiency Electric Chiller

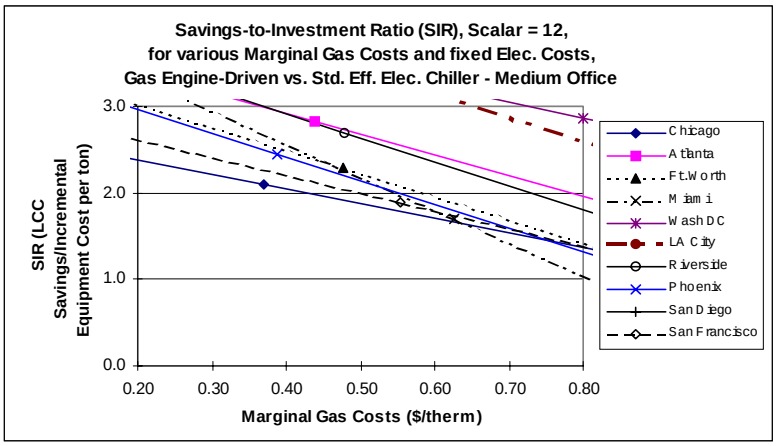
Bldg. Type	Location	Marg. Utility Rate		Scalar		
		Gas Rate	Elec.Rate	8	12	16
Medium Office	Chicago	0.37	0.13	1.40	2.10	2.80
	Atlanta	0.44	0.13	1.88	2.82	3.76
	Ft. Worth	0.48	0.11	1.53	2.29	3.06
	Miami	0.63	0.09	1.13	1.70	2.27
	Washington DC	0.80	0.19	1.91	2.87	3.82
	LA City	0.48	0.14	2.33	3.49	4.65
	Riverside	0.48	0.12	1.80	2.70	3.59
	Phoenix	0.39	0.11	1.63	2.45	3.26
	San Diego	0.70	0.16	2.29	3.44	4.59
	San Francisco	0.55	0.11	1.26	1.89	2.53
Large Office	Chicago	0.36	0.11	3.83	5.74	7.65
	Atlanta	0.45	0.14	6.56	9.84	13.13
	Ft. Worth	0.47	0.10	3.93	5.89	7.85
	Miami	0.60	0.08	2.12	3.19	4.25
	Washington DC	0.80	0.15	4.02	6.03	8.04
	LA City	0.33	0.14	13.63	20.44	27.25
	Riverside	0.33	0.13	12.16	18.24	24.32
	Phoenix	0.38	0.08	3.73	5.59	7.45
	San Diego	0.49	0.15	12.00	18.00	23.99
	San Francisco	0.55	0.15	9.27	13.91	18.55
Hospital	Chicago	0.34	0.13	15.31	22.97	30.62
	Atlanta	0.42	0.07	5.96	8.95	11.93
	Ft. Worth	0.47	0.06	3.63	5.44	7.26
	Miami	0.52	0.06	2.62	3.93	5.24
	Washington DC	0.80	0.10	2.78	4.17	5.56
	LA City	0.33	0.09	15.39	23.08	30.77
	Riverside	0.34	0.09	13.60	20.40	27.20
	Phoenix	0.31	0.07	8.71	13.06	17.42
	San Diego	0.43	0.11	16.22	24.32	32.43
	San Francisco	0.42	0.13	11.28	16.93	22.57

Figure 35 - SIR for Gas Engine-Driven vs. Std. Eff. Elec. Chillers

Bldg. Type	Location	Marg. Utility Rate		Scalar		
		Gas Rate	Elec.Rate	8	12	16
Hotel	Chicago	0.34	0.12	8.05	12.08	16.11
	Atlanta	0.42	0.10	8.48	12.72	16.96
	Ft. Worth	0.48	0.07	4.58	6.88	9.17
	Miami	0.57	0.06	2.94	4.41	5.87
	Washington DC	0.80	0.11	3.81	5.71	7.62
	LA City	0.36	0.12	11.60	17.40	23.20
	Riverside	0.36	0.11	10.22	15.33	20.43
	Phoenix	0.25	0.07	6.25	9.37	12.50
	San Diego	0.49	0.13	11.47	17.20	22.94
	San Francisco	0.42	0.14	7.35	11.02	14.69
Medical Clinic	Chicago	0.37	0.09	1.18	1.77	2.37
	Atlanta	0.57	0.09	1.34	2.01	2.68
	Ft. Worth	0.47	0.07	1.11	1.66	2.21
	Miami	0.58	0.07	0.97	1.45	1.93
	Washington DC	0.80	0.12	1.18	1.77	2.36
	LA City	0.35	0.10	2.67	4.01	5.35
	Riverside	0.34	0.10	2.45	3.68	4.90
	Phoenix	0.38	0.08	1.70	2.54	3.39
	San Diego	0.51	0.14	3.30	4.95	6.60
	San Francisco	0.55	0.10	1.61	2.42	3.22
School	Chicago	0.39	0.28	1.07	1.61	2.15
	Atlanta	0.46	0.15	0.90	1.35	1.80
	Ft. Worth	0.48	0.19	1.85	2.78	3.70
	Miami	0.63	0.11	1.31	1.97	2.62
	Washington DC	0.80	0.37	1.41	2.11	2.82
	LA City	0.55	0.38	1.81	2.71	3.61
	Riverside	0.55	0.21	0.85	1.28	1.70
	Phoenix	0.37	0.12	1.53	2.29	3.06
	San Diego	0.72	0.26	1.15	1.72	2.29
	San Francisco	0.53	0.25	0.36	0.54	0.72
Large Retail	Chicago	0.37	0.12	3.58	5.36	7.15
	Atlanta	0.42	0.16	7.32	10.98	14.64
	Ft. Worth	0.47	0.10	3.96	5.94	7.92
	Miami	0.60	0.07	1.04	1.57	2.09
	Washington DC	0.80	0.15	3.69	5.53	7.38
	LA City	0.43	0.15	7.06	10.59	14.12
	Riverside	0.43	0.17	8.56	12.84	17.12
	Phoenix	0.38	0.08	3.05	4.57	6.09
	San Diego	0.57	0.08	1.88	2.82	3.76
	San Francisco	0.55	0.11	2.76	4.14	5.51

Figure 35 (continued) - SIR for Gas Engine-Driven vs. Std. Eff. Elec. Chillers





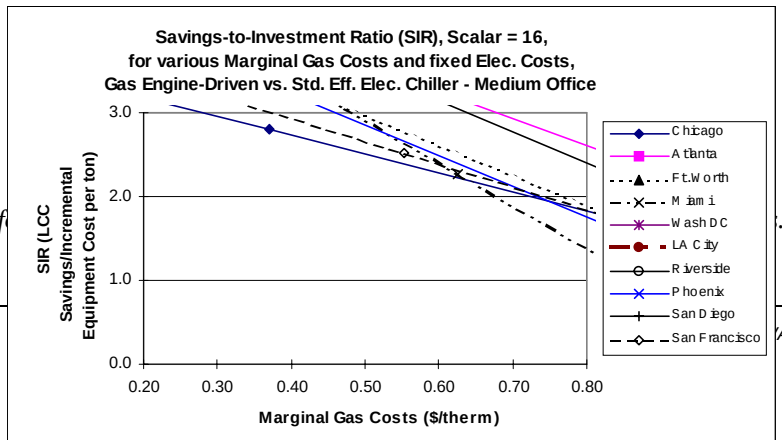
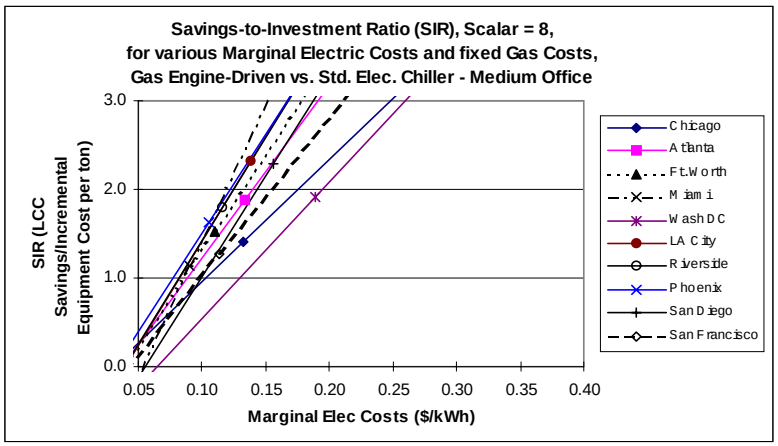
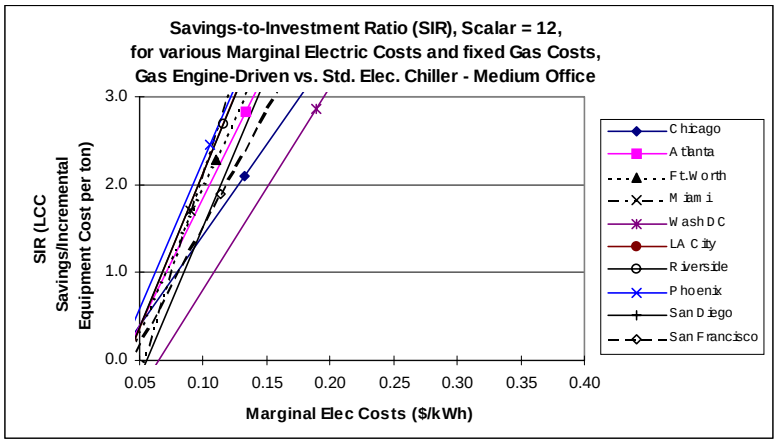


Figure 36 - SIR f . Std. Eff. Chiller





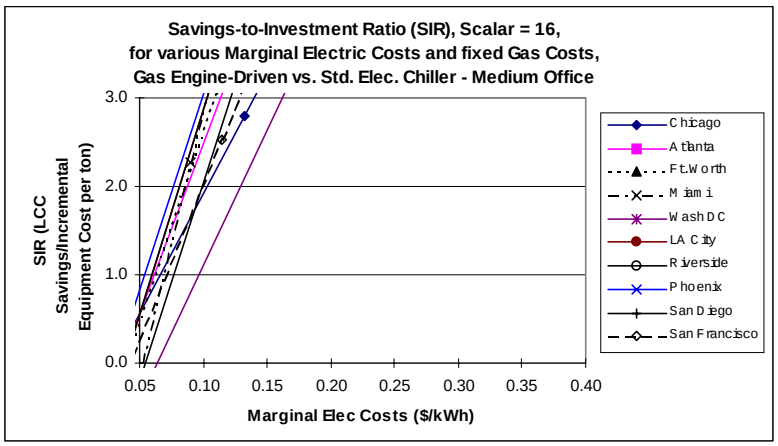
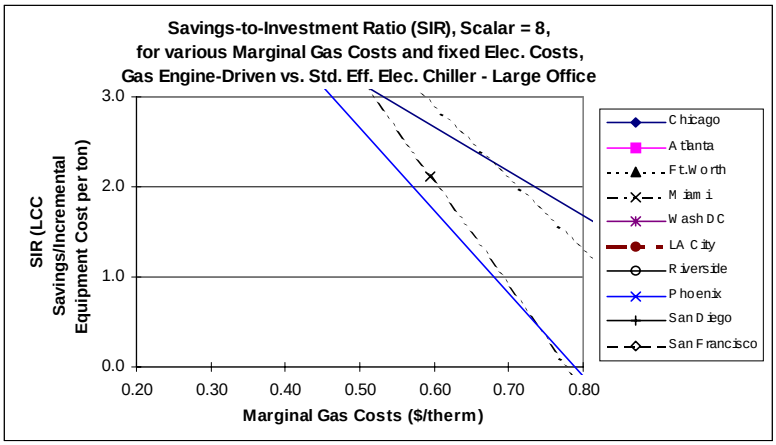
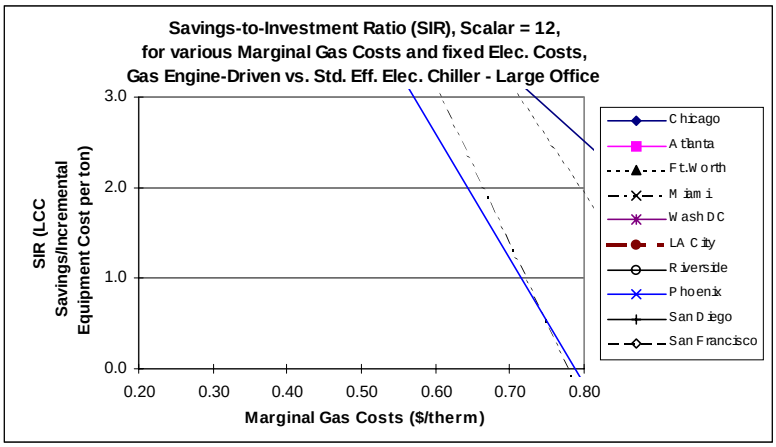


Figure 37 - SIR for various marginal electric costs for Medium Office, Gas Engine-Driven vs. Std. Eff. Chiller





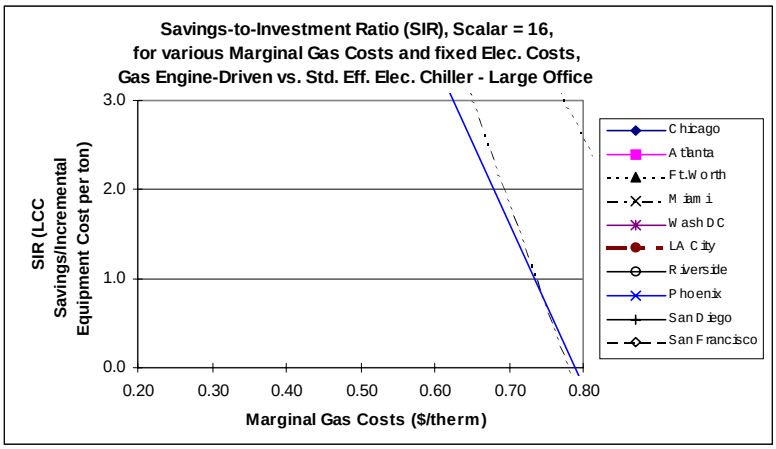
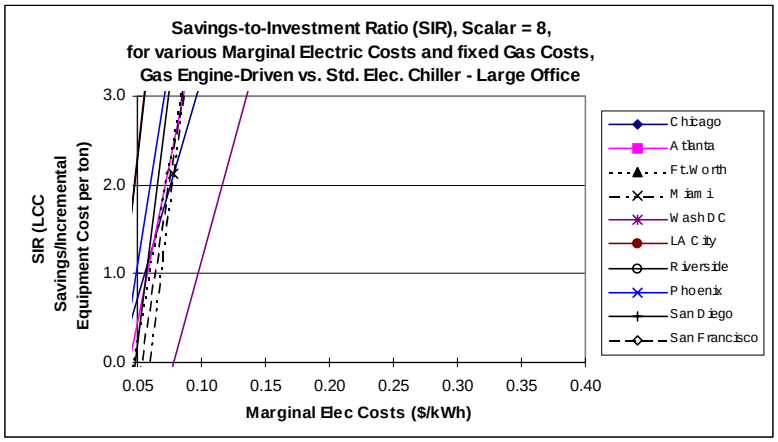
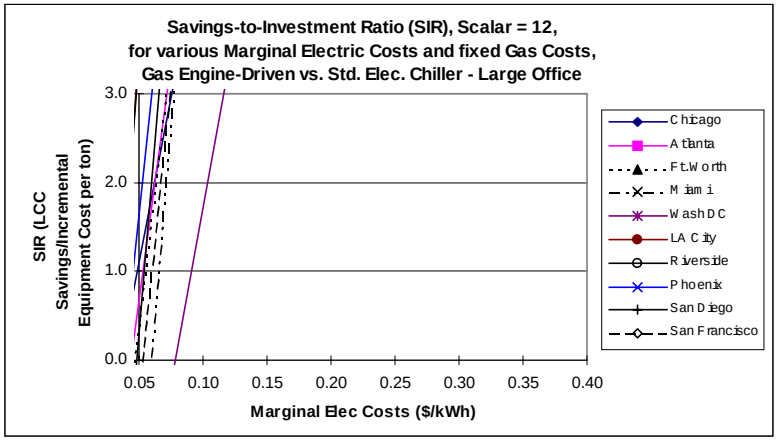


Figure 38 - SIR for various marginal gas costs for Large Office, Gas Engine-Driven vs. Std. Eff. Chiller





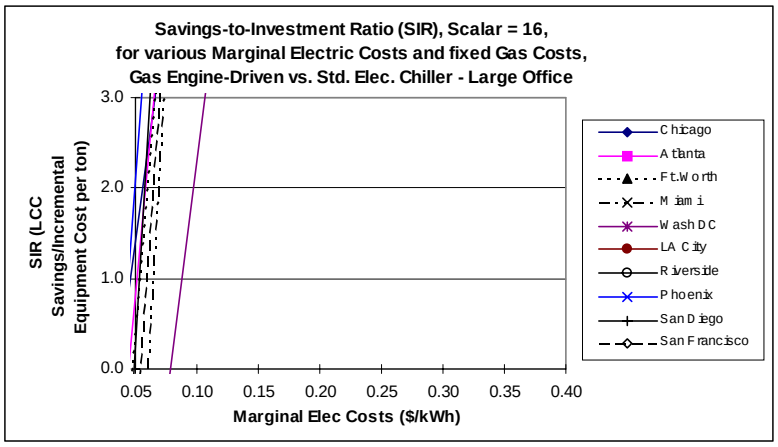
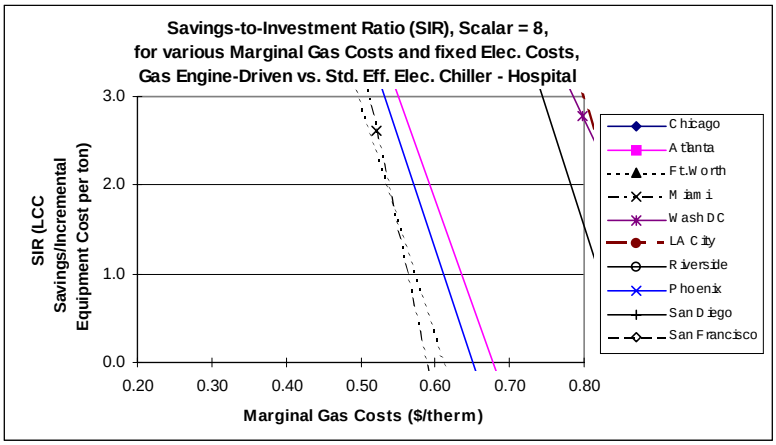
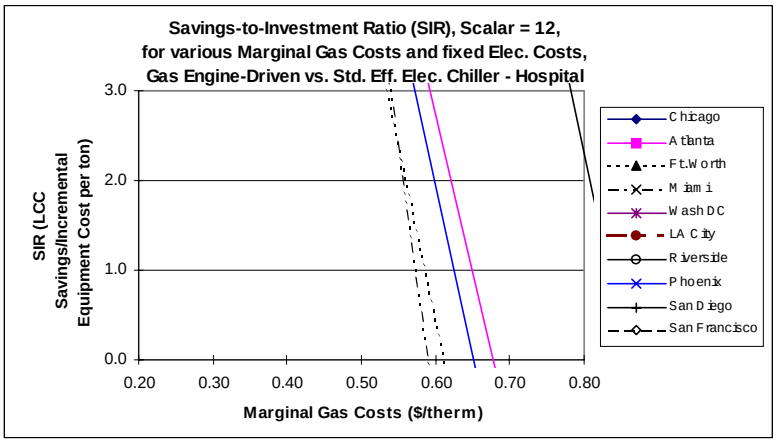


Figure 39 - SIR for various marginal electric costs for Large Office, Gas Engine-Driven vs. Std. Eff. Chiller





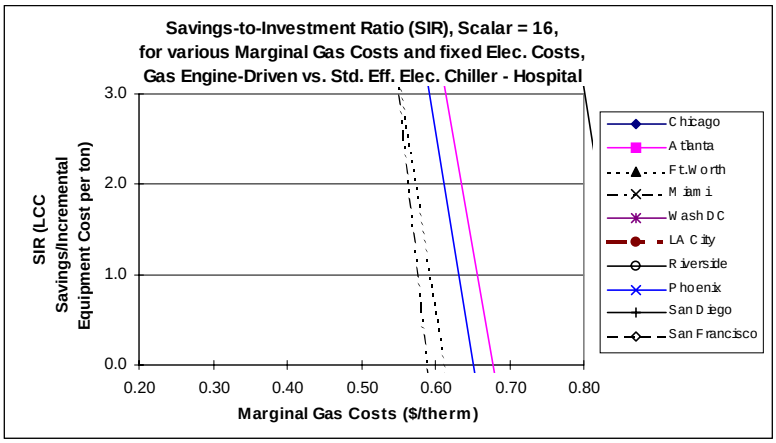
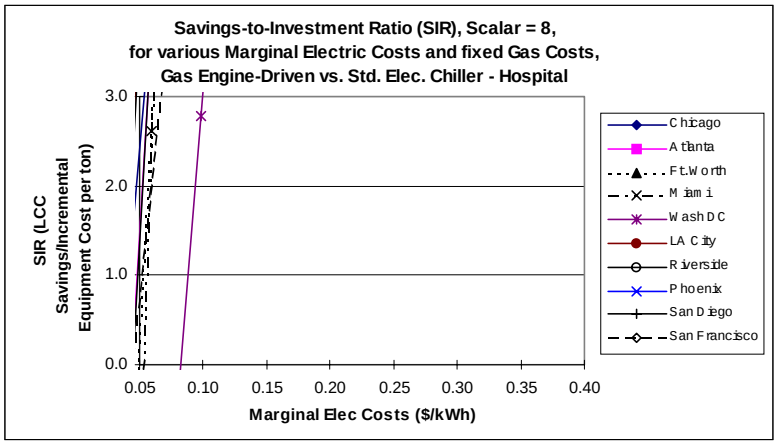
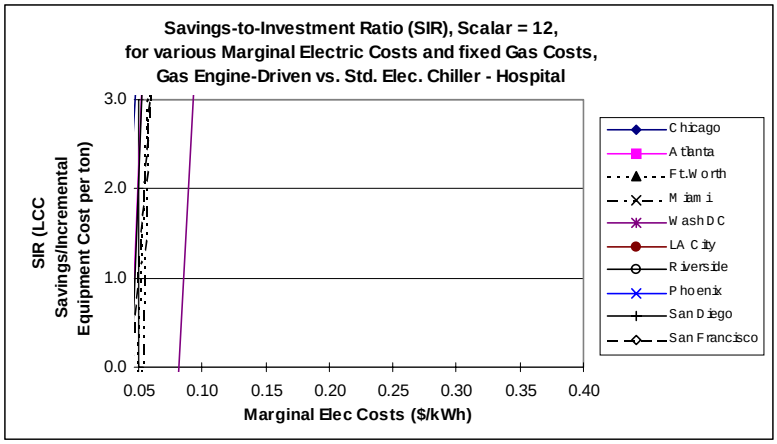


Figure 40 - SIR for various marginal gas costs for Hospital, Gas Engine-Driven vs. Std. Eff. Chiller





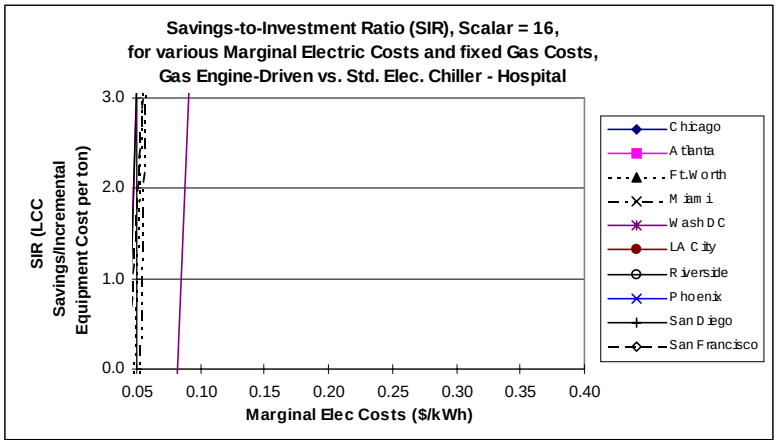
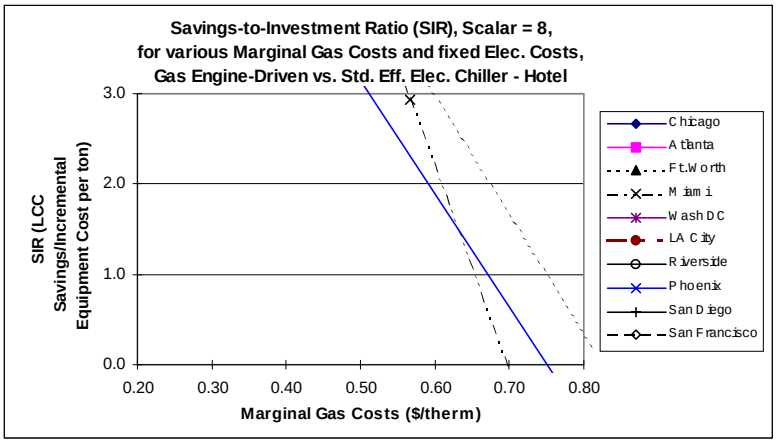
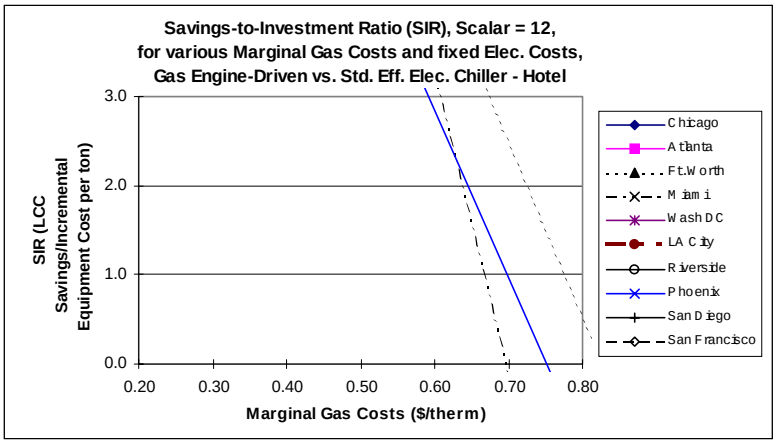


Figure 41 - SIR for various marginal electric costs for Hospital, Gas Engine-Driven vs. Std. Eff. Chiller





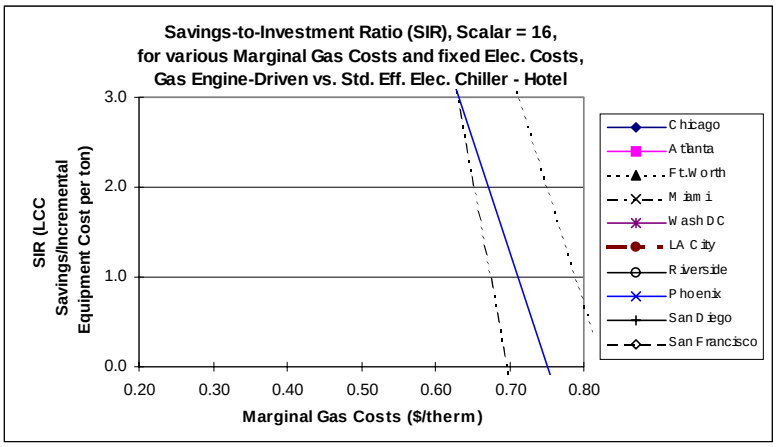
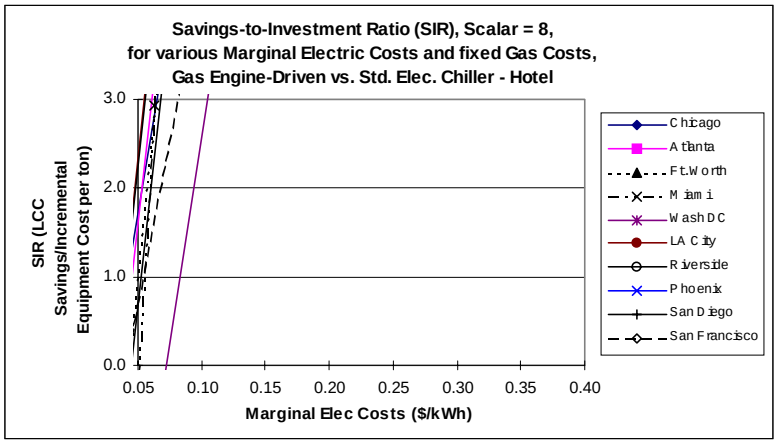
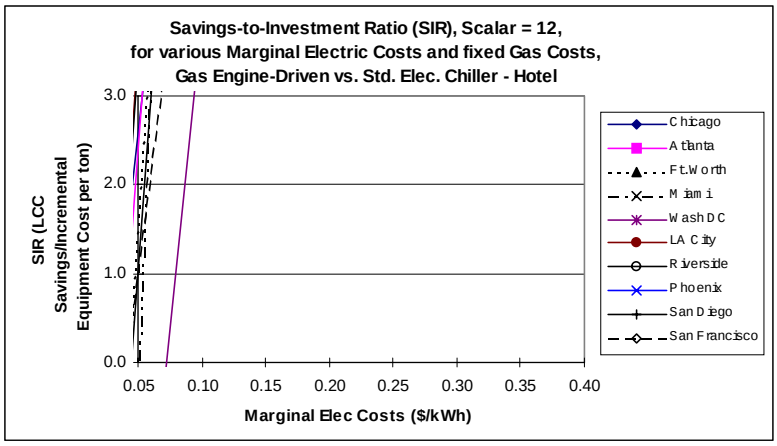


Figure 42 - SIR for various marginal gas costs for Hotel, Gas Engine-Driven vs. Std. Eff. Chiller





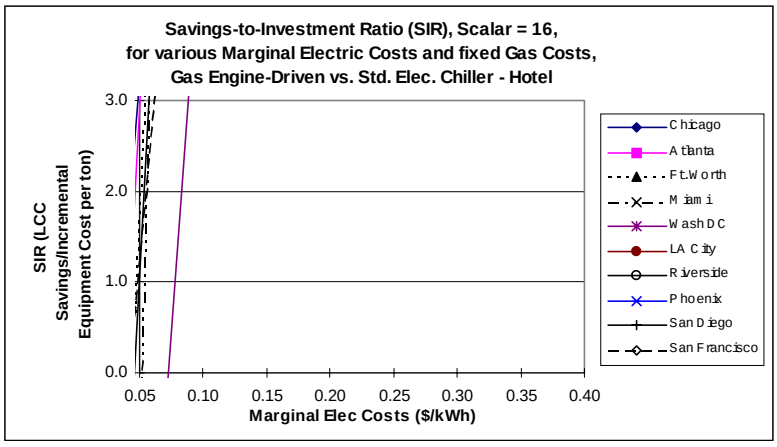
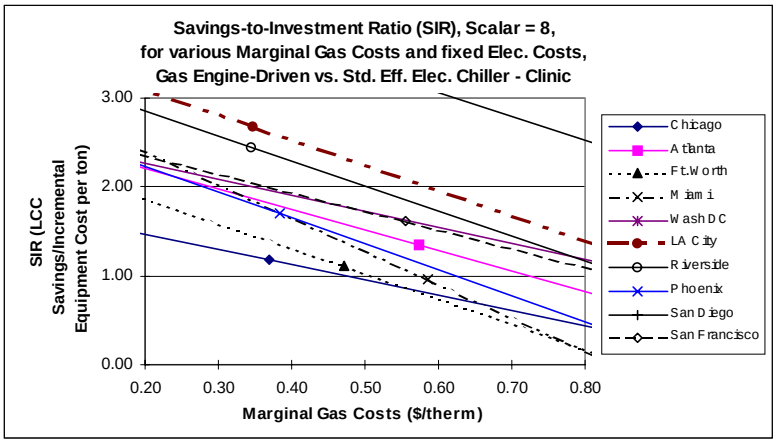
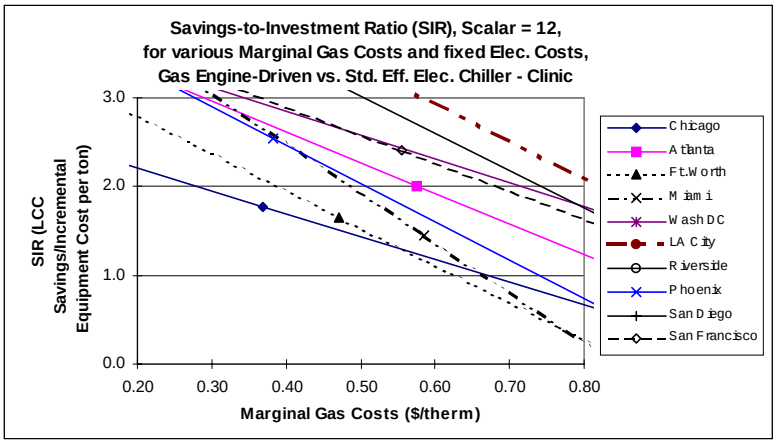


Figure 43 - SIR for various marginal electric costs for Hotel, Gas Engine-Driven vs. Std. Eff. Chiller





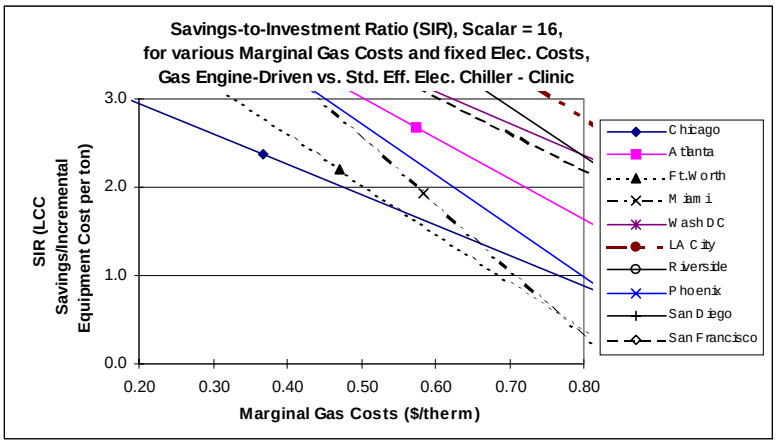
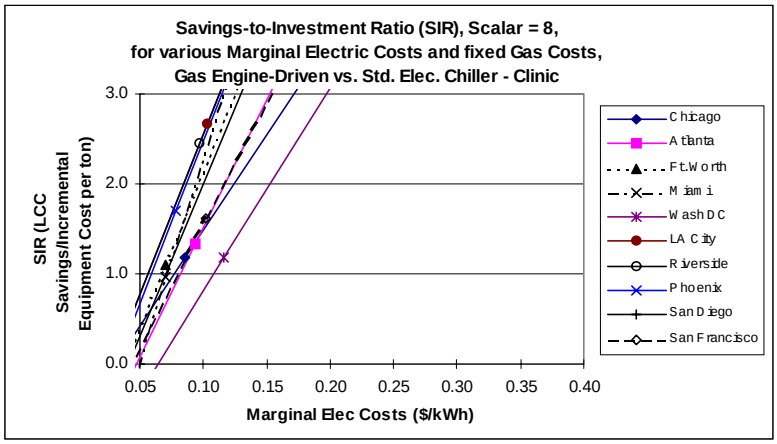
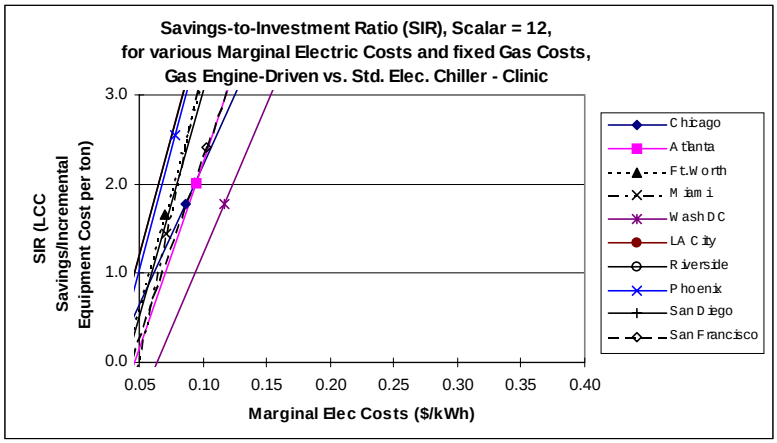


Figure 44 - SIR for various marginal gas costs for Clinic, Gas Engine-Driven vs. Std. Eff. Chiller





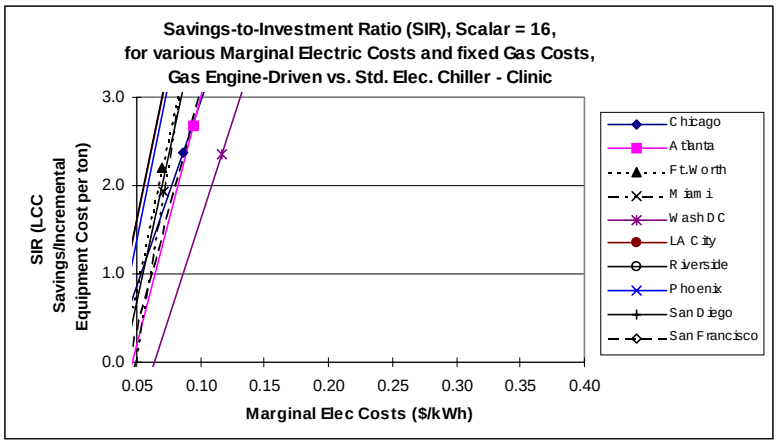
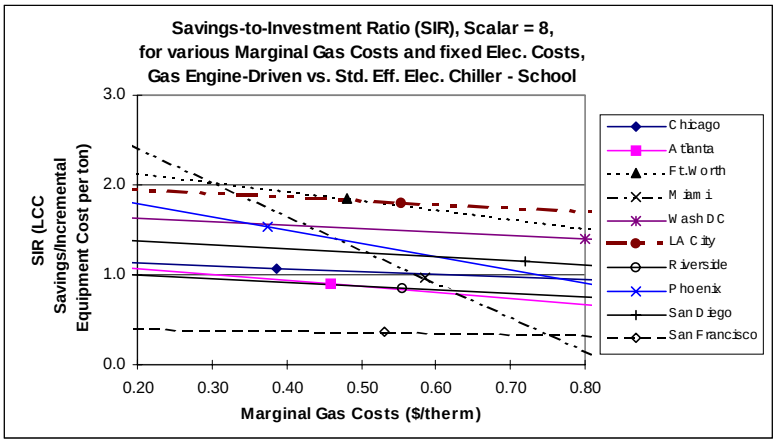
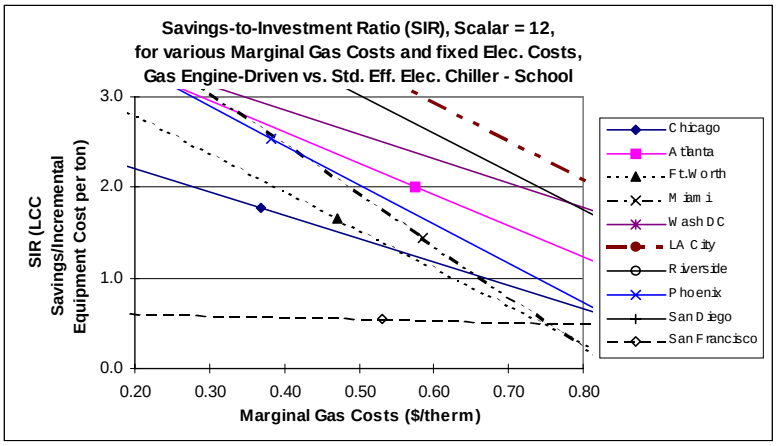


Figure 45 - SIR for various marginal electric costs for Clinic, Gas Engine-Driven vs. Std. Eff. Chiller





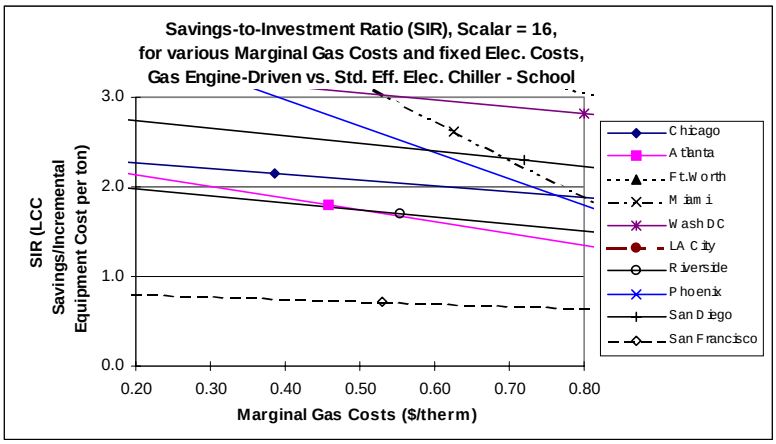
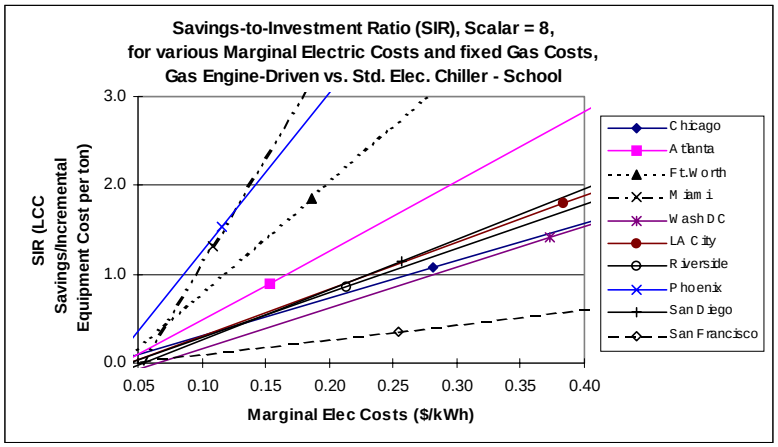
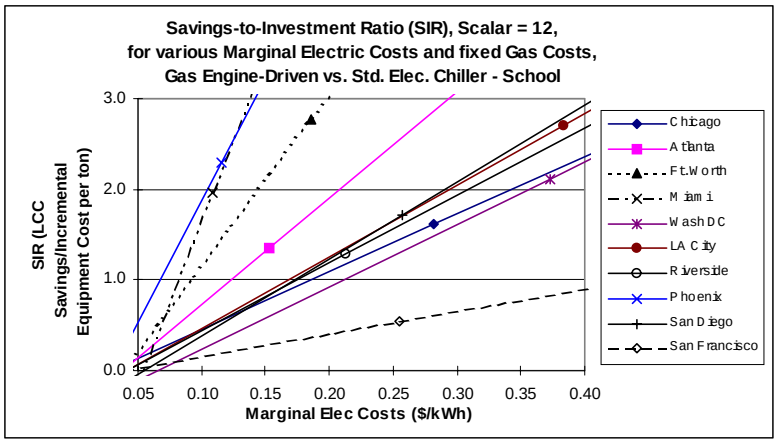


Figure 46 - SIR for various marginal gas costs for School, Gas Engine-Driven vs. Std. Eff. Chiller





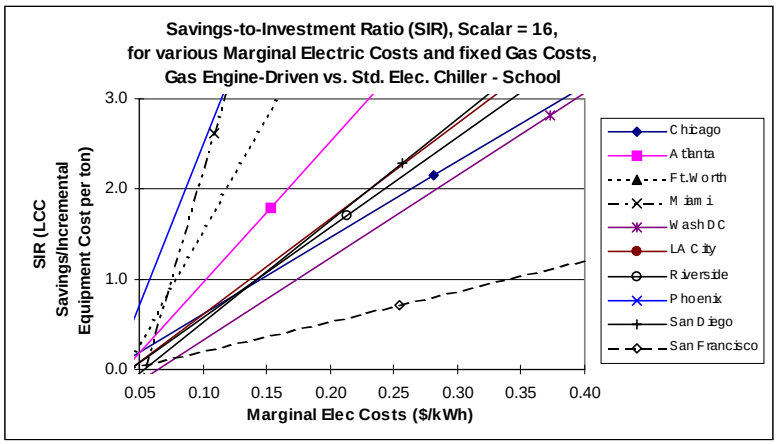
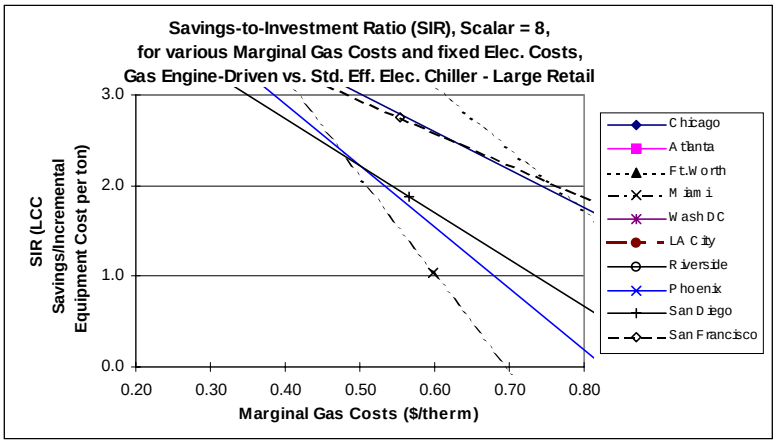
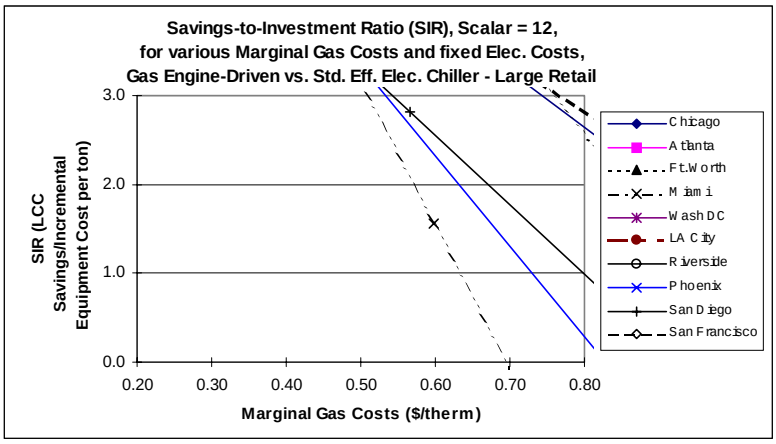


Figure 47 - SIR for various marginal electric costs for School, Gas Engine-Driven vs. Std. Eff. Chiller





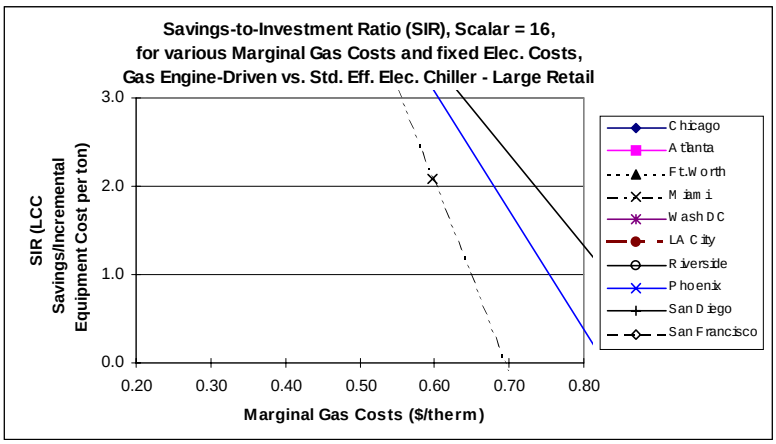
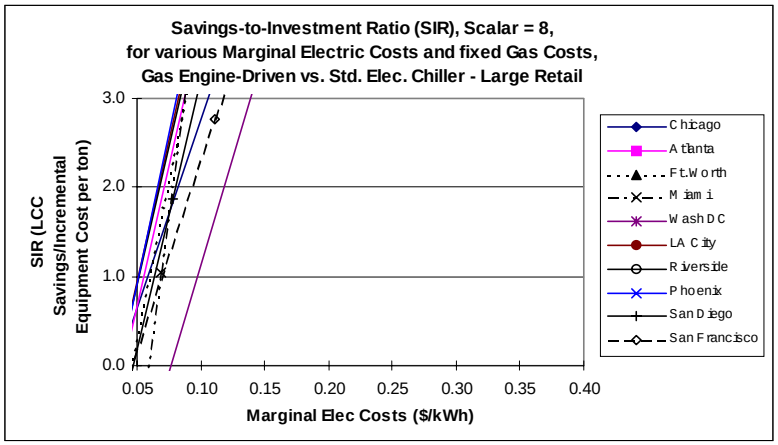
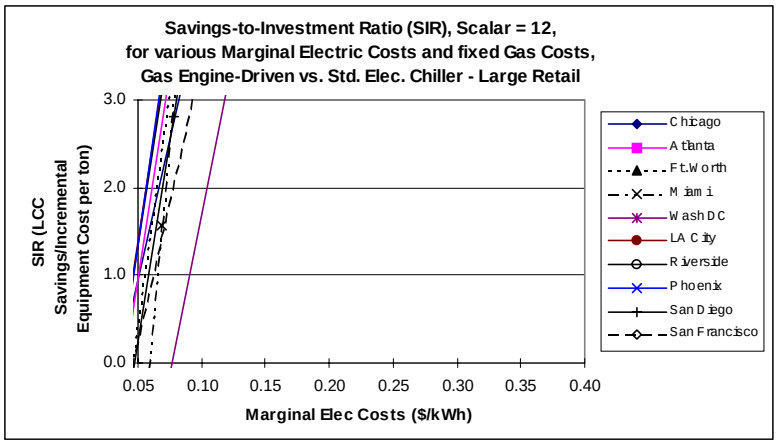


Figure 48 - SIR for various marginal gas costs for Large Retail, Gas Engine-Driven vs. Std. Eff. Chiller





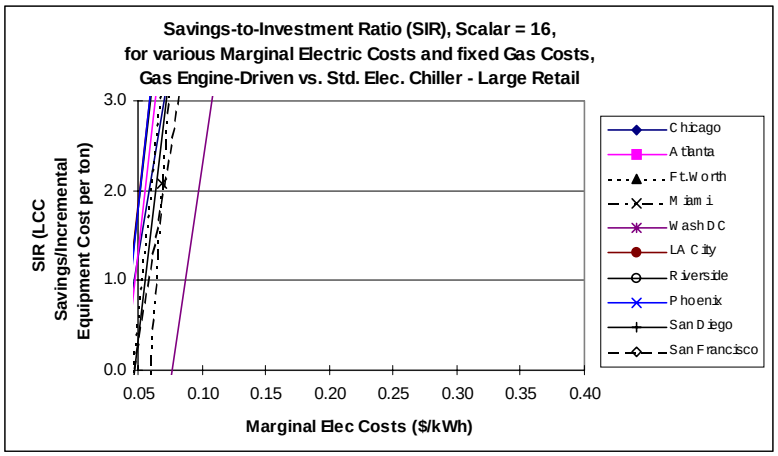


Figure 49 - SIR for various marginal electric costs for Large Retail, Gas Engine-Driven vs. Std. Eff. Chiller

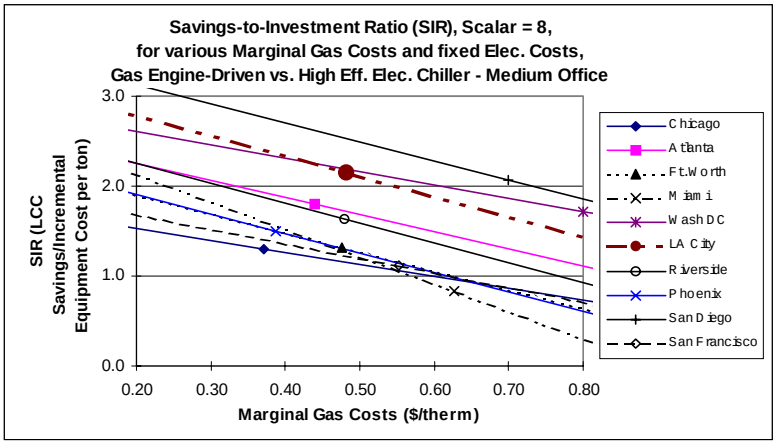
Gas Engine-Driven Chiller vs. High Efficiency Chiller

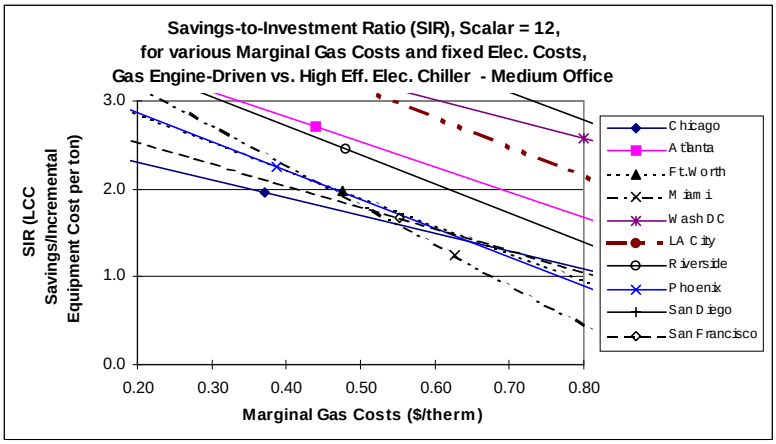
Bldg. Type	Location	Marg. Utility Rate		Scalar		
		Gas Rate	Elec.Rate	8	12	16
Medium Office	Chicago	0.37	0.13	1.30	1.95	2.61
	Atlanta	0.44	0.14	1.80	2.70	3.61
	Ft. Worth	0.48	0.11	1.32	1.98	2.65
	Miami	0.63	0.09	0.83	1.25	1.66
	Washington DC	0.80	0.19	1.72	2.58	3.44
	Los Angeles	0.48	0.14	2.15	3.22	4.30
	Riverside	0.48	0.12	1.63	2.45	3.27
	Phoenix	0.39	0.11	1.50	2.25	3.01
	San Diego	0.70	0.16	2.07	3.10	4.13
	San Francisco	0.55	0.11	1.11	1.67	2.22
Large Office	Chicago	0.36	0.11	3.44	5.16	6.88
	Atlanta	0.45	0.13	5.89	8.83	11.77
	Ft. Worth	0.47	0.09	3.02	4.53	6.04
	Miami	0.60	0.08	0.80	1.20	1.60
	Washington DC	0.80	0.15	3.20	4.80	6.39
	LA City	0.33	0.14	12.90	19.35	25.80
	Riverside	0.33	0.13	11.44	17.16	22.88
	Phoenix	0.38	0.08	3.08	4.63	6.17
	San Diego	0.49	0.15	11.05	16.57	22.10
	San Francisco	0.55	0.15	8.38	12.57	16.76
Hospital	Chicago	0.34	0.14	15.78	23.68	31.57
	Atlanta	0.42	0.07	4.34	6.51	8.68
	Ft. Worth	0.47	0.06	1.47	2.20	2.93
	Miami	0.52	0.06	-1.06	-1.59	-2.12
	Washington DC	0.80	0.10	0.24	0.35	0.47
	LA City	0.33	0.09	13.96	20.94	27.92
	Riverside	0.34	0.09	12.14	18.22	24.29
	Phoenix	0.31	0.07	7.39	11.08	14.77
	San Diego	0.43	0.11	14.34	21.51	28.68
	San Francisco	0.42	0.13	10.34	15.51	20.68

Figure 50 - SIR for Gas Engine-Driven vs. Std. Eff. Elec. Chillers

Bldg. Type	Location	Marg. Utility Rate		Scalar		
		Gas Rate	Elec.Rate	8	12	16
Hotel	Chicago	0.34	0.08	4.59	6.89	9.18
	Atlanta	0.42	0.10	8.11	12.16	16.21
	Ft. Worth	0.48	0.07	3.42	5.13	6.84
	Miami	0.57	0.06	0.59	0.88	1.18
	Washington DC	0.80	0.11	2.75	4.12	5.49
	LA City	0.36	0.12	11.82	17.73	23.64
	Riverside	0.36	0.11	10.26	15.40	20.53
	Phoenix	0.25	0.07	6.30	9.44	12.59
	San Diego	0.49	0.13	11.42	17.13	22.84
	San Francisco	0.42	0.14	7.30	10.94	14.59
Medical Clinic	Chicago	0.37	0.09	1.06	1.60	2.13
	Atlanta	0.57	0.09	1.07	1.61	2.15
	Ft. Worth	0.47	0.07	0.85	1.27	1.70
	Miami	0.58	0.07	0.57	0.85	1.14
	Washington DC	0.80	0.12	0.91	1.37	1.82
	LA City	0.35	0.10	2.50	3.75	5.01
	Riverside	0.34	0.10	2.29	3.43	4.57
	Phoenix	0.38	0.08	1.53	2.30	3.06
	San Diego	0.51	0.14	3.06	4.59	6.11
	San Francisco	0.55	0.10	1.40	2.10	2.80
School	Chicago	0.39	0.28	1.04	1.57	2.09
	Atlanta	0.46	0.16	0.92	1.38	1.84
	Ft. Worth	0.48	0.19	1.77	2.65	3.54
	Miami	0.63	0.11	1.08	1.61	2.15
	Washington DC	0.80	0.37	1.35	2.03	2.71
	LA City	0.55	0.38	1.76	2.65	3.53
	Riverside	0.55	0.21	0.81	1.21	1.62
	Phoenix	0.37	0.12	1.43	2.15	2.87
	San Diego	0.72	0.26	1.09	1.63	2.18
	San Francisco	0.53	0.25	0.35	0.52	0.69
Large Retail	Chicago	0.37	0.12	3.32	4.97	6.63
	Atlanta	0.42	0.16	6.92	10.38	13.84
	Ft. Worth	0.47	0.10	3.30	4.94	6.59
	Miami	0.60	0.07	-0.30	-0.44	-0.59
	Washington DC	0.80	0.15	3.04	4.55	6.07
	LA City	0.43	0.15	6.95	10.43	13.90
	Riverside	0.43	0.19	9.23	13.85	18.47
	Phoenix	0.38	0.08	2.61	3.91	5.21
	San Diego	0.57	0.07	0.56	0.84	1.13
	San Francisco	0.55	0.11	2.41	3.61	4.81

Figure 50 (continued) - SIR for Gas Engine-Driven vs. Std. Eff. Elec. Chillers





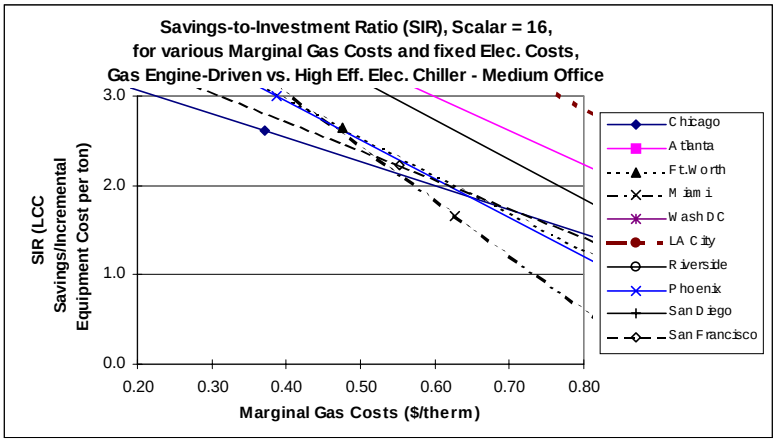
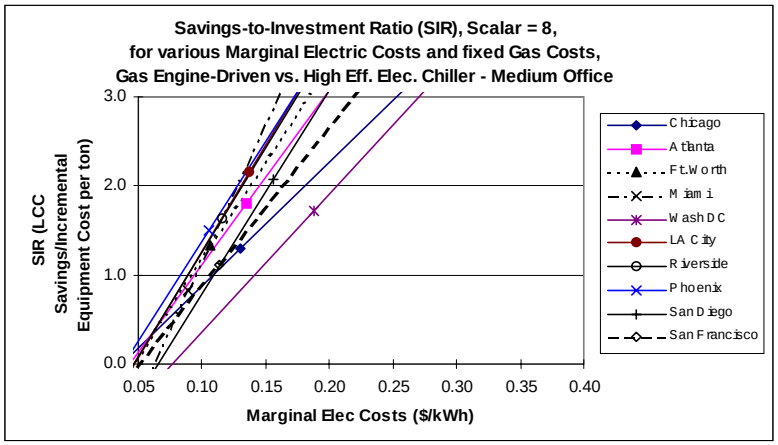
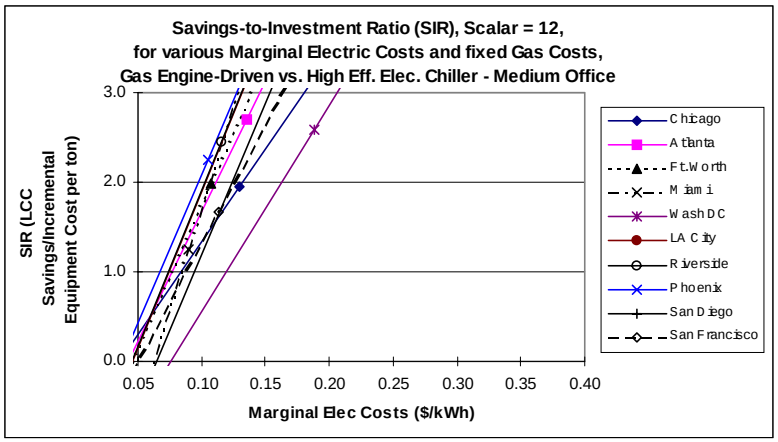


Figure 51 - SIR for various marginal gas costs for Medium Office, Gas Engine-Driven vs. High Eff. Chiller





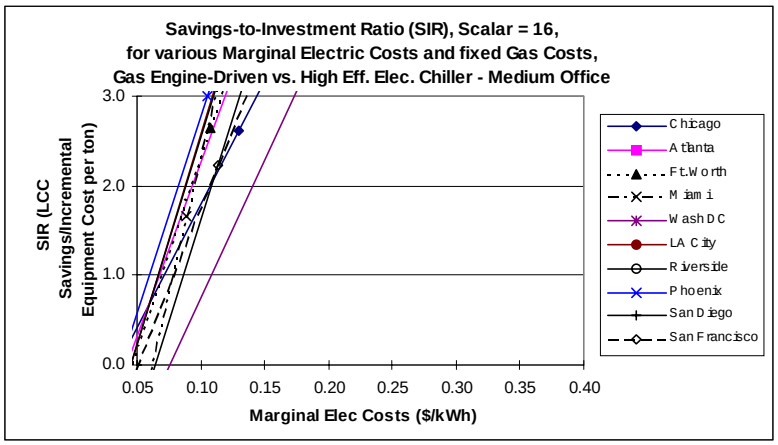
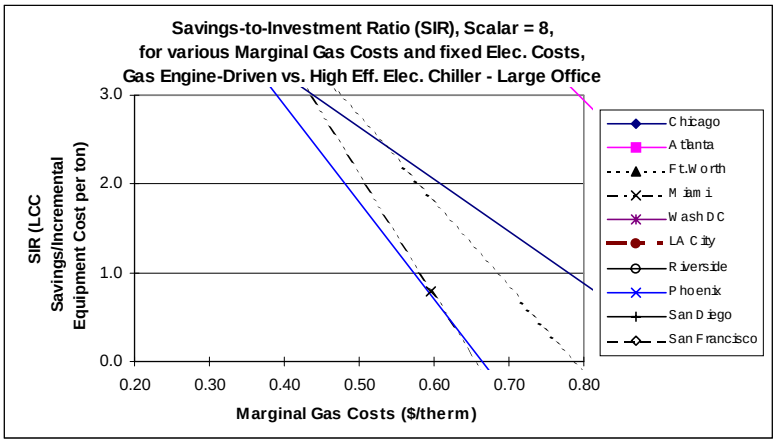
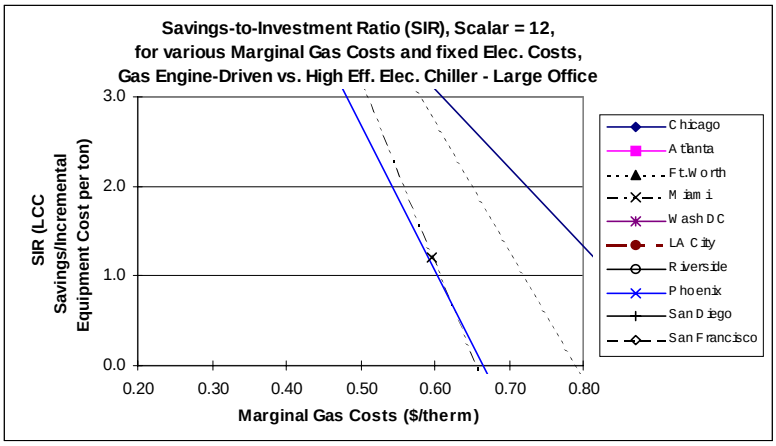


Figure 52 - SIR for various marginal electric costs for Medium Office, Gas Engine-Driven vs. High Eff. Chiller





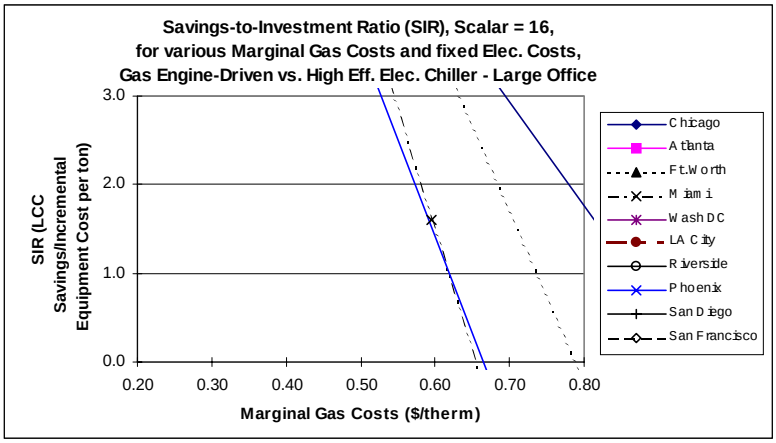
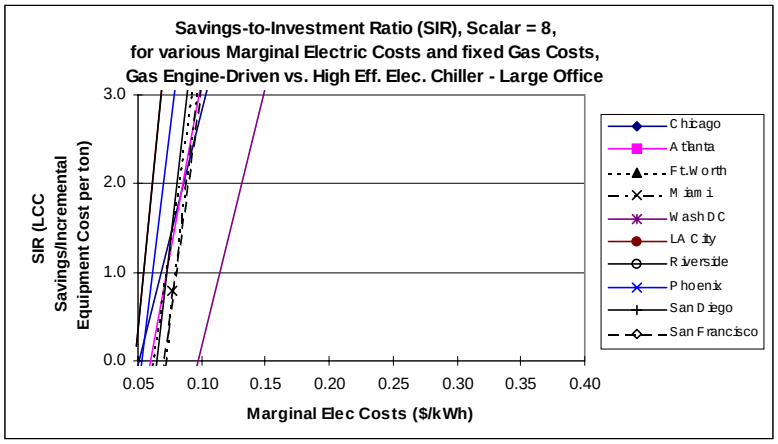
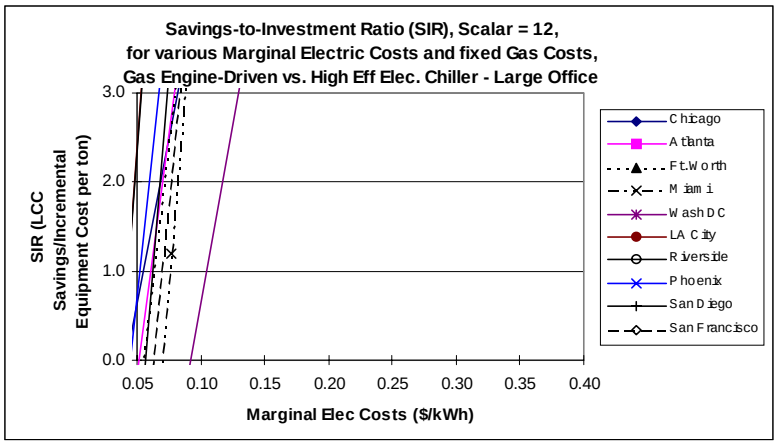


Figure 53 - SIR for various marginal gas costs for Large Office, Gas Engine-Driven vs. High Eff. Chiller





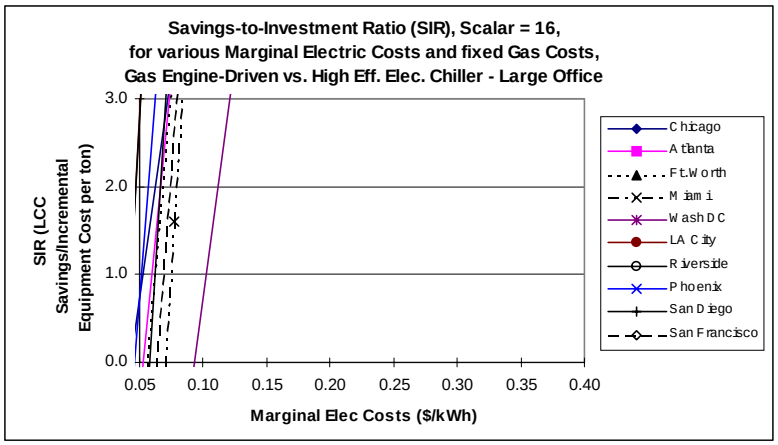
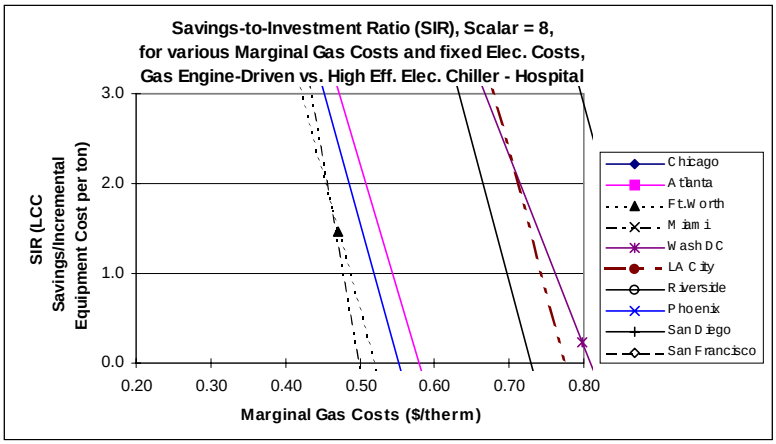
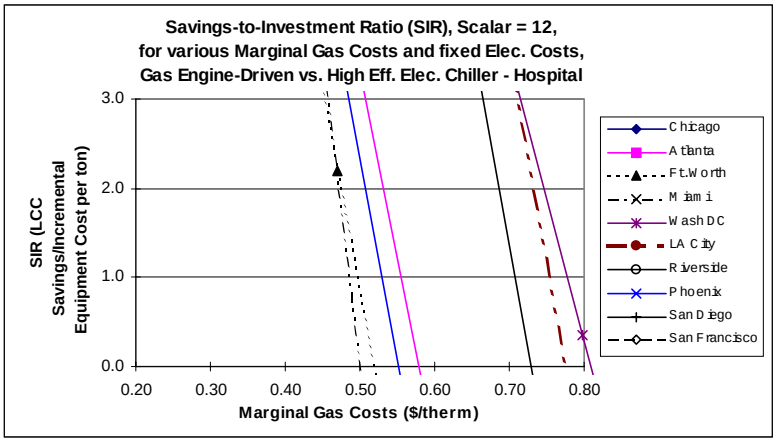


Figure 54 - SIR for various marginal electric costs for Large Office, Gas Engine-Driven vs. High Eff. Chiller





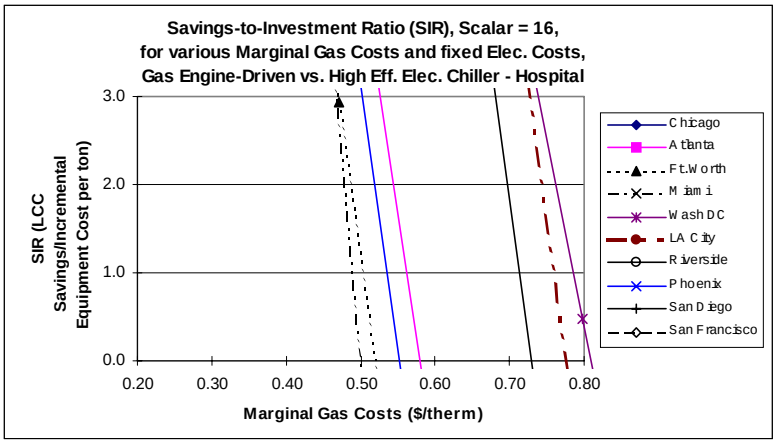
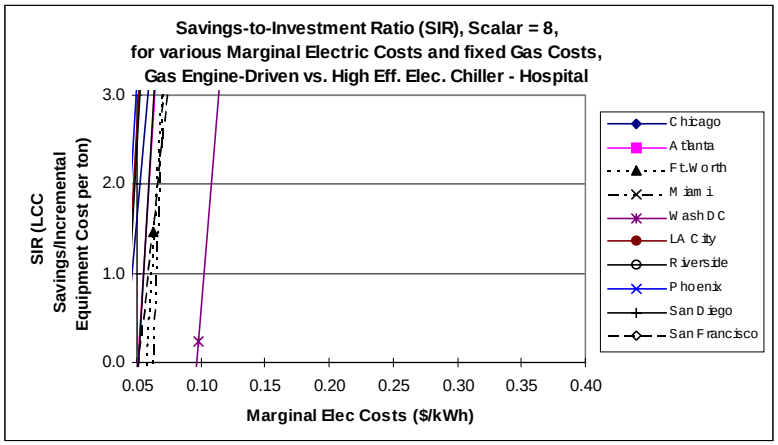
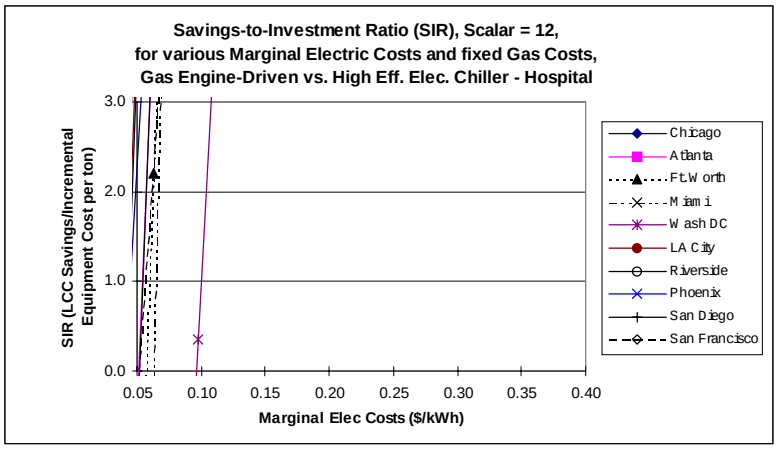


Figure 55 - SIR for various marginal gas costs for Hospital, Gas Engine-Driven vs. High Eff. Chiller





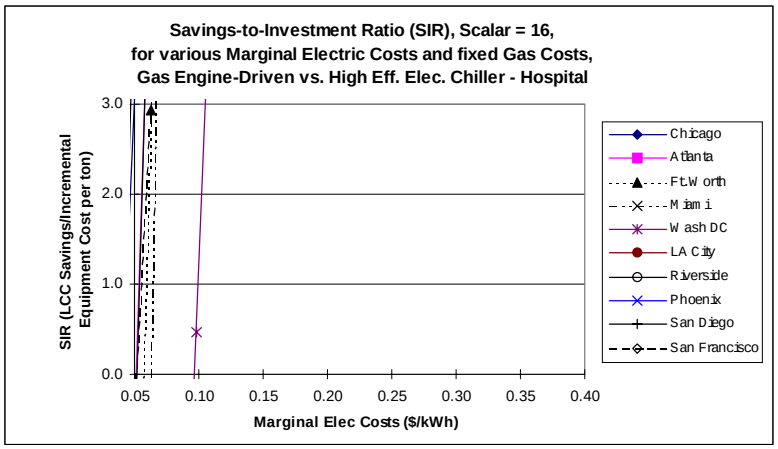
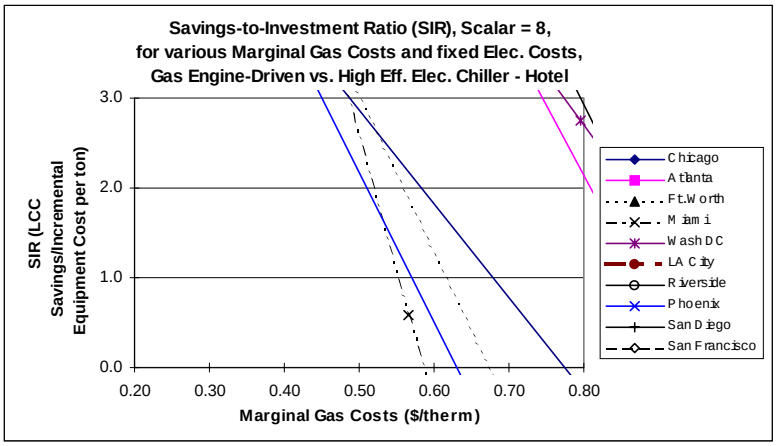
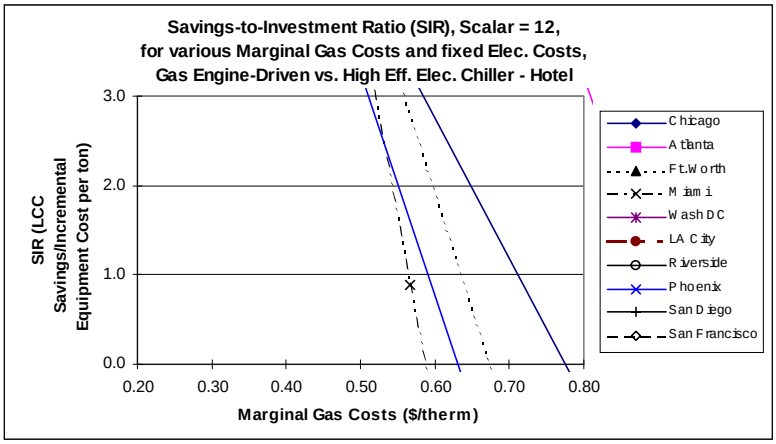


Figure 56 - SIR for various marginal electric costs for Hospital, Gas Engine-Driven vs. High Eff. Chiller





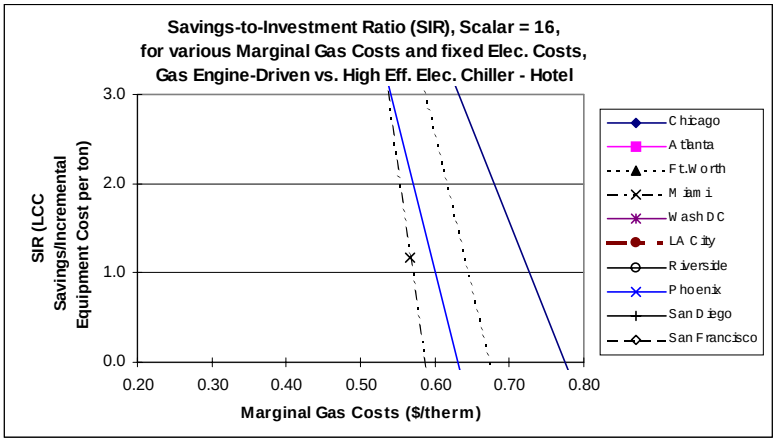
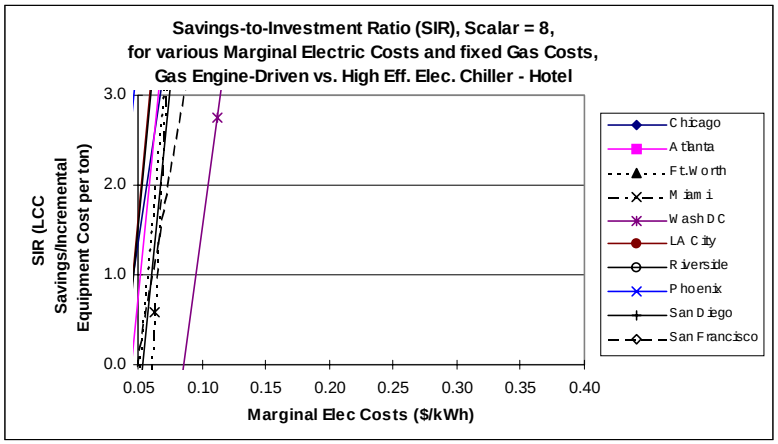
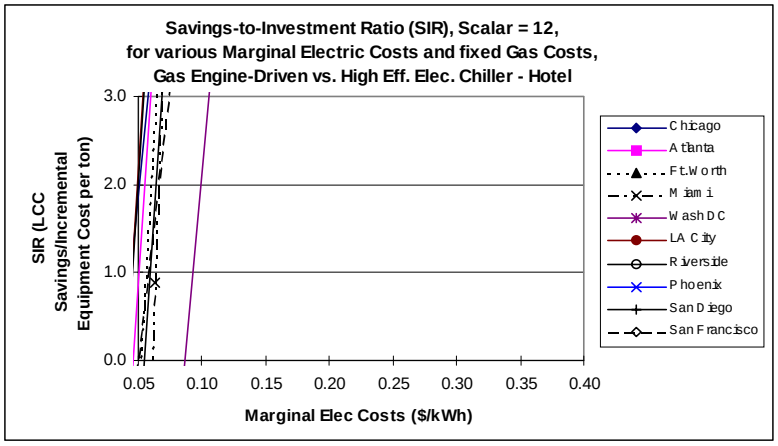


Figure 57 - SIR for various marginal gas costs for Hotel, Gas Engine-Driven vs. High Eff. Chiller





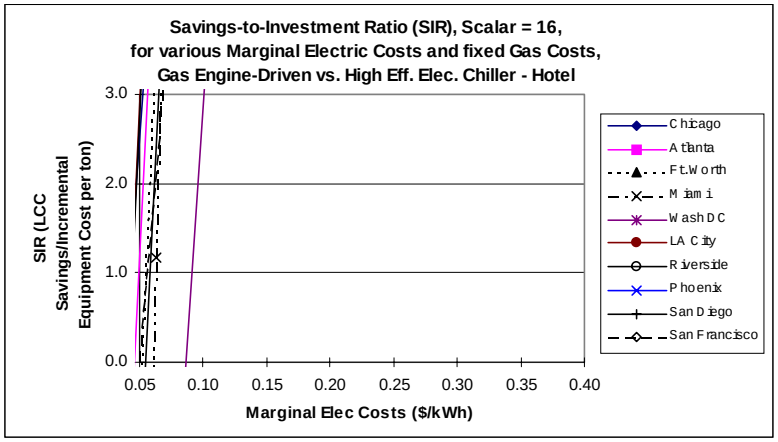
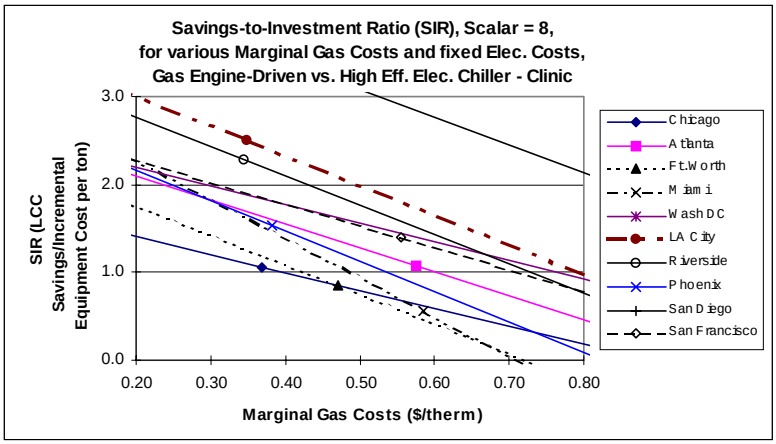
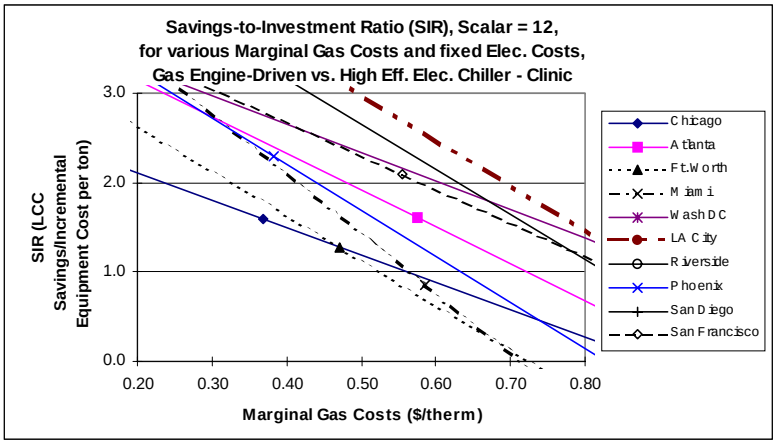


Figure 58 - SIR for various marginal electric costs for Hotel, Gas Engine-Driven vs. High Eff. Chiller





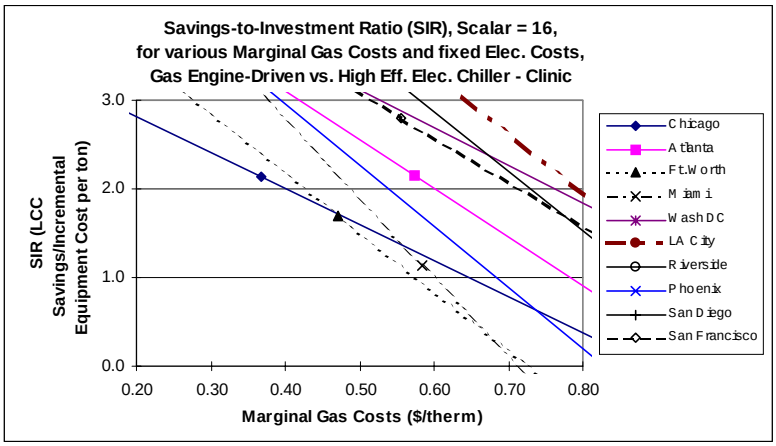
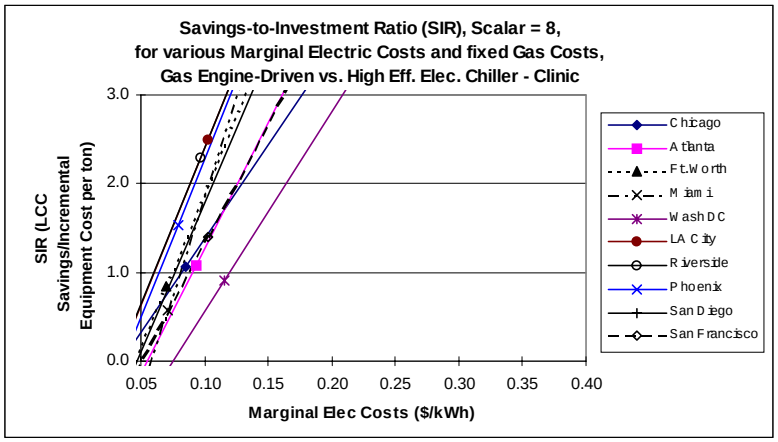
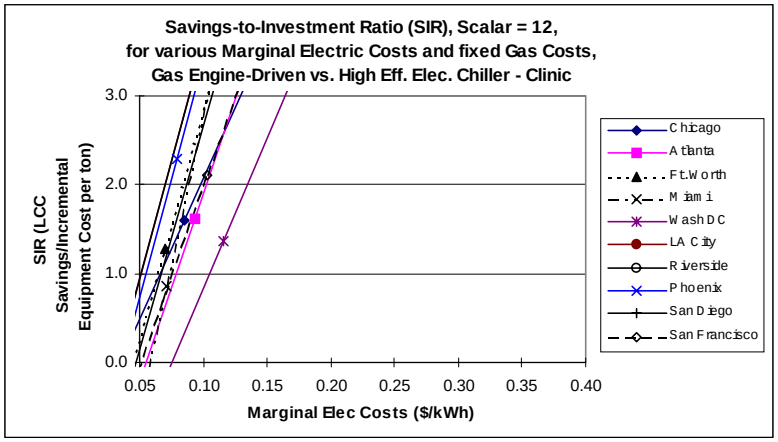


Figure 59 - SIR for various marginal gas costs for Clinic, Gas Engine-Driven vs. High Eff. Chiller





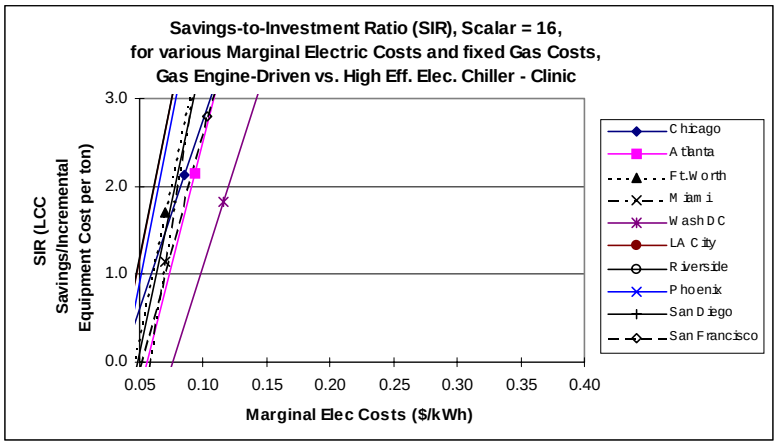
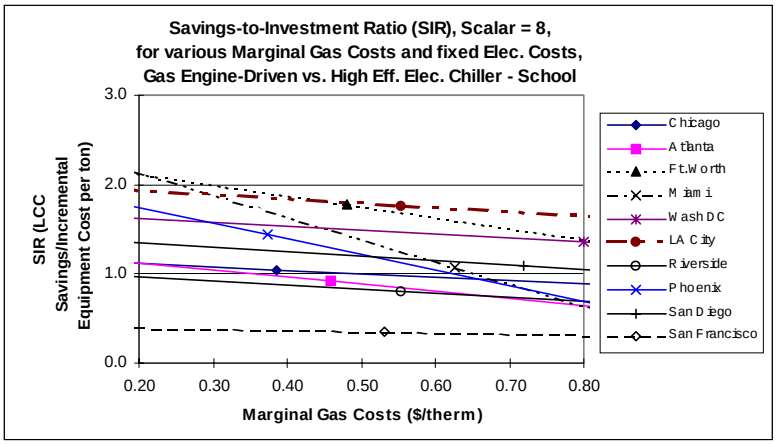
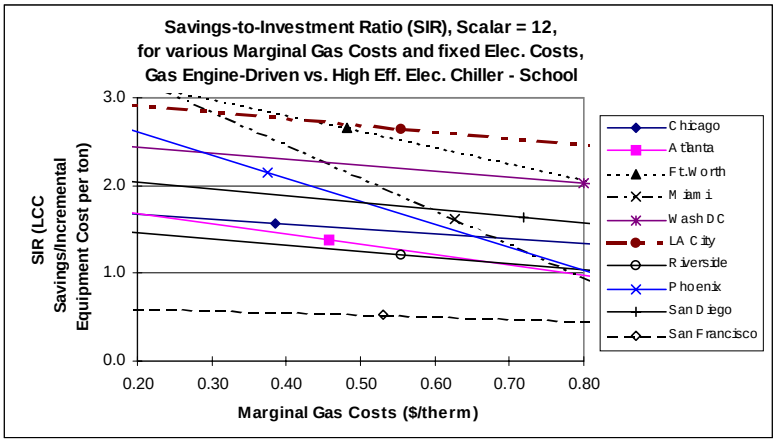


Figure 60 - SIR for various marginal electric costs for Clinic, Gas Engine-Driven vs. High Eff. Chiller





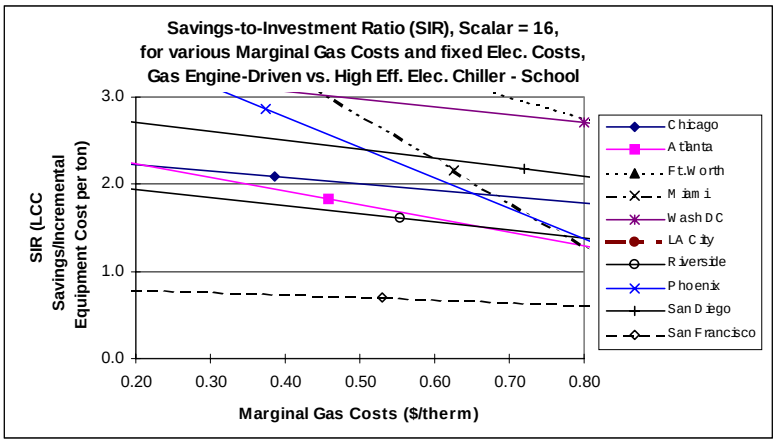
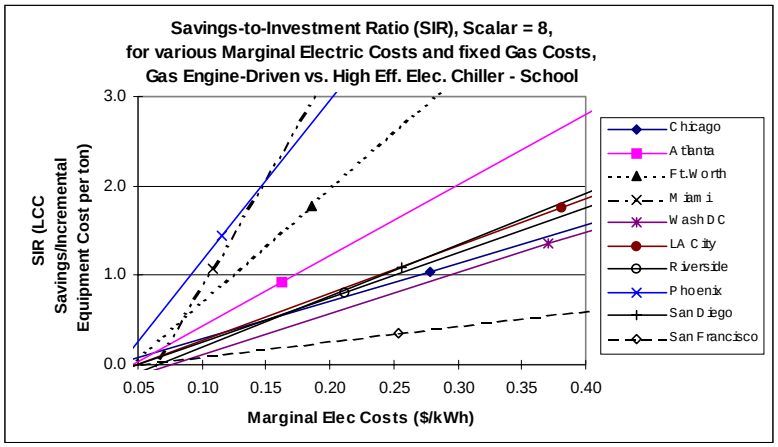
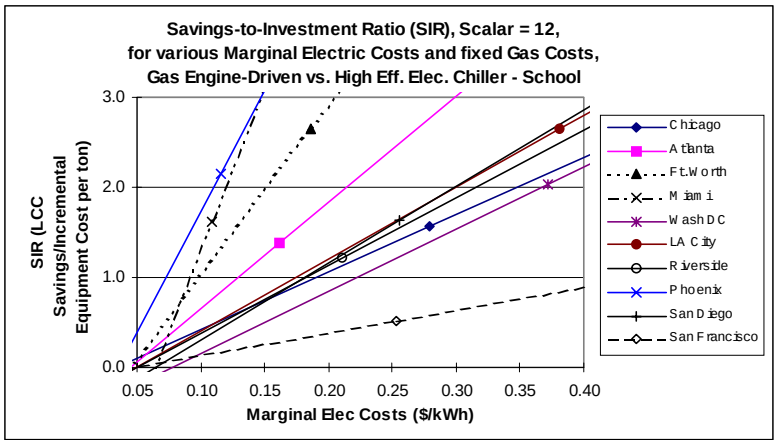


Figure 61 - SIR for various marginal gas costs for School, Gas Engine-Driven vs. High Eff. Chiller





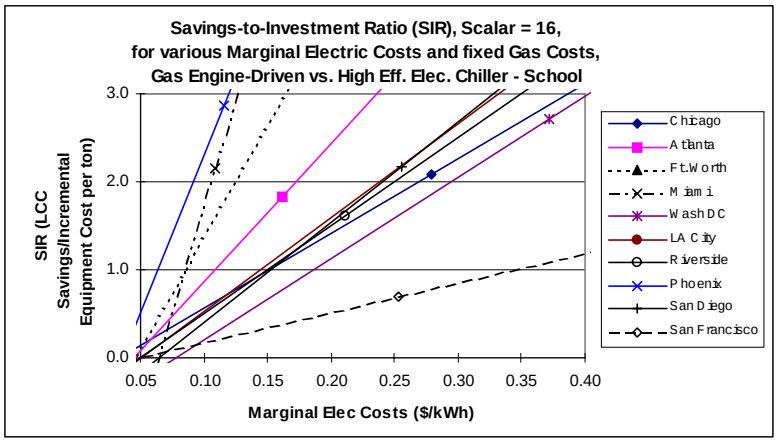
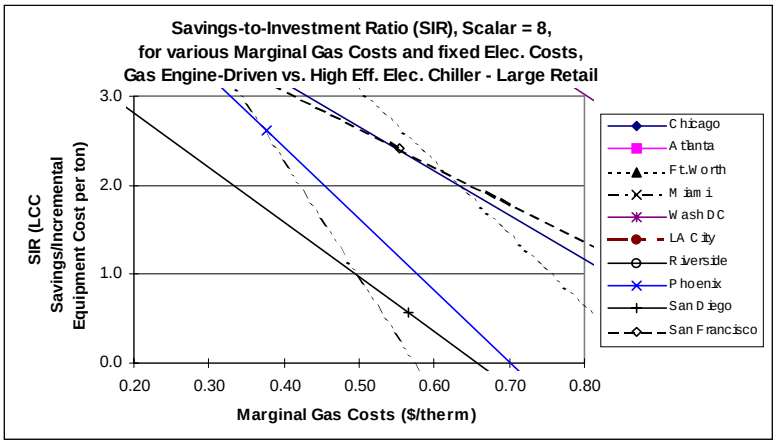
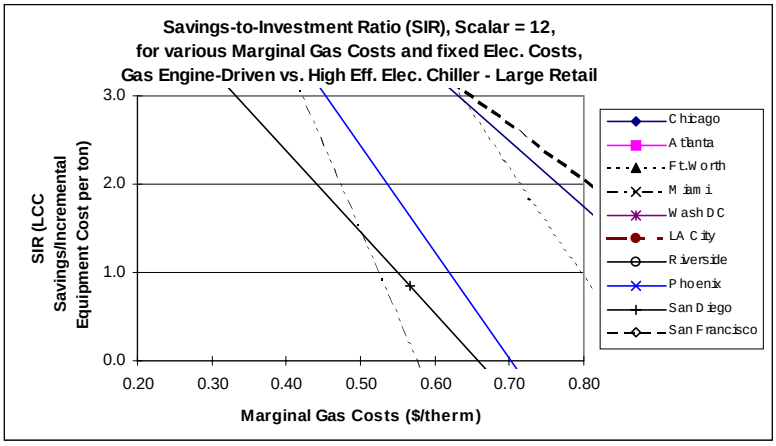


Figure 62 - SIR for various marginal electric costs for School, Gas Engine-Driven vs. High Eff. Chiller





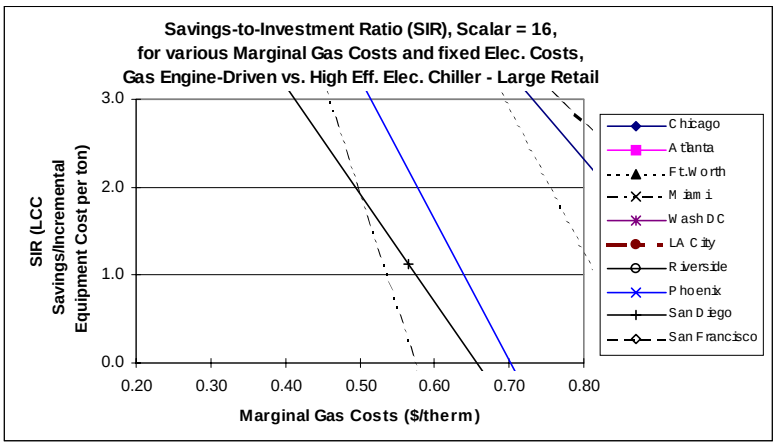
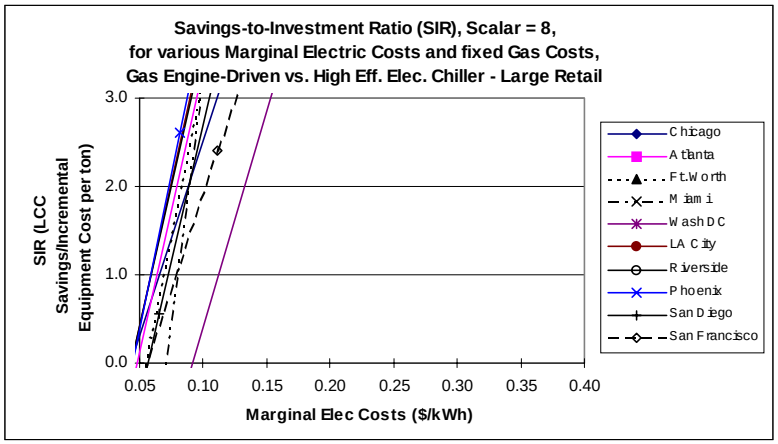
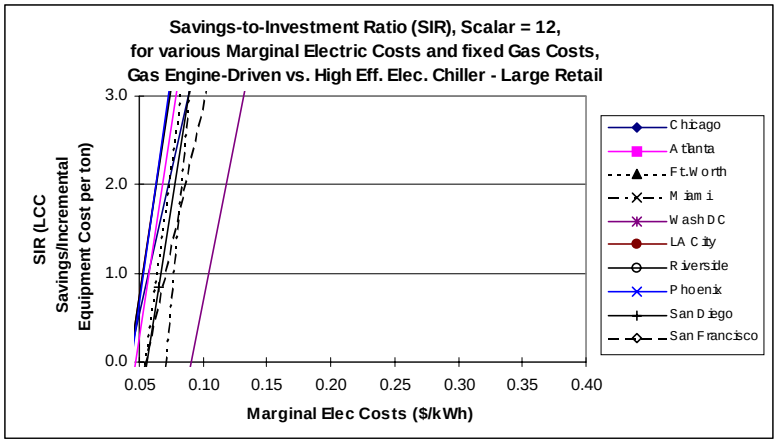


Figure 63 - SIR for various marginal gas costs for Large Retail, Gas Engine-Driven vs. High Eff. Chiller





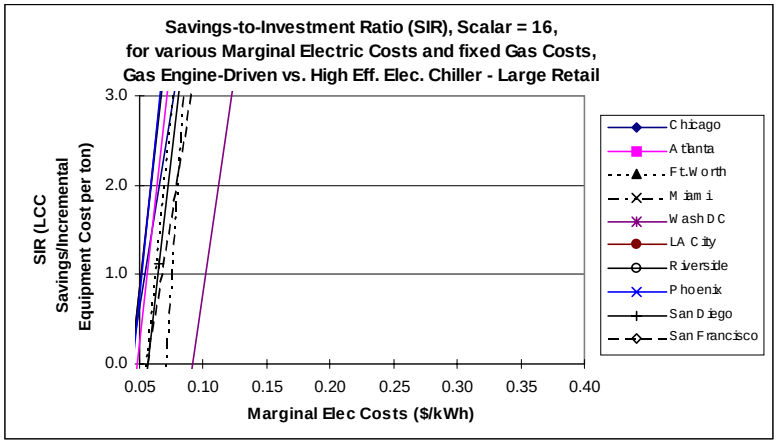


Figure 64 - SIR for various marginal electric costs for Large Retail, Gas Engine-Driven vs. High Eff. Chiller

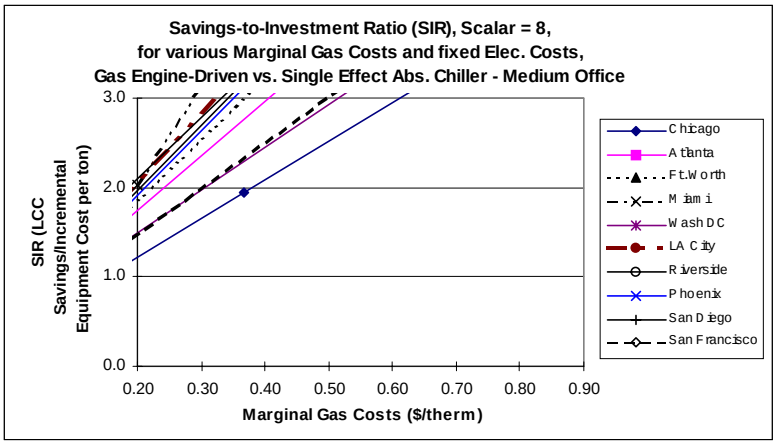
Gas Engine-Driven Chiller vs. Single Effect Absorption Chiller

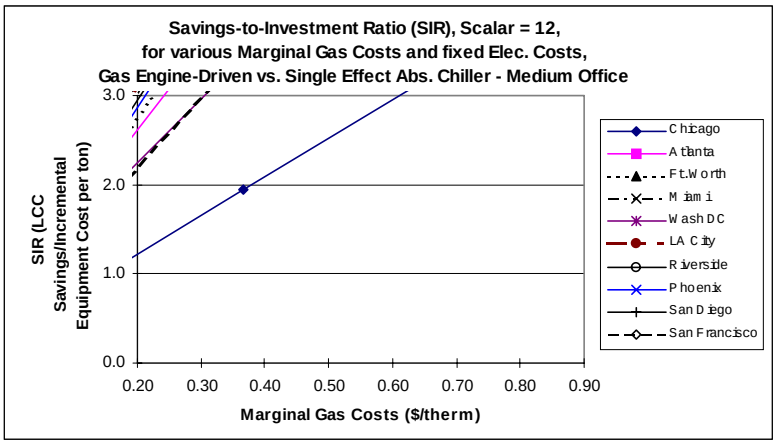
Bldg. Type	Location	Marg. Gas Rate	Scalar		
			8	12	16
Medium Office	Chicago	0.37	1.94	2.92	3.89
	Atlanta	0.43	3.14	4.71	6.28
	Ft. Worth	0.47	3.71	5.56	7.41
	Miami	0.63	6.85	10.28	13.70
	Washington DC	0.80	4.36	6.54	8.72
	LA City	0.40	3.54	5.31	7.08
	Riverside	0.40	3.40	5.10	6.80
	Phoenix	0.39	3.25	4.88	6.51
	San Diego	0.49	4.11	6.17	8.23
	San Francisco	0.55	3.27	4.91	6.55
Large Office	Chicago	0.34	7.53	11.30	15.07
	Atlanta	0.43	12.99	19.49	25.99
	Ft. Worth	0.47	16.21	24.32	32.43
	Miami	0.60	28.56	42.83	57.11
	Washington DC	0.80	17.78	26.67	35.56
	LA City	0.40	23.50	35.25	47.00
	Riverside	0.40	22.96	34.44	45.92
	Phoenix	0.38	15.40	23.11	30.81
	San Diego	0.47	24.99	37.48	49.98
	San Francisco	0.55	23.12	34.68	46.24
Hospital	Chicago	0.34	21.30	31.95	42.60
	Atlanta	0.42	36.49	54.74	72.98
	Ft. Worth	0.47	44.17	66.26	88.35
	Miami	0.57	79.86	119.79	159.72
	Washington DC	0.80	51.74	77.61	103.48
	LA City	0.36	36.50	54.76	73.01
	Riverside	0.36	35.82	53.72	71.63
	Phoenix	0.31	28.82	43.23	57.64
	San Diego	0.43	41.13	61.70	82.26
	San Francisco	0.42	24.44	36.66	48.88

Figure 65 - SIR for Gas Engine-Driven vs. Single Effect Absorption Chillers

Bldg. Type	Location	Marg. Gas Rate	Scalar		
			8	12	16
Hotel	Chicago	0.33	9.80	14.69	19.59
	Atlanta	0.40	17.17	25.76	34.34
	Ft. Worth	0.48	21.46	32.19	42.92
	Miami	0.77	58.13	87.19	116.26
	Washington DC	0.80	23.52	35.27	47.03
	LA City	0.37	17.49	26.23	34.98
	Riverside	0.37	17.01	25.52	34.02
	Phoenix	0.41	17.89	26.84	35.79
	San Diego	0.43	19.38	29.07	38.77
	San Francisco	0.42	5.59	8.38	11.17
Medical Clinic	Chicago	0.36	2.79	4.18	5.58
	Atlanta	0.49	4.88	7.31	9.75
	Ft. Worth	0.47	5.64	8.46	11.28
	Miami	0.60	9.34	14.01	18.68
	Washington DC	0.80	6.04	9.07	12.09
	LA City	0.40	5.14	7.72	10.29
	Riverside	0.40	5.06	7.59	10.12
	Phoenix	0.38	5.05	7.58	10.11
	San Diego	0.49	6.10	9.15	12.20
	San Francisco	0.55	5.01	7.51	10.01
School	Chicago	0.37	0.72	1.08	1.44
	Atlanta	0.43	1.54	2.30	3.07
	Ft. Worth	0.47	2.25	3.38	4.50
	Miami	0.60	5.40	8.11	10.81
	Washington DC	0.80	1.50	2.26	3.01
	LA City	0.53	1.16	1.74	2.33
	Riverside	0.53	0.95	1.42	1.90
	Phoenix	0.37	2.51	3.76	5.01
	San Diego	0.59	1.26	1.89	2.52
	San Francisco	0.53	0.35	0.53	0.70
Large Retail	Chicago	0.34	6.67	10.00	13.34
	Atlanta	0.41	11.42	17.13	22.84
	Ft. Worth	0.47	13.78	20.68	27.57
	Miami	0.79	34.31	51.46	68.61
	Washington DC	0.80	16.00	24.00	32.00
	LA City	0.40	9.56	14.34	19.12
	Riverside	0.40	9.19	13.78	18.38
	Phoenix	0.28	8.38	12.57	16.75
	San Diego	0.49	11.40	17.10	22.80
	San Francisco	0.55	8.23	12.35	16.46

Figure 65 (continued) - SIR for Gas Engine-Driven vs. Single Effect Absorption Chillers





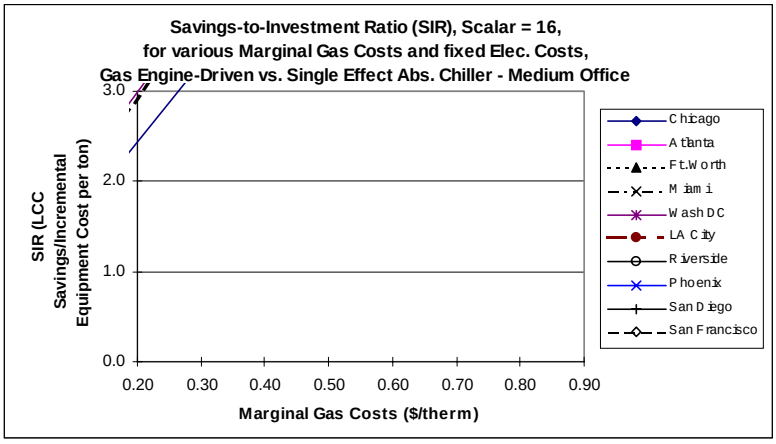
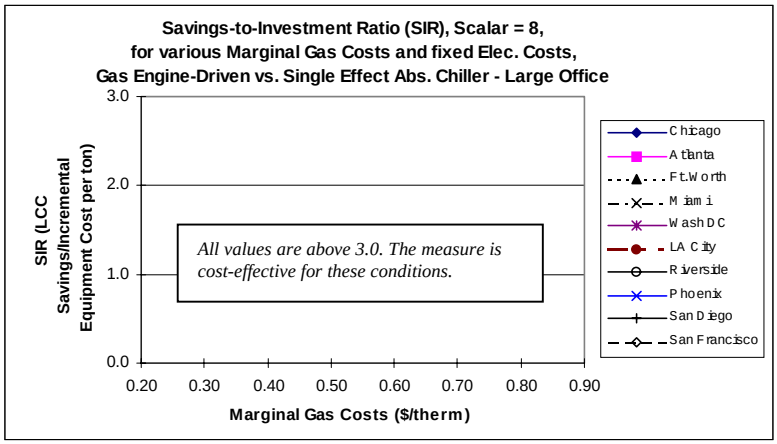
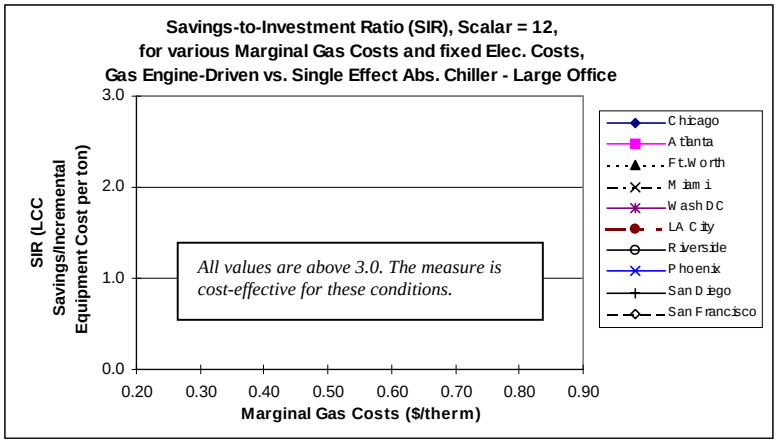


Figure 66 - SIR for various marginal gas costs for Medium Office, Gas Engine-Driven vs. Single Effect Absorption Chiller





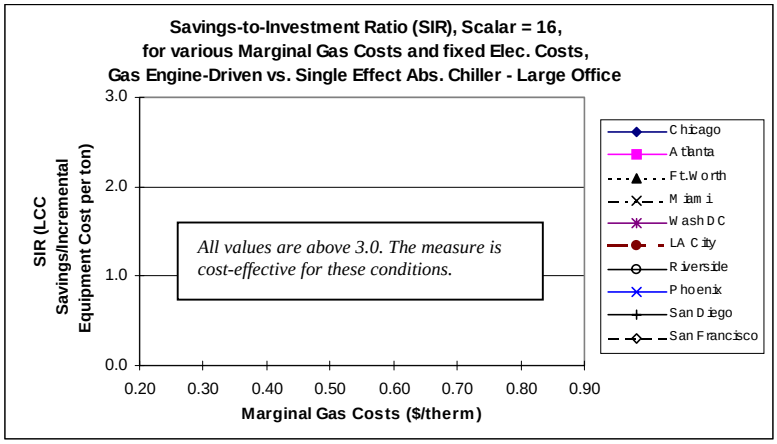
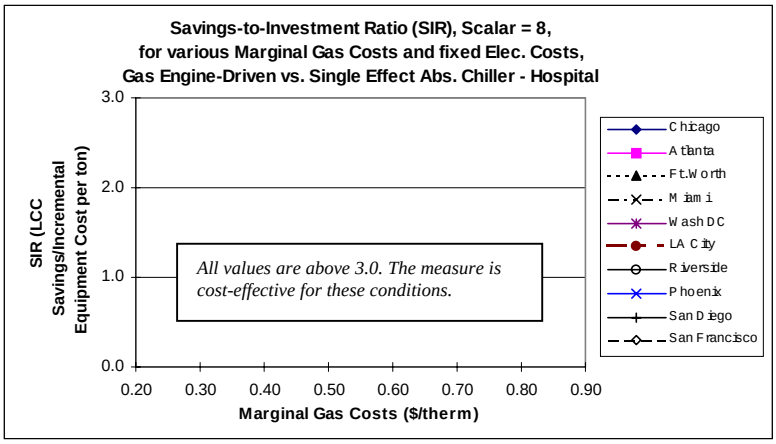
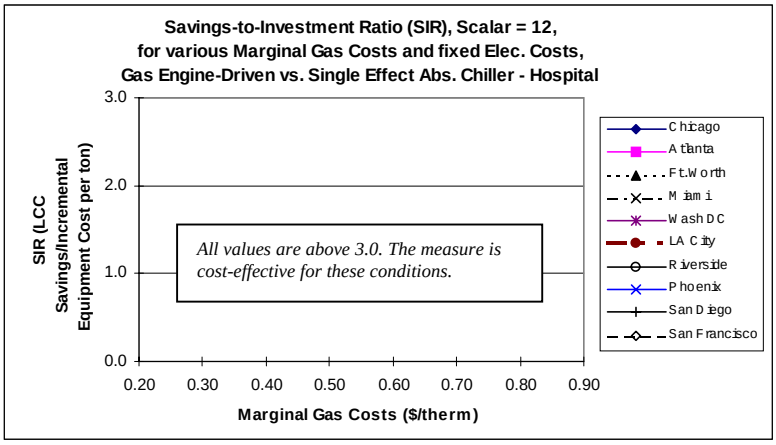


Figure 67 - SIR for various marginal gas costs for Large Office, Gas Engine-Driven vs. Single Effect Absorption Chiller





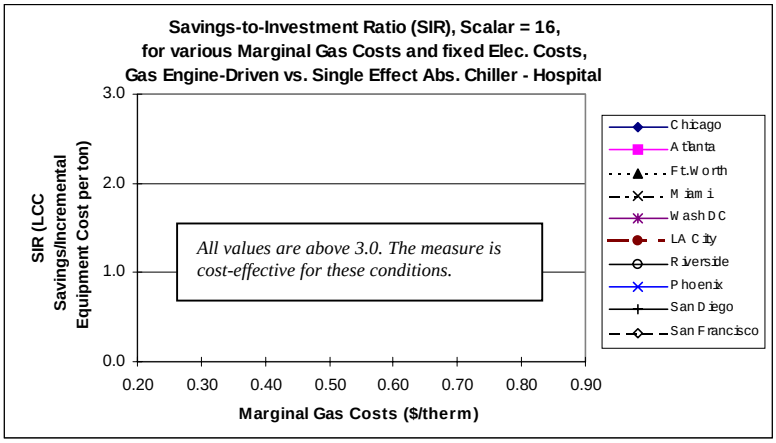
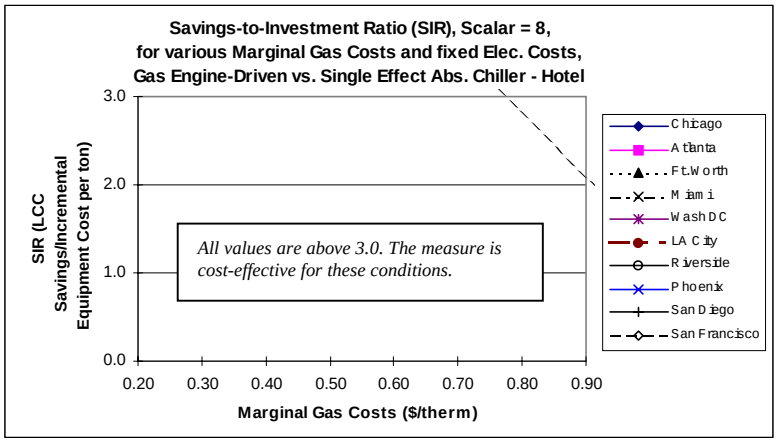
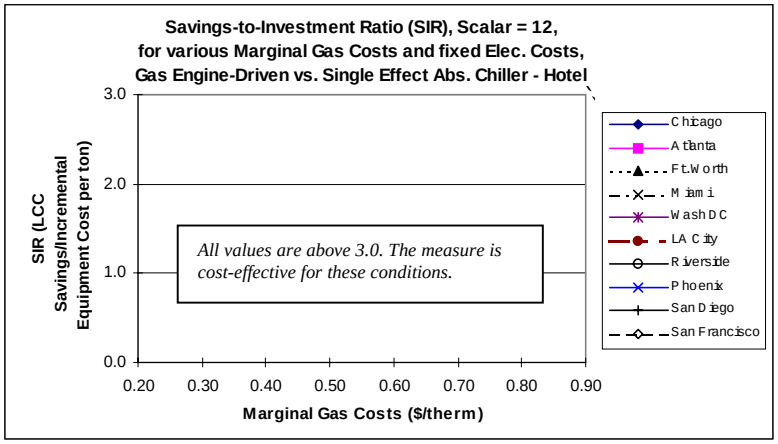


Figure 68 - SIR for various marginal gas costs for Hospital, Gas Engine-Driven vs. Single Effect Absorption Chiller





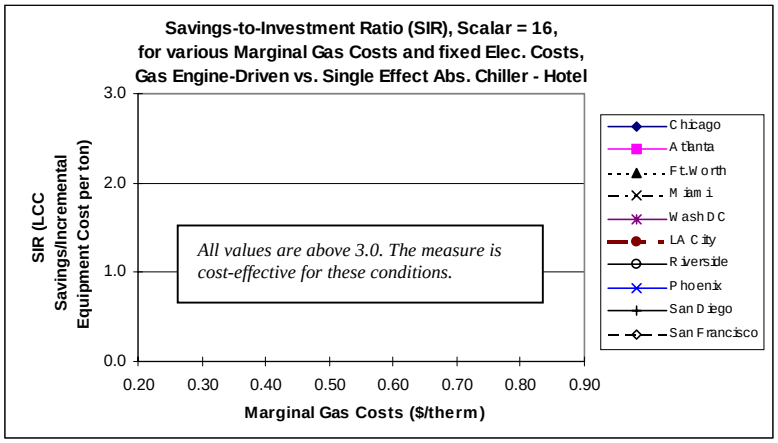
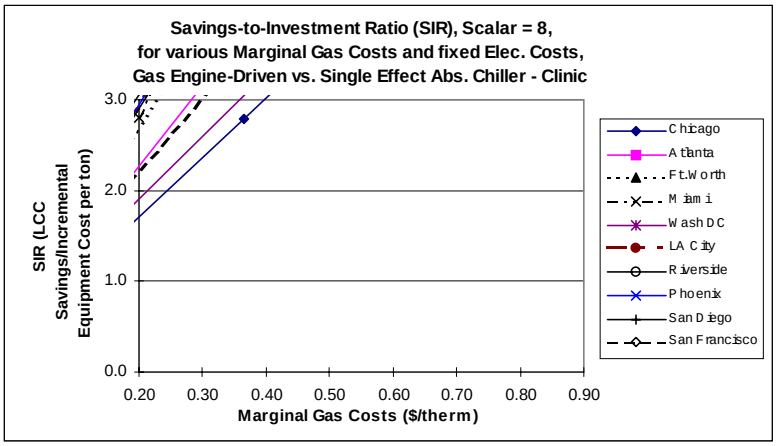
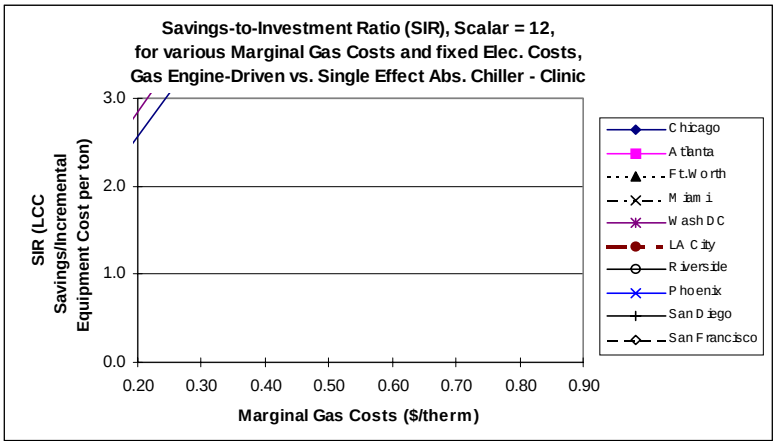


Figure 69 - SIR for various marginal gas costs for Hotel, Gas Engine-Driven vs. Single Effect Absorption Chiller





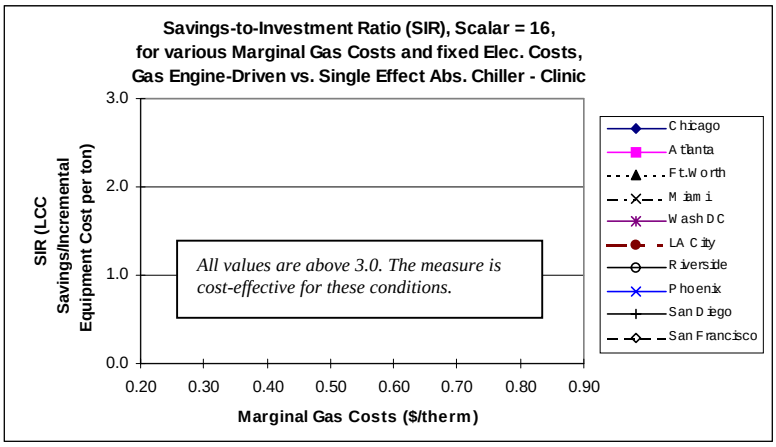
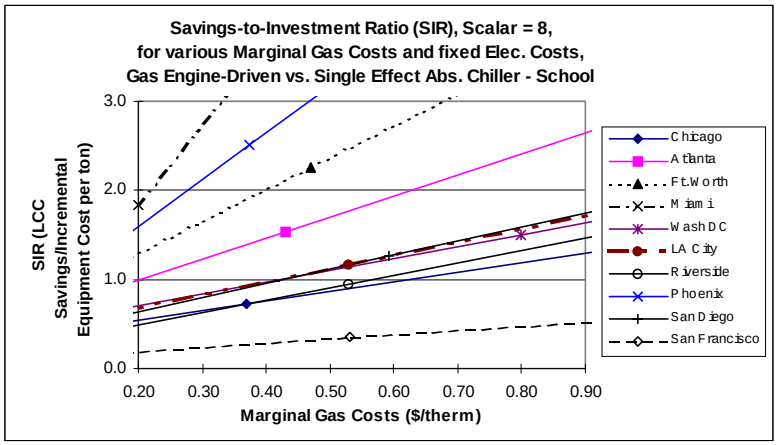
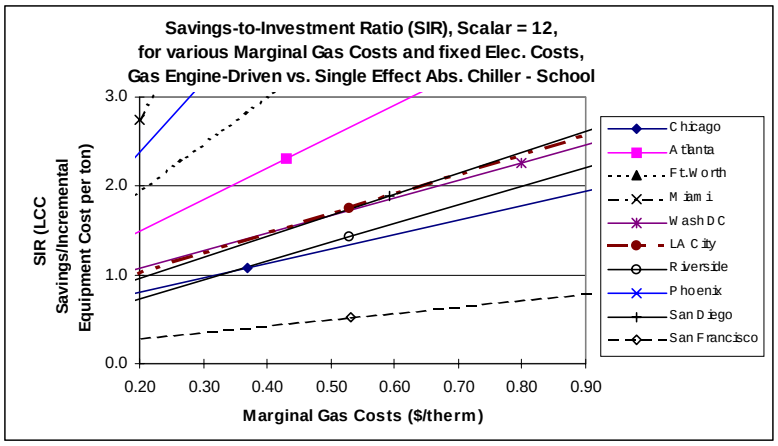


Figure 70 - SIR for various marginal gas costs for Clinic, Gas Engine-Driven vs. Single Effect Absorption Chiller





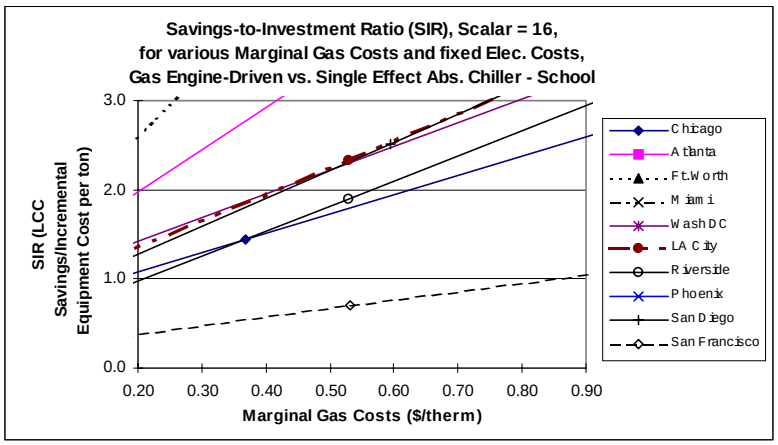
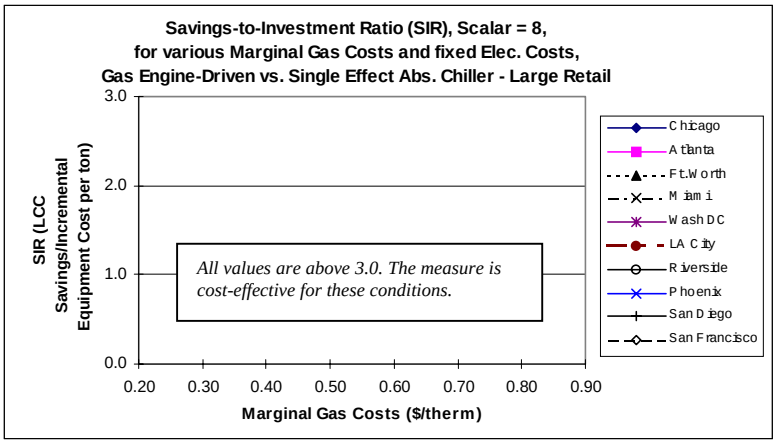
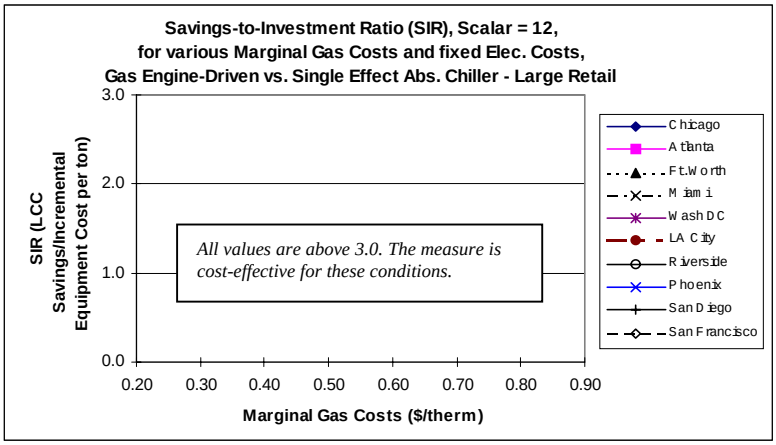


Figure 71 - SIR for various marginal gas costs for School, Gas Engine-Driven vs. Single Effect Absorption Chiller





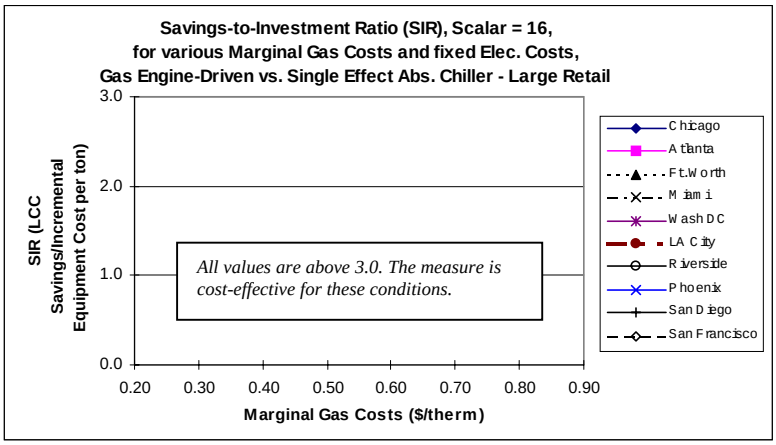


Figure 72 - SIR for various marginal gas costs for Large Retail, Gas Engine-Driven vs. Single Effect Absorption Chiller

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CHAPTER 7: APPENDIX

A. Building Type Descriptions

1. ***Medium Office Building***
   This building is a 49,000 sq. ft., 3-story structure made of precast exterior concrete panels. The glass is 36% of the wall area on all sides and is vertical. (The original building had sloped glass on the lower level. - is this comment of any significance, other than historical interest?) Occupancy is 330 people, 5 days a week plus half-day on Saturday, none on Sundays or holidays. The HVAC system has three powered induction units serving each floor separately, with variable-air-volume (VAV) air handling units on the roof. The chiller is DX air cooled and the heating is by a gas-fired hot water generator.

2. ***Large Office Building***
   This structure is a hexagonal shaped 38-story office building with 18,000 sq. ft. per floor (total of 684,000 sq. ft.). Construction is steel frame with limestone cladding. The glass area on the SE and NW sides is about 50%, with the other four sides having 15% glass. The building is occupied from 8AM to 6PM weekdays, 10% occupied during the same hours on Saturday and unoccupied Sundays and holidays. The HVAC systems are split into a core VAV system and a perimeter VAV system with reheat coils for the perimeter only. The chillers are centrifugal and heating is supplied by gas-fired hot water generators.

3. ***Retail Store***
   The retail store is a high quality department store located in a shopping mall. It is a 2-story masonry structure of 164,200 sq. ft. with 82% of the floor area devoted to merchandising and office and 18% devoted to storage and stock preparation. There is very little glass except for entry doors. External loads from the three sides of the building in thermal contact with the rest of the mall, are neglected. Operating hours are 10AM to 10PM, 6 days a week and 10AM to 6PM Sundays and holidays. The HVAC systems are constant volume variable temperature (CVVT) served by centrifugal chillers and gas-fired hot water generators.

4. ***Strip Retail***
   The strip store is a typical 9,600 sq. ft. end unit of a street mall with one portion of one side connected to another store. It is a slab-on-grade building of wood frame construction with display windows on the west and south walls. The west windows are shaded by a canopy, but on the south side there is no shading. The glazing on the west and south exposures is about 35% of the wall area. The store is open for business 10AM to 10PM, 6 days a week and from 10AM to 6PM on Sundays and holidays. The HVAC system is a rooftop packaged VAV unit with DX air cooled condensing unit. The heating is by a gas-fired hot water generator.

5. ***Hospital***
   The building is a 4-story, 272,200 sq. ft., 348-bed hospital. It is of face brick construction. There are multiple types of HVAC systems such as dual duct, 4-pipe induction, reheat constant volume, 4-pipe fan coil and CVVT. These units are all served by hermetic centrifugal chillers and gas-fired hot water generators.

6. ***Junior High School***
   The junior high school is a 50,000 sq. ft. building with combination auditorium/recreation space, multi-purpose rooms, and classrooms. The classroom section is 2-stories high. Walls are constructed of face brick and stucco. The building is modeled with

CVVT units with centrifugal chiller and gas-fired heaters.

7. ***Hotel***
This 350 room hotel is a medium size convention-type facility with 10 floors totaling 315,000 sq. ft. The space utilization divides as follows: 65% guest rooms, 30% public areas such as lobby, restaurants and meeting rooms, and 5% service area. The building is 70% glass on the west, 50% on the east and less than 10% on the south and north. Construction is of reinforced concrete. The HVAC system is a mix of VAV and CVVT in the public areas, with 4-pipe fan coil units in the guest rooms and CVVT for makeup air units supplying ventilation air to the corridors for guest room bathrooms.

8. ***Full Service Restaurant***
This full service restaurant is open from 7AM to 12 midnight all days including holidays. The building is a 1-story brick structure with 9,060 sq. ft. of floor space with a main dining area for 240 people and a lounge area for 60 people. The HVAC system includes a multi-zone unit serving the public areas and a CVVT unit serving the kitchen area. Makeup air requirements are about 65% of the total supply air. The primary cooling is provided by two reciprocating chillers with air cooled condensers. Heating is from two hot water generators.

9. ***Fast Food Restaurant***
The fast food restaurant is atypical major chain design with food preparation, food storage and food service and dining areas. The restaurant is a single floor, 2,000 square foot building with wood frame construction, brick veneer, and a built-up roof. The restaurant has 4 five-ton DX packaged rooftop units with 150,000 Btuh input gas heating each. Windows are present on the north, south, and west walls. Floor-to-roof height is 12 feet. Maximum occupancy is 81 persons. Typical periods of occupancy are from 5AM to midnight, 7 days per week.

B. Summary of Utility Rates

Summary of Gas Utility Rates Used

City	Utility	Rate Name	Rate Type	Minimum (Therms/Mo)	Maximum (Therms/Mo)	Summer (¢/therm)
Chicago	NiCor	4	General Service	0	No Limit	33
Washington DC	Washington Gas Light	2	General Service	0	No Limit	79
Dallas/Ft. Worth	Lone Star Gas	General Service	General Service	0	No Limit	48
Los Angeles City	So. Cal. Gas	GN-10	General Service	0	<20800	34-51
		GN-20	General Service	20800	No Limit	34-48
		G-AC	Air Conditioning	0	No Limit	38
Riverside	So. Cal. Gas	GN-10	General Service	0	<20800	34-51
		GN-20	General Service	20800	No Limit	34-48
		G-AC	Air Conditioning	0	No Limit	38
San Diego	San Diego G & E	GN-1	General Service	0	<20800	49
		GN-2	General Service	20800	No Limit	42
San Francisco	Pacific G & E	G-NR1	General Service	0	<20800	53
		G-NR2	General Service	20800	No Limit	41
Atlanta	Atlanta Gas Light	G-11	General Service	0	<2000 th/day	78
		G-11 AC	Air Conditioning	0	<2000 th/day	36
		G-12	Heating Only	0	<2000 th/day	82
		G-13 LLF	General Service	0	<5000 th/day	74
		G-13 AC LLF	Air Conditioning	0	<5000 th/day	36
Phoenix	Southwest Gas	CG-25 Small	General Service	0	600	62
		CG-25 Medium	General Service	>600	15000	53
		CG-25 Large	General Service	>15000	No Limit	34
		CG-40	Air Conditioning	0	No Limit	32
Miami	Peoples Gas	SGS	General Service	0	108	85
		GS	General Service	>108	2708	73
		GSLV-1	General Service	>2708	54166	70
		GSLV-2	General Service	>54166	No Limit	63
		Rider LE	Air Conditioning	0	No Limit	40% of above

Summary of Electric Utility Rates Used

City	Utility	Rate Name	Rate Type	Min Demand (kW)	Max Demand (kW)	Summer On Peak (¢/kWh)	Summer On-Peak ($/kW)
Chicago	ComEd	6	Non TOU	0	<1000	3	14
		6L	TOU	1000	<10000	5	16
Washington DC	Potomac Electric	GS-Non Demand	Non TOU	0	<25	12	0
		GS-Demand	Non TOU	25	<100	8	12
		GT	TOU	100	No Limit	6	24
Dallas/Ft. Worth	Texas Utilities	GS	Non TOU	10	No Limit	5	14
Los Angeles City	LA Dept W & P	A-1 (Rate A)	Non TOU	0	<30	10	3
		A-2 (Rate A)	Non TOU	30	<500	5	18
		A-3 (Rate C)	TOU	500	No Limit	8	14
Riverside	So. Cal. Edison	GS-2	Non TOU	20	<500	4	25
		TOU-8	TOU	500	No Limit	9	24
San Diego	San Diego G & E	A (No Demand)	Non TOU	0	<20	14	0
		AD (Demand Metered)	Non TOU	20	500	9	10
		AL-TOU	TOU	>500	No Limit	9	27
San Francisco	Pacific G & E	A-10	Non TOU	0	<500	9	7
		E-19S	TOU	500	<1000	9	17
		E-20S	TOU	1000	No Limit	9	17
Atlanta	Georgia Power	PLS-2	Non TOU	0	<30	9-10	16
		PLM-2	Non TOU	30	<500	6-10	18
		PLL-2	Non TOU	500	No Limit	6-10	18
Phoenix	Arizona Pub Serv	E-32	Non TOU	0	No Limit	8	6
Miami	Florida P & L	GSD-1	Non TOU	20	<500	5	9
		GSLD-1	Non TOU	500	<2000	4	9
		GSLD-2	Non TOU	2000	No Limit	4	9

C. Equipment First Cost

	Size (tons)	Cost ($/ton)
Electric Screw	100-350	360
Hi Eff. Electric Screw	100-350	414
SE Steam Absorption	100-350	510
DE Direct-Fired Absorption	100-350	740
Engine-Driven Screw	100-350	700
Electric Centrifugal	350-450	259
Hi Eff. Electric Centrifugal	350-450	349
SE Steam Absorption	350-450	264
DE Direct-Fired Absorption	350-450	627
Engine-Driven Centrifugal	350-450	528
Boiler		$11 per 1000 Btuh
Cooling Tower		$55 per AC ton

Notes:

1) Chiller costs from 1997 manufacturer's data, FOB price plus 20%

2) 15% cost premium for high efficiency electric screw chiller versus standard screw chiller per ASHRAE 90.1 cost analysis.

3) 35% cost premium for high efficiency electric centrifugal chiller versus standard centrifugal chiller per ASHRAE 90.1 cost analysis.

4) Boiler and cooling tower cost from Means.

D. Scalar Ratio and SIR

Throughout the Guidelines, the terms scalar ratio and SIR (savings to investment ratio) are used to describe the economic analysis of measures. A scalar ratio is a mathematical simplification of life cycle costing (LCC) analysis. An SIR compares the life cycle savings to the initial investment. An LCC analysis is preferable to a simple payback analysis, because it enables a more realistic assessment of all the costs and savings to be expected over the life of an investment. While LCC analysis can be quite complicated and difficult to understand, a scalar ratio and an SIR are relatively simple to use. This discussion explains their meaning and derivation, and provides some guidance on how to use them in better understanding the analysis graphs in these Guidelines.

Scalar Ratios Simplified

In technical terms, the scalar ratio represents the series present worth multiplier. This can be understood by assuming a simple situation: an initial investment in an energy efficiency measure, followed by a series of annual energy savings realized during the lifetime of the measure. The annual energy costs are assumed to escalate at a steady rate over the years and an annual maintenance cost, when included, is assumed to escalate at a different steady rate. Once the included costs and savings are laid out over the life of the investment, each year's net savings is discounted back to present dollars, and the resulting present worth values are summed to arrive at the life cycle energy savings. This number is then divided by the net savings for the first year, to obtain the scalar ratio. Once the scalar ratio is determined, it can be applied to other investment scenarios that share the same economic rates of energy cost and maintenance cost escalation. One simply calculates the first year's energy savings and multiplies it by the scalar ratio to obtain the net present worth of the savings.

The process of discounting these future dollars back to present dollars is a straightforward calculation (most spreadsheets have built-in present worth functions). The present worth of a future dollar earned (or saved) is a function of the number of years in the future that the dollar is earned, and of the discount rate. The discount rate may be thought of as the interest rate one would earn if the first cost dollars were put into a reliable investment, or as the minimum rate of return one demands from investments. If the investment is a good one, the present worth of the discounted savings will exceed the cost of the investment. If the present worth of savings does not exceed the investment cost, then the investment will not provide the minimum rate of return and could be better spent on another investment.

Of course, in the case where the net cost of the higher efficiency equipment is lower than that of the base case equipment, <u>any</u> positive present worth of energy savings indicates a sound investment. In some cases more efficient equipment allows downsizing of other equipment in the building, such as the electrical load center and service drop. These savings can be significant enough to offset the incremental cost of the more efficient equipment, resulting in a lower overall first cost. To be conservative, in the development of these Guidelines, we have ignored these potential related savings.

Likewise, maintenance costs were not included because there are too many variables and the additional complication would not have increased the clarity or accuracy of the analysis.

Figure 73 shows a simple spreadsheet illustrating how this basic scenario would be calculated. In the example, the first year's savings are $1,051. The annual energy savings escalate at 4% per year, and the annual maintenance costs escalate at 2% per year. If you simply add up these costs after five years, you will expect to save $5,734. The discounted present worth is calculated using the spreadsheet's net present value (NPV) function using the string of annual totals and the discount rate. If the discount rate is 15%, these savings have a present worth of $3,799, which is 3.6 times the first year's savings (scalar ratio = 3.6). If the initial investment to achieve these savings was less than $3,799, then it meets the investment criteria and will provide a rate of return greater than 15%. On the other hand, if the discount rate is 3%, the present worth of the savings is $5,239 and the scalar ratio is 5.0. Investors with high discount rates have higher expectations for their returns on investment, and are therefore less willing to invest in efficiency measures that have lower savings. On the other hand, public agencies and most individuals have lower discount rates and accept lower rates of return in exchange for reliable returns. A discount rate of 3% in this example yields a scalar ratio of 5.0 and indicates that a substantially higher initial investment of $5,239 could be justified.

Year:	1	2	3	4	5
Energy Savings (escalated 4%/yr);	$1,200	$1,248	$1,298	$1,350	$1,404
Maint. costs (escalated 2%/yr):	($150)	($153)	($156)	($159)	($162)
Annual totals:	$1,051	$1,097	$1,145	$1,195	$1,246
			(Sum of Annual totals:		$5,734)
Discounted Present Worth: (15% discount rate)	$3,799	/ $1,051 = Scalar:	3.6		
Discounted Present Worth: (3% discount rate)	$5,239	/ $1,051 = Scalar:	5.0		

Figure 73 - Example Present Worth Calculation

Selecting a Scalar Ratio

To use the cost-effectiveness analysis graphs in this Guideline, one must select a scalar ratio by deciding on the economic conditions for their efficiency investments. The example discussed here has been rather simplistic, and the five-year analysis period is quite short for most energy efficiency measures. In selecting a scalar, users should decide on at least the following:

- Period of Analysis - This is the number of years the energy efficiency investment is expected to provide savings. Some users will have a long-term perspective, and will choose a period of analysis that approaches the expected life of the measure. For long life measures, such as building insulation, the period of analysis may be thirty years or more. For mechanical system measures, the period may be fifteen years. Other users may choose a shorter analysis period because they are interested in their personal costs and benefits and are not expecting to hold the property for a long time. Public policy agencies setting energy codes may choose a societal perspective, based on the principle that building investments impinge on the environment and the economy for a longer period of time, and so may select a long period of analysis.

- Discount Rate - This is the real rate of return that would be expected from an assured investment. A rate of return offered by an investment instrument is the investment's nominal interest rate and must be adjusted, by the loss in real value that inflation causes, to arrive at the real interest rate. Nominal discount rates must likewise be adjusted for inflation to find the real discount rate. In order to simplify the analysis, we assumed a zero inflation rate, which then makes the nominal and real discount rates the same. As discussed in the example above, different kinds of people may have different expectations. A lower end interest rate (and discount rate) might be the rate of return expected from savings account or a money market fund (2% - 4%). An upper end might be the rate of return that an aggressive investor expects to produce with his money (10% - 20%), although it is difficult to argue that this represents an "assured investment." Another way to think of the real discount rate is the real rate of return that competing investments must provide in order to change the choice of investments that the organization makes.

The table in Figure 74 shows a range of typical scalars. It presents the resulting scalars for 8, 15 and 30-year study periods, discount rates ranging from 0% to 15% and escalation rates ranging from 0% to 6%.

Savings to Investment Ratios (SIRs)

An extension of the present worth and scalar concepts is the *Savings to Investment Ratio (SIR)*. As indicated above, one is interested in both the incremental first cost of an investment (how much more it costs than the base case) and in the present worth of its cost savings. The SIR provides a simple way to compare the two: divide the present worth of the savings by the incremental first cost (or its present worth if the investment extends over time). If this ratio is greater than one, then the discounted savings are greater than the first cost, and the return on investment will be greater than the discount rate. The cost-effectiveness analysis graphs presented in this Guideline use the SIR on the vertical axis. Thus any points on the curves that lie above an SIR value of one are deemed to be cost effective.

Advanced Economic Analysis

The economic analysis could be more elaborate than the examples discussed here, of course, and could account for more factors. For example, there could be other maintenance costs that recur every few years, the energy cost escalation factors could be non-linear, or the tax

deductions for the operating and maintenance costs could be included. In addition, the first costs could be spread out over the years as loan payments and interest cost deductions. All of these costs would be discounted back to present dollar values and summed to arrive at the net present value, which compares the life cycle costs to the life cycle savings[1].

Analysis for different purposes will include both different types of inputs as well as varying levels for the input types chosen. For example, while a commercial building owner is likely to be interested in the economic impacts within a relatively short time frame, e.g., 8-10 years, a state energy office is likely to be more concerned with the societal economic impacts over a much longer term, like 30 years for residential energy codes. A business owner, who is looking at energy efficiency investments relative to other business uses of her capital, might also feel that a discount rate of 15% reflects her value for future energy savings. On the other hand, an energy efficiency program planner or energy code developer could justify a 0% discount rate as representative of the future value of resource savings.

The table in Figure 75 provides guidance on selecting between the range of potential scalars.

A more comprehensive economic analysis might also consider measure interactions and analyze the impacts of numerous building elements as a system. For example, increasing the level of roof insulation can lead to the ability to downsize the cooling equipment. Selection of a gas chiller could potentially allow the downsizing of the electric service drop and load center for the building. The analysis in this Guideline did not include such synergies because of the complication of identifying situations in which the additional savings could be expected.

Appendix section A described the base case buildings that were used in the analysis for these Guidelines. A more comprehensive, targeted analysis would begin with an examination of these building descriptions to determine whether they are representative of the location of interest. The building design can greatly increase or decrease the cost effectiveness of various measures. For example, a base case office building with effective daylighting, reducing internal gains from lighting systems, and high performance glazing on the south, east and west, may have a small enough cooling load that high efficiency equipment will be less cost effective.

Finally, it is assumed in this analysis that a decision about the cost effectiveness of options is being made at the time of new construction. For program designers focusing on retrofit applications of these technologies, additional first costs will need to be included. This is less of an issue when the change-out is due to equipment failure and replacement is required. In the case of replacements for equipment that is still functioning, the incremental first cost will be the full cost of the new equipment minus the salvage value of the equipment removed. Obviously, the energy savings must be of much greater value to justify replacing equipment before the end of its useful life.

As this discussion illustrates, a thorough economic analysis of energy efficiency investments can require considerable thought and calculation. The scalar and SIR approach used throughout these Guidelines provide a convenient method for simplifying the economic analysis task. For many purposes, this will be sufficient, provided the decision-makers who will be relying on this analysis understand its limitations.

[1] For a more in-depth description, see *Plant Engineers and Managers Guide to Energy Conservation*, by Albert Thumann, Fairmont Press, Lilburn, GA 1989.

	Scalars for 8 year period				Scalars for 15 year period				Scalars for 30 year period			
	Escalation rates				Escalation rates				Escalation rates			
Discount Rates	**0%**	**2%**	4%	**6%**	**0%**	**2%**	**4%**	**6%**	**0%**	**2%**	**4%**	**6%**
0%	8.0	8.8	9.6	10.5	15.0	17.6	20.8	24.7	30.0	41.4	58.3	83.8
3%	7.0	7.7	8.4	9.1	11.9	13.9	16.2	19.0	19.6	25.9	35.0	48.3
5%	6.5	7.0	7.7	8.4	10.4	12.0	13.9	16.2	15.4	19.8	26.0	34.9
7%	6.0	6.5	7.1	7.7	9.1	10.4	12.0	13.9	12.4	15.5	19.9	26.0
9%	5.5	6.0	6.5	7.1	8.1	9.2	10.5	12.1	10.3	12.6	15.7	20.0
11%	5.1	5.6	6.0	6.5	7.2	8.1	9.3	10.6	8.7	10.4	12.8	15.9
13%	4.8	5.2	5.6	6.1	6.5	7.3	8.2	9.3	7.5	8.8	10.6	12.9
15%	4.5	4.8	5.2	5.6	5.8	6.5	7.4	8.3	6.6	7.6	9.0	10.8

Figure 74 - Range of Typical Scalars

INPUT	IF INPUT:	THEN SCALAR TENDS TO:
Measure Life	Increases	Increase
Discount Rate	Increases	Decrease
Energy Cost Escalation Rate	Increases	Increase
Maintenance Escalation Rate	Increases	Decrease
Inflation Rate	Increases	Decrease
Mortgage Interest Rate	Increases	Decrease
Tax Advantage	Increases	Increase

Figure 75 - Variable Effects on Scalar