An Advanced
Technical Article

(Editor's Note: This is an important and complex analysis of a fundamental cogeneration subject.)

Distributed Cogeneration vs. Centralized Generation:

A Technical Comparison

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ABSTRACT

Three distributed cogeneration (DG) and three centralized electricity technologies were compared for fuel use, private costs and externality costs from CO_2, SO_2 and NO_X emissions. This generalized feasibility comparison investigated the benefits of Cogen/DG over a range of heat to power ratios (HPR). IC engines are found to be both economical and environmentally friendly. Micro-turbines are even better. Therefore, Cogen/DG provides economic, fuel use, and emissions savings in applications with well matched and consistent demands for electricity and heat.

1. INTRODUCTION

Natural gas-fired distributed cogeneration (DG) units are highly energy efficient (up to 90% HHV*) due to cogeneration of electricity and heat, and avoidance of electricity transmission losses. An emerging family of gas-fired DG technologies (internal combustion [IC] engines, micro-turbines, fuel cells, Stirling engines etc.) have attracted considerable interest of policy makers for their potential to reduce CO_2 emissions (European Commission, 1997; NREL, 2000). IC engines are currently the most established gas-fired Cogen/DG technology¶.

Cogen/DG represents an alternative paradigm of energy generation and supply. Continuing technical and economic developments in DG may lead to the integration of the electric and natural gas supply industries through on-site energy production (Patterson, 2000). However, a vigorous debate continues on the system implications of generating energy near the point of demand (Cogen Europe, 1999).

This article details a comparison between six gas-fired energy technologies (3 are DG, 3 are centralized), to meet electrical demands and space and water heating requirements. The comparison is made in terms of fuel use, economic costs and emissions characteristics. The technology comparison includes energy losses and costs incurred in transporting energy. For a meaningful comparison, a technology's ability to meet a range of heat to power ratios† (from 0 to 4) is compared. This comparison builds upon earlier studies (for example, Porter and Mastanaiah, 1982; Horlock, 1987; Pak and Suzuki, 1990), by considering a wider range of technologies, specifically new DG technologies.

2. TECHNOLOGY COMPARISON

2.1. Fuel Use Comparison

In comparing the six technologies, plant operation methodology (heat led vs. electricity led), generation efficiency and heat to power ratio (HPR) are technology and site specific. Therefore, an electrical load

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*Higher Heating Value.

¶For example, as of 1998 IC engines of <1MWe accounted for 6% (i.e. 1,500 MWe) of installed electrical capacity in the Netherlands (EnergieNed, 1999).

†For reference, Florida has an average HPR of around 1:1, with New York at around 3:1.

of 1 and a heat load of HPR are used. By varying the HPR along the x-axis, we can make meaningful comparisons for technologies depending on the site's mix of energy requirements. This methodology is used throughout the article.

For each technology the electricity load is first met dependent on electrical efficiency (HPR=0). At this stage all heat is dumped (considered useless). As the HPR rises (i.e. heat is required) the cogen heat is used. As HPR increases further the cogeneration heat is exhausted and additional boilers are required to meet this heat load. Table 1 summarizes the comparison methodology.

Table 1. Summary of Cogeneration Comparison Methodology

	Electric efficiency (η_{CHP})	Max. HPR	Description of comparison methodology
CCGT	55%	0.73	Distribution losses are for electricity for conversion and transmission, Boiler conversion and distribution losses for heat
Cogen steam turbine	27%	2.52	Lowered electric efficiency for steam turbine in a district heating scheme. Distribution losses are for electricity for conversion and transmission, 50% heat loss in cogen heating and sequentially boiler conversion and distribution losses for heat
Cogen gas turbine	36%	1.64	Distribution losses are half gas/half electricity for conversion and transmission, 15% heat loss in cogen heating and sequentially boiler conversion and distribution losses for heat
IC Engine	29%	2.28	Distribution losses are for gas for conversion and transmission, NO heat loss in cogen heating and sequentially boiler conversion and distribution losses for heat
Micro-turbine	26%	2.65	Distribution losses are for gas for conversion and transmission, NO heat loss in cogen heating and sequentially boiler conversion and distribution losses for heat
Fuel Cell	45%	1.11	Distribution losses are for gas for conversion and transmission, NO heat loss in cogen heating and sequentially boiler conversion and distribution losses for heat

For a meaningful comparison, losses from the electricity, gas and heat networks is taken into consideration. Gas delivery is much more efficient than electricity transmission which is much more efficient than heat distribution. DG technologies (and boilers) will have gas distribution losses as this is the energy transfer method. Centralized plant transfers energy as electricity. Cogeneration heating networks have a distribution loss that is dependent on scale. We can define realistic values for boiler efficiency (η_B), baseline grid electrical efficiency (η_C), cogeneration electrical efficiency (η_{CHP}), and cogeneration heating efficiency (λ) including heat losses.

$$\eta_B \text{ (real)} = \alpha\, \eta_B$$

where α is the average gas distribution efficiency
= 98.7% (source: IEA, 1995).

$$\eta_C \text{ (real)} = \beta\, \eta_C$$

where β is the average electricity distribution efficiency
= 91.7% (source: EIA, 1999).

η_{CHP} (real) = $\alpha\, \eta_{CHP}$; for DG technologies
(gas as the transfer mechanism)

η_{CHP} (real) = $\alpha\, \eta_{CHP}$; for centralized technologies
(electricity as the transfer mechanism)

η_{CHP} (real) = $(\alpha + \beta)/2\ \eta_{CHP}$; for intermediate technologies
(gas turbines)

Lastly heat losses are related to scale, and thus the relative heat losses will be greater for a larger plant.

$$\lambda \text{ (real)} = \gamma\, \lambda$$

where γ is the heat loss percentage.
γ = 8% for distributed,
γ = 15% for intermediate and
γ = 50% for centralized plant.
(source: IDEA, 1983).

Therefore, Figure 1 gives the units of fuel to meet an electricity requirement of 1 and a heat requirement of HPR. This graphical representation will be followed throughout this technology comparison.

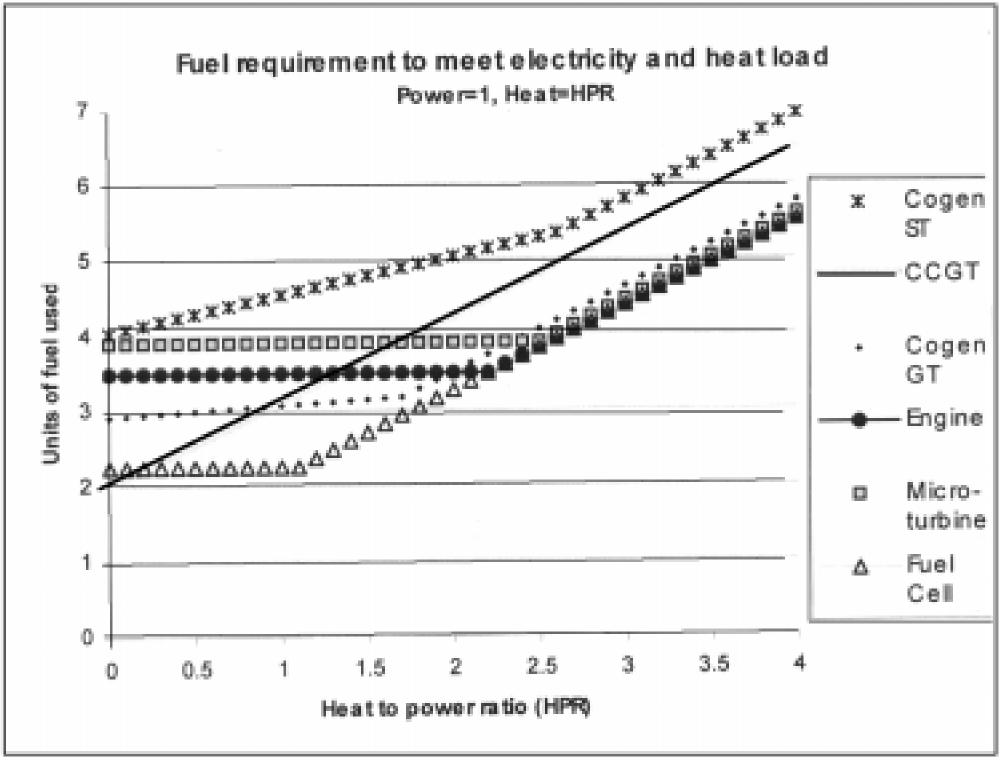

Figure 1: Fuel Use of Competing Energy Technologies.

When HPR=0 (y-intercept) the comparison is based on electrical efficiency and the distribution losses. These losses are low for DG technologies as the transfer medium is natural gas, and higher for centralized sources due to losses on an electricity network. For cogeneration sources the initial gradient is due to heat losses when utilizing the heat (DG sources have no heat loss over such a small network).

This gradient continues up to the limit of available heat from the cogeneration source. Past this point extra boilers are needed to supply the heat and their use determines the second gradient. Technologies that are not used as cogeneration (district heating) have their y-intercept determined by their electrical efficiency and the gradient by the use of boilers for heat.

Comparing the fuel use of technologies, we see the fuel cell is impressive with a high electrical efficiency and minimal heat losses. The other DG technologies are also attractive especially as more heat is required. Electrically efficient centralized CCGT plant is competitive at lower HPRs but use of boilers to replace the discarded heat makes them less attractive at higher HPRs. Cogen steam turbines are the most inefficient fuel-using technologies. Centralized steam turbines together with on-site boilers are still the most common electricity and heat generation method in developed countries.

On a fuel use basis, DG technologies provide an opportunity to improve overall efficiency of supply. This is especially true considering the average HPR of New York is around 3, and thus the full utilization of heat is even more attractive.

Therefore, looking at the dominant technologies over the range of expected HPR, DG technologies are consistently more fuel efficient than centralized technologies with or without cogeneration. For example, compared to CCGTs, fuel cells are more efficient if the HPR>0.3, gas turbines if HPR>0.7, engines if HPR>1.4, and micro-turbines if HPR>1.7. Comparing DG technologies to gas turbines, fuel cells are always more efficient, engines are if HPR>2 and micro-turbines are if HPR>2.4.

On a fuel-use only basis the policy implication, if saving energy (or CO_2 as all technologies are gas-fired) is the goal, would be to support the adoption of fuel cells and other DG energy technologies.

2.2. Cost Comparison

The underlying technology characteristics determining private costs for an investor in energy plant are captured in a simple model.

Similarly to the fuel use comparison, the technology comparison is based on meeting an electrical load of 1 and a heat load of HPR. In order to convert to monetary values this output is defined as power load = 1kW and heat load = HPR*kW. Thus the cost parameters can be expressed in terms of US¢/kWh and the overall comparison is in US¢ to meet the required power and heat loads. Table 2 details the technology parameters.

Parameters are taken from a number of sources, notably (EIA, 2000; EEBPP, 1994; Cler and Shepard, 1996; and UK DTI, 1998). The parameters used are designed to be representative and sensitivity analysis was carried out on a parametric basis. Sensitivity analysis on rising gas prices is detailed in this article. Major difficulties in parameter estimation include accurate costing for capital and maintenance costs which are influenced by site specific requirements and method of financing and ownership. The infrastructure costs of heat distribution are particularly difficult to generalize and have been extrapolated from the infrastructure costs of a gas distribution network.

The structural costs and network losses from electricity and gas distribution systems have been represented using the proxy of energy prices based on user categories. That is, the largest (centralized) installations have been allocated the lowest price band to reflect the ease of supplying gas or electricity to them. As the size threshold moves down to intermediate and decentralized sites the electricity and gas prices increase reflecting the investment cost to transport energy. The model is indexed by energy technology (j), thus:

$$\begin{aligned} T(j) &= \text{fuel cost } (j) \\ &+ \text{capital costs } (j) \\ &+ \text{O\&M costs } (j) \\ &+ \text{distribution infrastructure costs} \end{aligned}$$

where T(j) are the technology costs (in US¢) to meet power load of 1 and heat load of HPR*kW

and:

- Fuel cost is fuel required * representative (1999 US average) gas price (1.1¢/kWh or 2.93$/MCF)
- Capital cost (discount at 10% over 10 years) and O&M costs are incurred at HPR=0.

Table 2: Economic Model Parameters

	Units	*Steam turbine*	*CCGT*	*Gas turbine*	*Engine*	*Micro-turbine*	*Fuel cell*	*Boiler*
Capital cost	($/kWe)	500	550	600	700	800	3000	200
Capital cost (over 10 years)	(¢/kWh	0.833	0.917	1.000	1.167	1.333	5.000	0.167
O&M cost	(¢/kWh)	0.4	0.55	0.6	1.5	0.75	0.75	0.25
Electricity price	(¢/kWh)	5.483	5.483	6.834	8.209	8.209	8.209	-
Electricity transmission cost to point of use	(¢/kWh)	2.726	2.726	1.375	0	0	0	-
Gas price	(¢/kWh)	1.1	1.1	1.258	1.643	1.643	1.643	1.643
Gas transmission cost cost to point of use	(¢/kWh)	0	0	0.14	0.525	0.525	0.525	0.525
Heat transmission cost	(¢/kWh)	0.525	0.525	0.14	0	0	0	0
Efficiency (HHV)	%	27-36	45-55	36	29	26	45	90
Maximum HPR	number	2.52-1.64	1.11-0.73	1.64	2.28	2.65	1.11	-
Heat network efficiency	%	50	50	85	92	92	92	95

- Boiler O&M costs are given per HPR
- Electricity transmission cost (based on electricity price bands) is incurred at HPR = 0 for centralized plant, with half this cost for gas turbines and NO cost for distributed generation
- The gas transmission cost (based on gas price bands) is incurred at HPR=0 for DG plant (and boilers), with half this cost for gas turbines and NO cost for centralized generation
- The heat transmission cost is extrapolated from gas pipelines, and depends on the size of the centralized cogeneration scheme

Figure 2 combine the fuel costs with capital and operation costs to give the total private costs a user would pay to meet electricity and heat requirements.

Comparing for electricity production only (HPR=0), centralized CCGT plant is the lowest cost, with gas turbines second. Micro-turbines are the best DG technology, with fuel cells becoming uncompetitive due to high capital costs.

However, when we compare at an HPR of 3 (which is the average New York demand) and utilize boiler plant as supplemental heat, a very different picture emerges. Now DG (micro-turbines and IC engines) are superior, as heat produced at the point of use is utilized. Gas turbines are also competitive, but CCGTs with most heat from additional boiler plant are less attractive. For reference and to ensure the model results are realistic, Table 3 compares the technologies to what a 1999 consumer would have paid (using the US technology portfolio) to meet consistent electricity and heat requirements.

The US technology portfolio is largely electricity-only steam turbines and heat boiler plant. For electricity requirements (HPR=0), efficient centralized plant (CCGT) is best, but CCGT become less attractive as more heat is required. Cogen technologies become more attractive as their heat utilization rises and then more expensive as more supplemental boiler plant is used. DG technologies look excellent as HPR is in the common range of demand (HPR from 1 to 3), and at an HPR of 2, micro-turbines have total private costs of supply of only 55% of conventional energy costs. This supports promotion of DG.

As this technology comparison is focused on gas-fired technologies, this section briefly considers the cost effect on DG of increasing natural gas prices. Figure 3 illustrates the impact of a range of natural gas price increases from the 1999 US average (2.9 $/MCF) on savings

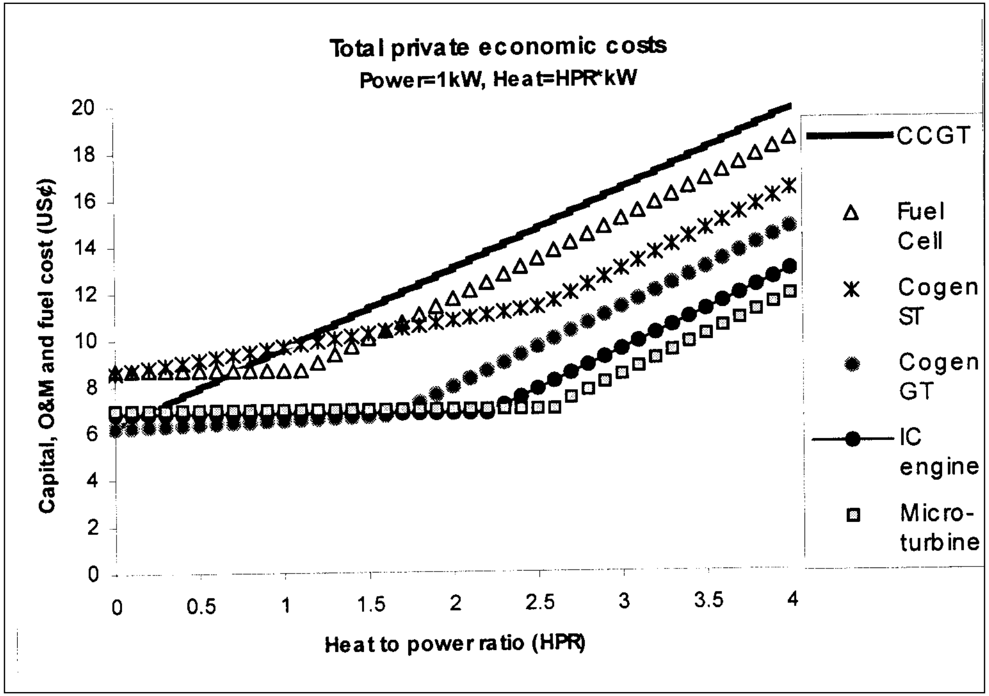

Figure 2. Costs of Competing Energy Technologies

Table 3. Technology Ranking of Total Private Costs

	Cost relative to US technology portfolio			
Technology (+ heat boilers)	HPR = 0	HPR = 1	HPR = 2	HPR = 3
Cogen steam turbine	104.5%	94.4%	87.6%	90.2%
CCGT	75.5%	93.7%	105.5%	114.0%
Cogen gas turbine	75.9%	63.5%	64.5%	78.8%
IC engine	83.0%	66.4%	55.3%	66.2%
Micro-turbine	84.7%	67.7%	56.4%	58.7%
Fuel Cell	105.8%	84.5%	95.2%	105.1%
US technology portfolio	100%	100%	100%	100%

delivered by IC engine cogen relative to gas-fired CCGT and coal-fired steam turbines. The comparison is made both for an HPR of 1:1 and an HPR of 3:1.

Even a 100% price increase in natural gas does not outweigh the cost savings of engines. Engines are more attractive at higher HPRs as their heat load is fully utilized. CCGT plant becomes more expensive than centralized coal generation under significant gas price hikes. Comparing the costs savings of engines relative to CCGT plant, higher gas prices result in greater savings only at higher heat requirements. This is because at lower heat needs, some of the heat output from an engine is not used and overall gas use is higher than the combination of CCGT and boiler plant.

2.3. Social Cost Comparison

The emission of four pollutants from the six energy generation technologies are considered: carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_X) and carbon monoxide (CO). Main sources used

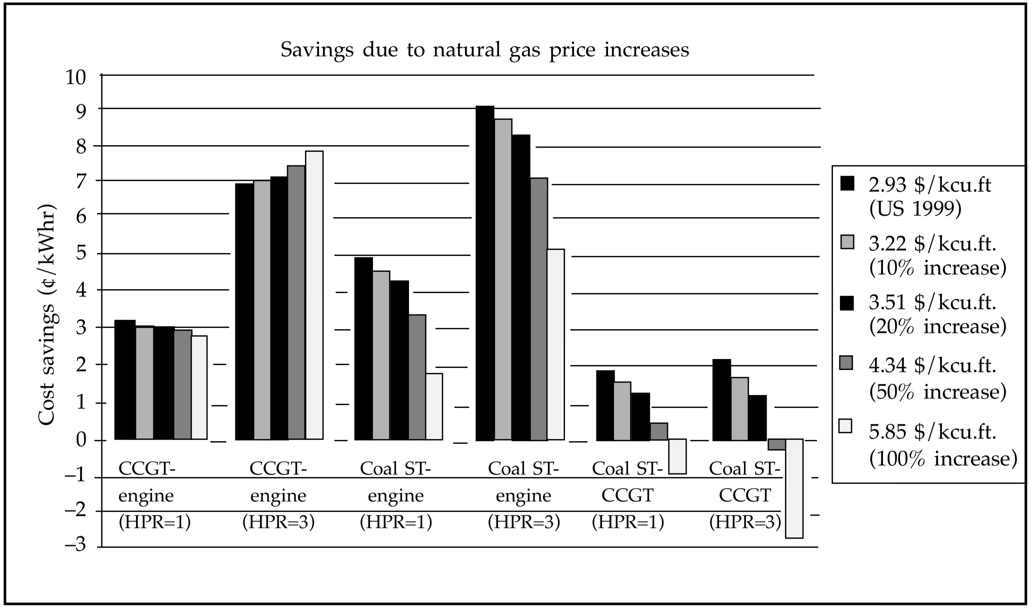

Figure 3. Distributed Cogeneration Cost Savings and Natural Price Increases.

for data on emissions, control options and control costs are (EPA, 1998; EEBPP, 1994; Flagan and Seinfeld, 1988; STAPPA and ALAPCO, 1994; UK DTI, 1998).

Emission of CO_2 and SO_2 are only related to the amount of carbon and sulfur in the fuel and by the efficiency of energy production. To compare our six technologies as well as illustrate the improvements in switching to a gas fired technology, we will include a reference case of a portfolio of current US generation plant. The largest proportion of this portfolio is dominated by coal-fired generation. Table 4 details emissions in kg/MWhr* for CO_2 and SO_2.

Table 4: CO_2 and SO_2 Emission Factors.

Technology	*Plant efficiency (%)*	*CO_2 (kg/MWhr)*	*SO_2 (kg/MWhr)*
Steam turbine	27-36	667-500	0
CCGT	45-55	400-327	0
Gas turbine	36	500	0
Engine	29	621	0
Micro-turbine	26	692	0
Fuel cell	45	400	0
US technology portfolio	36	770	9¶
Gas-fired boiler	90	200	0

Emissions of nitrogen oxides and carbon monoxide are defined by the combustion characteristics of the technology. NO_X emissions and common control methods and their effectiveness are given in Table 5. Thermal NO_X control options together with their effectiveness are also given.

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*kg/MWhr is an output measure and so accounts for efficiency of production. To convert from kg/MWh to the input measure of lbs/MMBtu, multiply by the efficiency, multiply by 0.293 for MWh to MMBtu and multiply by 2.2 for kg to lbs

¶SO_2 emissions of 9 kg/MWhr output measure corresponds to 2.1lbs/MMBtu (input measure). For reference the Clean Air Act standard for US plants in year 1995 is 2.5lbs/MMBtu (10.7kg/MWhr) and in year 2000 is 1.2lbs/MMBtu (5.2kg/MWhr).

Table 5: NO_X and CO Emission Factors.

	NO_X (kg/MWhr)	CO (kg/MWhr)	Gas-fired plant NO_X control technology	NO_X reduction (%)
Steam turbine	1.05	0	Low NO_X burners Lean burn Over-firing SCR	10-25 10-45 30-50 80-95
CCGT	0.78	0	H_2O injection SCR	70-90 90
Gas turbine	0.18	0	H_2O injection SCR	70-90 90
IC engine	(0.8-1.2) - controlled (8-12)	(0.2-0.3) controlled (2-3)	Lean burn Ignition timing SCR	5-30 0-20 90
Micro-turbine	0.03	0	SCR	90
Fuel cell	negligible	0	—	—
US technology portfolio	1.7	0	—	—
Gas-fired boiler	0.5	0	—	—

Using shadow prices to quantify the environmental externalities of emissions offers a tool to incorporate emissions reductions into economic and policy tools. Median estimates of shadow prices by Oak Ridge National Laboratory (1995) on US electric utilities and via a meta-study of externality estimates by Matthew and Lave (2000), are presented in Table 6. These shadow prices are based on a series of in-depth case studies on emissions from the US electric utility sector.

Table 6: Shadow Prices from Electric Utility Emissions.

	US $/kg
Carbon Dioxide: CO_2	0.017
Sulfur Dioxide: SO_2	1.800
Nitrogen Oxides: NO_X	1.086
Carbon Monoxide: CO	0.562
Methane: CH_4	170
Volatile Organic Compounds: VOC	398
Nitrous Oxide: N_2O	2,981

In keeping with the methodology used in the previous comparison sections, Figure 4 compares the emission externalities of our comparison cogeneration technologies in meeting an electricity load of 1kW and a heat load of HPR*kW.

As we are only comparing gas fired technologies, there are no sulfur emissions. This is contrasted to the figure for the US average which has a significant amount of centralized coal plant (>50% of installed capacity) as well as oil fired peaking plants. All gas fired technologies offer significant externality savings compared to the current US generation mix.

CO_2 emissions are dependent on the efficiency of the plant with CCGT and fuel cells producing least CO_2. IC engines that are not controlled via a catalytic converter pay a large externality penalty in terms of NO_X and also CO emissions. With a catalytic converter fitted, these emissions are reduced by 90% and emission externalities from engines

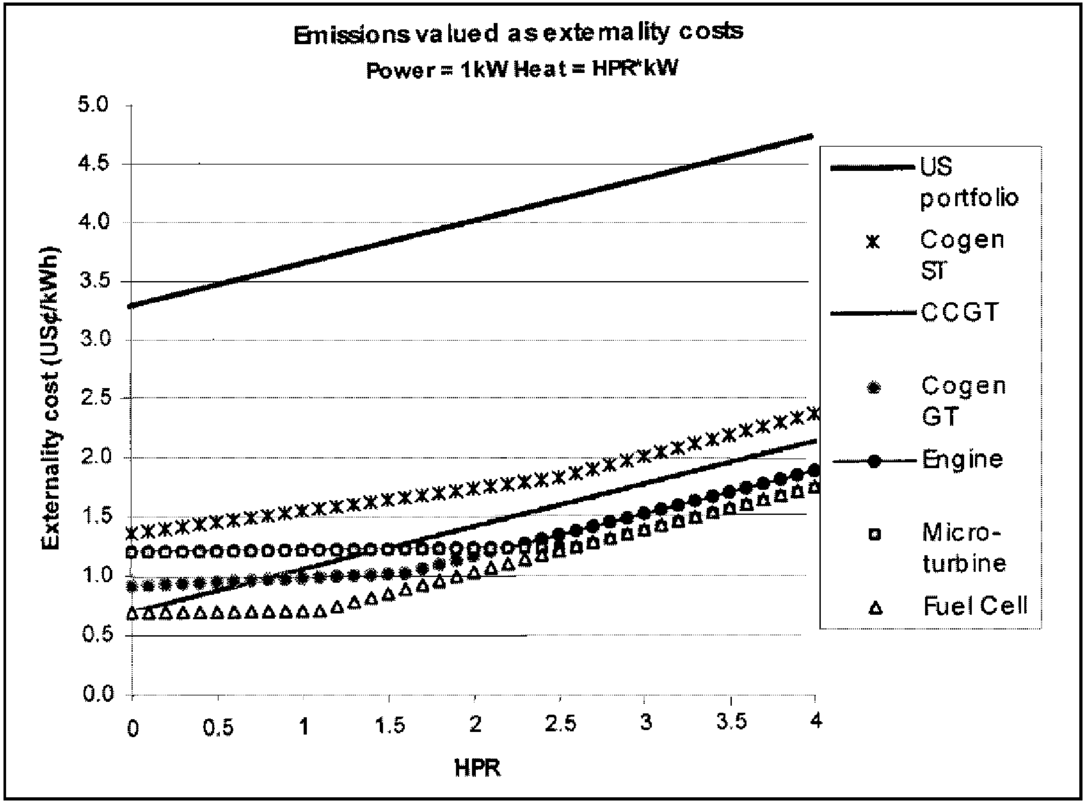

Figure 4: Emission costs of Competing Energy Technologies.

become comparable with other energy technologies. The rest of our comparison considers catalytic controlled IC engines.

Fuel cells, gas turbines and CCGT plant have the lowest externality costs. At higher HPRs micro-turbines and IC engines are also very competitive due to the use of cogen heat and the minimal distribution losses. It is noted that externality costs are significant, at approximately 15% of private economic costs.

2.4. Final Technology Comparison

Finally, we can combine the fuel costs, the technology costs (capital, O&M and infrastructure) and emissions externality costs. This gives the most complete gas-fired technology comparison, as detailed in Figures 5a and 5b (in more detail). Note that this comparison is still from the end-user perspective.

Micro-turbines are the lowest cost technology, especially at higher heat loads. IC engines are also very competitive providing their NO_X and CO emissions are controlled. Gas turbines (in this comparison located at an intermediate stage in the distribution process) also offer low overall costs especially at lower heat loads. Centralized plant suffers due to high distribution costs and losses. Cogeneration (or district heating) improves their performance. Fuel cells offer excellent fuel use and externality costs, but their current high capital costs reduce their competitiveness.

3. DISCUSSION

3.1. Technology Comparison Conclusions

Distributed cogeneration (DG) and centralized technologies were compared to meet different demand requirements. This was carried out over a range of heat to power ratios (HPR). Heat only boilers were employed for supplemental loads. Fuel use, private costs and emission externalities were considered.

On fuel use alone, the most efficient technologies over the range of expected HPR were investigated. Comparing DG technologies to CCGT plus heat boiler plant, fuel cells are more efficient if the HPR>0.3, gas turbines if HPR>0.7, engines if HPR>1.4, and micro-turbines if HPR>1.7. Comparing DG to gas turbines, fuel cells are always more efficient, engines are if HPR>2 and micro-turbines are if HPR>2.4.

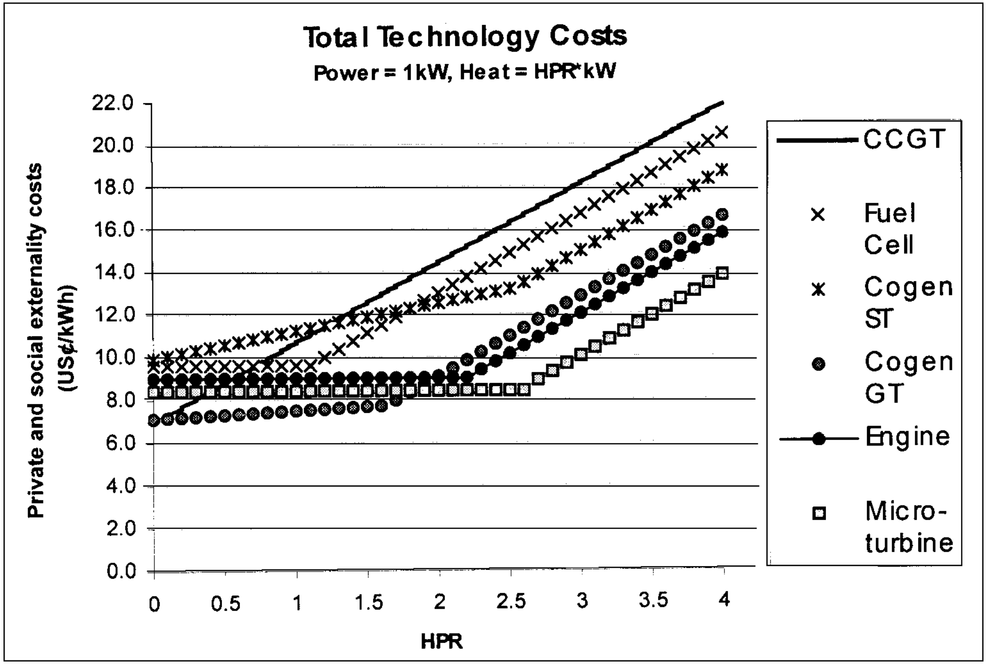

Figure 5a: Total Costs (private economic and emissions externalities) of Competing Energy Technologies.

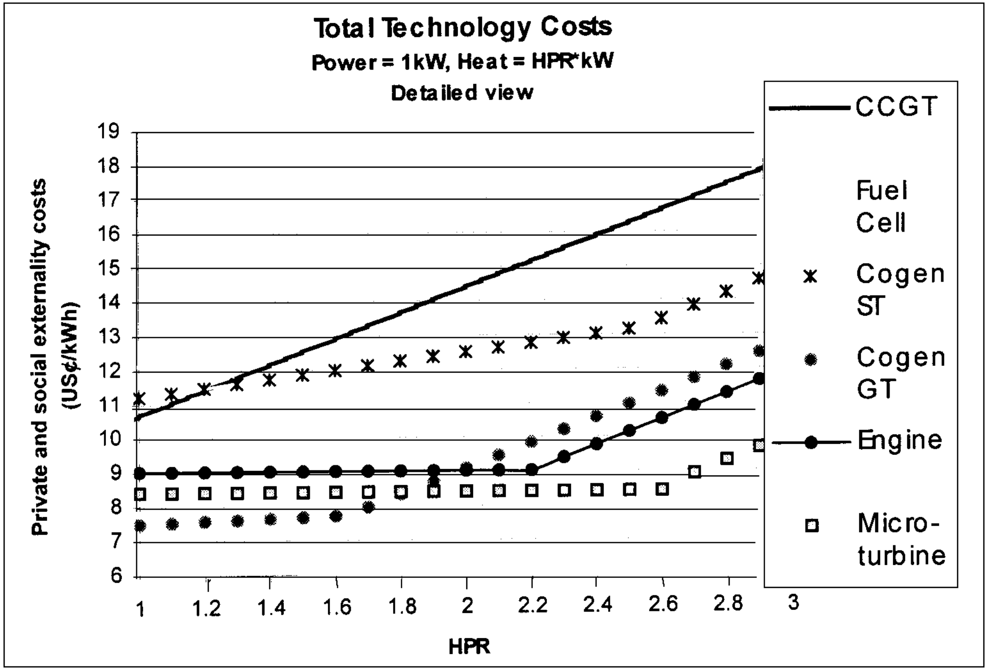

Figure 5b: Detailed View of Total Costs (private economic and emissions externalities) of Competing Energy Technologies.

In comparing technologies on total private costs, again it is crucial what energy demand these technologies meet. Comparing for electricity production only (HPR=0), centralized CCGT plant is the lowest cost, with gas turbines second. Micro-turbines are the best DG technology, with fuel cells becoming uncompetitive due to high capital costs.

However, comparing at an HPR of 3 (which is the average NY demand) and utilizing boiler plant as supplemental heat, a very different picture emerges. Now DG (micro-turbines and IC engines) are superior, as heat produced at the point of use is utilized. Gas turbines are also competitive, but CCGTs with most heat from additional boiler plant are less attractive.

For comparison, at an HPR of 2, micro-turbines have total private costs of only 55% of what a 1999 end user would pay to meet electricity and heat requirements. These cost advantages when meeting consistent energy demands support promotion of DG.

Finally, the fuel costs, the technology costs (capital, O&M and infrastructure) and emissions externality costs were combined. Micro-turbines are the lowest cost technology, especially at higher heat loads. IC engines are also very competitive providing their NO_X and CO emissions are controlled. Gas turbines also offer low overall costs especially at lower heat loads. Centralized plant suffers due to high distribution costs and energy losses.

Cogeneration improves their performance. Fuel cells offer excellent fuel use and externality costs, but their current high capital costs reduce their competitiveness. In conclusion, considering emission externalities increases the attractiveness of distributed cogeneration technologies.

3.2. Ongoing Work: System Comparison

The technology comparison demonstrated the cost and emission advantages of DG for single applications with consistent energy requirements. Ongoing work examines the implications of DG use in an integrated electricity and natural gas system. This research is discussed in (Strachan and Dowlatabadi, 2001).

If an integrated electricity and heat production and delivery system was constructed with no prior generation or delivery infrastructure, what would be the optimal system architecture? An optimization model was developed to minimize total investment and operating costs to meet seasonally varying power and heat requirements over a 15 year time horizon. This "green-field" model assumes no initial plant or networks to compare optimal DG and conventional supply systems. A mixed integer linear program (MILP) selects fixed investments in energy technologies and their operation regime, from a variety of centralized-distributed and electricity-heat-cogeneration options.

Unless distributed cogeneration (DG) has a significant market penetration, it cannot be an important tool for energy and emissions savings. Widespread use of DG represents an alternative system architecture for the generation and delivery of electricity and heat. The greenfield cost optimization found system cost savings from DG are substantial, at around 25% (depending on heat demand matching). Sensitivity analysis (especially for increased gas prices) found DG savings were robust over reasonable parameter values. Therefore, the cost savings of DG apply to an integrated electricity and natural gas system.

Widespread use of DG also reduced natural gas use by around a quarter. This reduction in natural gas use translate into comparable savings of CO_2. The DG solution saves annual CO_2 emissions by 24% compared to a gas steam turbine solution and by 50% when coal fired steam turbines are used. DG also produces considerable savings in SO_2 emissions and costs compared to coal steam turbines.

This model is a generalized feasibility study, and shows the advantages of a system based on DG vs. a system based on conventional electricity and heat only technologies.

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Neil obtained his Ph.D. from the interdisciplinary department of Engineering and Public Policy (EPP) at Carnegie Mellon University in December 2000. The Ph.D. thesis investigated the adoption and supply of distributed generation as a new structural paradigm for energy supply. From 1997 through 2000, Neil was a graduate researcher in the NSF Center for the Human Dimensions of Global Change. This major research center considers social and economic mechanisms are as important as technological developments in any solution to global climate change.

Prior to coming to the US, Neil was a technical and policy specialist in the UK government's energy efficiency and policy analysis division. He helped develop UK government strategy for energy efficiency and technology diffusion as energy markets were liberalized. Neil also holds an MS in science and technology policy from Sussex University (UK), and a BS (1st class) in physics from Leicester University (UK).

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