AN ASSESSMENT OF BIOMASS-POWERED MICROTURBINES AND THE POTENTIAL FOR APPLICATION IN RURAL CHINA

Paul M. Henderick

PU/CEES Report No. 322

January 2000

Center for Energy and Environmental Studies
Princeton Environmental Institute
Princeton University
Princeton, NJ 08544-5263
(609) 258-5445
www.princeton.edu/~cees

This paper is submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering from Princeton University, 2000.

ABSTRACT

A new, sub-megawatt power generation technology called the "microturbine" has just become commercial and is being targeted primarily for stationary, natural-gas-fueled power generation applications. This thesis considers the possibility of fueling microturbines with "producer gas," which is an unconventional, biomass-derived, low-Btu fuel. The motivation behind this investigation lies in a number of attractive characteristics of the microturbine relative to the standard reciprocating internal combustion engine.

In addition to reviewing the microturbine's status, origins and principles of operation, a model is constructed based on the recuperated Brayton cycle using ASPEN Plus, a flowsheet simulator. The model is used to establish the sensitivity of thermal conversion efficiency to a host of parameters. As a result, insight is gained into general behavior of the microturbine as well as considerations to make when integrating it into a larger system.

Issues surrounding the use of producer gas as a fuel for microturbines and potential solutions are discussed. To resolve the issue of handling the large mass flow of low-Btu fuel, use of catalytic combustion together with co-compression of air and fuel emerges as an attractive possibility. A concern with using producer gas is the host of contaminants it may carry, though limits for use in microturbines are not well-defined at present. Gas cleaning technologies will have to be employed. Use of a wet scrubber is an effective means for significantly reducing the loading of a variety of contaminants, and a fabric filter is essential for getting particulate loading down to levels that are likely acceptable by the microturbine.

The role a microturbine may be able to play in the context of a village in Jilin Province, China, is investigated. Systems that use crop residues to provide a 100-household village with (1) cooking gas, heat and power, (2) cooking gas and power, and (3) heat and power are described and compared. Economic success depends on a number of factors, in particular the ability to sell excess power generated to the grid at a good price. Overall success also depends on many social considerations, a number of which are just touched on here.

ACKNOWLEDGEMENTS

No thesis is the result of the efforts of a single person, hence the necessity of this page. First and foremost, I would like to thank the many individuals at the Center for Energy and Environmental Studies for their support: Dr. Eric Larson for his guidance and for always addressing my questions, Dr. Robert Williams for his insightful ideas and in particular for his extensive contributions to Chapter 4, my advisor Professor Robert Socolow for his "big-picture" thinking which helped pull the thesis together and for his encouragement, and Dr. Thomas Kreutz for instructing me in the ways of ASPEN and for some fruitful discussions. I extend a sincere "xie xie" to Dr. Haiming Jin and fellow graduate student Chao Chen for making communication with Chinese officials possible (我的中文不好 !). Furthermore, I would like to thank my thesis reader Professor Judy Wornat for reviewing my work and providing helpful feedback.

I gratefully acknowledge the sponsors of my graduate studies, without whom none of this would have been possible. They are the Department of Energy, W. Alton Jones Foundation, and the Energy Foundation.

As most graduate students tend to be human beings, there is a lot that goes into keeping them sane and in good spirits. For me, interaction with students from all over the world at the Graduate College and at the office during those long nights has been indispensable. Many thanks to them and to Princeton University for bringing them all together. As a student not only of engineering but more broadly of life, I would also like to thank the many people in the Dao community with whom I am learning that there is far more to life than "form and color, name and noise."

This thesis carries the identification 3056-T in the records of the Department of Mechanical and Aerospace Engineering.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 A NEW, SMALL PRIME MOVER

With the spread of electric utility deregulation, many businesses have realized that the time is ripe for innovation. New technologies for meeting electricity needs are being introduced and continue to be developed. Businesses and consumers alike now have more alternatives, ranging from the familiar electric utility to start-up companies dedicated to a new idea.

This thesis is concerned with one such new technology often called the "microturbine." Microturbines are small (~30-300 kW) gas turbines that have only very recently become commercial. The only other commercial options for power at this scale have traditionally been reciprocating internal combustion engines fueled by diesel, gasoline, or natural gas. The microturbine is a very different option for meeting the same needs. Advantages include greater fuel flexibility, mechanical simplicity arising from far fewer moving parts, lower maintenance and, in a number of designs, no need for oil lubrication. Disadvantages include a somewhat lower efficiency (with some designs) and higher prices at this market-entry stage of their development.

Current intended uses for the microturbine are quite varied. There is some exploration of uses for mobile power generation[1], but more attention is being given to stationary applications with natural gas as the primary fuel. Baseload power, peak shaving, standby power, cogeneration (power and hot water), and portable power are being given consideration. A much less

---

[1] Capstone Turbine Corporation, for instance, has one of its natural-gas-fueled units recharging the batteries of a hybrid electric bus in Chattanooga, Tennessee. After 23,000 miles of breakdown-free operation, the

conventional use is power generation using flare gas for fuel. Gas emitted from oil wells, which can be very high in hydrogen sulfide (dubbed "sour gas"), is often flared for lack of a better use. Capstone Turbine Corporation's microturbines are currently being used with this fuel in Alberta, Canada, where flare gas reduction is a serious issue[2].

The subject of this thesis is the use of the microturbine with another unconventional fuel – "producer gas" – and the potential for application in rural China. The following section describes what producer gas is and where it comes from. Section 1.3 motivates why application in China is being considered.

1.2 SMALL-SCALE BIOMASS GASIFICATION

Biomass gasification is the conversion of solid plant matter (e.g. wood chips, corn stalks, rice hulls, and nut shells) into a gaseous form called "producer gas." Converted to this state, the chemical energy in the carbonaceous biomass is much more versatile. With adequate cleaning, producer gas can be used in gas burners, various engines, fuel cells, and also for making other hydrocarbon fuels as in Fischer-Tropsch synthesis. A representative composition of the primary components in cleaned producer gas (as well as natural gas for comparison) is shown in Table 1.1. Indeed, gasification is key for solid fuels to be used in a multitude of interesting ways.

There are various designs and sizes of biomass gasifiers but one stands out as being appropriate for fueling a microturbine: the fixed-bed, air-blown downdraft gasifier. For biomass fuel capacities greater than about 1 megawatt, other designs, in particular fluidized beds, are the preferred technology (Larson, 1998). Fixed-bed gasifiers are much simpler and more economical

---

only maintenance required by the microturbine has been to change the air filter (Capstone product literature, 1999). See also O'Brien (1998) for information on AlliedSignal's activities in the hybrid vehicle area.

Table 1.1 Representative Fuel Gas Compositions

	Cleaned Producer Gas[a] (molar %)	Natural Gas[b] (molar %)
CO	19	
H_2	19	
CH_4	2.5	94.7
CO_2	9	0.2
N_2	50.5	2.3
C_2H_6		2.8
LHV (MJ/kg)	4.95	47.7
HHV (MJ/kg)	5.30	52.9

[a] primary constituents of producer gas generated by an air-blown downdraft gasifier after cleaning (Anonymous, 1998), (Mukunda et al, 1994)
[b] high quality Louisiana natural gas (Katofsky, 1993)

at the sub-megawatt scale of interest here. While it is true that use of oxygen instead of air would yield producer gas with a significantly greater heating value by avoiding dilution with nitrogen, it would also be prohibitively expensive at such small scales[3]. Economies of scale are unfavorable for oxygen plants just as they are for fluidized bed gasifiers. The reason that the downdraft gasifier is the fixed-bed gasifier of choice (except in applications just calling for heat) is that it destroys more of the tar[4] generated during pyrolysis than any other design. Unlike other designs, it supports a combustion and reduction zone through which tars must pass. The result is that most of the tar generated is burned and/or cracked. This is important because (1) tar can gum up equipment the producer gas comes into contact with, (2) oxygen-containing organics in tar can be strong acids, and (3) it is both costly and difficult to remove tar from a gas stream (see

---

[2] See the press releases at http://www.capstoneturbine.com/1/1.html for more information.

[3] A small PSA (pressure swing adsorption) unit for generating enough oxygen for a gasifier that produces 400 m^3/hr of producer gas is estimated to cost some $120,000 including an air compressor (see www.ogsi.com). This one unit could single-handedly double the total investment costs of an energy system for Jilin Province (see Appendix E).

[4] Here, the term "tar" loosely stands for the multitude of heavy organic species that can condense on surfaces they come in contact with potentially causing significant operational problems.

Section 3.3 for a discussion on gas cleaning). For small-scale power generation using biomass for fuel, air-blown downdraft gasification is the key technology[5].

Although downdraft gasifiers are not a commonplace technology today, they are certainly not a new one. Gasification appears to have been done with coal as early as the late 1700's (Foley et al, 1982). Experience with coal served as the basis for biomass gasification. The first significant application of small downdraft gasifiers using biomass was in Europe during World War II when oil restrictions came into effect. By 1942, about 900,000 vehicles (mostly in Europe) were being fueled by downdraft gasifiers with the most common fuel being wood (Foley et al, 1982). The eventual return of cheap oil put gasifier development on hold. Notable recent contributions to the development of downdraft biomass gasifiers come from India in particular where a number of designs that generate a gas containing remarkably little tar have been constructed and commercialized (DeLaquil, 1998; Mukunda et al, 1993).

A schematic showing a downdraft gasifier is presented in Figure 1.1. As biomass slowly flows down through the gasifier, it undergoes different processes in different regions. These regions, or zones, are labeled in the figure according to the dominant process that takes place there. Biomass at the top of the heap undergoes drying from exposure to heat being generated below. Underneath the drying zone is the pyrolysis zone, pyrolysis being the thermal breakdown and vaporization of matter in the absence of air[6]. For biomass, pyrolysis occurs typically at temperatures between 300 – 600 °C. As most of the matter in biomass is volatilizable – some 70-90% (Larson, 1993) – pyrolysis is a major step in the gasification process. A host of substances

---

[5] The extent to which this is true for an externally heated prime mover such as the Stirling engine depends on the type of fuel in question (see Section 1.4.2)

[6] This is true of closed-top gasifiers. In the more recent open-top gasifiers, biomass undergoes "flaming pyrolysis" in which some air is present but not enough for full oxidation. For discussion on closed-top versus open-top designs, see Mukunda et al (1993).

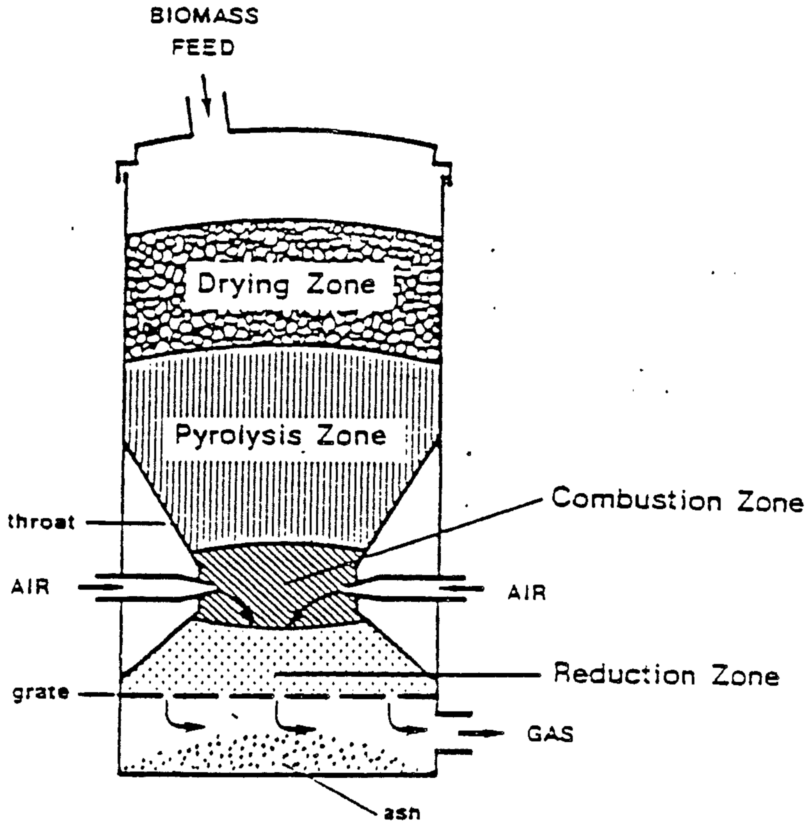


Figure 1.1 Downdraft gasifier schematic (Foley et al, 1982)

are generated during pyrolysis including gases, light and heavy liquids, water, and char[7] (Klass, 1998). It is in the pyrolysis step that tar and its precursors are formed. Parameters that determine the yield of these various substances are temperature, heating rate, biomass composition, particle size, and reaction time (Klass, 1998).

The products of pyrolysis next enter the combustion zone around which there are typically nozzles that admit a controlled amount of air for combustion. Many designs employ a throat at the combustion zone to create a uniformly hot region in which tars can be burned and/or cracked[8]. Tar and char combustion provide the heat necessary to drive the pyrolysis above.

---

[7] "Char" is the solid, carbon-rich component left behind after pyrolysis.

[8] Cracking a large organic compound means breaking it down into smaller (ideally non-condensing) organic species.

The characteristic process in the last zone is reduction of CO_2 and H_2O. Hot gases from the combustion zone are intercepted by unburned char sitting atop a grate below. Carbon in the char endothermically reduces the hot CO_2 and H_2O thereby producing more CO and H_2. After the char has been oxidized, the remaining mineral matter passes through the grate in the form of ash together with char remnants. Some form of mechanical removal mechanism is often employed to this end. In a downdraft gasifier that is operating properly, tar that survives the combustion zone gets cracked in the char bed of the reduction zone.

After leaving the reduction zone, producer gas is typically cleaned by some arrangement of contaminant removal technologies (described further in Section 3.3) because it carries a number of substances that could be harmful depending on the application. Particulate matter (soot and ash fragments) and tars are the contaminants that receive the most attention for the majority of applications. Another substance of concern is ammonia, which is derived from fuel-bound nitrogen in the feedstock. Ammonia readily oxidizes to NO_x when the producer gas is burned. Biomass also contains sulfur, though at much lower levels[9] than coal. Gasification converts sulfur primarily to H_2S which, like ammonia, readily oxidizes and forms SO_x. Sulfur can also be problematic in applications that involve catalysts which it may be able to poison by bonding to active sites (Katofsky, 1993). More will be said of producer gas contaminants, problems they cause, and methods for their removal in Sections 3.2 and 3.3.

A distinguishing feature of producer gas relative to more conventional fossil fuels is its low heating value. Because air is the only economically realistic oxidant to use for small-scale gasifiers, the resulting producer gas is heavily diluted with nitrogen thereby reducing the heating value of the gas (see Table 1.1). Typical air-blown downdraft gasifiers will produce a gas consisting of about 50% nitrogen and having a lower heating value between 4-6 MJ/Nm^3, which is about 10-15% of the heating value of natural gas (Stassen, 1995). How this low heating value relates to use with a microturbine is addressed in Section 3.1.

Today, there are a number of companies that manufacture and sell small gasifiers in various countries all over the world. The Biomass Energy Foundation webpage[10] lists some 30 companies from around the world that are involved with small gasifiers, though not many are fully commercial. The company which appears to have the most experience and the greatest number of commercial installations (more than 400) is Ankur Scientific Energy Technologies, or ASCENT. Not surprisingly, this Indian company also has one of the lowest tar producing gasifiers available. Its units are being used primarily for thermal energy supply and to fuel diesel engines to pump water and generate power (DeLaquil, 1998).

1.3 OPPORTUNITY IN RURAL CHINA

A special opportunity for the advancement of biomass-derived energy currently presents itself in many eastern provinces of China. Often, an abundance of agricultural residues is available that is increasingly in excess of local needs. As farmers' incomes grow, they turn away from using traditional fuels like corn stalks for cooking and heating and instead turn to fuels like coal which are more costly but much more convenient to use. The open burning of excess residues in the fields has resulted in an air pollution problem significant enough to have necessitated closure of airports, to say nothing of human health effects. Recent legislation has

---

[9] Typically 0.01 to 0.1% by weight as compared with coal which can be up to 5% by weight sulfur (Katofsky, 1993).

[10] See http://www.webpan.com/bef/small.htm

gone so far as to make burning crop residues a criminal act under certain circumstances[11]. Instead of just imposing laws, however, authorities are interested in finding ways to constructively turn this problem of excess biomass into an asset.

One possibility involves the gasification of the crop residues to generate producer gas. Having converted most of the chemical energy of the corn stalks into a gaseous form, the resource becomes much more versatile. Although poisonous due to its high carbon monoxide content, producer gas can be piped into homes with an added odorant for use as a cooking gas. This is currently being done in Shandong Province with numerous installations. If the producer gas is also used to fuel a prime mover to generate electrical power, waste heat can be used for residential heating, a need which far outweighs that for power during the cold winters of the northern provinces. To be sure, much can be done with crop residues once they have been converted to an adequately-cleaned gas.

In addition to investigating the possibility of fueling a microturbine with producer gas, a preliminary evaluation of the role it may play in Jilin Province (in northeastern China) will be performed in the last chapter of the thesis.

1.4 REVIEW OF TECHNOLOGICAL OPTIONS

While this thesis focuses on microturbines, the present section gives a brief characterization of a number of different small-scale prime movers as they relate to being fueled by producer gas. Performance, cost, and compatibility with producer gas are used to distinguish them. In so

---

[11] from the Xinhua Beijing News Agency, 5/25/1999. Critical areas are within a 15 kilometer radius of airports and within a 4 kilometer swath along railroads and highways.

doing, some of the important potential advantages and disadvantages of microturbines are highlighted.

1.4.1 INTERNAL COMBUSTION ENGINES (ICEs)

At present, the reciprocating internal combustion engine (primarily diesel) is the only prime mover used by commercial small-scale power plants that employ biomass gasification (termed BiG/ICEs). The reason for this is that ICEs have until recently been the only off-the-shelf technology at such a small scale.

ICEs for stationary power generation are mechanically quite similar to their automotive counterparts, but last significantly longer. An old car engine may have 200,000 miles on it which corresponds to about 5,700 hours at 35 miles per hour. In contrast, some Caterpillar ICE generator sets can go for 15,000 to 20,000 hours before needing a complete overhaul depending on the type and size. All ICEs are mechanically complicated having many moving parts such as pistons, valves, belts, pumps and the like, but are nevertheless a familiar technology. Maintaining a clean lubrication oil supply is critical for engine performance and life. This means having an oil tank, distribution system, filter, and pump not to mention the issue of disposing of dirty oil. A water cooling system is also needed to keep the engine from overheating and damaging itself.

When using producer gas to fuel ICEs, its tar and particulate content become critical parameters in determining whether operation is sustainable. Historically, tar has been the primary culprit behind many ICE failures when they were fueled with producer gas. Tar can condense on sensitive parts, like valves, and cause them to stick. Because tar is such a serious problem and needs to be better understood, Milne et al (1998) recently produced a report that, among other things, conducted a wide survey of the literature. Different estimates are given for ICE tar tolerance levels, but less than 30-50 mg/Nm^3 seems to have a lot of agreement. Particulate matter is also troublesome because it can greatly accelerate engine wear when it gets trapped in the lubricating oil and grinds away at the piston-cylinder interface. Limits usually given by engine manufacturers are less than 50 mg/Nm^3 but preferably less than 5 mg/Nm^3 (Stassen, 1995).

In addition to fuel contaminants, reciprocating internal combustion engines face the issues of supplemental fuel dependence and power output derating. The most common commercial small-scale system today uses a diesel engine supplemented by diesel fuel to assist ignition of the low-Btu producer gas. The supplement is necessary because producer gas/air mixtures do not auto-ignite under the brief high temperatures and pressures associated with diesel engine compression. Producer gas can typically displace about 70% of the engine's normal diesel consumption. While this significantly decreases fuel costs in situations where biomass is cheap, diesel fuel is still a necessity. Furthermore, the maximum output of a diesel engine (as well as a spark-ignition engine) will be lower than its rating when fueled with producer gas. ICEs combust one fixed volume of fuel-air mixture at a time. One of the main causes of derating is the lower energy content of the fuel-air *mixture* in the cylinder (fixed-volume). A stoichiometric mixture of air and producer gas has 70% of the energy of the *same volume* of a gasoline-air mixture (Reed et al, 1988). This means that 30% less chemical energy is available per cycle of the engine. Supplementing with diesel fuel partially alleviates this problem by enhancing the heating value, though derating is still quite variable with diesel engines. Field units have shown maximum power output can decrease from 10 to 40 percent (Stassen, 1995). ASCENT systems typically have a derating of 20% (Jain, 1998).

One way to avoid supplemental fossil fuel dependence is to burn only producer gas in a spark-ignition engine. Derating, however, increases typically to 50% (Stassen, 1995) partly due to the lack of a high-Btu supplement. Another drawback with gas engines is that they are significantly more expensive than diesel engines, about twice as much for the same power output (McKeon, 1998).

1.4.2 STIRLING ENGINES

The design space for Stirling engines is quite large as shown by the wide variety of patented designs that exist[12]. Regardless of their diversity, they all share the common characteristic of having a contained working gas. Figure 1.2 shows one simple Stirling engine design with all the basic components. Pistons are mechanically arranged in such a way as to shuttle the gas back and forth between hot and cold regions, with periodic expansions and compressions. Heat is transferred to the contained working gas in the heater, causing it to expand and do work on the pistons. The gas rejects heat to a cool region, which is typically maintained at a low temperature by some cooling system. A regenerator (typically some kind of dense metal mesh) enhances thermal efficiency by cooling hot gas before it enters the cold region and heating cool gas before it enters the hot region.

---

[12] To get a good idea of the spectrum of designs, see Walker (1980).

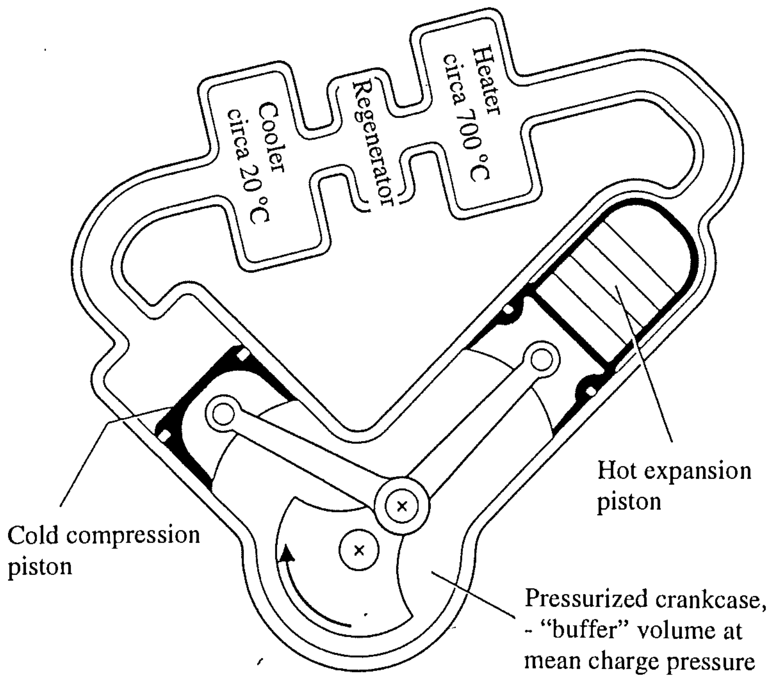


Figure 1.2 Stirling engine schematic (Hislop et al, 1993)

Although not commercially available, Stirling engines have a strong advantage over both ICEs and microturbines: because they are external combustion devices which rely on heat exchange, fuel gas contaminants never reach any of the sensitive moving parts of the engine. Particulates, for instance, never have the opportunity to erode pistons. Also, because producer gas doesn't need to be cooled before use, tars can be kept in the gas phase and burned thereby providing useful thermal energy and avoiding a tar disposal problem.

It needs to be mentioned, however, that this advantage is limited when dealing with biomass that has high ash and alkali content (such as corn stalks). A lesson can be learned from the Danish experience with wheat straw fired boilers (Jensen et al, 1997). Direct combustion of the straw gives rise to severe deposition on boiler surfaces. This is largely attributed to the straw's high potassium content (note that corn straw has a similar composition). In addition to fouling of surfaces, corrosion will be a serious concern especially for high temperature Stirlings. With combustion gas temperatures between 800-900 °C, these engines will be susceptible to Type I hot corrosion (see Section 3.2) arising from the presence of alkali sulfates and chlorides. Corrosion of thin heat transfer surfaces that contain a high-pressure working gas could be catastrophic. Some degree of gas cleaning, then, would be needed. With low alkali-content fuels like wood, such measures would most likely not be necessary. This was demonstrated, for instance, by Stirling Thermal Motors with wood chips (Ziph, 1998).

As mentioned earlier, the Stirling engine design space is large, and this may one day allow for its commercialization. Even so, Hislop and Packer (1993) comment that most modern Stirling engine companies have been focusing on design ideas developed by Philips of the Netherlands between 1940 and 1960. These designs call for high-speed, high-pressure operation with a low molecular weight working gas like hydrogen or helium to allow for better heat transfer and lower flow losses. While characteristics such as these do enhance efficiency[13] and power-to-weight ratios, they also dramatically increase cost. Preventing the high-pressure, low molecular weight working gas from leaking requires costly seals for instance. Components using expensive materials machined to very high tolerances are abundant. Hislop is investigating lower-pressure, lower-speed air-charged designs with the hope of eliminating most of the high-cost components of Philips-inspired designs (Hislop et al, 1993). It remains to be seen how such changes will ultimately affect cost and performance.

---

[13] The Stirling engine of this class which is perhaps the furthest along in its development is Stirling Thermal Motors' STM 4-120 model. It is reported to have a fuel-to-shaft efficiency of 40% using natural gas or gasoline (STM product literature).

1.4.3 FUEL CELLS

Today's fuel cell "rave" is centered around their automotive application. The particular kind of fuel cell in the spotlight is the PEM (proton-exchange membrane) design, which has an operating temperature of about 80 °C and exclusively uses hydrogen as a fuel. Unfortunately, PEM catalysts are readily poisoned by even very low concentrations of CO, one of the primary fuel components of producer gas. Units such as water-gas shift reactors and preferential oxidizers (PROX) would be needed to eliminate the CO prior to use by the PEM. While mass production of PEM fuel cells and fuel processing equipment in the future for automotive applications would certainly make PEMs more cost competitive with ICEs and microturbines, this has yet to occur.

A more suitable match for producer gas would be high-temperature fuel cells such as the solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC), both of which can use CO in addition to H_2 as a fuel. The water-gas shift reaction (which produces H_2) occurs readily within these fuel cells and CO does not bond strongly to active catalyst sites.

Another attractive feature of high temperature fuel cells is that their exhaust is sufficiently high-grade to power some kind of bottoming cycle, perhaps employing a gas turbine. Never-before-achieved efficiencies (fuel heating value to electricity) are achievable with these combined cycles. George (1997) estimates between 62 and 72%, depending on size, configuration and choice of equipment. Though attractive in a number of ways, SOFCs and MCFCs are further from commercialization than even PEMs. Consultants to DOE have projected $1000/kW installed costs for 3 MW SOFC systems in large volume production (George, 1997). Even so, contexts with high biomass prices could perhaps tip the scale in favor of fuel cells because of their superior efficiency.

Using the information in the microturbine column in Appendix A, a lifecycle levelized cost (LLC) equivalent to that of the diesel engine case is obtained for a \$1000/kW unit with 50% efficiency. For such a fuel cell to begin to compete with the microturbine would require biomass that is an order of magnitude more costly than that used in Table A1. The fuel cell gains an economic advantage for prices upwards of \$4/GJ (in which case the LLC of each would be in excess of 10 cents/kWh).

1.4.4 MICROTURBINES

Compared to the technologies previously discussed, microturbines have both advantages and disadvantages. Although less efficient than fuel cells and some stirling engines of comparable size, microturbines are a commercial technology based on proven technology. While it is difficult to talk about the cost microturbines are expected to attain once production ramps up, it is even more difficult with fuel cells and Stirling engines. ICEs, however, are a mature, familiar technology with a well-established infrastructure. Because of this, it would be more interesting and relevant to compare the microturbine with ICEs a bit more closely.

One prominent difference between microturbines and ICEs is the mechanical simplicity of the former. Fuel gas compressor aside (if needed), several microturbine designs have only one moving part: the shaft onto which the compressor, expander, and permanent magnet generator are attached (see Figure 1.3). This is in stark contrast with the mechanical complexity of the ICE. Further contributing to the microturbine's simplicity is the use of air bearings by a number of manufacturers. These bearings use airfoil structures to create a film of air upon which the high-RPM shaft is suspended. As a result, there is no need for an oil lubrication system that traditional bearings would require (i.e. no oil to buy regularly, no oil pump, oil filter, tank, lines,

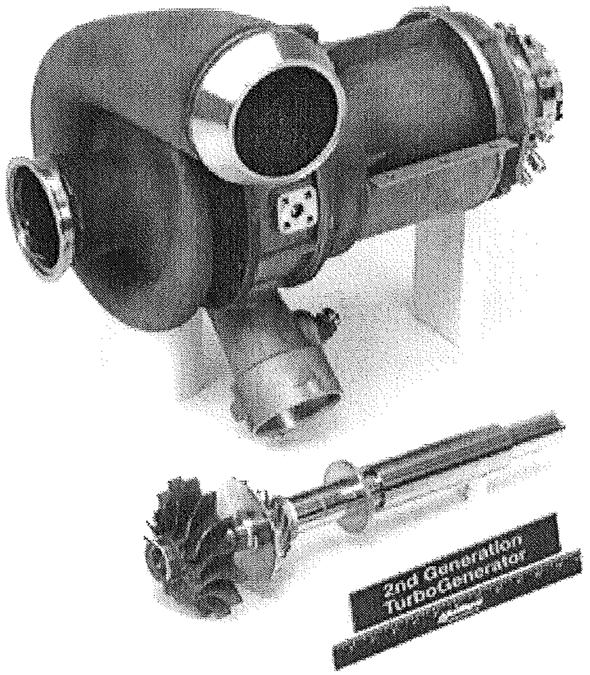


Figure 1.3 Microturbine engine core (source: AlliedSignal)

or dirty oil disposal to worry about). Other simplifications of some designs include no water cooling system and no starter motor[14]. Accompanying greater simplicity is the existence of a smaller number of failure modes and less maintenance.

With regard to being fueled with producer gas, the microturbine offers both advantages and disadvantages relative to ICEs. One very significant advantage is that it appears the microturbine can be configured to operate without derating (Chapter 3 discusses use with producer gas in detail). With gas turbines, operation is steady-state. There is no fixed volume of mixture with lower-than-conventional energy content that is periodically combusted. Instead, fuel is continuously combusted with a small fraction of the air from the compressor, and

---

[14] Start-up with Capstone and AlliedSignal models is achieved by using the generator in reverse as a motor. Power for doing this can either come from the grid or batteries.

subsequently mixed with the rest of the air to bring the temperature down. Achieving the same turbine inlet temperature with a low-Btu gas means having a larger fuel/air mass flow ratio. What makes this possible is the fact that normal operation is very lean. Therefore, air flow can be displaced by additional fuel flow without the concern of insufficient oxygen for combustion. A second significant advantage, in this case specifically over diesel engines, is that no supplemental fuel is required. The combination of these two advantages allows a much more expensive unit to compete with ICEs as shown in Appendix A.

One significant disadvantage gas turbines have with regard to fueling by producer gas is their greater sensitivity to contaminants. Turbine blades are susceptible to erosion, deposition, and corrosion caused by particulate matter and chemically aggressive species like alkali metals. Fuel quality concerns are discussed further in section 3.2.

1.5 THESIS ROADMAP

Microturbines, which have received little attention in the biomass arena, have just recently come to the marketplace and have some considerable advantages and disadvantages over alternatives like ICEs. All of the technologies described above may have a role to play with biomass, but the microturbine is selected here for further study.

Chapter 2 explains the origins of this technology, its commercial status, principles of operation, and looks at how the variation of different parameters affects performance. Chapter 3 proceeds to investigate use of producer gas in microturbines, addresses fuel quality concerns, and explores different gas cleaning technologies. The possibility of application in rural China is discussed in Chapter 4 with a focus on Jilin Province in particular. Concluding remarks as well as suggestions for future work are presented in the final chapter.

Chapter 1 References

Anonymous. (1998). "Power and Heat from Biomass Gasification," BG Systems product literature.

DeLaquil, P. (1998). "Small Scale Biomass Gasification Systems For Agricultural and Forest Product Industries," *Proceedings of Workshop on Small-Scale Power Generation from Biomass,* Working Group on Energy Strategies and Technologies, China Council for International Cooperation on Environment and Development, Changchun, China, 12-13 January, p.50-58.

Foley, G. and Barnard, G. (1982). "Biomass Gasification in Developing Countries," Final Report to the World Bank, Earthscan Technical Report #1, December.

George, R. (1997). "Westinghouse Program Overview," presented at Fuel Cells '97 Review Meeting, Morgantown, West Virginia, August 26-28.

Hislop, D. and Packer, J. (1993). "A Technical and Economic Assessment of Small Stirling Engines for Combined Heat and Power," ETSU Future Practice Report No. 32, January.

Jain, B.C. (1998). Ankur Scientific Energy Technologies, personal communication.

Jensen, P.A., Stenholm, M., Hald, P. (1997). "Deposition Investigation in Straw-Fired Boilers," *Energy & Fuels*, v11, n5, p.1048-1055.

Klass, D.L. (1998). *Biomass for Renewable Energy, Fuels, and Chemicals,* Academic Press, San Diego.

Katofsky, R.E. (1993). "The Production of Fluid Fuels from Biomass," Princeton University, Center for Energy and Environmental Studies Report No. 279, June.

Larson, E. (1993). "Technology for Electricity and Fuels from Biomass," *Annual Review of Energy and the Environment*, v18, p.567-630.

Larson, E. (1998). "Small-Scale Gasification-Based Biomass Power Generation," *Proceedings of Workshop on Small-Scale Power Generation from Biomass,* Working Group on Energy Strategies and Technologies, China Council for International Cooperation on Environment and Development, Changchun, China, 12-13 January, p.26-45.

McKeon, M. (1998). Foley Power Systems, personal communication.

Milne, T.A., Abatzoglou, N. and Evans, R.J. (1998). "Biomass Gasifier 'Tars': Their Nature, Formation, and Conversion," National Renewable Energy Laboratory report NREL/TP-570-25357, November.

Mukunda, H.S., Dasappa, S., Paul, P.J., Rajan, N.K.S., Shrinivasa, U. (1994). "Gasifiers and combustors for biomass – technology and field studies," *Energy for Sustainable Development*, v1, n3, September, p. 27-38.

Mukunda, H.S., Dasappa, S., and Shrinivasa, U. (1993). "Open-Top Wood Gasifiers," in *Renewable Energy: Sources for Fuels and Electricity*, eds., Johansson, Kelly, Reddy and Williams, Island Press, Washington D.C., p. 699-728.

O'Brien, P. (1998). Engineer, AlliedSignal, personal communication.

O'Brien, P. (1998). "Development of a 50-kW, Low-emission Turbogenerator for Hybrid Electric Vehicles," Paper No. 98-GT-400, American Society of Mechanical Engineers, New York.

Reed, T.B. and Das, A. (1988). "Handbook of Biomass Downdraft Gasifier Engine Systems," Solar Energy Research Institute, SERI/SP-271-3022, March.

Stassen, H.E. (1995). "Small-Scale Biomass Gasifiers for Heat and Power: A Global Review," World Bank Technical Paper Number 296, Energy Series, October.

Walker, G. (1980). *Stirling Engines*, Oxford University Press, New York.

Ziph, B. (1998). Engineer, Stirling Thermal Motors, personal communication.

2. MICROTURBINE TECHNOLOGY AND PRINCIPLES

2.1 BACKGROUND AND STATUS

As of 1999, microturbines for commercial use are now available for purchase. Capstone Turbine Corporation's 30 kW MicroTurbine™ was the first model to enter the marketplace. AlliedSignal's Parallon™ 75, a 75 kW turbogenerator, is expected to be commercial in the third quarter of 2000. Other companies like NREC are still in the testing phase of development. None too surprising, prices are high at this market-entry stage. The Parallon 75, for example, is estimated to have an installed cost of about $900/kW for a single unit. This is with a capital cost of about $52,000 and an installation cost of $15,000. Comparably small diesel generator sets, by comparison, will have capital costs of less than $200/kW. Installation can easily add 50% to give an installed cost of perhaps $300/kW. Because microturbines will be primarily natural gas fueled, however, a more fair comparison is made with natural gas engines, which can be considerably more expensive than diesel engines. Caterpillar's G3306NA gas reciprocating engine (85 kW and 100 kW at low and high compression ratios, respectively) has an uninstalled price of $35-40,000. This is $350-470/kW depending on the compression ratio. With a 50% installation cost, the total would be $530-710/kW, which is not as dramatic a departure from what is estimated for the Parallon 75.

Although it is only very recently that microturbines have become commercially available for small-scale power generation, small gas turbines have been in use in a number of other applications for decades. Military applications include turbojet engines for missile propulsion, stationary and mobile ground power, engine starting systems, and aircraft auxiliary power units

(APUs)[1]. Turbogenerators for aerospace applications have been in production for 30 to 40 years and currently sell for about $500/kW at the 60 kW scale (Myers, 1997).

This price, however, can not be taken to be indicative of what commercial microturbines will sell for when they also have matured. Turbogenerators for aerospace must meet many different and often more stringent requirements, as discussed by Myers (1997), and therefore call for more costly designs. For example, while the weight and volume of turbogenerators for aerospace are of utmost importance, they are much less so for commercial stationary power. While this fact would tend to make the former more costly, unit cost is a much lower consideration for the military than in the commercial marketplace. Because the annual production scale for military turbogenerators from a given manufacturer is relatively low, in the tens to hundreds, there may be significant economic gains to be made by virtue of larger-scale production for the commercial marketplace. All of the above strongly support Myers' point that a completely different approach needs to be taken for producing commercial turbogenerators.

A familiar technology that at first glance bears a strong resemblance to the engine core of commercial turbogenerators is the automotive turbocharger. The function of a turbocharger is to provide compressed air to engine cylinders thereby allowing more fuel to be burned every cycle. Consequently, an engine of a given size can achieve a greater power output. A typical turbocharger consists of a small radial compressor and radial turbine on the same shaft. Hot exhaust from an automobile's engine drives the turbine whose sole purpose is to power the compressor. With production in the millions per year, automotive turbochargers have retail[2] prices ranging from $500-$1,000 per unit, depending on the model and application.

---

[1] For photographs and further information, see http://www.microturbinc.com/Product.html

[2] Myers (1997) gives a manufacturing cost of $200 for a typical automotive turbocharger.

As with the turbogenerators for aerospace applications, turbochargers are a significantly different technology than commercial microturbines. In an analysis by Rodgers (1997) that addresses the issue of convertibility of turbochargers to turbogenerators, it is made clear that different design requirements give low prospects for conversion. Turbochargers have much lower demands on turbomachinery efficiency as well as life. Rodgers points out that even if the turbomachinery could be used in a turbogenerator, the cost of the additional components needed (controls, power conditioning or gearbox, recuperator, etc.) would make the turbocharger's contribution to cost-savings a small one.

While it is true that commercial microturbines are a distinct technology from both military turbogenerators and automotive turbochargers, certain aspects of these technologies are nevertheless being borrowed. A good example of this is AlliedSignal's turbogenerator. The idea of using air bearings together with a permanent magnet generator on the same shaft is based on the AlliedSignal APU which was developed for the U.S. Army's Armored Systems Modernization Program between 1991 and 1994 (O'Brien, 1998). The air bearings themselves have been manufactured by AlliedSignal since 1957 and are a part of cooling turbines which are used in over 45 kinds of aircraft like the DC-10 as well as in ground vehicles like the M1A1 main battle tank. Aspects of turbocharger technology are also being borrowed. An example is Northern Research and Engineering Corporation's (NREC) PowerWorks gas turbine cogeneration system, which features a "simple, 'ruggedized' turbocharger-based design."[3] This eclectic nature of microturbine technology has certainly assisted its development, but as a recent DOE meeting indicates, further development would be highly desirable.

The U.S. Department of Energy's (DOE) Office of Industrial Technologies (OIT) held a Microturbine Technology Summit in December of 1998 to discuss both where the technology stands and its prospects for the future (OIT, 1998). With efficiencies close to those of small spark-ignition gas engines but greater initial capital costs, microturbines will have a hard time competing with this more mature alternative in spite of its lower expected maintenance costs. The extent to which capital costs will come down with significant production volume is unknown. Manufacturers' price targets, however, include Capstone's $300/kW. To enhance performance, the idea of using ceramic components was raised, as were efficiency targets of 35% by 2005 and 40% by 2010. If such targets could be reached, the microturbine would be significantly more attractive than any reciprocating engine.

2.2 PRINCIPLES OF OPERATION

2.2.1 **THERMODYNAMICS**

The thermodynamic cycle through which large, conventional gas turbines extract power is called the Brayton cycle (refer to Figure 2.1). The turbine's compressor draws in air and raises its pressure and temperature (state $1 \rightarrow 2$). Fuel is burned in the combustor thereby heating the air to the turbine/expander inlet temperature (state $2 \rightarrow 3$). The hot, high-pressure gases expand through the expander (state $3 \rightarrow 4$) which extracts enough power to both drive the compressor and generate electricity. The simple, ideal Brayton cycle is depicted in the temperature-entropy plot alongside the gas turbine schematic in Figure 2.1. It is marked by perfectly isentropic turbomachinery and has no pressure drops or heat losses. Note that the lines connecting states 2 to 3 and 1 to 4 are isobars.

---

[3] NREC product literature

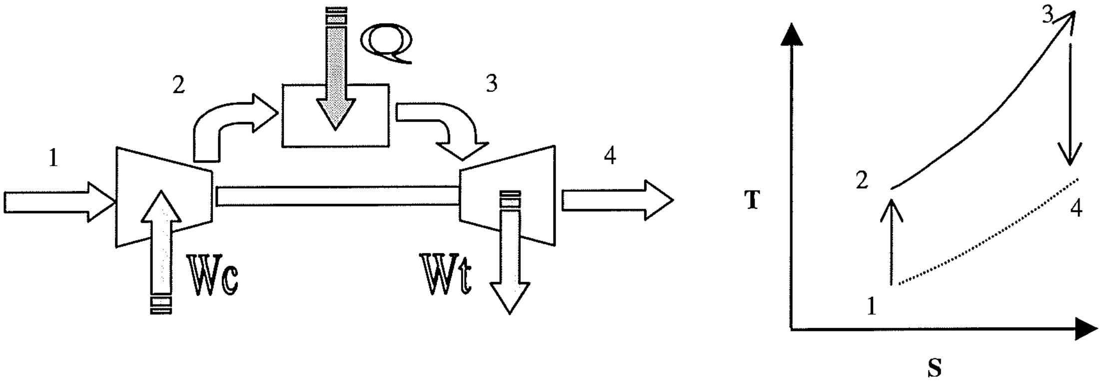


Figure 2.1 Gas turbine schematic and ideal Brayton cycle T-S diagram

Approximating the working fluid – typically air – as a perfect gas with constant specific heats, one can perform a simple energy balance on the compressor, combustor, and expander and arrive at the following expression for the thermal efficiency of the gas turbine:

$$\eta = \frac{\text{net work}}{\text{heat input}} = \frac{\mathrm{W_t} - \mathrm{W_c}}{Q} = \frac{c_p(T_3 - T_4) - c_p(T_2 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

This expression, derived from energy balances, has not made any claims of isentropic processes. As a result, it can be reasonably accurate. Consider General Electric's LM2500 gas turbine for instance. It has a published thermal efficiency of 37% corresponding to the conditions $T_1 = 15$ °C, $T_2 = 412$ °C [4], $T_3 = 1212$ °C, and $T_4 = 528$ °C. With these values, the simple energy balance gives a thermal efficiency of 36%.

The next step that the standard engineering thermodynamics textbook takes is to use the relationship for an isentropic process involving an ideal gas with constant specific heats:

---

[4] The compressor outlet temperature was determined using the published pressure ratio of 18 and approximate isentropic efficiency of 90%. Other temperatures are published in GE literature.

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

States 1 and 2 have the same entropy, and γ is the ratio of specific heats. With the further assumption of no pressure losses, the ratios of the temperatures of states 2 to 1 and 3 to 4 are equivalent, as seen through the expression above. A bit of algebra, as shown in Reynolds and Perkins (1977), leads to the simple expression:

$$\eta = 1 - \left(\frac{1}{PR}\right)^{(\gamma-1)/\gamma},$$

where PR is the pressure ratio. Applying this result to the LM2500 again, with its PR of 18, the ideal Brayton cycle efficiency expression gives a value of 56% ($\gamma = 1.4$). As pressure losses are not nearly great enough to explain such a large deviation from the ideal efficiency, the bulk of the inaccuracy is rightly attributed to the isentropic assumption. Nevertheless, this elegant expression correctly suggests the trend of higher PRs for greater efficiency (which in practice is true to a point). It does not, however, reveal the well-known significance of the turbine inlet temperature (TIT) in real-world gas turbines. Quite to the contrary, it suggests that the efficiency is *independent* of the TIT. This is because of the unrealistic assumption that $T_2/T_1 = T_3/T_4 = T_i/T_j$ for any T_i and T_j that correspond with an isentropic expansion over the same pressure ratio. A non-isentropic compression will result in a higher T_2, and a non-isentropic expansion will result in a higher T_4 thereby destroying the equivalence of the aforementioned ratios.

To understand why increasing the TIT improves performance, one must consider the expression for thermal efficiency before the isentropic assumption was made. For a higher TIT to increase η, the ratio of temperature differences must have a negative partial derivative with respect to the TIT, which is T_3.

$$\frac{\partial}{\partial T_3}\left[\frac{T_4-T_1}{T_3-T_2}\right]=\frac{\frac{\partial T_4}{\partial T_3}(T_3-T_2)-1(T_4-T_1)}{(T_3-T_2)^2}=\frac{\alpha(T_3-T_2)-(\alpha T_3-T_1)}{(T_3-T_2)^2}=\frac{T_1-\alpha T_2}{(T_3-T_2)^2}$$

The relationship $T_4 = \alpha T_3$, where $\alpha = \alpha(\eta_{exp}, PR, \gamma)$, has been used. It follows easily from the definition of isentropic efficiency[5] for an expander with the assumption of constant specific heats[6]. We find that the ratio of temperature differences has a negative partial derivative if the condition $\alpha > T_1/T_2$, or equivalently $T_4/T_3 > T_1/T_2$, is satisfied. Recall that if the compression and expansion were isentropic, we would have $T_4/T_3 = T_1/T_2$. However, both are non-isentropic resulting in larger values for T_4 and T_2, and consequently it is always true that $\alpha > T_1/T_2$ for a real process.

Conventional, large gas turbines therefore experience improvements in performance with higher TITs. The use of very special alloys and blade-cooling has allowed for quite high TITs to be sustained without damaging the expander. Long-life industrial gas turbines have TITs in excess of 1200 °C. Combined with very high compressor and expander isentropic efficiencies, these engines are able to achieve thermal efficiencies up to just over 40% (as is the case with GE's LM6000).

The new breed of tiny gas turbines, however, has neither the very high TITs nor high isentropic efficiencies. The small scale of the microturbine makes blade-cooling economically impractical and high isentropic efficiencies difficult to obtain with cost-effective turbomachinery. Efficiencies of about 15% result from typical conditions in which TIT = 875 °C, $\eta_{comp} = 78\%$, and

---

[5] $\eta_{exp} \equiv \frac{h_3 - h_4}{h_3 - h_{4s}} = \frac{c_p(T_3 - T_4)}{c_p(T_3 - T_{4s})}$ where the "s" subscript refers to a state that would result from an isentropic expansion. Note that the gas has been taken to be perfect and with constant specific heat.

$\eta_{exp} = 84\%$. The simple Brayton cycle does not serve microturbines nearly as well as their larger cousins.

To deal with the issue of dreadfully low efficiency, microturbine manufacturers have chosen to exploit the high-grade thermal energy in the exhaust of the expander. By passing the compressor and expander outlet streams through a heat exchanger called a "recuperator," formerly "waste" heat transferred to the compressor outlet stream serves to displace fuel energy Joule for Joule (see Figure 2.2).

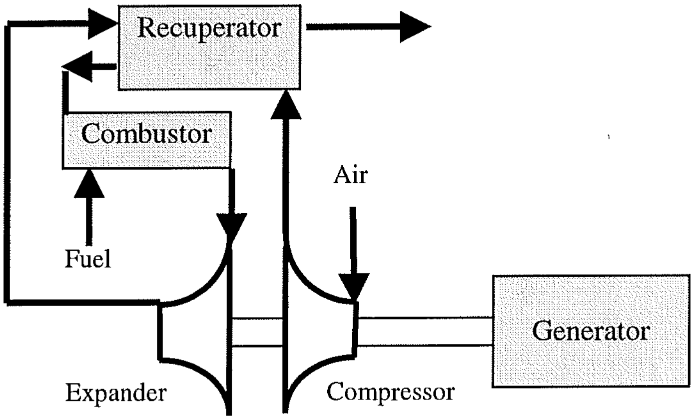


Figure 2.2 Recuperated microturbine schematic

The addition of a recuperator significantly affects the behavior of the system relative to the simple Brayton cycle. Consider the case of perfect recuperation. That is, the expander outlet stream heats the compressor outlet stream up to the expander outlet temperature, and the expander outlet stream is cooled to the compressor outlet temperature. In such a case, the heat input required to achieve the TIT is only $c_p(T_3-T_4)$. As before, energy balances give:

---

[6] Using ASPEN Plus to model an expander with an isentropic efficiency of 92% and PR of 18 over a range of TITs from 800 to 1400 °C reveals that α varies by only 4.5% from its lowest to highest value, which

$$\eta = \frac{\text{net work}}{\text{heat input}} = \frac{\mathrm{W_t} - \mathrm{W_c}}{Q} = \frac{c_p(T_3 - T_4) - c_p(T_2 - T_1)}{c_p(T_3 - T_4)} = 1 - \frac{(T_2 - T_1)}{(T_3 - T_4)}$$

Applying the isentropic relationship used previously to this new expression, it is found that:

$$\eta = 1 - \frac{PR^{(\gamma-1)/\gamma}}{T_3 / T_1}$$

The ideal, recuperated Brayton cycle[7] has a dramatically different form than that of the ideal, simple Brayton cycle. It indicates that performance improves with *lower* pressure ratios and has explicit dependence on both the TIT and compressor inlet temperature. This is made readily understandable upon observing a temperature-entropy plot of a low-PR Brayton cycle, as shown in Figure 2.3.

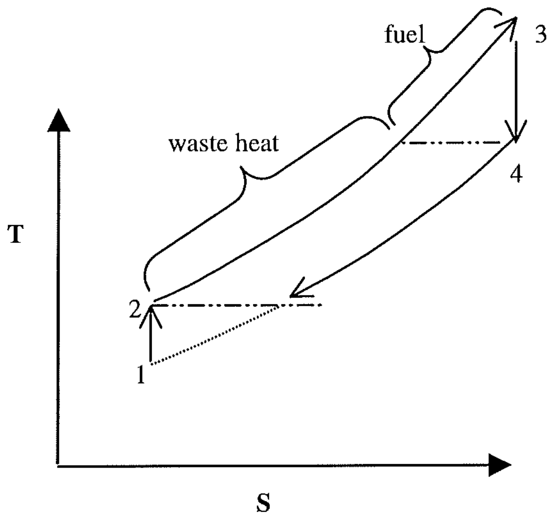


Figure 2.3 T-S diagram for a low PR, ideal recuperated Brayton cycle

Lowering T_1, raising T_3, and lowering the PR all have the same effect: more heat can be transferred from the expander outlet stream to the compressor outlet stream. Obviously, if T_4 is less than T_2, recuperation would not be possible. Such may be the case with higher PRs.

---

slowly increases with the TIT. This small variation is likely due to changes in specific heats.

The high efficiency predicted by the equation for the ideal recuperated Brayton cycle should not be surprising. For a conservative TIT of 875 °C with $T_1 = 15$ °C and PR = 3.5, an efficiency of 64% is calculated. Of course, this assumes isentropic turbomachinery and perfect recuperation. In practice, thermal-to-shaft energy efficiencies for microturbines are in the low 30s primarily because of recuperator effectivenesses in the mid to upper 80s and far from isentropic turbomachinery.

The basic thermodynamics having been reviewed, components of a typical microturbine will now be briefly walked through.

2.2.2 MICROTURBINE COMPONENTS

The recuperated Brayton cycle (see Figure 2.2) begins with the microturbine's compressor which is centrifugal rather than axial like those of larger gas turbines. Air is drawn into a centrifugal compressor axially and then turned to flow radially outward. For very small-scale flows, centrifugal compressors turn out to be more efficient than the axial design. Walsh et al (1998) point out that this is due to fixed manufacturing tolerances. As the scale of axial turbomachinery decreases, there are increasing relative levels of tip clearance, thickness of blades' leading and trailing edges, and surface roughness. Furthermore, centrifugal compressors have much lower unit costs, can give much larger pressure ratios over a single stage, are less prone to damage by foreign objects in the air, maintain better performance in the face of deposit build-up on blade surfaces, and can operate over a wider range of mass flows at a given rotational speed (Walsh et al, 1998; Cohen et al, 1987). A number of these characteristics will turn out to

---

[7] The recuperated Brayton cycle is discussed in many engineering thermodynamics textbooks, sometimes using the name "regenerative" instead of "recuperated." See Reynolds and Perkins (1977), for example.

be particularly attractive for the scenario in which producer gas and air are co-compressed (discussed in Section 3.1.2).

Centrifugal compressors consists of two components: the impeller and the diffuser. The impeller rotates at high speed imparting a large velocity to the air as well as a increase in static pressure. The flow subsequently enters the impeller's stationary housing – the diffuser. The diffuser has diverging flow channels which decelerate the flow thereby completing its increase in static pressure. Single-stage centrifugal compressors can easily achieve pressure ratios of 4:1 using aluminum-alloy impellers, but ratios such as 8:1 and greater require materials like titanium which can withstand the great stresses that accompany the elevated rotational speeds (Cohen et al, 1987).

After leaving the diffuser, the flow is directed through the recuperator where it picks up heat from the expander exhaust. As shown in the previous section, it is the recuperator which allows the microturbine to enter the arena of small-scale power generation. Without it, efficiencies would be dramatically lower than those of other alternatives. A high-performance recuperator is certainly important, but the amount of available heat it is able to transfer depends on the pressure drop, size, and cost that are willing to be tolerated. More will be said of the recuperator in section 2.4.2.

Having been heated in the recuperator, the air enters the combustion chamber, or simply the "combustor." Most microturbines will employ a non-catalytic combustor that employs some clever technique to mitigate NO_x emissions. Capstone's model, for instance, has a combustor that is based on the "RQL concept" (Craig, 1997). In this staged, premixed system, a Rich burn is followed by a Quick quench with additional air and ultimately a Lean burn. After the lean burn, the remainder of the air from the recuperator is mixed in thereby lowering the temperature to a value tolerable by the expander. The rich burn helps to maintain flame stability over the range of expected operating conditions. At the same time, oxygen levels are kept low thereby stemming NO_x formation. The lean burn keeps NO_x levels down via its low flame temperature. Capstone indicates that its microturbine emits less than 9 ppmv NO_x at 15% O_2. Less conventional ways to achieve low NO_x include cataytic combustion, which is described in Section 3.1.2.

Hot pressurized gases from the combustor expand through a radial expander. Like the centrifugal compressor, the radial expander has both stationary and moving components. Instead of a ring of diverging vanes, the radial expander has a ring of nozzles (converging vanes) that serve to give the flow a high velocity and direct it inwards to the rotor. The rotor is the rotating component that turns the flow to an axial direction and extracts power that subsequently drives both the compressor and the generator. Many of the reasons for using a radial expander over an axial one parallel those mentioned for the centrifugal compressor: higher isentropic efficiency at the small scale, much lower unit cost, and the ability to sustain much higher pressure ratios over a single stage.

As stated earlier, the expander does not have blade-cooling and so TITs are significantly lower that those of larger gas turbines. Superalloys like Inconel are used because of their ability to hold together under the extreme conditions of high temperature combined with large stresses that arise from high rotational speeds. There is some freedom afforded to the choice of TIT, but the tradeoff always faced for a higher temperature is shorter operational life. Because microturbines intended for the stationary power generation market must be long-lived, the trend is towards lower TITs such as 850-900 °C. Gases leave the expander at slightly above atmospheric pressure to allow for passage through the recuperator and possibly a heat recovery unit for providing hot water.

In microturbine designs that have the compressor, expander and generator all on the same shaft, high frequency AC power is generated. Such is the case with Capstone and AlliedSignal models which employ permanent magnet generators. To be put into useable form (e.g. 60 or 50 Hz), the high frequency power (e.g. 1600 Hz from Capstone's unit) is often first rectified to DC and then inverted to low frequency AC by power electronics. The efficiency of this conversion can be between 85 and 95% depending on the particular technology used and soundness of design (Hoffman, 1999). Power electronics are not the only solution, however. NREC's microturbine design uses a free turbine (on a separate shaft) connected to a gearbox, essentially trading electronic complexity for additional mechanical complexity.

Last but certainly not least, air bearings deserve a word of mention. Though not a new technology, as pointed out in Section 2.1, air bearings are being applied to commercial, small-scale power generation for the first time. They simplify the overall system by doing away with the need for lubricating oil and the associated pump, storage, and piping. Such simplifications are possible because the air bearings, both journal and thrust (see Figure 2.4), create a thin film of air which the rotating shaft rests upon. The spinning shaft creates a whirling flow of air around it which the airfoils in the bearings decelerate to increase the flow's static pressure. A pressurized film of air results which is sufficient to suspend the shaft in the case of the journal bearings and to handle axial loads in the case of the thrust bearings. No external supply of pressurized air is required (O'Brien, 1998).

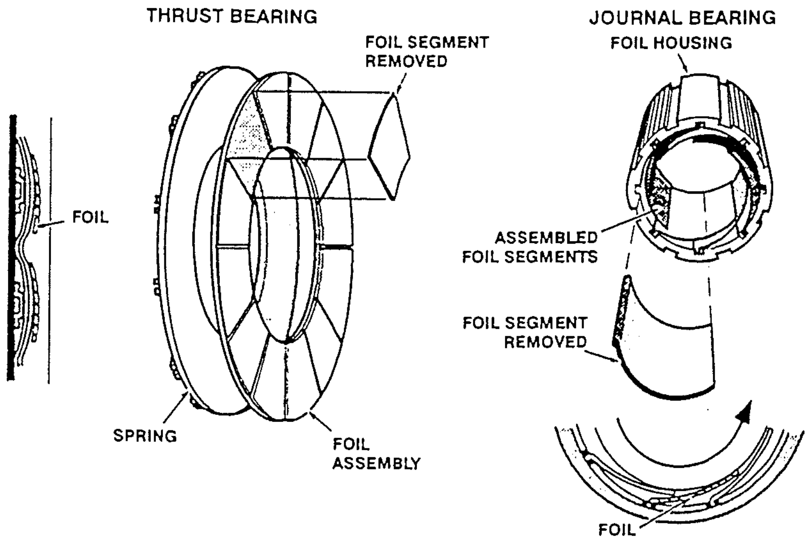


Figure 2.4 Air bearings schematic (O'Brien, 1998)

2.3 MODELING WITH ASPEN PLUS

To better understand what performance of the microturbine depends on (explored in section 2.4), a model of a recuperated gas turbine has been constructed using ASPEN Plus 10.0, a steady-state flowsheet simulator that is popular in industry. ASPEN can calculate equilibrium compositions, keeps track of flows of chemical species, mass, heat, and work, and allows the user to input his or her own FORTRAN code for customized operations. A flowsheet composed of blocks (compressors, reactors, heaters, etc.) connected by streams is constructed with all necessary input parameters supplied (such as the isentropic efficiency of a compressor or the heat duty of a reactor). Through an iterative process, ASPEN determines stream properties like temperature, pressure, and composition, and heat and work flows.

ASPEN is appropriate for basic modeling of microturbine performance on account of the microturbine's relative simplicity. With only one shaft, one stage of compression and expansion, and no blade-cooling, the microturbine is perhaps the simplest gas turbine in existence. Complex fluid mechanical calculations, such as those required to ascertain the effect of blade-cooling flows on performance, are beyond the scope of the program as well as this thesis. While off-design performance prediction would require empirical data, in particular turbomachinery performance maps, such an analysis will not be done here.

A schematic of the recuperated gas turbine ASPEN model is presented in Figure 2.5. The particular configuration depicted allows for investigation of two different ways in which the microturbine can be fueled: (1) with natural gas which is compressed using a separate fuel compressor (the conventional case) and (2) with producer gas which is compressed along with the air in the microturbine's compressor ("co-compression"). The first case is characteristic of the kinds of microturbines that are now becoming commercial. It will be used to calibrate the model. The second case is promising in that while it would require catalytic combustion (see Section 3.1.2), it avoids the use of a costly, inefficient fuel compressor.

To illustrate the inner workings of the model in more detail, the second case will be described further, as it is more relevant to the thesis. First, the compositions, temperatures, pressures and mass flow rates of the producer gas and air streams entering the compressor are specified. For the compressor block, pressure ratio and isentropic efficiency are entered. This determines the compressor work requirement and all information for the outlet stream which is directed to the recuperator. A small program called a "FORTRAN block" was written to calculate the temperature of the hot-side outlet of the recuperator (a heat exchanger block) based on a user-selected effectiveness. This determines the amount of heat transferred to the compressor outlet stream, and therefore the combustor inlet temperature. The block selected for the combustor is called a "Gibbs reactor," which determines the equilibrium composition of the input streams by minimizing the Gibbs free energy of the mixture. Such an approach is adequate

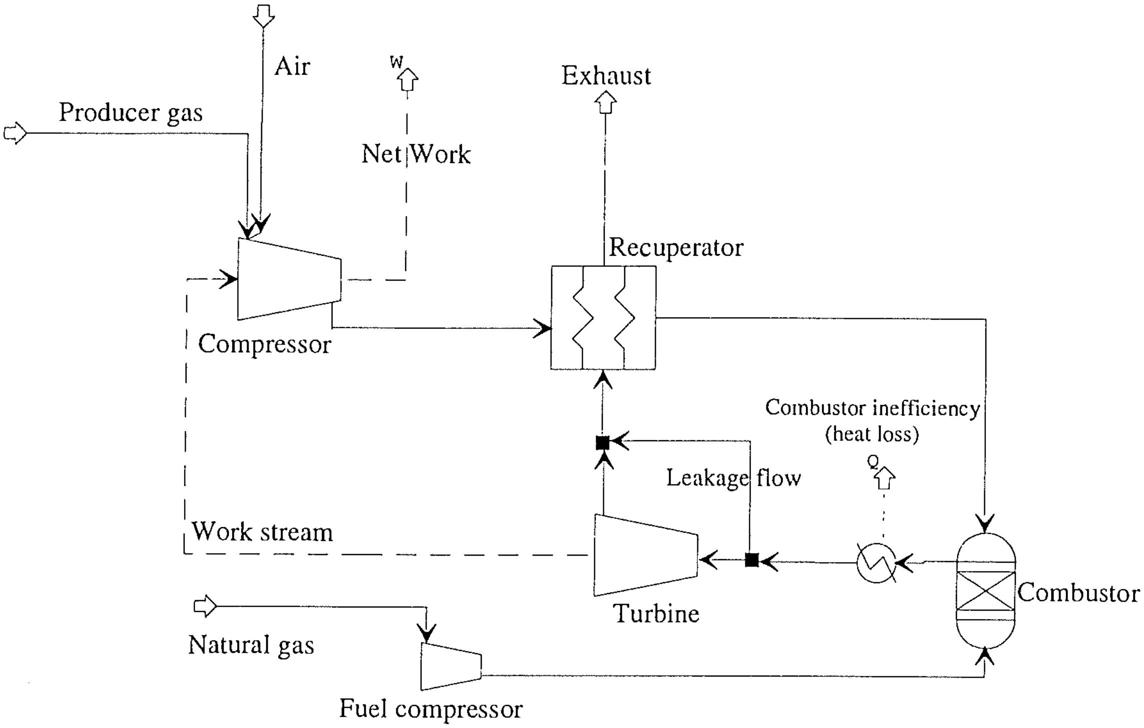


Figure 2.5 ASPEN model schematic

for modeling most kinds of combustors from an energetic standpoint since combustion efficiencies are typically in excess of 99%[8]. Because, in this case, the heat duty is set to zero, the heat released as a result of the Gibbs free energy minimization all goes towards raising the temperature of the equilibrium products. The Gibbs reactor calculates the resulting temperature and iterates as needed to converge on a compatible composition and temperature.

Following the Gibbs reactor is a heater which simulates the combustor's small inefficiency by removing an appropriate amount of heat (in this case, 0.5% of the fuel's heating value). The temperature at this point, just prior to the turbine, must be tightly controlled. A

---

[8] Non-equilibrium products of concern, like NO_x for instance, cannot be modeled this way.

"design specification" has been used to this end. It achieves the desired turbine inlet temperature by varying the airflow into the compressor in an iterative process. A stream splitter before the turbine inlet is used to simulate the small amount of flow leakage through the turbine which is not available to extract work from. The turbine block, like the compressor, is provided with an isentropic efficiency and in this case the outlet pressure. Another FORTRAN block determines the value of this outlet pressure based on an input pressure drop through the recuperator and a specified minimum recuperator outlet pressure. The same block assigns pressure drops to the recuperator and combustor as well. The last step is for the hot turbine exhaust to pass through the recuperator and transfer heat to the compressor outlet stream. Given the tightly coupled nature of the blocks in the model, ASPEN's usefulness readily becomes apparent, in particular when the effect of changing one parameter wants to be quickly ascertained.

A reference case based on performance and parameters of a natural gas-fired microturbine akin to that of AlliedSignal and Capstone is here established to calibrate the ASPEN model. It has been scaled to 75 kWe, the size of AlliedSignal's unit. The values input to the model and its output are shown in Table 2.1. The natural gas reference case is to stand for what one can expect from an off-the-shelf microturbine generator set operating on-design.

For the assumptions given in the table, the ASPEN model agrees well with AlliedSignal's published efficiency at full output and ISO conditions. The inputs, therefore, are assumed to be characteristic of actual microturbines and will be used with the other fueling configurations where appropriate. For the sensitivity analysis in the next section, the air/producer gas co-compression scheme will be used because of its greater relevance later in the thesis.

Table 2.1 Natural Gas Reference Case

MODEL INPUTS		COMMENTS
Turbine inlet temperature (°C)	875	About right for an uncooled microturbine (Prabhu, 1998). Relatively low TIT promotes longer life.
Pressure ratio	3.5	Low pressure ratios are associated with single-stage compressors, but this is favorable for recuperated cycles as shown in Sec 2.4.4
Compressor inlet temp (°C)	15	ISO conditions
Compressor inlet pressure (atm)	1	
Compressor isentropic efficiency (%)	78	78 and 84% are fairly characteristic design-point values for 50 kW turbogenerators with a single-stage compressor and turbine (Rodgers, 1997) but values vary from design to design.
Turbine isentropic efficiency (%)	84	
Turbine leakage fraction	0.0062	Fraction of turbine flow unavailable for extraction of work (Sieben, 1992)
Recuperator effectiveness (%)	86	Rodgers' base value is 85%, O'Brien (1998) reports 86%.
Combustion efficiency (%)	99.5	O'Brien gives >99.5% for AlliedSignal's catalytic combustor (intended for automotive application).
Recuperator pressure drops (%)	3	Good for hot-side pressure drop, a bit high for the cold-side (GRI, 1989)
Combustor pressure drop (%)	3	About 3% given in early AlliedSignal co-compression catalytic combustor scheme (GRI, 1989)
Gas compressor power requirements at full output (kW)	4	Berg (1999) reports 3-5 kW for the fuel compressor depending on the conditions of the fuel
Exhaust pressure (atm)	1.017	(GRI, 1989)
Natural gas flow rate (kg/hr)	19.7	
Generator efficiency (%)	94	O'Brien reports 93.8%
Power conditioning (%)	90	High speed permanent magnet generators produce high frequency AC power. Converting it to e.g. 60 Hz requires rectification and inversion.
MODEL OUTPUT		
Net AC Power Output (kWe)	75	Does not take into account fuel compressor power requirements
Air flow rate (kg/hr)	2685	Set by the desired TIT
Turbine outlet temperature (°C)	639	
Exhaust temperature (°C)	238	
Thermal efficiency (%) HHV	25.9	
LHV	28.7	28.5% minimum guaranteed at ISO conditions including auxiliaries less gas compressor; target is 30% (AlliedSignal website: www.alliedsignal.com/parallon/quickspec.html)
Net thermal efficiency (%) LHV	27.2	includes gas compressor

2.4 SIGNIFICANCE OF THERMODYNAMIC PARAMETERS

The goal here is to determine the relative significance that various parameters have to the overall performance of the microturbine when operating in a co-compression configuration with producer gas, the merits of which are described in Section 3.1.2. Several key parameters will be varied in the ASPEN model, and the effects will subsequently be compared. In each case, only one parameter will be varied at a time. All other parameters will be left at their reference value. Note that this is not, for instance, an off-design analysis in which numerous parameters can change by altering one. This analysis is not fixed on one particular microturbine, but rather seeks to understand what different collections of parameters mean as far as performance is concerned.

2.4.1 COMPRESSOR/TURBINE ISENTROPIC EFFICIENCY

The isentropic efficiency of turbomachinery is an indicator of performance. For compressors, it is the ratio of the work needed to isentropically raise the pressure of a fluid to the actual work requirement. High values mean that little work is wasted through frictional heating of the fluid above and beyond the heating which results from isentropic compression. For turbines, the isentropic efficiency is the ratio of the actual work extracted from a fluid to the work that could be extracted through an isentropic expansion. Fluid exiting a real turbine will be at a higher temperature than from an isentropic one, meaning some energy is not recovered. Efficiencies of these components play a pivotal role in determining the overall performance of a turbine, as indicated in Section 2.2.1.

One of the challenges faced by compressor and turbine wheel designers is always the same: how can the isentropic efficiency of the device be increased without an unreasonable increase in manufacturing cost? Along with this question is that of how significant an improvement would be to the overall system's performance.

Plotted in Figure 2.6 is the thermal efficiency of the microturbine generator set versus isentropic efficiency of both the turbine and the compressor. Note that their reference values are 0.84 and 0.78, respectively, as indicated by the enlarged data points. For the compressor at the design value, a 1 point increase (0.78 to 0.79) results in a 0.49 point increase in thermal efficiency, a sizeable effect. The analogous change in turbine performance yields a 0.57-point thermal efficiency gain for an even greater improvement. Because decreases in these parameters will have comparably large effects on performance, the importance of simply *preserving* them at design values becomes clear. This is part of the motivation behind minimizing the amount of particulate matter and corrosive substances that enter a gas turbine.

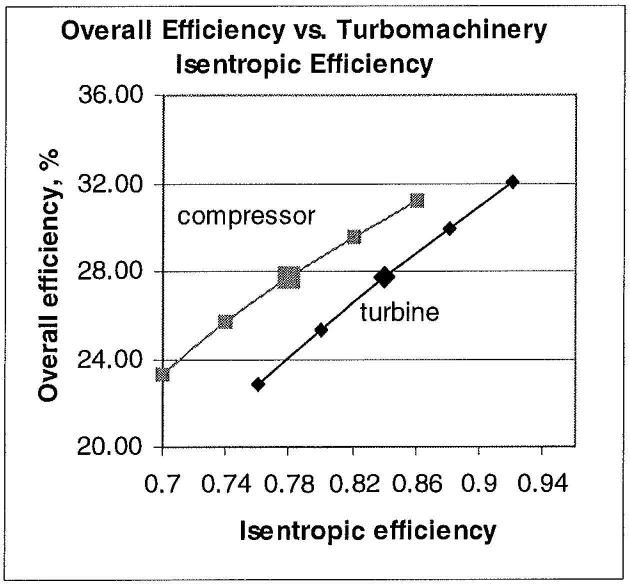


Figure 2.6

2.4.2 RECUPERATOR EFFECTIVENESS

The importance of having a recuperator in a small gas turbine is made quickly apparent given that overall efficiency would be about half its current value without one. Large gas turbines perform well without recuperators because they have significantly more efficient turbomachinery, higher TITs, and much greater pressure ratios (which are desirable in non-recuperated Brayton cycles as shown in Section 2.2.1).

Improvements in the effectiveness of the recuperator would allow for more waste heat from the turbine exhaust stream to be transferred to the compressor outlet stream. For every Joule of heat transferred, one Joule of fuel is saved. The penalty for increasing the effectiveness typically involves both an increase in the pressure drop as well as the requirement of a larger, more costly recuperator.

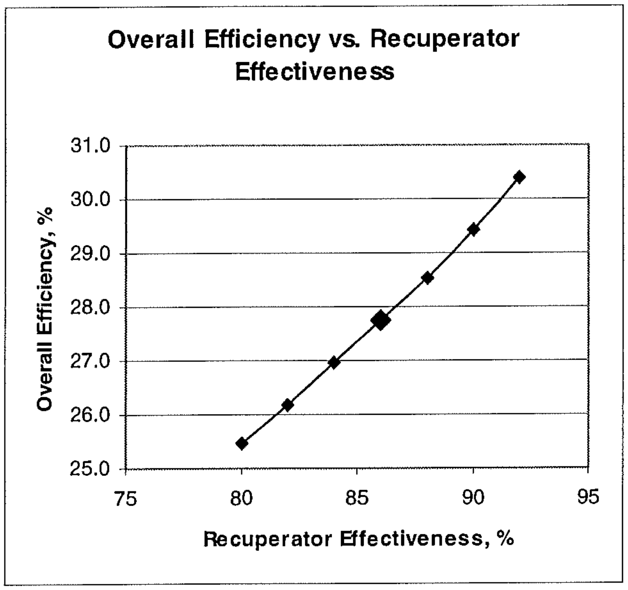


Figure 2.7

Figure 2.7 shows the variation of overall efficiency with recuperator effectiveness. If the effectiveness is increased by 2 points up to 88%, which can certainly be realized, the overall efficiency would increase by about 0.8 percentage points. This gain, however, assumes the same pressure drop through the recuperator. While this may be possible by utilizing a different recuperator design, large increases in effectiveness would almost certainly involve pressure drop penalties.

A microturbine employing a recuperator with a high effectiveness is currently being developed by Northern Research and Engineering Corporation, or NREC (Watts, 1999). Dubbed “PowerWorks,” an effectiveness of about 91% is expected to enable an electrical efficiency of 33% LHV. This performance is 2.5 points better than what NREC gives for a microturbine using a recuperator with an 85% effectiveness with the same turbine inlet temperature of 870 °C (note that a similar increase with the ASPEN model gives a 2.2 point increase). NREC’s approach breaks away from other manufacturers' tendency to use compact, lower-effectiveness recuperators that evolved from efforts to develop a gas turbine automobile engine.

2.4.3 TURBINE INLET TEMPERATURE

The decision of which turbine inlet temperature to operate at comes out of the competition between higher thermal efficiencies (associated with higher TITs) and longer life (associated with lower TITs). Temperatures in the range 850 – 900 °C are characteristic of the microturbines of today. Because with larger turbines it becomes cost-effective to employ blade cooling, TITs are significantly higher. In the future, ceramics may be able to markedly increase the allowable TIT of un-cooled gas turbines.

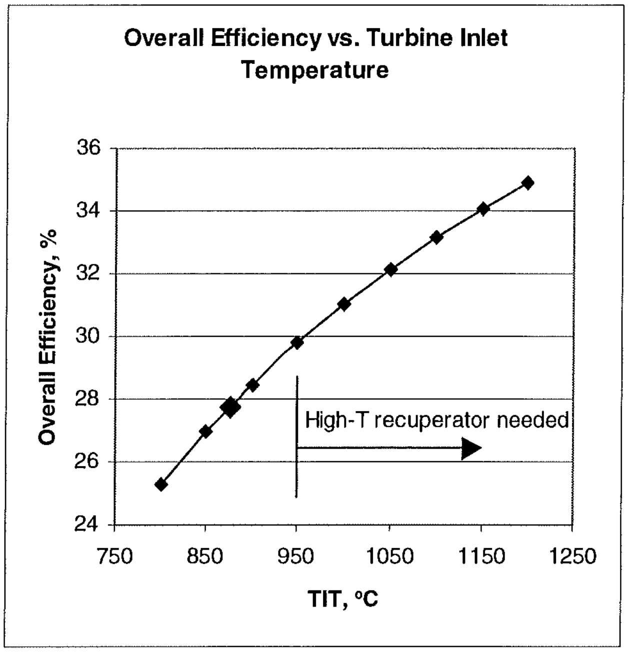


Figure 2.8

Refer to Figure 2.8 for a plot of overall efficiency versus TIT. A 10 degree increase in TIT from the reference value of 875 °C increases the thermal efficiency by 0.35 points. Of course, not stated here is the corresponding decrease in life expected. It is interesting to note that this concern may be moot if particulate erosion , corrosion and the like become real issues. In the hypothetical scenario where relatively inexpensive turbine wheels are periodically replaced for these reasons, it might be feasible to push the TIT higher[9]. Answering the question of what will

---

[9] It may be of interest to manufacturers to investigate both the cost of manufacturing "disposable" turbine wheels as well as any associated environmental costs.

kill the turbine wheel first will determine what kind of TIT one can get away with. Note that this kind of thinking is unique to microturbines. Preservation of the elaborate, multi-stage, blade-cooled expanders of large gas turbines takes a much higher priority.

Before leaving the subject of TIT, it needs to be noted that while use of ceramics may allow very high TITs, doing so will put greater demands on the recuperator. For a given pressure ratio, increasing the TIT increases the turbine outlet temperature (TOT) as well. If the TOT is such that the recuperator inlet temperature exceeds about 700 °C (Rodgers, 1997), a material more heat-resistant than stainless steel would have to be employed. For the microturbine configuration selected, this will occur for TITs greater than about 950 °C as indicated in Figure 2.8.

2.4.4 PRESSURE RATIO

Perhaps the most interesting behavior exhibited by any of the parameters is that of the compressor pressure ratio. Because recuperated Brayton cycle performance depends on the difference between the turbine outlet and compressor outlet temperatures, lower pressure ratios are preferable, as discussed in Section 2.2.1.

The ASPEN model's output for different pressure ratios and two different values for the recuperator effectiveness is shown in Figure 2.9. Notice that as one would expect, the performance improves as the pressure ratio is decreased from a value of 7. However, in continuing to drop the pressure ratio, a maximum is encountered beyond which performance drops dramatically. This is not predicted by the ideal recuperated Brayton cycle efficiency because it is due to non-ideal behavior. The ideal case has isentropic compression and expansion, no pressure losses, and a recuperator with 100% effectiveness. Regardless of the expander's isentropic efficiency, the power it extracts from the flow decreases monotonically as the pressure

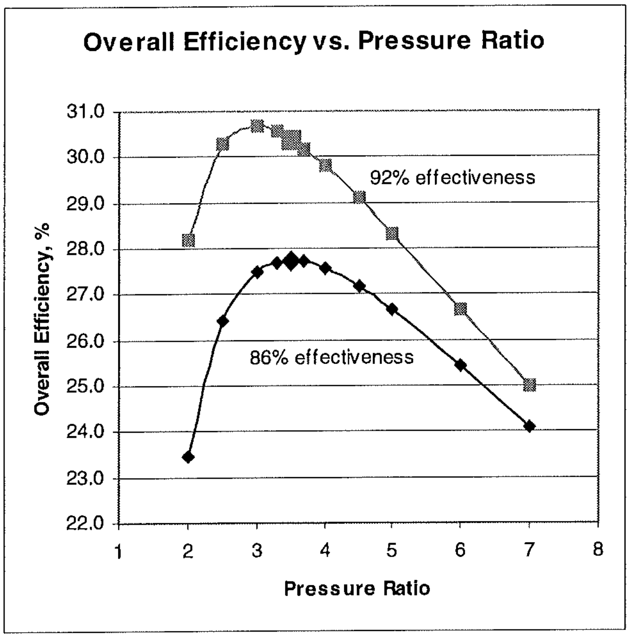


Figure 2.9

ratio drops (reaching zero before the PR reaches 1 in the non-ideal case). The power generated in excess of the compressor's needs also therefore decreases, and losses, such as heat that is not recovered by the imperfect recuperator, become large by comparison. This explains the drop off at low pressure ratios. Sieben (1992) points out that the more ideal the system, the lower the pressure ratio at which peak performance occurs (as can be seen in Figure 2.9).

The reference system's pressure ratio is 3.5, which gives about optimal performance for the given configuration. Notice, however, the effect of the recuperator effectiveness. Increasing effectiveness means a greater fraction of the available heat from the turbine exhaust is transferred to the compressor outlet stream. This lowers the pressure ratio at which losses begin to get large with respect to the net power generated. Consequently, the optimal pressure ratio shifts to a lower value.

2.4.5 COMPRESSOR INLET PRESSURE

For the application in mind, it is important to know the significance of the compressor inlet pressure. Co-compression of air and producer gas may involve having the compressor draw air through the gasifier and clean-up system as is often the case when using reciprocating ICEs. Depending on the particular design, there could be a large pressure drop by the time it gets through all the cleaning steps. The effect of inlet pressures as low as 0.8 bar are shown in Figure

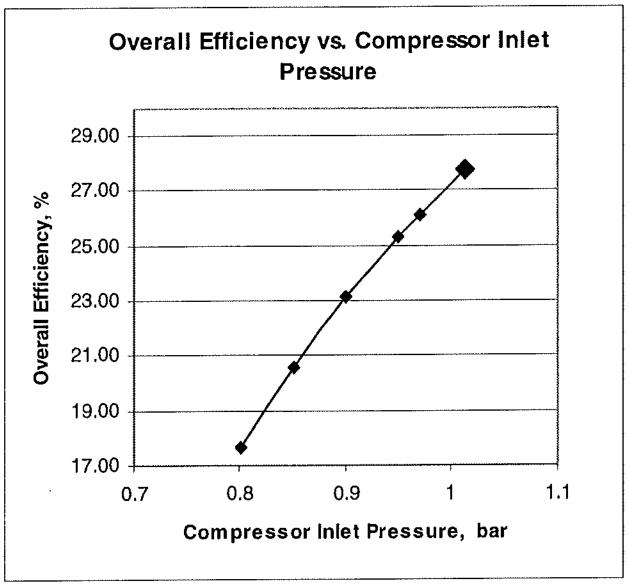


Figure 2.10

2.10. Note, again, that all other parameters are held constant. For a microturbine operating under off-design inlet pressures, there would likely be additional compressor efficiency penalties. Even without taking such penalties into account, however, it is clear that lower inlet pressures can significantly affect performance. A drop of 4% below atmospheric pressure reduces the efficiency by 1.6 points. This clearly suggests it would be worthwhile to investigate configurations in which such pressure drops can be avoided (see Section 4.4.1 for an attractive option).

2.4.6 TURBINE OUTLET PRESSURE

To extract as much work as possible from a gas stream, the outlet turbine pressure should be as low as possible. Since atmospheric pressure is an absolute floor, the outlet pressure is constrained. The type and number of devices the exhaust stream must flow through between the turbine outlet and the atmosphere will also play a role in determining how low the turbine outlet pressure can be. In the case of the recuperated Brayton cycle, the exhaust has to flow through the recuperator before finally leaving the system. If cogeneration is employed, there will be a second heat exchanger to take into consideration. Figure 2.11 shows thermal efficiency for various possible turbine outlet pressures.

Consider moving from the reference point (1.062 bar) to one which allows an additional 3% pressure drop for a second heat exchanger. This moves the TOP to 1.094 bar and yields a thermal efficiency of 26.6%, a 1.1-point drop. Clearly, what needs to be established is the relative importance of recoverable heat versus electricity. If, for example, electricity is the primary product and fuel is expensive, a heat exchanger with a lower effectiveness and hence lower pressure drop could be designed. In a place like Jilin Province, China, however, heat in the wintertime is far more important than an additional kilowatt-hour of power.

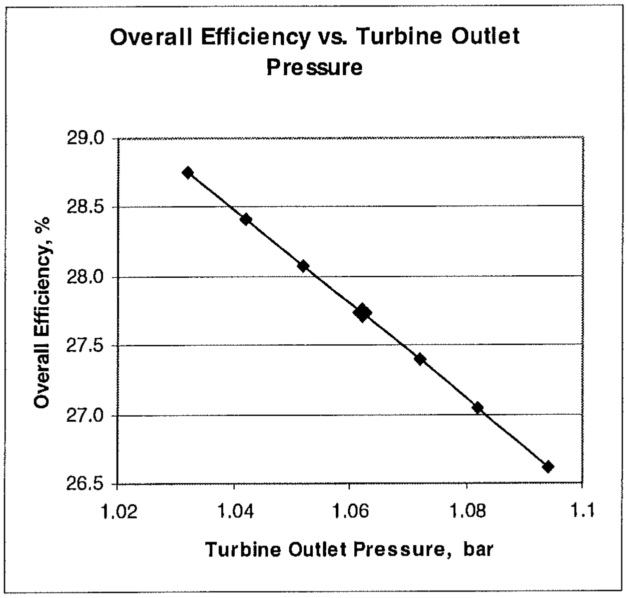


Figure 2.11

To estimate what kind of pressure drop may be expected from a heat recovery unit downstream of the recuperator, a heat exchanger design calculation was performed (see Appendix B). For the parameters shown in Appendix B, a gas-side pressure drop of almost 1% is estimated for the heat recovery unit. Together with a recuperator pressure drop of 3%, the turbine outlet pressure would need to be about 1.073 bar to allow for a slightly above-atmospheric exhaust pressure (1.03 bar). Referring to Figure 2.11, this corresponds with an overall thermal efficiency of 27.4%, a small drop from the base case value of 27.7%.

2.4.7 SENSITIVITY TO PARAMETERS

To examine the six parameters above side by side, the response of the thermal efficiency to a 1% increase in each has been plotted in Figure 2.12. It should be noted that comparing equivalent fractional changes may be of very limited usefulness because it does not identify the likelihood or cost of any of them. Still, it does indicate the relative significance of such changes.

The thermal efficiency appears to be sensitive to small changes in all the parameters except the pressure ratio which, as seen earlier, is already at the optimal value.

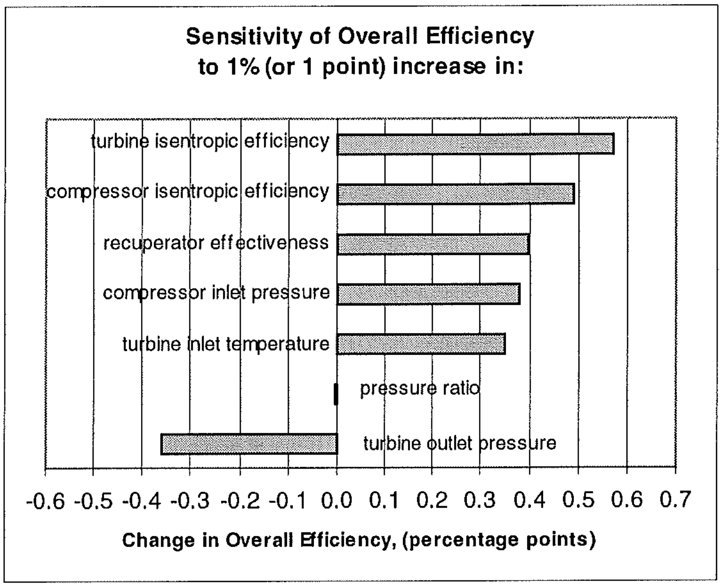


Figure 2.12

Chapter 2 References

Berg, J. (1999). Public Service Gas and Electric, personal communication.

Cohen, H., Rogers, G.F.C. and Saravanamuttoo, H.I.H. (1987). *Gas Turbine Theory*, 3rd edition, Longman Scientific & Technical, New York.

Craig, P. (1997). "The Capstone Turbogenerator as an Alternative Power Source," Society of Automotive Engineers, Inc., paper 970292.

GRI. (1989). "Advanced Energy System Program," Second Annual Report, March 1987-October 1988, GRI-89/0080, February.

Hoffman, K. (1999). Lecturer in power electronics, Queensland University of Technology, personal communication.

Myers, P.F. (1997). "Economics and Design Approaches for Small Commercial Turbogenerators," Paper No. 97-GT-364, American Society of Mechanical Engineers, New York.

O'Brien, P. (1998). "Development of a 50-kW, Low-Emission Turbogenerator for Hybrid Electric Vehicles," Paper No. 98-GT-400, American Society of Mechanical Engineers, New York.

OIT. (1998). *Summary of the Microturbine Technology Summit,* sponsored by the U.S. DOE Office of Industrial Technologies, December 8-9, Orlando, Florida. DOE/ORO 2081

Prabhu, E. (1998). President of Reflective Energies, personal communication.

Reynolds, W.C. and Perkins, H.C. (1977). *Engineering Thermodynamics*, McGraw-Hill, Inc., New York.

Rodgers, C. (1997). "Thermo-Economics of a Small 50 kW Turbogenerator," Paper No. 97-GT-260, American Society of Mechanical Engineers, New York.

Rodgers, C. (1997). "Turbochargers to Small Gas Turbines?," Paper No. 97-GT-200, American Society of Mechanical Engineers, New York.

Sieben, M. (1992). "Small Recuperated Gas Turbines for Power and Heat Generation," Master's thesis draft, Princeton University, Center for Energy and Environmental Studies, July.

Walsh, P.P. and Fletcher, P. (1998). *Gas Turbine Performance*, co-published by Blackwell Science Ltd. and the American Society of Mechanical Engineers.

Watts, J.H. (1999). "Microturbines: A New Class of Gas Turbine Engine," *Global Gas Turbine News*, v39, n1, p. 4-8.

3. FUELING MICROTURBINES WITH PRODUCER GAS

3.1 LOW-BTU GAS IN A GAS TURBINE

3.1.1 **ISSUES**

There are a number of fundamental issues that are raised when trying to fire a gas turbine on a fuel with a much lower heating value than the kind it was designed to use. These include flame stability, combustor design, fuel delivery to the combustor, and the issue of driving the compressor towards surge.

The stability of a flame is affected by many factors, such as the equivalence ratio, gas flow rates, combustor geometry, and the composition of the fuel being combusted (which determines properties like heating value and adiabatic flame temperature). Out of these, the biggest constraint faced is the composition of the producer gas. Testing done by General Electric (Neilson et al, 1998) indicates that for an LM2500 combustor, a stable flame can be maintained with producer gas at *all* power levels when two criteria are met. First, more than 80 molar percent of the combustible species in the fuel needs to be composed of CO and H_2. Typically, CO and H_2 are the most prevalent combustibles in cleaned producer gas, but methane and a few other higher hydrocarbons (including traces of tars) are present in small quantities as well. Completion of their oxidation, under equivalent conditions (e.g. same temperature, equivalence ratio, etc.), takes longer than for CO and H_2 because there are more reactions that must take place[1]. The faster chemistry of the CO/H_2 mixture helps to maintain flame stability. The second criterion is that the lower heating value (LHV) of the fuel should be at least about 3.7 MJ/m^3.

---

[1] Hydrocarbon oxidation involves many reaction mechanisms but ultimately goes through CO/H_2/O_2 chemistry. Of particular importance is the reaction step CO + OH → CO2 + H which occurs late in

GE tested two different gas compositions (one simulating the product of a pressurized gasification process, the other from a low-pressure process) and found both to be satisfactory for the LM2500 combustor[2]. It should be pointed out that these two criteria are by no means general. Their value lies in exhibiting those characteristics of producer gas which were observed to be important for flame stability: H_2-CO content and heating value. What the criteria turn out to be for a given application will depend on the particular gas turbine in question.

The extent to which a combustor needs to be redesigned to handle the combustion of low-Btu gas depends on the particular type of combustor one starts with. The LM2500 combustor testing described above showed that only minor modifications were necessary. In order to accommodate the increased fuel flow rate, a dual-fuel type nozzle was employed. A high-Btu gas, used for startup, would flow through the inner circuit (see Figure 3.1). At full power, the producer gas would take advantage of the capacity of both the inner and outer circuits. A "quick fix" to a relatively simple problem. For a Solar Spartan (225 kW) gas turbine, however, Craig (1998) anticipates that a dramatically redesigned combustion chamber is called for. He contrasts this small gas turbine with most large industrial turbines saying that the latter have sufficient volume to combust low-Btu gas and only require a modified fuel delivery and injection system. Given findings with the 22 megawatt LM2500, this observation would appear to be applicable to some aeroderivative gas turbines as well.

---

hydrocarbon oxidation (Glassman, 1996). CO and H_2 are products of partial oxidation, and so require less time to complete oxidation.

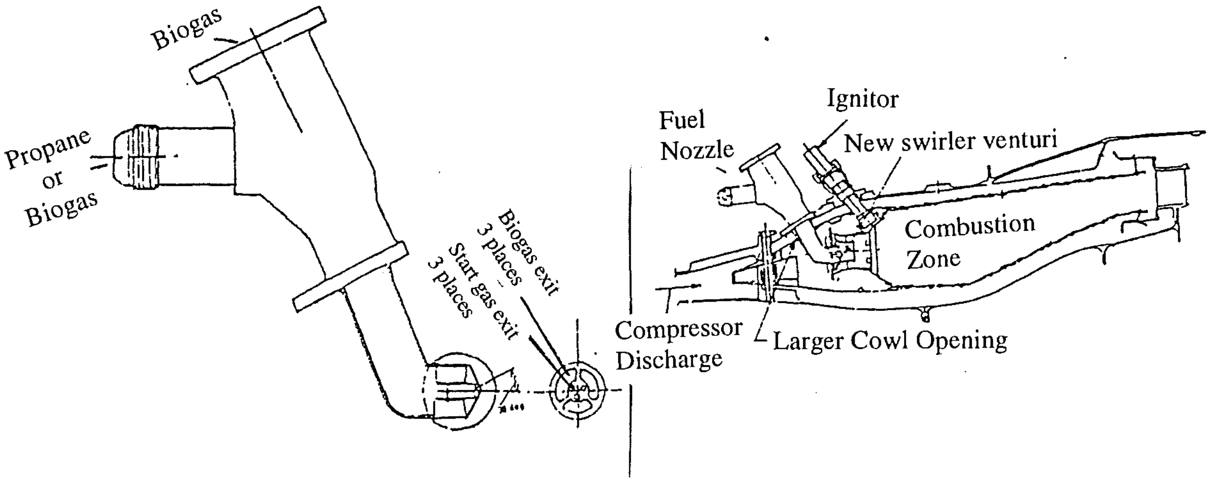


Figure 3.1 Dual-fuel nozzle and combustion chamber used in LM2500 tests (Nielson et al, 1998)

Driving the compressor towards surge is not a simple issue and requires a bit of explanation. When a gas turbine is operating at full power, the flow is choked at the inlet to the turbine section (just downstream of the combustor). That is to say, the mass flow of gas through the turbine is at a maximum that depends on thermodynamic conditions, the gas, and geometry. The amount of power a turbine can deliver goes as the mass flow of air, so having the maximum flow of air is desirable. The equation for this maximum (choked flow) for an ideal gas is given by (Johnson, 1992):

$$m = P_t A^* \sqrt{\frac{MW}{RT_t}\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}},$$

---

[2] Producer gas from air-blown, downdraft gasifiers typically meets both criteria. See the producer gas given in Table 1.1 for instance.

where P_t is the total pressure, T_t is the total temperature, A^* is the critical area (where sonic conditions are found), MW is the molecular weight, γ is the ratio of specific heats, and R is the universal gas constant. To begin with, consider operation with natural gas. When we replace the natural gas with producer gas, the fuel mass flow would have to increase typically tenfold to deliver the same chemical enthalpy to the air stream. This is true for the producer gas from an air-blown downdraft gasifier which has a heating value about 1/10 that of natural gas on a mass basis (see Table 1.1). If we hold the airflow through the compressor constant, this requires that the value for the choked mass flow must somehow increase. Johnson (1992) discusses the various ways one can deal with this problem, but we will focus on what he describes as the likely solution: decrease the airflow through the compressor and increase the pressure ratio. Decreasing the airflow gives more room for the fuel, and increasing the pressure ratio increases P_t and hence the choked mass flow. By looking at a compressor performance map (Figure 3.2), one can see that decreases in airflow and increases in pressure ratio occur hand in hand along a constant rotational speed line[3], though gains in the pressure ratio are small when starting at the design point. Notice also that they move the operating point closer to the left-hand boundary of the performance map. This is the surge line. The surge margin is said to be narrowed, and the phenomenon of compressor surge becomes more likely.

Surge is the off-design phenomenon that occurs as a result of severe stall. If the flow rate decreases enough, the angle of incidence of the flow relative to the compressor blades becomes too large and aerodynamic instability results. The flow through the compressor can experience a violent, periodic flow reversal in which air momentarily flows away instead of towards the combustor. If a compressor experiences surge long enough, irreversible damage can be incurred (Boyce, 1982).

---

[3] Note that the constant rotational speed line is equivalent to the constant corrected speed line for a fixed

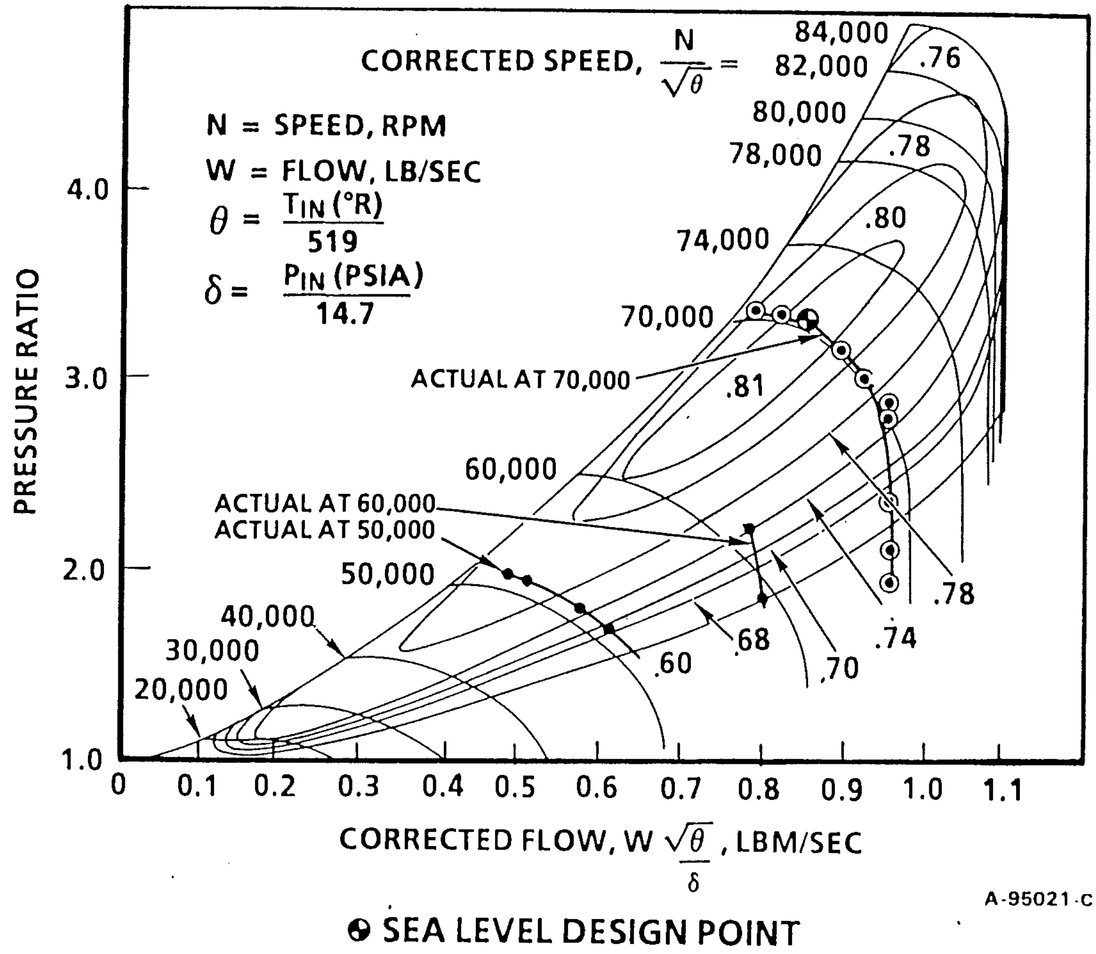


Figure 3.2 Centrifugal compressor performance map (GRI, 1989)

Another likely issue with having a large fuel flow rate is that of fuel compression. If ten times the fuel mass flow is needed, that is ten times more gas to compress to a pressure above the compressor outlet pressure. If an atmospheric biomass gasification system is used, a separate fuel compressor will be needed, thus adding to the cost and complexity of the overall system. Of course, if an adequately pressurized supply is already available, this is a non-issue.

---

inlet temperature.

3.1.2 STRATEGIES FOR ACCOMMODATING LOW-BTU GAS

While lowering the mass flow through the compressor increases the risk of surge, it is nevertheless worthwhile to estimate the performance one can expect as well as just how risky this possibility would be. From the natural gas reference case in Section 2.3, design-point operation for a 75 kW microturbine is characterized by a 2685 kg/hr mass flow of air in the compressor and a fuel flow rate of 19.7 kg/hr. The total choked mass flow rate is then 2705 kg/hr. Using the same pressure ratio and turbine inlet temperature, the corresponding choked flow for the producer gas/air post-combustion mixture would be only slightly greater at 2713 kg/hr. Such a flow would be the result of a compressor flow of 2529 kg/hr (5.8% less than natural gas case) and a producer gas flow of 184 kg/hr (which would give the same TIT).

A comparison of the microturbine's performance using the two fuels is shown in Table 3.2 below. It very clearly illustrates the significance of having to compress what amounts to 8.7 times as much fuel on a volumetric basis[4]. Although dramatically poorer "net" performance is observed with producer gas, actual performance is likely to be even worse owing to off-design operation of the microturbine's compressor. The excessive power requirement alone is an adequate reason to dismiss the option of separate fuel compression when using producer gas. However, for the sake of completeness, the issue of surge margin narrowing will be briefly addressed.

Table 3.2 Microturbine performance using a separate fuel compressor

Configuration (using fuel compressor)	Gross power (kW)	Gross efficiency (%)	Net power (kW)	Net efficiency (%)
Natural gas	75.0	28.7	71.0	27.2
Producer gas	80.2	31.7	45.4	17.9

"Gross" refers to 60 Hz power generated not including fuel compressor power demand

---

[4] The compressor power requirements were simply taken as 8.7 multiplied by the natural gas compressor power demand of 4 kWe. Actual performance may not be as bad given that a larger gas compressor with perhaps better performance would be used.

Consider again the compressor performance map shown in Figure 3.2. It corresponds to a centrifugal compressor used in a 50 kW microturbine. Suppose that the design point shaft speed of 70,000 rpm may not be exceeded in order to avoid prolonged excessive stresses in the high-speed turbomachinery[5]. Different mass flows and pressure ratios can be achieved with the compressor operating at fixed speed through the use of a simple valve at the compressor inlet, as was done to generate the constant speed lines on the performance map (GRI, 1989). For the 75 kW microturbine fueled with producer gas as described above, it was found that the mass flow through the compressor had to be decreased by 5.8% relative to the natural gas design point case. If a 5.8% mass flow decrease is applied to the 50 kW microturbine compressor, which is nominally at 0.85 lbm/sec, a flow of 0.8 lbm/sec results. Climbing up the 70,000 rpm line to the left, this mass flow decrease cuts the design-point surge margin in half and lowers the compressor efficiency by about 1.5 points. It appears that a significant price must be paid with this option for fueling microturbines with producer gas.

Currently, a more promising approach to the low-Btu problem is being developed by Reflective Energies in California for microturbines (Capstone units in particular). To begin with, both the producer gas and the air are compressed together in the compressor. This does away with the need for an inefficient, costly fuel compressor[6]. Because the microturbine's compressor would then handle a mass flow that is closer to design-point, the surge issue as well as the significant isentropic efficiency drop would be avoided.

Pre-mixing and compressing the fuel/air mixture raises two concerns: 1) the mixture is too lean to support a stable flame and 2) auto-ignition prior to combustion. By employing

---

[5] AlliedSignal's microturbine, for instance, is controlled such that the shaft speed corresponding to full output, 65,000 rpm, is not exceeded.

catalytic combustion , Reflective Energies claims to be able to circumvent the first issue[7]. An additional benefit is that there is no zone in the combustor where the temperature is high enough to form appreciable thermal NO_x. Confidential auto-ignition testing at the Combustion Laboratory of the University of California at Irvine suggests that the approach is an auspicious one for the expected operating conditions (Prabhu, 1998). What would at first seem to support this result is the fact that producer gas/air mixtures alone cannot be used in a standard compression-ignition (diesel) engine. In spite of pressure ratios in the 14-22 range, the mixture will not auto-ignite. The pressure ratio expected in the microturbine is only about 4, meaning temperature rise due to compression will be much lower. However, this example says nothing about residence time. Inside a microturbine, the mixture will not only be heated further in the recuperator, but will also be at elevated temperature and pressure for a much longer time than in a diesel engine. This explains the motivation for testing. UCI's results have encouraged Reflective Energies to continue pursuing the development of its co-compression approach.

ASPEN simulations of the air/fuel co-compression scheme indicate that departures from the parameters and performance of the reference case will be small. This is illustrated in Table 3.3. When employing a separate fuel compressor, producer gas was found to have dismal performance relative to the natural gas reference case (as shown in Table 3.2). With co-compression, however, it actually performs slightly better (Table 3.3). One of the advantages of co-compression, whether it be for the natural gas or producer gas case, is that use of a small-

---

[6] The retail price of GE's "Turbo Alternator" (80 kW model) is $49,500 with the natural gas compressor and $41,000 without (Anonymous, 1998). This is $620/kW versus $510/kW on account of a compressor.

[7] An older design of the AlliedSignal Turbogenerator employed catalytic combustion and the co-compression scheme described here (GRI, 1989). The main reason was to solve the thermal NOx problem, but a non-catalytic combustor was later found to have adequately low emissions and replaced the catalytic design.

capacity, less-efficient fuel compressor is avoided. The larger-capacity, more-efficient microturbine compressor can be used for both fuel and air compression.

Table 3.3 Comparison of reference case with producer gas/air co-compression

Case	Fuel	Configuration	Fuel flow (kg/hr)	comp mass flow (kg/hr)	turb mass flow (kg/hr)	net power (kW)	η_{lhv}
1	Natural Gas	separate fuel compressor	19.7	2685	2705	71.0	27.2
2	Producer Gas	co-compression	187.0	2685	2685	71.3	27.7
3	Producer Gas	co-comp; choked flow	188.9	2713	2713	72.0	27.7

All calculations are for a recuperated Brayton cycle with turbine inlet temperature of 875 °C, isentropic compressor and turbine efficiencies of 78 and 84% respectively, recuperator effectiveness of 86%, and a pressure ratio of 3.5

Two different cases for the co-compression configuration are presented in Table 3.3 along with the natural gas reference case. Case 2 shows that for the same mass flow through the compressor, co-compression with producer gas yields slightly more power and has a half-point greater efficiency. Using the estimated choked flow for producer gas/air combustion products, Case 3 indicates that up to 72 kW may be generated. These results were calculated using the same values for TIT, pressure ratio, turbomachinery isentropic efficiencies, etc. as in the natural gas reference case. However, slightly different values for the isentropic efficiencies would be observed in practice because of the small differences in gas composition[8] and mass flows[9].

Co-compressing producer gas and air in the microturbine's compressor appears to be an auspicious way of handling a large fuel flow rate. Little, however, has yet been said about the key technology which enables this scheme to be realized: catalytic combustion.

---

[8] For instance, the gases in the compressor have a molecular weight which is 1.3% lower than that of air

[9] Relative to the natural gas reference case, the expander flow is 0.7% lower in Case 2 and 0.3% greater in Case 3. Also, the compressor flow in Case 3 is 1% larger.

3.1.3 CATALYTIC COMBUSTION

A mixture of fuel and oxidant will combust when it has sufficient thermal energy to sustainably overcome the activation barrier associated with the reactions that generate active radical species. A stoichiometric mixture of hydrogen and oxygen, for instance, will not react if it is at room temperature and atmospheric pressure. However, in the presence of a platinized, gamma alumina-coated (for enhanced surface area) catalyst, it will indeed burn (Tucci, 1982). Catalysis effectively lowers the energy required to achieve combustion, something particularly attractive for very lean combustion.

If a fuel/air mixture is too lean, as with the producer gas/air mixture, it may not be combustible in the traditional sense. A spark, for example, might be able to initiate the combustion of a few nearby fuel molecules, but the thermal energy and any active species generated are quickly spread out too thinly into a sea of nitrogen and oxygen, thereby halting the propagation of any reactions. Instead of depending exclusively on communication of heat and active species, catalytic combustion is strongly surface area dependent. The typical catalytic combustor provides many parallel flow channels (the "monolithic" design) with a coating that enhances surface area. Catalysts like platinum encourage reactions between fuel and oxidant molecules when physical contact is made with them, hence the significance of surface area.

The main interest in catalytic combustion today is with its low NO_x-producing character. Because catalytic combustion is "flameless" combustion, there are no hot spots that can form appreciable thermal NO_x. Catalytica Combustion Systems has developed a catalytic combustion system for gas turbines dubbed "XONON" which has received a lot of attention[10]. It produces

---

[10] Both Pratt & Whitney Canada and General Electric have made agreements with Catalytica to commercialize XONON with their gas turbines. The first commercial installation of a XONON system was

typically less than 3 ppm NO_x, most of which comes from the use of a pre-burner which may or may not be necessary depending on the temperature of combustor inlet gases (Solt, 1998). Furthermore, less than 10 ppm CO and UHC (unburned hydrocarbons) are produced.

One of the most attractive features of Catalytica's system is how it addresses a primary issue with catalytic combustors: catalyst life. It has long been known that exposure to high temperatures shortens catalyst life (Tucci, 1982), but that high turbine inlet temperatures are needed for gas turbines to have any kind of worthwhile efficiency. To get around this, the XONON system combusts about half of the fuel in the catalyst section of the combustor and then the remainder burns homogeneously ("flamelessly") downstream (Solt, 1998). By having only a portion of the fuel's chemical enthalpy released within the catalyst section, the catalyst is kept cooler and its life is prolonged[11]. Keeping the catalyst cool does not prevent high TITs. XONON technology has the ability, as Solt (1998) points out, to provide TITs ranging from 825 to 1500 °C. Such a range makes it appropriate for everything from microturbines to futuristic high-TIT gas turbines.

As noter earlier, AlliedSignal has done some work with catalytic combustion in microturbines. O'Brien (1998) reports on efforts to develop a 50 kW microturbine to be used in hybrid electric vehicles. To begin with, a preheater is used at start up only until the catalyst reaches its active temperature of 500 °C. This takes about 20 seconds for the "Generation 1" turbogenerator, and at the time of the report, this was expected to be cut down to 10 seconds. To accommodate standard automotive liquid fuels like diesel and gasoline, the particular combustor design described uses fuel injectors. Still, other fuels like natural gas and alcohol fuels are said

---

in a gas turbine at the Gianera Generating Station of Silicon Valley Power, California, in October 1998 (see Catalytica's website: http://www.catalytica-inc.com/combustion/news.html) to be compatible with the catalytic combustor as well. Testing reveals that NO_x emissions are almost exclusively dependent on the particular fuel's nitrogen content. All fuels tested had emissions at 6 ppm or less (propane's was < 1 ppm). With diesel fuel, the combustion efficiency was found to be 99.9% when achieving a turbine inlet temperature of 1013 °C. Note that this relatively high TIT for a microturbine is likely due to the fact that here its intended use is in an automobile where a much shorter life is acceptable (as opposed to a stationary power application).

Catalytic combustion is already being used in gas turbines using conventional fuels, but its use with producer gas is as of yet largely unexplored. More will be said of this in the next section.

3.2 FUEL QUALITY CONCERNS

The performance of a gas turbine is strongly dependent on shape: the shape of the compressor, expander, and other flow passages. Anything that alters geometry from the original design is cause for concern. Three ways for alterations in geometry to occur are erosion, deposition, and corrosion. Insufficiently cleaned producer gas can do all three.

3.2.1 EROSION

The source of particulate matter in producer gas is typically soot particles, bits of ash, and also contaminants like dirt that may not have been removed from the biomass prior to gasification. Erosion in a gas turbine can occur when particles traveling with the high-velocity gas collide with surfaces like turbine blades and take pieces away with them. As one would expect, erosion

---

[11] Another advantage of having a cooler catalyst is that a metallic substrate can be used instead of a ceramic one which is less durable.

is a concern more with the larger-sized particles. This is reflected in the limits General Electric established for turbine inlet gases (Consonni and Larson, 1994) shown in Table 3.4.

Table 3.4 Representative particulate concentration limits for gas turbines

Turbine Inlet Concentration limits (ppbw)	Producer Gas Concentration limits (ppbw)*	Particle diameter (microns)
< 600	< 8600	< 10
< 6	< 86	10-13
< 0.6	< 8.6	> 13

* air/fuel ratio of 13.4

Such limits are estimated based on limited experimentation and are thought to be conservative. Limits for small, radial gas turbines are not readily available, in large part because they are so new and are being targeted for conventional fuels like natural gas which do not carry with them a particulate concern.

3.2.2 DEPOSITION

Particulates can deposit on turbine surfaces, accumulate and disfigure their shape leading to degraded aerodynamic performance. Furthermore, deposition sets the stage for corrosion to occur.

Deposition rates on turbine blades have been found to be highly dependent on turbine inlet temperature (DeCorso et al, 1996). In an experiment, two orders of magnitude more deposits were formed at an air temperature of 1093 °C than at 982 °C. It is believed that this dramatic change in behavior is due to the 1093 °C air stream being above the melting point of some component of the particulates present. Particulates have a much greater propensity to deposit when they are partly molten.

Because the microturbine will operate at lower temperatures, around 850-875 °C, it may seem that deposition will be less of an issue than for the high temperature engines. However, the chemistry of ash is quite complex, and several compounds may be present which have low melting points. Good examples of this are a number of mixtures that are formed between silica (SiO_2) and potassium oxide (K_2O) as shown later in Figure 4.1. It can be seen that a number of compositions have melting points below 850 °C. This example is particularly relevant for corn stalks since silicon and potassium are the most prevalent metals in its ash.

Another material in producer gas that may be problematic where deposition is concerned is tar. If both fuel and air are to be compressed together at low temperature, tars have the opportunity to condense on and adhere to the compressor. Besides degrading performance, accumulation may become sufficient over time to cause the impeller to seize. Since some tar species can remain in the liquid form at temperatures as high as 500 °C, there can even be tar condensation inside the narrow passageways of the microturbine's recuperator. Tar is not a contaminant gas turbine makers have given much attention to in determining tolerances. When biomass is considered for use with gas turbines, it is often in the context of hot-gas clean up, in which tars remain in vapor phase and are combusted along with fuel. The ICE limit of less than 30-50 mg/Nm^3 discussed earlier is probably reasonable to borrow for the microturbine since here, too, the fuel gas is cool and tars can condense on sensitive components like the compressor (which may or may not be as sensitive as intake valves in an ICE). Furthermore, because the producer gas is diluted with air at a ratio of 1:13 prior to entering the microturbine, the ICE limit could be a very conservative one.

3.2.3 CORROSION

Once material has deposited on a surface, depending on the local temperature and composition, it may lead to corrosion. Ash fragments high in alkali silicates can have very low melting points as previously discussed. Softening or molten particulates stick more readily to surfaces. While alkali silicates are themselves not corrosive, their deposition succeeds in getting the alkalis onto surfaces thereby setting the stage for corrosion. If there is any sulfur present, it will likely combine with the alkalis to form highly corrosive alkali sulfates. Hence it is desirable to remove both alkalis and sulfur from the fuel gas.

The particular kind of corrosion most relevant to the microturbine would be Type I hot corrosion, which occurs at metal surface temperatures between 790-955 °C (DeCorso et al, 1996). Responsible compounds include both sulfates and chlorides of alkali and alkaline earth metals (K, Na and Mg, Ca respectively). These salts provide the electrolyte necessary for rapid corrosion.

Corrosion testing performed by GE in 1977 led to a tolerance specification of 24 ppbw for sodium plus potassium in the turbine inlet gas (Podolski et al, 1995). To achieve a TIT of about 875 °C with a low heating value (~ 5 MJ/kg) producer gas, a large fuel to air ratio of about 1 to 13 is called for. Therefore, if the turbine inlet gas is 7% fuel-derived, 24 ppbw translates to about 340 ppbw in the fuel gas.

Condensation of acids like HCl and H_2SO_4 can corrode lower temperature components downstream of the microturbine, such as heat exchangers (Consonni and Larson, 1994). This is yet another reason to remove sulfur from the fuel gas.

3.2.4 CATALYTIC COMBUSTOR ISSUES

According to catalytic combustor designer Catalytica, if a fuel is suitable for a gas turbine, it is suitable for their catalytic combustor. In other words, it will be the gas turbine which determines fuel quality requirements and not the combustor. However, one could envision the scenario in which a microturbine is designed to allow for relatively often replacement of a cheap turbine wheel thereby relaxing contaminant constraints. Such a situation would require an experimental evaluation of the effects of producer gas contaminants on the catalytic combustor (Solt, 1999).

Still, there are a few general comments that can be made. Three factors contribute to loss of catalytic activity: (1) contaminants that poison the catalyst, (2) erosion of surfaces, and (3) exposure to high temperature. The first two are added incentives to remove as much of the particulate matter and chemically aggressive species (like sulfur) as possible. Alkali content in the hundreds of parts per billion range is likely to be detrimental, while a few ppb may be tolerable (similar to the turbine limit mentioned earlier). The third factor is already solved by XONON technology, for example, as described in section 3.1.3 (Solt, 1999).

3.2.5 CONVENTIONAL GAS TURBINES VS. MICROTURBINES

A comment should be made with regard to standard conceptions of using producer gas with gas turbines. In the typical multi-megawatt gas turbine, the expander represents a large share of the capital cost. This is because there are several stages, each having numerous precision-made blades (see Figure 3.3, which shows GE's LM2500 gas turbine). Alternating with the stages are sets of stators as well. Several of the stages near the combustor are especially expensive due not only to use of high-temperature alloys but also blade cooling which requires serpentine internal air channels within the blades. As a result, repairing damages to the expander section can be very costly. Because of the size of the machinery that must be manipulated, such repairs are also big operations.

The situation is quite different with microturbines (compare Figures 3.4 with 3.3). Both the compressor impeller and expander rotor consist of only one piece of metal each and have diameters of about 6 inches or less. One stage of compression, and one stage of expansion. Furthermore, no blade cooling is employed. For these reasons, the turbine and compressor represent a small fraction of the initial capital cost. It may be possible to have a number of spare turbine wheels on hand in the event that blade damage occurs at an appreciable rate. The concern of turbine blade damage is made a much smaller one. A more costly microturbine component is the recuperator. Fortunately both erosion and corrosion concerns are likely to be minimal owing to the low flow velocity[12] and lower temperatures encountered in the recuperator.

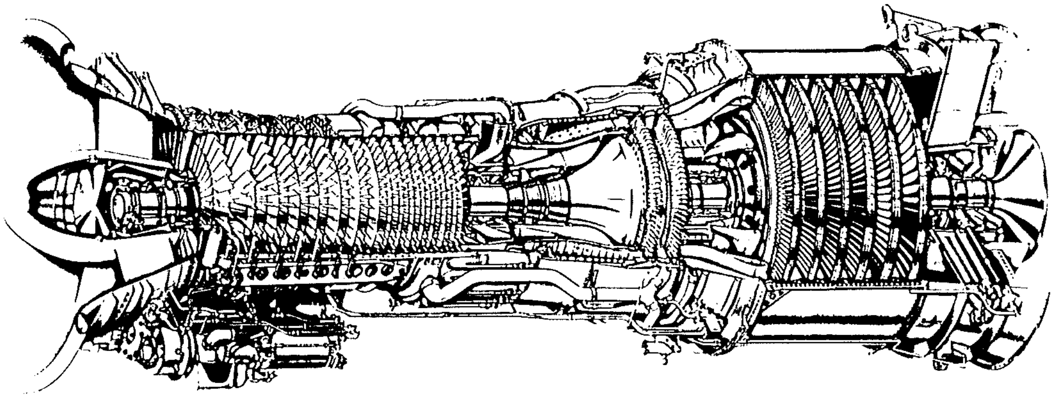


Figure 3.3 GE LM2500 gas turbine (22 MW)

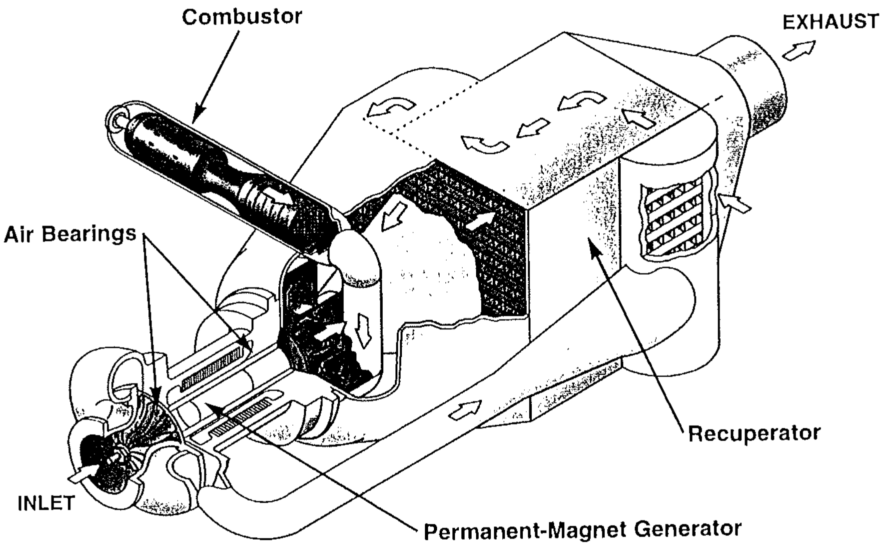


Figure 3.4 Microturbine schematic including recuperator (source: AlliedSignal)

3.3 GAS CLEANING FOR MICROTURBINES

Given the myriad of issues associated with the various contaminants found in producer gas, it is important to consider now the technologies that exist for their removal. This is done in Section 3.3.1. After familiarization with a number of technologies, Section 3.3.2 considers their integration into a clean-up system appropriate for a small-scale gasification system intended to fuel a microturbine.

3.3.1 CLEAN-UP TECHNOLOGIES

CYCLONES

Fortunately, large particles with high erosion potential are the easiest to remove. One of the least expensive clean-up devices, the cyclone, can remove particulates that are larger than 10

---

[12] The cross-sectional flow area of the recuperator is large compared to that within the flow passages of either the expander or the compressor. Flow velocities are correspondingly lower by continuity.

microns in diameter (Reed et al, 1988). The cyclone uses the particles' own inertia to separate them out of the gas stream. Other cleaning devices will be necessary for removal of smaller, lighter particulate matter.

WATER SCRUBBING

Use of water (such as in a spray) to clean a contaminant-laden gas is highly desirable for a number of reasons. First, it thermally matches use with a microturbine where fuel and air will be compressed simultaneously in the compressor. This is because at the scrubber exit, the gas is cooled markedly and hence requires less work for pressurization. Employing a scrubber also does away with the need for a heat exchanger to cool the gas. Note that the sensible enthalpy carried by the gas stream from the gasifier will be lost to the scrubber water and ultimately to the environment.

Contaminants that a scrubber removes to varying extents are listed below:

- particulates
- tars
- alkali metals
- ammonia
- inorganic halogenated compounds (like KCl)
- other water soluble compounds

There are a variety of scrubber designs, each with a different particle capture efficiency. A number of them are briefly reviewed by Hasler et al (1997). All remove at least 90% of particles greater than about 2 microns in diameter. The venturi scrubber captures the greatest size range of particles at the highest efficiency, but exacts a high pressure drop from the gas (Mycock et al,

1995) and is more costly than other options. This is the type of scrubber used by BG Systems, which can apparently reduce their particulate loading to 300 mg/Nm^3 (DeLaquil, 1998).

Tar removal for scrubbers is typically about 60% (Hasler, 1998). Water is not particularly effective at removing tars. A much more effective fluid would be oil because of its affinity for tars. Unfortunately, oil is significantly more costly than water and would be much more difficult to clean-up once contaminated if re-use is desired.

Alkali metals dispersed throughout plant matter in the cells are quite volatile. The resulting alkali vapors typically condense on particulate matter when cooled below about 600 °C (Kurkela et al, 1991). This means that particle separation technologies can simultaneously remove alkali metals if the process occurs at a low enough temperature. Still, measurements of vapor phase sodium after hot filtration by Kurkela et al showed that even down to 500 °C, sodium vapors were getting through (40 ppbw level). Water scrubbers will drop temperatures much lower, so better alkali condensation on particles should result. Furthermore, KOH and NaOH are both soluble in water and their removal is excellent. Calcium and magnesium hydroxide are unfortunately not water soluble, which means they have better chances of getting past a scrubber. This can be problematic because these compounds are corrosive and stick to surfaces well (Taylor, 1998). Additional particulate capture devices should follow the scrubber.

Ammonia is not a problem for the gas turbine, but readily converts to NO_x when combusted. NO_x which derives from ammonia does not require the high temperatures that thermal NO_x formation does because the N-H bond is much easier to break than the N-N triple bond of N_2. Water scrubbing is fortunately a very effective way to remove ammonia from a gas stream because of ammonia's high solubility in water.

Nearly all of the inorganic halogenated compounds present in a gas stream can be removed with water scrubbing (Hasler et al, 1997). The primary compounds here are HCl, NaCl, and KCl, all of which can contribute to corrosion of surfaces they may deposit on.

The problem with water scrubbing is that hazardous contaminants are not destroyed or rendered into a harmless or useful state, but rather just become water contaminants. The gas cleaning problem is transformed into a water cleaning problem. Among other problematic species, scrubber effluent will contain phenols which are known to be highly toxic hydrocarbons. Activated carbon can apparently do an adequate job of removing phenols (Mukunda, 1998). Char produced in the gasifier itself can be used to this end as will be discussed in section 3.3.3.

FILTERS

Two generic classes of filters are high and low temperature filters. Low-temperature fine filtration will be considered here for economic reasons[13]. For a high degree of particulate removal (~ 99.9%) at relatively low-temperature, fabric filters can be used. The temperature limit for conventional fabric filters is about 260 °C, which fiberglass can tolerate (Mycock et al, 1995). What allows a fabric filter to achieve its exceptional collection efficiency is not the filter material itself, but rather the dust cake that develops on the surface (Mycock et al, 1995). Because the pressure drop across the filter increases as the cake builds, some mechanism is needed to remove the cake periodically. A commonly used technique employs a jet of reverse-directed gas through the filter. If, however, the gas stream has a relatively low particulate

---

[13] With higher temperature streams, filters such as the SiC ceramic filter may be used. Ceramic filters, like fabric filters, have excellent removal characteristics and in addition are highly corrosion resistant. The primary problem at the present time is cost. An estimate for a ceramic filter clean-up unit for a 100 kWe-sized power plant came to about $20,000 (Eggerstedt, 1998). That is an order of magnitude more costly than a fabric filter and would be comparable to half the cost of the microturbine itself.

loading (as should be the case for a system that first employs a cyclone and a wet scrubber), the increase in pressure drop with time is slow, making reverse-pulse cleaning unnecessary. In such a situation, simple pleated-cartridge filters may be used. With this less expensive option[14], filters can be removed, washed, and replaced for repeated use.

To keep a fabric filter operating properly, tar condensation on the surface should be avoided. It can clog the material and may necessitate frequent disposal and replacement. Herein lies the advantage of hot-gas filtration. Condensables like tar can be kept above their condensation temperature. While particulate matter gets removed, vapor phase tars would pass through. Since low-temperature fine filtration will be considered here for economic reasons, tar condensation needs to be kept in mind when devising cleaning systems (e.g. a fabric filter would be placed downstream of the other clean-up units where tar in the producer gas is at a minimum).

In addition to tar, moisture in the gas can be problematic for a number of fabric filters. For non-plastic fabrics like cotton, moisture can get absorbed into the fibers causing them to swell. This swelling can constrict gas flow channels in the fabric. Fortunately, there is an abundance of plastic fabrics made from common materials like polypropylene, nylon, and polyester.

THERMAL AND CATALYTIC TAR CRACKING

Thermal and catalytic tar cracking have received a lot of attention with those kinds of gasifiers that produce much more tar than downdraft gasifiers, such as updraft (Pedersen, 1992)

---

[14] Estimates from Torit (designer and manufacturer of air filtration and pollution control systems; 1998) for a reverse-pulse baghouse filter treating a 1000 cfm (cubic feet per minute) flow are about \$5-6/cfm. For a pleated cartridge filter unit, \$3-4/cfm is expected. Note that 1000 cfm corresponds to the producer gas flow that would produce about 600 kWe at 28% conversion. Smaller filter units will cost more per cfm. If a 300 cfm unit costing \$6/cfm is used with a 100 kWe system, the cost is \$18/kW.

and fluidized bed designs. In such cases, the tar content of the fuel gas can represent a significant fraction of the gas' heating value. Assuming the gas is needed at a temperature lower than tar condensation temperatures, it is critical to avoid the fouling problems tars cause, such as jamming valves in IC engines, contaminating lube oil, fouling and blocking passageways and heat transfer surfaces, etc. With a well-designed downdraft gasifier, however, very little tar is produced. An excellent example is the BG Systems gasifier which is advertised as producing less than 5 mg/Nm^3 tar (Anonymous, 1998). This represents less than 1% of the gas' chemical energy. Furthermore, it has been shown that for prevalent tar crackers like dolomite to be effective, operation needs to be at 900 °C or higher (Alden et al, 1992). Downdraft gasifier exit temperatures are typically in the range 400 to 800 °C (Hasler et al, 1997). Using stalk-like biomass, the BG Systems gasifier exit temperature will be between 300-400 °C (Jain, 1998). Clearly, there is a thermal mismatch. One might guess that 800 °C is high enough, but Alden et al (1992) show dramatic reduction in performance at that temperature.

The best way to avoid problems with tar is to prevent it from escaping from the gasifier as best as possible. This means sound gasifier design, as exemplified by the BG Systems gasifier among others.

SULFUR REMOVAL

If it is determined that the catalytic combustor of a microturbine is sensitive to the small amount of sulfur present in producer gas, an inexpensive bed of zinc oxide may be employed to effectively remove it (Katofsky, 1993). It should also be noted, however, that while H_2S is not particularly soluble in water, the presence of ammonia can greatly enhance its solubility (Probstein and Hicks, 1982). Solutions which are alkaline will also be able to absorb H_2S (Kohl and Riesenfeld, 1960). Recycled scrubber water accumulates ammonia and may also be alkaline, especially if the feedstock is high in hydroxide-forming alkali metals. Therefore, scrubber water would be able to remove H_2S to some degree, perhaps doing away with the need for a zinc oxide bed or other removal step. This is supported by recent experiments performed by Sharan et al (1997) which indicate that 80 to 95 % of the sulfides in the gas get removed in the gas clean-up system. Sulfides were detected in the scrubber wastewater.

3.3.2 CLEAN-UP SYSTEMS

Because of the variety of contaminants present in producer gas and the stringent requirements of gas turbines, designing an appropriate gas clean-up system is challenging. System performance estimates are made following some elementary system design considerations.

The first decision is whether to use wet or dry cleaning. Dry cleaning has the advantage that there is no waste water to clean-up. Even so, some amount of condensate (water plus some tars) will still form *somewhere* if the gas is to be cooled significantly, and will have to be dealt with. In addition, dry cleaning has a number of significant disadvantages given the context at hand:

- Components like tar crackers require higher temperatures than what is likely to be available. This leaves the tar problem unresolved. While wet scrubbing does not remove a very high fraction of the tar in a gas stream, it certainly does help.
- By choosing not to use wet cleaning, a very effective method for the removal of water-soluble inorganic compounds (HCl, alkalis, etc.) is forsaken.
- Ammonia will not be removed in a dry cleaning system unless something like a costly high temperature (> 850 °C) nickel catalyst is used (Leppalahti et al, 1993).

- Since the producer gas must ultimately be cooled, a dry clean-up system will require a heat exchanger of sorts. Tar condensation in such a heat exchanger will be troublesome to deal with.

For these reasons, wet clean-up will be pursued further. Having made this decision, the structure of a clean-up system can begin to take shape. For gas turbine applications, it will be necessary to have a high efficiency (99.9%) particulate removal device. Because wet clean-up is being considered here, there is no reason to use a high-cost ceramic filter. A low-temperature fabric filter can instead be employed. To help prevent tar from gumming up the filter and ensure a sufficiently low gas temperature, it is a good idea to put the fabric filter last in the line of clean-up units, as mentioned previously. If water scrubbing is used in conjunction with a fabric filter, three modes of alkali metal removal are made available, namely removal of water soluble compounds (like KCl, NaCl, KOH, NaOH), alkali-coated particles by impaction with water droplets, and alkali-coated particles through filtration.

CLEANING SYSTEM EVALUATIONS

Having decided on the key technologies to include in the clean-up system, it is now desirable to get a sense for how effective the system may be. To help in this end, data from two leading gasification systems developed in India will be drawn upon.

- **BG Systems clean-up: venturi scrubber + fabric filter**

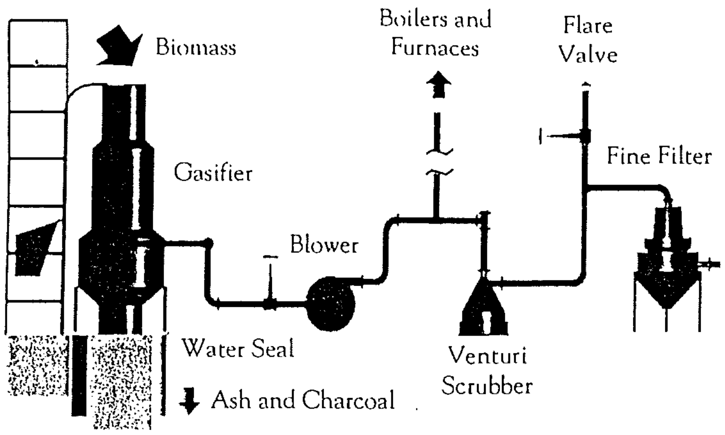


Figure 3.5 BG Systems gasifier and clean-up system (Anonymous, 1998)

DeLaquil (1998):	*300 mg/Nm^3*	*particulate content after the venturi scrubber*
Anonymous (1998):	*< 5 mg/Nm^3*	*tar produced by gasifier*

Note that the tar produced is already well below the 30-50 mg/Nm^3 limit for ICEs (which is being borrowed for the microturbine for lack of something better). Passage of the gas through the venturi scrubber would reduce the tar content even further, by perhaps 60% (Hasler et al, 1997).

Assume 300 mg/Nm^3 of particle matter reach the fabric filter that has a removal efficiency of 99.9% :

$$300 - 300(0.999) = 0.3 \text{ mg/Nm}^3 = 280 \text{ ppbw}^{15}$$

If all we need to get is less than about 8600 ppbw in the producer gas, about 31 times the 280 ppbw level calculated here would be acceptable. Achieving 8600 ppbw would correspond to an average filtration efficiency of about 97%. BG Systems offers an optional fine filter that appears

---

[15] With a molecular weight of 24.2 g/mole, the producer gas in Table 1.1 has a density of 1.08 kg/Nm^3.

to have this level of performance (DeLaquil, 1998). It lowers particulate loading to less than 10 mg/Nm^3 (< 9300 ppbw).

A 280 ppbw particulate loading already meets the hypothesized producer gas alkali maximum of 340 ppbw. Just for reference, the average alkali content of corn stalk ash (K + Na) is 22.9% according to NREL compositional data (see section 4.2.1). If this fraction is assumed to be present in the particulates, our 280 ppbw would contain 64 ppbw alkali. If Mg and Ca content are thrown into the equation, the alkali plus alkaline earth content is 32.7%, which corresponds to 92 ppbw. Both of these crude estimates fall well below the estimated 340 ppbw alkali tolerance. It should be pointed out, however, that alkali condensation on the 250 ppbw particulates that get through the clean-up system has not been taken into account here.

- **Indian Institute of Technology (IISc) clean-up: cyclone + spray towers + sand beds + fabric filter**

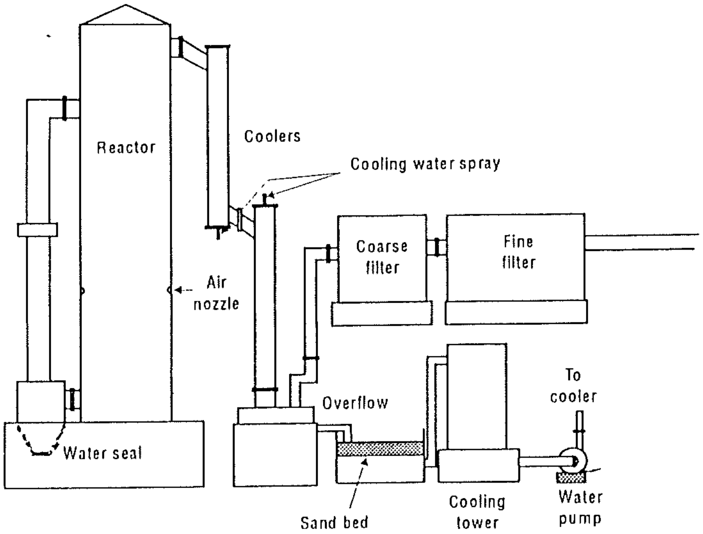


Figure 3.6 IISc gasifier and clean-up system (Mukunda et al, 1994)

Buhler et al, 1997: 45-87 mg/Nm^3 *particulate content after sand beds*
10-146 mg/Nm^3 *tar after sand beds*

In the case of the IISc gasification system, lower particulate matter and higher tar concentrations are encountered. Heavy tar separation by fabric filters is expected to be about 70% (Hasler et al, 1997). This would satisfactorily reduce even the high end of the reported tar concentration, but may be problematic with the filters themselves.

Assuming 87 mg/Nm^3 of particulates reach the fabric filter, only 0.087 mg/Nm^3 or 81 ppbw make it through (two orders of magnitude lower than the 8600 ppbw fuel gas limit). In this case, a filter with an average separation efficiency of 89% would suffice.

It needs to be noted that accurate prediction of particle removal depends on precise knowledge of particulate size distribution and corresponding performance data of a particular fabric. Still, these calculations do show the importance of having another filtration step.

3.3.3 WASTEWATER TREATMENT

The usefulness of wet gas clean-up has already been described, but leaves the issue of treating a potentially hazardous effluent. The presence of phenols and polyaromatic hydrocarbons (PAHs) make the wastewater a toxic substance. In addition, other organics, ammonia, dissolved acidic and basic gases, alkali metals, sulfurous compounds, and particulate matter are present in the wastewater. A number of possibilities exist for treating this contaminated mixture.

ACTIVATED CARBON

Activated carbon is an effective and commonly used adsorbent. Carbon, typically from charcoal, is said to be "activated" when it has an extensive open pore structure. This pore structure gives the carbon an enormous surface area per unit mass and thus its excellent adsorptive properties. The usefulness of activated carbon for water treatment has been known for centuries. Today, activated carbon is the most commonly used adsorbent in industry.

Two aspects of activated carbon make it attractive for use in scrubber wastewater treatment. First, although it can remove a wide range of contaminants, it has a special affinity for adsorbing dissolved organics such as phenols, naphthalene and other PAHs. Second, activated carbon can be produced by the gasifier to some extent. Gasifier char is likely not quite as fully activated as commercial activated carbon (Wetzel, 1998) which is made with high temperature steam, but its adsorptive ability has nevertheless been demonstrated (Hasler, 1997).

Before design with activated carbon can be attempted, experimental work is essential, as emphasized by Cheremisinoff (1993). The adsorption process is very sensitive to temperature (lower is better) and the chemical composition of the aqueous solution being treated. Phenol adsorption, for example, is successful only for pH's lower than about 7 (Wetzel, 1998). This may be an issue if too much KOH and NaOH are caught by the scrubber, which would tend to make the water basic[16]. Furthermore, there are issues concerning inter-species competition for adsorption sites. The complexity of the contaminant mixture in wastewater necessitates empirical information. The only such reported work comes from the Swiss company Dasag's testing of the IISc gasifier (Sharan et al, 1997). Preliminary testing showed that 70% of chemical oxygen demand[17] (COD) was removed after 30 minutes of mixing with char from the gasifier in a 250 ml sample containing 2,000 mg/l COD. Ash from the gasifier was also shown to adsorb organics quite effectively.

---

[16] Mukunda's group at the IISc gasified a high potassium weed which ended up giving them an excessively basic water seal (Mukunda, 1998). That weed has the same fractional weight of potassium that corn stalks do.

There are a number of ways tar-laden activated carbon can be disposed of once its adsorptive capacity has been exhausted. To recapture the energy content of both the char and a large fraction of the adsorbed species, the char can be recycled back to the gasifier. Another option is to regenerate the char for repeated use. Mukunda (1998) has proposed using a central facility to perform this function. He uses a 400 °C nitrogen stream to flush the adsorbates from the char and then burns the effluent. A third possibility is to simply burn the char, thereby destroying organics and char alike. While it was mentioned that ash also has adsorptive ability, it may be useful for other purposes such as restoring mineral matter to the fields it originated from.

TAR SKIMMING

Some tar components will not be soluble in the wastewater, making their removal using adsorbents impossible. This brings up the possibility of tar skimming. If wastewater is allowed to settle out, insoluble tars may be removed by mechanically skimming them off of the surface. Such a technique will be employed in the BIOSYN system being developed in Canada (Milne et al, 1998). This large-scale (MW range) system employs a higher-tar gasifier. Because there is significant energy content in the skimmed tar, it will be recycled back to the gasifier. This will not likely be the case at the small-scale using a low-tar downdraft gasifier, where it might be simplest to burn skimmed tars.

AERATION / AIR STRIPPING

Aeration and air stripping are useful techniques for removing dissolved substances that are highly volatile, like ammonia and hydrogen sulfide. Air is either bubbled through the wastewater (aeration) or forced up through water flowing down a bed of packing material (air stripping). The idea is to maximize the water/air contact area thereby accelerating the rate at

---

[17] COD gives information on the amount of organic pollutants present (Sharan et al, 1997).

which contaminants diffuse into the air. Something like the small cooling tower shown in Figure 3.6 already performs this function to some extent.

OTHER IDEAS / CONSIDERATIONS

Use of wet oxidation and biological treatment are being considered as possible methods for wastewater tar treatment. Their operating costs, which are expected to be high, will be directly proportional to the amount of organics that must be removed. This is yet another reason it is desirable to have a low tar gasifier (Hasler, 1997).

EXPERIENCE IN ZHEJIANG PROVINCE, CHINA

Zhejiang province is home to a number of rice husk gasification plants. Prior to 1989, wastewater from a 200-kW plant in Shaoxing city was disposed of in a river causing serious pollution. In 1989 a water treatment system was devised which eliminates drainage of contaminated water. It allows for cleaning and recycle of scrubber water. Rice husk char produced in the gasifier is used for cleaning, but no further details are available. The local Environment Protection Department has praised the solution (Luo, 1998).

EXPERIENCE WITH ASCENT GASIFIERS

Experience with ASCENT gasifiers[18], which produce very little tar, indicates that scrubber water can be recycled for prolonged periods of time (Jain, 1998). Very low-tar producer gas certainly helps to make this possible. Another factor is that most ASCENT systems employ a cooling tower for the scrubber water thereby providing some degree of aeration. It is speculated that if there ever is a need to discharge scrubber water, only the pH may need to be adjusted (Jain, 1998).

---

[18] ASCENT gasifiers are used in systems designed by BG Systems.

3.4 CONCLUSION AND RECOMMENDATIONS

Although co-compression of low-Btu fuel and air coupled with catalytic combustion is an attractive design option, the proof will be in the testing. The sensitivity of the catalytic combustor to producer gas contaminants should be experimentally determined, if only to learn the effect of occasional declines in fuel cleanliness. Also, particulate and alkali tolerances for small, lower temperature radial turbomachinery need to be established through experimentation. Values used in this analysis were for larger, higher temperature axial machines. Because microturbines have only just entered the marketplace, not much attention has be paid to fuels like producer gas. This should not be the case indefinitely, as evidenced by companies like Reflective Energies and perhaps AlliedSignal as well, which has plans to investigate markets in China and India in the future.

Because there are many more fabric filter options than were described here, further investigation is merited. For example, there is the possibility of using cheap, disposable filters that are designed to be loaded up to a certain weight with particulates (and tars for our purposes) and then thrown away (or maybe burned to destroy the tars). Perhaps instead of disposal they can be manually cleaned on a periodic basis. The feasibility of this and health issues should be investigated.

Wet gas clean-up combined with a high-efficiency fabric filter is an auspicious method for providing a clean fuel gas for a microturbine. To more accurately design a clean-up system will require knowledge of particulate size distribution and composition. A further level of complexity is that the character of the particles at the compressor inlet can be quite different from those at the turbine inlet due to phenomena like particle agglomeration (Hamed, 1998). Such behavior may alter gas clean-up requirements.

Given the options available for treatment of dirty scrubber water, this should not be a technological barrier to adopting wet gas cleaning. The question is more one of cost-effectiveness than anything else. It is entirely possible that water treatment systems for small-scale gasification systems can be economically unfeasible, as suggested by Milne et al (1998). However, what if a very low-tar gasifier is used, adsorbent is generated on site by the gasifier, and labor is cheap? This situation can be realized in a place like Jilin. Also bearing in mind that a solution has been devised in Zhejiang, water treatment is likely not an economic barrier.

Chapter 3 References

Alden, H., Bjorkman, E., Carlsson, M. and Waldheim, L. (1993). "Catalytic Cracking of Naphthalene on Dolomite," in *Advances in Thermochemical Biomass Conversion*, ed. Bridgwater A.V., Chapman & Hall, Glasgow, vol 1, p. 216-32.

Anonymous. (1998). "Power and Heat from Biomass Gasification," BG Systems product literature.

Anonymous. (1998). "GE Turbo Alternators," General Electric product literature.

Boyce, M.P. (1982). *Gas Turbine Engineering Handbook*, Gulf Publishing Co., Houston, Texas.

Cheremisinoff, N.P. and Cheremisinoff, P.N. (1993). *Carbon Adsorption for Pollution Control*, Prentice-Hall, New Jersey.

Craig, J.D. and Purvis, C.R. (1998). "A Small Scale Biomass Fueled Gas Turbine Engine," Paper No. 98-GT-315, American Society of Mechanical Engineers, New York.

Decorso, M., Newby, R., Anson, D., Wenglarz, R. and Wright, I. (1996). "Coal/Biomass fuels and the gas turbine: utilization of solid fuels and their derivatives," Paper No. 96-GT-76, American Society of Mechanical Engineers, New York.

Eggerstedt, P.M. (1998). Industrial Filter & Pump Mfg. Co., personal communication.

Glassman, I. (1996). *Combustion*, 3rd ed., Academic Press, San Diego.

Hamed, A. (1998). Professor of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, personal communication.

Hasler, P., Buehler, R. and Nussbaumer, T. (1997). "Evaluation of Gas Cleaning Technologies for Small Scale Biomass Gasifiers," Final Report to the Swiss Federal Office of Energy and the Swiss Federal Office for Education and Science, July.

Jacob, K. and Dhodapkar, S. (1997). "Gas-solid separations," in *Handbook of Separation Techniques for Chemical Engineers*, ed., Schweitzer, P.A., McGraw-Hill, New York.

Jain, B.C. (1998). Ankur Scientific Energy Technologies, personal communication.

Johnson, M.S. (1982). "Prediction of Gas Turbine On- and Off-Design Performance When Firing Coal-Derived Syngas," *Journal of Engineering for Gas Turbines and Power*, April, Vol. 114, p.380-385.

Katofsky, R.E. (1993). "The Production of Fluid Fuels from Biomass," Princeton University, Center for Energy and Environmental Studies Report No. 279, June.

Kohl, A.L. and Riesenfeld, F.C. (1960). *Gas Purification,* McGraw-Hill Book Co., New York.

Leppalahti, J., Kurkela, E., Simell, P. and Stahlberg, P. (1993). "Formation and Removal of Nitrogen Compounds in Gasification Processes," in *Advances in Thermochemical Biomass Conversion*, ed. Bridgwater A.V., Chapman & Hall, Glasgow, vol 1, p. 160-74.

Luo, W.H. (1998). "The Gasification and Electricity Generation System Employed with Rice Husk in Zhejiang Province," presented at the Workshop on Small-Scale Power Generation from Biomass, Changchun, China, 12-13 January.

Milne, T.A., Abatzoglou, N. and Evans, R.J. (1998). "Biomass Gasifier 'Tars': Their Nature, Formation, and Conversion," National Renewable Energy Laboratory report NREL/TP-570-25357, November.

Mukunda, H.S. (1998). Dept. of Aerospace Engineering, Indian Institute of Science, personal communication.

Mukunda, H.S., Dasappa, S., Paul, P.J., Rajan, N.K.S., Shrinivasa, U. (1994). "Gasifiers and combustors for biomass – technology and field studies," *Energy for Sustainable Development*, v1, n3, September, p. 27-38.

Mycock, J.C., McKenna, J.D. and Theodore, L. (1995). *Handbook of Air Pollution Control Engineering and Technology*, CRC Press Inc., Boca Raton.

Neilson, C.E., Shafer, D.G. and Carpentieri, E. (1998). "LM2500 Gas Turbine Fuel Nozzle Design and Combustion Test Evaluation & Emission Results with Simulated Gasified Wood Product Fuels," Paper No. 98-GT-337, American Society of Mechanical Engineers, New York.

O'Brien, P. (1998). "Development of a 50-kW, Low-emission Turbogenerator for Hybrid Electric Vehicles," Paper No. 98-GT-400, American Society of Mechanical Engineers, New York.

Pedersen, K. (1993). "Catalytic Hydrocracking of Tar From Gasification of Straw," in *Advances in Thermochemical Biomass Conversion,* ed. Bridgwater A.V., Chapman & Hall, Glasgow, vol 1, p. 246-64.

Podolski, W.F., Swift, W.M. and Miller, S.A. (1995). "Air emissions from pressurized fluidized bed combustors," in *Pressurized Fluidized Bed Combustion*, eds. Cuenca M.A. and Anthony E.J., Chapman & Hall, Glasgow.

Prabhu, E. (1998). President of Reflective Energies, personal communication.

Prabhu, E. (1999). President of Reflective Energies, personal communication.

Probstein, R.F. and Hicks, R.E. (1982). *Synthetic Fuels*, McGraw-Hill Book Co., New York.

Reed, T.B. and Das, A. (1988). "Handbook of Biomass Downdraft Gasifier Engine Systems," Solar Energy Research Institute, SERI/SP-271-3022, March.

Rodgers, C. (1997). "Thermo-economics of a Small 50 kW Turbogenerator," Paper No. 97-GT-260, American Society of Mechanical Engineers, New York.

Sharan, H., Buhler, R., Giordano, P., Hasler, P., Salzmann, R., Dasappa, S., Sridhar, B. and Girish, B. (1997). "Adaptation of the IISc-Dasag Gasifier For Application in Switzerland," Final Report to the Swiss Federal Office of Energy, August.

Taylor, T. (1998). President of Thermogenics, personal communication.

Sieben, M. (1992). "Small Recuperated Gas Turbines for Power and Heat Generation," Master's thesis draft, Princeton University, Center for Energy and Environmental Studies, July.

Solt, J.C. (1998). "The Ultimate NOx Solution for Gas Turbines," Paper No. 98-GT-287, American Society of Mechanical Engineers, New York.

Solt, J.C. (1999). Catalytica Combustion Systems Inc., personal communication.

GRI. (1989). "Advanced Energy System Program, Second Annual Report," Gas Research Institute report no. GRI-89/0080, February.

Tucci, E.R. (1982). "Use catalytic combustion for LHV gases," *Hydrocarbon Processing*, March, p. 159-166.

Wetzel, J. (1998). Filtration and Media Group Inc., personal communication.

Wiant, B.C., Bachovchin, D.M., Onischak, M., Carty, R.H. and Ratcliff, M. (1996). "Biomass Gasification Hot Gas Filter Testing Results," Paper No. 96-GT-336, American Society of Mechanical Engineers, New York.

4. THE MICROTURBINE FOR BIO-POWER IN CHINA

As mentioned in the introduction, rural China currently presents a widespread opportunity for innovative use of crop residues. The combination of farmers' rising incomes and decreasing dependence on crop residues for energy needs has resulted not only in growing air pollution from open residue burning but also a greater means for adopting cleaner, more efficient ways of meeting energy needs. Gu and Duan (1998) of Tsinghua University describe the situation:

> Of the whole country's crop straw resources in 1996, 279.64 million tons, about 39.6%, was used as rural domestic fuel, equal to 119.97 Mtce; 27.5%, about 194 million tons was used as poultry feed; 2.7%, about 19 million tons was used as industrial raw material (papermaking, handicrafts, etc.), and 15%, about 106 million tons was used as crop fertilizer or lost during collection. The left 107 million tons crop straw was abandoned or directly burnt in cropland. This is caused mainly by two reasons. One reason is that the traditional cooking pattern using wood stove has become unsuitable to the newly developed life behaviour of prosperous peasants because it is time-consuming and not very clean in cooking, etc., and they begin to use more and more conventional energy resources, such as coal. In some prosperous rural areas, clean fuels such as LPG are even commonly used. The other reason is that because the weather in northern China is very drought and the temperature is low, straw cannot rot within short time after being returned to cropland. Together with that the multiple crop index of China's cropland is rather high, the return of straw to cropland not only cannot improve but also even will reduce crop yield. Returning straw to cropland is also time-consuming and labour-consuming, so in northern China, straw is rarely returned to cropland in practice. But the abandoned straw resource has a great potential of being changed into high-grade commercial energy such as gas fuel or power and so can be fully utilized if suitable advanced conversion technologies can be used.

Sun, Wang, and An (1998) of the Energy Research Institute of the Shandong Academy of Sciences report that:

> With the rapid increasing of agriculture and rural economy, the rural area, especially in the east part of China where the agriculture developed better, appear a harmful phenomenon of surplus of crop straws. Whenever in the harvest season, a large quantity of straws was put in the field or along the road and burned up directly. Thus caused serious air pollution and vegetative cover destroying. It is difficult to estimate exactly the amount of burned straws annually. However some statistics point out that 100 million tons is a conservative estimation. ... Chinese government has paid great attention to the problem. To transfer 100~150 million tons of agricultural residuals annually to other usage, especially to energy, is an urgent demand in Chinese rural area.

In addition to environmental reasons for seeking innovative ways to use agricultural residues, there are public health reasons as well. Though in a state of transition, rural cooking and heating methods still largely employ indoor direct combustion of crop residues. This practice can lead to the development of serious respiratory diseases. In fact, respiratory disease is a leading public health threat in China with indoor biomass and coal combustion being a primary culprit (Florig, 1997). Particulates small enough to lodge themselves deep in the lungs reach dangerous concentrations inside households. In cold northeastern provinces like Jilin, the traditional method for heating homes involves the use of "kangs," which are large bed-like, simple box furnaces made of brick that are slept on top of at night. Residues are piled in and set to smolder continuously for periods as long as two months with a newer, more efficient kang design (Cao et al, 1998). Although exhaust products are vented outdoors, there are still potential problems such as prolonged, low-level CO poisoning that can result from leaks. This and other related health problems are suggested by studies done in northeastern industrial cities which found that lung cancer risk increased with increasing years of kang use (Xu et al, 1989; Wu-Williams et al, 1990). Furthermore, it needs to be pointed out that chronic CO exposure is very often misdiagnosed because symptoms mimic those of a host of other health problems (Walker et al, 1999). Finding a cleaner way to meet cooking and heating needs is important to protecting public health. Energy conversion systems involving gasification of residues, currently being explored in a number of provinces including Jilin, are a promising solution.

4.1 AN INITIAL FOCUS ON JILIN PROVINCE

China is an immense country with a variety of climates and resources, and therefore different energy needs are to be found in different provinces. For the purposes of the current study, Jilin Province in northeastern China is the focus. The provincial government of Jilin is keenly interested in finding ways to utilize its enormous crop residue resource in a manner that will benefit the farmers and make economic sense. This interest is demonstrated by active participation in the China Council for International Cooperation on Environment and Development[1] (CCICED) and the funding of demonstration projects. Between 2001 and 2010, Jilin's government plans on investing a total of 600 million Yuan ($72 million) to propagate biomass power industries based on gasification in its villages[2].

The role that microturbine technology may be able to play in Jilin will be investigated in this chapter. It should be pointed out that analysis and design of an energy conversion system which encompasses all the critically important human factors is beyond the scope of this thesis. The emphasis here is to illustrate what the microturbine may be able to offer a village. To begin with, a word must be said about gasification of corn stalks, the primary residue in Jilin, because this conversion step is the foundation for all the energy conversion steps that follow.

4.2 GASIFICATION OF CORN STALKS

4.2.1 ISSUES AND A STRATEGY FOR GASIFICATION

Corn stalks, like most agricultural residues, are widely regarded by the gasification community as a large but difficult to utilize resource. The primary reason is their high ash and alkali metal content relative to that of wood, for example (Table 4.1). Notice how much more ash, potassium as well as silicon are found in corn stalks[3]. Alkali metal compounds, like potassium oxide, can form mixtures with silica (the primary oxide in ash) that have a very low

---

[1] "China Council for International Cooperation on Environment & Development (CCICED), a high level non-governmental advisory body, was established by the State Council of China in 1992. Its stated purpose is 'to further strengthen cooperation and exchange between China and the international community in the field of environment and development.' " (http://www.harbour.sfu.ca/dlam/purpose.html)

[2] http://www.harbour.sfu.ca/dlam/Working%20Groups/energy.html

[3] Note that the composition in Table 4.1 refers to one sample of corn stalks, most likely grown in the U.S. Composition can be expected to vary from one region to another.

eutectic temperature (Miles et al, 1993). Figure 4.1 shows the phase diagram for potassium oxide and silica. The melting point for pure silica, to the far right of the composition spectrum,

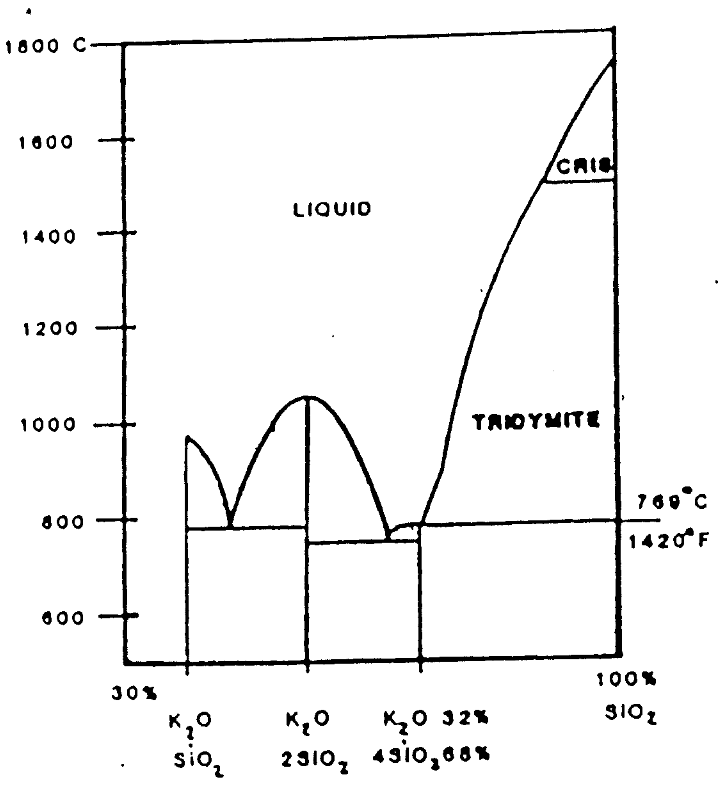


Figure 4.1 Phase diagram for K_2O-SiO_2 (Miles et al, 1993)

is shown to be about 1750 °C. As more potassium oxide is added to the mixture, we move to the left on the x-axis and the melting point plummets dramatically until the eutectic point is reached. The eutectic composition and temperature are 32% K_2O/68% SiO_2 and 769 °C, respectively. Such mixtures can melt in hot zones of a gasifier and subsequently resolidify in lower, cooler regions forming what is called “slag.” Slag accumulation can block gas flow channels resulting in poor performance and even shutdown of the gasifier. A second aspect of corn stalks that makes gasification troublesome – their low bulk density – is less serious. Biomass needs to be able to freely flow down the gasifier as it gets consumed. Low bulk density can contribute to “bridging” in which unreacted biomass gets stuck higher up in the gasifier. The low bulk density issue is readily solved through some form of physical processing (chopping, pelletizing, etc.), but the slagging issue is not so simple.

Table 4.1 Corn stalk and Eucalyptus Compositional Data

Proximate Analysis (weight % as received)	**Corn stalks**	**Eucalyptus**
Ash	4.75	0.48
Volatile	75.96	78.52
Fixed Carbon	13.23	11.66
Moisture	6.06	9.34
Heating Value, dry (HHV)	18.1 MJ/kg	19.2 MJ/kg
Ultimate Analysis (weight % as received)		
Moisture	6.06	9.34
Carbon	43.98	44.89
Hydrogen	5.39	5.21
Oxygen*	39.10	39.92
Nitrogen	0.62	0.13
Sulfur	0.10	0.03
Chlorine**	0.25	0.05
Ash Composition (weight % as received)		
Silicon	1.20	0.04
Iron	---	---
Aluminum	0.05	0.02
Sodium	0.006	0.02
Potassium	1.08	0.038
Calcium	0.294	0.091
Magnesium	0.175	0.021
Phosphorus	0.180	0.061

* oxygen by difference
** not usually part of an ultimate analysis
Source:
http://rredc.nrel.gov/biomass/doe/nrel/comp/alki/appendix.html

While the most straightforward approach to avoiding the formation of slag would appear to be lowering gasifier temperatures, doing so can have the adverse effect of reducing tar destruction (which is facilitated by high temperatures). Solving this problem requires designing the gasifier such that it operates in the appropriate window of temperature and residence time (Mukunda, 1999). Simply put, tar will crack when subjected to high temperatures as well as when subjected to somewhat lower temperatures provided the residence time is sufficiently long.

Fortunately, increasing the residence time and lowering the peak temperature go hand in hand. For a fixed gas production rate, increasing the diameter of a gasifier reduces the air flux through it and increases the residence time of the gas inside the gasifier. Since gasifiers operate under fuel rich conditions, decreasing the air flux lowers the peak temperature. The basic lesson in the world of gasification is that gasifiers must be designed to accommodate the particular kind of biomass to be used.

4.2.2 CANDIDATE CORN STALK GASIFIERS

INDIAN INSTITUTE OF SCIENCE (IISC) AT BANGALORE

The aforementioned approach for gasifying biomass that has a propensity to slag has proven effective for the gasifiers developed by Professor H.S. Mukunda's group at the Indian Institute of Science (IISc) at Bangalore. Units have been successfully tested on fuels like cotton stalks, for instance, which Reed et al (1988) describe as having a severe degree of slagging. Because corn stalks have an important use as fodder in India, testing has not been done with them. However, after being presented with the elemental and ash composition of corn stalks (Larson, 1998), Mukunda saw no problem with using them in his gasifier. Bulk density is the primary constraint of the fuel, which Mukunda says should be above 150 kg/m^3. Based on the requirements of the following two candidate corn stalk gasifiers, achieving an adequate bulk density may be possible by simply cutting the stalks down to sufficiently small pieces.

BG SYSTEMS

BG Systems, a United States company, has a commercial gasification-based power generation system using gasifier technology developed in India by Ankur Scientific Energy Technologies (ASCENT). Fuels that the ASCENT gasifier is qualified to use include wood chips, stalks of cotton, tuver, and lentil, maize cobs, coconut shells, palm nut shells, rice hulls, soy husks and sawdust (DeLaquil, 1998). As with the IISc gasifier, the ASCENT unit has not been tested with corn stalks. However, based on experiments with other kinds of stalks, such as mustard, there is a "reasonable level of confidence" that corn stalks would be an acceptable fuel (Jain, 1998). Dr. Jain of ASCENT comments that the stalks would need to be cut down to less than about an inch in size with a moisture content below 20%.

One of the highlights of the Ankur gasifier is that it produces very little tar, nearly all of it being cracked inside. Less than 5 mg/Nm^3 of tar escape the gasifier according to product literature (Anonymous, 1998). If operated properly, the charcoal bed in the reduction zone maintains itself at a height appropriate for the type of biomass being used. The height needs to be great enough to give a sufficient residence time for tars that escape the combustion zone to be cracked. The primary purpose of gas clean-up, as a result, is particulate removal (DeLaquil, 1998).

SHANDONG ENERGY RESEARCH INSTITUTE

Although the government of China has given attention to biomass energy R&D since the 1970s, it has really been in the last ten years that technology for biomass gasification has developed quickly and has had successful application (Sun et al, 1998). A primary player in this progress has been the Energy Research Institute of the Shandong Academy of Sciences. It has developed a crop straw gasification system for providing villages with cooking gas that is currently being demonstrated in Jilin Province as well. The gasifiers are fixed-bed, downdraft designs that come in three sizes: ~ 165, 275, and 550 kW$_{th}$. As with the ASCENT gasifier, feedstock needs to be cut to pieces about 2-3 cm in length with moisture content below 20%. After limited gas cleaning (dry), the gas is reported to contain 100 mg/m^3 combined particulates and tar. While this has apparently not been problematic for pipelines, it has required that the gas stoves be cleaned monthly. The addition of a small fine filter upstream of the stove and gas meter has solved this problem, however. Efforts are underway by researchers to improve the gas quality. Over 120 cooking gas systems were scheduled to be up and running by the end of 1998 (Sun, 1998).

Ralph Overend of the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) traveled to China and obtained first hand information on these systems (Overend, 1998). Apparently, tar aerosol (fine droplets) is getting as far as the gas burners in village homes. Though this is not a problem for the burners, Overend suspects the gas quality is not sufficient for IC engines. Overall gasifier performance is described as "acceptable," owing in part to the willingness of the Chinese to deal with high maintenance (labor is inexpensive).

Three different gasifier designs appear to be promising candidates for the use with corn stalks. Given these circumstances, it seems highly unlikely that sustainable corn stalk gasification will be a technological obstacle. The quality of corn stalk producer gas needs to be experimentally determined, but does not appear to be especially problematic given positive experience with comparable stalk-like biomass. Having indicated that corn stalks are a viable candidate fuel for small-scale gasification, it is now appropriate to consider the biomass resources Jilin has to offer as well as the energy demands they will be expected to satisfy.

4.3 BIOMASS AVAILABILITY AND VILLAGE ENERGY DEMANDS IN JILIN PROVINCE

4.3.1 BIOMASS RESOURCES

Jilin Province is one of the largest grain producers of China, the principal crop being corn. Associated with large grain production is large crop residue production, such as corn stalks. According to 1996 statistics (Cao et al, 1998), a total of 33.23 million tons of exploitable crop residues were generated that year (80% of total residue generation is considered to be exploitable). Out of this recoverable amount, 28.05 million tons were corn stalks. With a 1996 agricultural population in Jilin of 14.37 million, the total recoverable resource corresponds to about 2.31 tons of residues per capita. There are some 3.5 million farm households in Jilin, having an average of 4.1 people in each. On a per household basis, the annual residue resource is nearly 9.5 tons.

The other large biomass resource in Jilin is human and animal manure. At 34.32 million tons of exploitable manure, this resource is just about equal in mass to that of crop straws. About 90% of the manure resource is used to fertilize farmlands after being composted (Cao et al, 1998).

4.3.2 COOKING GAS AND HEAT DEMANDS

Traditionally in Jilin villages, direct combustion of corn stalks is employed to both provide heat during the frigid winter and cook food with. Farmers with greater incomes are turning towards coal briquettes, but the primary fuel is still corn stalks. The current crop straw use distribution is depicted in Figure 4.2.

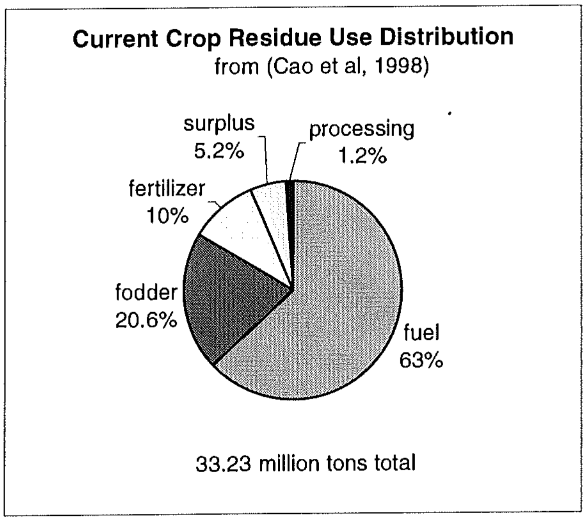


Figure 4.2

Fuel	Cooking (per hh per day)	Cooking + Heating[a] (per hh per day)
Corn stalks	4.5 kg 74 MJ	17.5 kg 290 MJ
Producer gas	6 m^3 2.6 kg stalks[b] 30 MJ	20 m^3 8.7 kg stalks[b] 100 MJ

[a] Average daily winter consumption

[b] Required for gasification

Corn stalks LHV	16.5	MJ/kg
Producer gas LHV	5	MJ/m^3
Cold-gas efficiency	0.7	

Table 4.2 Estimated daily household energy use

Each household of roughly 4 people consumes 4-5 kg of corn stalks per day for cooking purposes and 15-20 kg per day in the winter for both cooking and heating[4] (Larson, 1998). Cooking and heating are linked because stove exhaust is usually directed through the kang before ultimately being vented. This practice transfers some of the sensible enthalpy of the stove's combustion products to the home. Table 4.2 compares this traditional daily household consumption with a case where all heating and cooking is done with producer gas derived from residues, as estimated by Cao et al (1998).

Given the producer gas consumption estimate in Table 4.2, it is quickly apparent that using producer gas to meet both cooking and heating needs may result in significantly lower corn stalk consumption. In the case of cooking, about 40% less biomass is required. This can be attributed to a more complete combustion of the corn stalks[5] as well as to gas stoves which more efficiently transfer the chemical energy of the producer gas to the food being cooked. Heating with producer gas is clearly more efficient as well. Traditionally, residues slowly burn inside kangs which have no special heat transfer surfaces (like fins) at all. They are simply brick boxes that diffuse heat to the room. More efficient heating methods, described in the next paragraph, are now being tested. All together, estimates indicate that a household's daily biomass consumption would drop by almost 9 kg, which is a 50% reduction. Consequently, a greater residue resource is available for uses like generating power.

At the present time, the estimated large reduction in household biomass use is far from definite primarily because of uncertainties surrounding the daily household gas demand estimate

---

[4] The heating season lasts typically about 5 months, during which time temperatures are less than 5 °C (Larson, 1998).

of 20 m^3 during the heating season. While there is actual experience[6] to support the estimate for cooking gas demand, there is as of yet very little experience with the gas demand of a northeastern-China household for heating. Preliminary experiments are being conducted in Jilin with three different heating methods (Jia, 1999), but little is yet known about how a family would use gas for heating in practice. One heating method produces hot water at the household scale (simple water heater plus radiator), another hot air (simple furnace), and a third uses the kang already installed in a household (Jin, 1999). The last option is said to be as efficient as the energy-saving underground kang, a relatively new design that allows a kang's efficiency to allegedly exceed 50% (Cao et al, 1998). That is, about the same amount of heat is transferred to a household with smoldering crop residues in the energy-saving kang as when the same amount of residues is first gasified at 70% efficiency and then burned within the kang. Because the energy-saving kangs are about 50% efficient, the burner/kang arrangement would then have to transfer about 70% of the producer gas' chemical enthalpy to the home since the efficiency of the gasifier is about 70% as well (0.7*0.7 = 0.5). When the gas for cooking is subtracted, the 20 m^3/day estimate provided by Cao et al (1998) reduces to 14 m^3/day exclusively for heating. If we restrict this amount of gas to heating bedrooms at night over a 12-hour period, it would provide:

$$14\ m^3(5000\ kJ/\ m^3)/(12\ hr)/(3600\ s)\ \eta = (1.6\ kW)\ \eta,$$

where η is the efficiency with which the gas' chemical enthalpy is transferred to the room. Taking η = 70%, about 1.1 kW of heat would actually be transferred to the home for a 12-hour period (or only 0.56 kW over a 24-hour period). As shown in Appendix C, it is highly unlikely that such a low heat input would be able to maintain an indoor household temperature of 15 °C, for instance, unless significant insulation exists. The 60-70% heat loss reductions demonstrated

---

[5] Partial oxidation occurs in the gasifier. Oxidation (combustion) is completed in the gas stove. There is more time for combustion than in the case of direct combustion which produces a lot of smoke and particulates (products of incomplete combustion).

[6] See the description of the Tengzhai village cooking gas system in Dai et al (1998).

in Appendix C after adding insulation and tightening the home support the idea that because home retrofits can be so effective, they should go hand in hand with the design of any kind of heating system. Vast amounts of energy could be saved, and limited resources could be far more efficiently used. Without serious retrofits, 1.1 kW would likely be adequate only for heating a very localized region within a home, such as near the bed at night. Whether this is true to what villagers would demand in practice with the advent of a new method of heating is unknown at this stage.

In light of the uncertainties involved, the primary analysis in this thesis will simply assume that 100% of the chemical enthalpy of the 20 m^3 is to be transferred to a given home on an average heating-season day. This will be in addition to the daily gas consumption for cooking. Such a situation would allow for 1.2 kW of continuous heat addition, 24 hours a day.

One method of interest for providing this heat is a hot water district heating system that employs waste heat recovery from a microturbine. If we use the heat exchanger calculation in Appendix B (sized to the exhaust flow of a 75 kW_e microturbine), a total of about 140 kW of thermal power is available to households if indoor radiators bring the inlet 83 °C water down to 50 °C (for the time being neglecting heat losses in the piping). If there are 100 households, each will have a mass flow of 0.01 kg/s of hot water providing 1.4 kW of continuous heat. If heat loss from pipes were as great as 14%, the 75 kW_e microturbine would still be able to meet a 1.2 kW heat load. The district heating system is described further in Section 4.4.1, as is the significance of meeting cooking and heating needs through a combination of producer gas and waste heat distribution.

4.3.3 ELECTRICITY DEMAND

A discussion on electricity demand needs to be prefaced by a few comments on the significance of being grid-connected. While it is true that some 90% of rural Chinese have electricity, the supply is characterized as neither sufficient nor guaranteed (Sun et al, 1998). Although apparently not adequate or reliable, being grid-connected – as all of the villages in the Jilin corn belt are (Larson, 1998) – can be quite advantageous for small-scale distributed power generation. If the grid is sufficiently large, it could allow for excess power generated by a small village plant to be sold to the grid at any time of day. Having access to a market which is hungry for power 24 hours a day allows for high capacity factors as well as 24-hour-a-day cogeneration. Another benefit of being able to sell to the grid is that a power plant can be oversized (resources permitting) while at the same time maintaining a high capacity factor. This would allow for a wide spectrum of local needs to be met, ranging from low initial consumption in the home to significantly larger future consumption if local industries develop as a result of the availability of reliable power. As will be seen shortly, having an oversized prime mover is just what would happen if the microturbine were sized to meet the heat load discussed in Section 4.3.2.

According to the Jilin Province Energy Resources Institute, average daily household electricity consumption amounts to 0.6 kWh. Put into more familiar terms, this is equivalent to 100 W for 6 hours. Village power needs are about double this during the spring (irrigation) and fall (crop processing). Therefore, during these times of agricultural activity in a 100 household village, 120 kWh/day would be consumed. If a 75 kWe microturbine were to be operational for 16 hours each day, 1200 kWh would be produced. This is an order of magnitude more power than could be locally consumed on average today, indicating that a sizeable portion of power would be available for sale to the grid or to any local industries that may develop. With regard to meeting peak demand, consider the following. If the entire village's 100*1.2 kWh = 120 kWh energy usage takes place over only 2 hours, a 75 kWe unit would more than suffice with 150 kWh output.

Certainly, different villages at different levels of economic development will have different electricity demands. Also, given the continuing rise in standard of living (which is giving rise to the stalk surplus) it is wise to consider a growing demand. Taking daily household energy consumption to be at 5.4 kWh, Overend (1998) estimates a peak power demand of 165 kW for a Jilin village of 326 households. Scaling this down to a 100 household village, about a 51 kW peak can be expected (assuming the same 5.4 kWh/day/household). Even at this rate of consumption, a 75 kW unit is still suitable. By sizing the microturbine to be able to meet average winter heat demand, power demand is far more than adequately met.

4.4 ALTERNATIVE ENERGY CONVERSION STRATEGIES FOR JILIN PROVINCE

Because gasification of biomass is being considered here, one can exploit the inherent versatility of having a gaseous fuel by examining a host of usage configurations. It is not automatically obvious which configuration will be the most feasible in a Chinese village when economics are taken into account. For instance, it may turn out that although it would be most efficient to capture waste heat from the microturbine for district heating, the capital cost of a district heating system could be excessive. It may turn out that supplying households with gas alone for cooking and heating makes more economic sense.

The first energy conversion system investigated will be referred to as a "trigeneration" plant: one which provides cooking gas, heat, and power. The trigeneration alternative as well as a few variants will be considered in this section. Gas production and distribution alone has already been explored for the Chinese context elsewhere (Dai et al, 1998; Cao et al, 1998). Therefore, in addition to the trigeneration case, variants considered here will instead provide (1) gas and power, and (2) hot water and power.

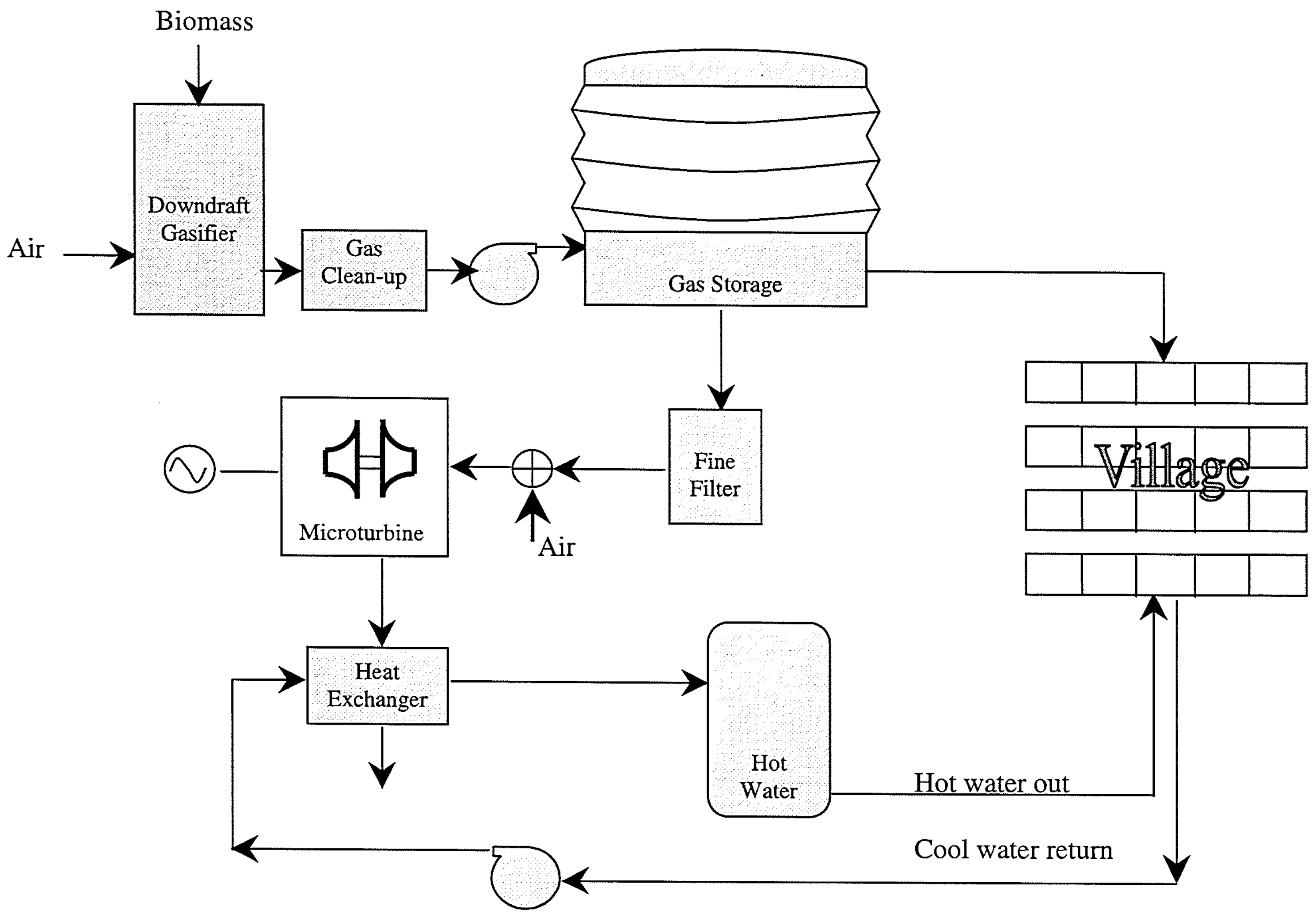
4.4.1 TRIGENERATION: COOKING GAS, HEAT, AND POWER

The function of the plant being considered here is to convert the chemical energy in crop residues like corn stalks into three convenient, domestically useable forms: cooking gas, heat, and electricity. The general layout of the trigeneration plant is shown in Figure 4.3. After being cut down to an appropriate size, residues are gasified in a downdraft gasifier. The resulting producer gas is cleaned and subsequently fed to a gas holder which maintains a constant gas pressure. Gas is available for both the cooking gas distribution system and the microturbine, as indicated in the schematic. Heat can be recovered from the microturbine exhaust and piped to homes in the form of hot water.

Available to provide all three forms of energy is the equivalent of residues currently used for cooking and heating as well as surplus residues. Looking again at Figure 4.2, this amounts to $(0.63 + 0.052)*33.2 = 22.6$ million tons per year, or about 6.5 tons per household. This quantity is taken to be the constraint on how much of a given energy product may be generated.

A 100-household village, as mentioned earlier, is well served by a 75 kWe microturbine. Meeting cooking gas needs requires about 0.95 tons per household per year leaving 5.5 tons per household for heat and power. As shown later, this amount allows the microturbine to achieve high capacity factor. As mentioned earlier, a 75 kWe microturbine's waste heat will be able to meet the estimated average winter heat demand when the unit is operating at full output. Because the needs of a 100-household village turn out to be compatible with existing sizes of microturbine

Figure 4.3 The Trigeneration System



(75 kWe), gasifier (400 m^3/hr), and gas holder (250 m^3), this particular village size is the focus of the present investigation.

4.4.1.1 MEETING ABOVE-AVERAGE HEAT DEMAND

While knowledge of the average winter heat demand may be useful in sizing the microturbine, the overall system design needs to be able to meet above-average demand. The magnitude of this demand is estimated using a technique involving "heating degree months" shown in Appendix D. It is there found that an estimated 15.7% of the total heating season's heat demand will surpass the microturbine's design-point heat output. In terms of gigajoules, this is:

$$0.157*(100\text{ hh})*(1.2\text{ kW})*(150\text{ d})*(24\text{ h})*(3600\text{ s})*(10^{-6}\text{ GJ/kJ}) = 244\text{ GJ}$$

Therefore, approximately 250 GJ extra heat output must be supplied to the village over the 5-month heating season. Note that peak demand is not being used to size the microturbine because villages are taken to have a residue supply constraint. A microturbine that could meet the peak demand when operating at its design point would turn out to have a very low capacity factor over the course of a year. This section explores three other ways to meet peak heat loads. One will be selected with which to perform a more detailed analysis of the complete trigeneration system.

CASE 1: LONG-TERM HOT WATER STORAGE

One possibility for meeting heat demands that exceed the microturbine's thermal output is long-term hot water storage. At times when the microturbine's output is greater than the heat demand, excess hot water can be stored in a large, insulated tank. This will be the most efficient case of the three considered here because no additional residues need be consumed. Therefore, all residues available for power and heat (552 tons for a 100 household village) can be gasified for use in the microturbine. Consequently, the power that can be generated annually is:

$$552 \text{ tons}*(901 \text{ kWh/ton}^{7}) = 497{,}000 \text{ kWh}$$

In order to direct all residues to power generation, a large storage tank is needed. Enough hot water must be stored to allow for the transfer of about 250 GJ of thermal energy to the homes. Neglecting heat losses for the time being, water from the heat recovery unit carries about 140 kJ/kg of transferable heat. Storage of 250 GJ then corresponds to a required volume of:

$$250 \text{ GJ}*(10^{6} \text{ kJ/GJ})*(\ 1 \text{ kg}/140 \text{ kJ}) = 1780 \text{ tons} = 1780 \text{ m}^{3} = 471{,}000 \text{ gallons},$$

since water's density is about 1 ton/m^3. If storage is in a cylinder where the diameter equals the height, then these dimensions will be 13 meters each.

The first question to answer in assessing long-term storage is whether it is feasible to keep the water's temperature drop over the period of months sufficiently low. Consider a tank with diameter and height equal to 13 meters coated with the standard polyurethane insulation. The maximum heat transfer rate from the tank would occur when the outer surface of the insulation is actually at the ambient air temperature. This extreme case will be applied to the circumferential, top and bottom surfaces of the cylindrical tank. Heat loss over time will be estimated using the lumped-heat-capacity method, i.e. small temperature gradients within the water will be ignored and only a single temperature will be used. For unsteady conduction through the insulation, this method will give a maximum heat transfer rate since it will impose the

---

[7] For a 28% efficient microturbine, a gasifier with a 70% cold-gas efficiency, and crop residues with a 16.5 MJ/kg lower heating value.

greatest temperature at the insulation's inner surface[8] (the tiny thermal resistance of the metal wall will be neglected).

The governing equation is formed by setting the heat transferred through the insulation equal to the heat lost by the body of water within:

$$Q = \frac{2\pi kH(T - T_a)}{\ln\frac{r_2}{r_1}} + \frac{2kA}{w}(T - T_a) = -c_p \rho V \frac{dT}{dt}$$

The parameters are the thermal conductivity of the insulation (k), the height of the tank (H), the water's uniform temperature (T), the ambient temperature (T_a), the radius to the inner and outer surface of the insulation (r_1 and r_2, respectively), the area of the top and bottom of the tank (A), the thickness of the insulation (w), and the specific heat, density, and volume of the water (c_p, ρ, and V). Note that the expression for heat transfer through the top and bottom surfaces ignores any 3-dimensional effects.

The initial condition for this problem is that at t=0, $T=T_i$ where T_i is the initial water temperature. It gives rise to a simple exponential solution for T as a function of time:

$$T = T_a + (T_i - T_a)\exp - \left[\left(\frac{2\pi kH}{\ln\frac{r_2}{r_1}} + \frac{2kA}{w}\right)\frac{t}{c_p \rho V}\right]$$

Using Ta = -7.4 °C (the average heating-season temperature in Jilin), T_i = 85 °C, k = 0.023 W/m°C for the polyurethane foam and choosing an insulation thickness of w = 0.5 meters, it is found that after just over 120 days (4 months) the temperature of the water will drop to 80 °C. The reason for this perhaps surprising result is primarily due to two factors: the low value for k

---

[8] This method does not allow the water temperature at the edges to be lower than at the center of the tank.

and the enormity of the $c_p\rho V$ term, which is about 7.2 GJ/°C. Using the conduction equation above it is found that Q = 3470 J/s when T = 85 °C. This value for Q is the *greatest* heat transfer rate for all time because it is the initial rate. Applying this rate continuously over the course of a five-degree temperature drop would require $5*(7.2 \times 10^9 \text{ J}) / (3470 \text{ J/s}) = 120$ days. Operation of the microturbine 13 hours a day in which 1 kg/s of hot water is generated carrying 140 kJ/kg of transferable heat will require about 40 days to accumulate 250 GJ. It is concluded, then, that long-term hot water storage is technically feasible. The real obstacle is economics.

For a 500,000 gallon steel water storage tank with polyurethane foam insulation, the installed price in the United States is roughly \$170,000[9]. The same product made in China may have a significantly lower price. For simplicity, choose \$80,000, or about 50% of the U.S. price (see Table 4.4 presented later in Section 4.4.1.4). A discount rate of 12% with a time period of 20 years gives a capital recovery factor of 0.134. The simple levelized cost is then 0.134*\$80,000 = \$10,720 per year. Not taking maintenance or engineering into account, the marginal cost of the additional heat is then:

$$\$10{,}720 / 250 \text{ GJ} = \$43/\text{GJ}$$

As will soon be made clear in the next two cases, this option will be far too expensive. Long-term hot water storage would only appear economical if a novel approach could be found that would drive this cost down by about an order of magnitude.

CASE 2: BURNING EXTRA GAS IN STOVES

The next possibility for meeting above-average heat demand involves burning extra producer gas in a household's stove. In the trigeneration framework, homes are already provided with producer-gas-burning stoves. If they can be used for producing extra heat, this would avoid the cost and complexity of long-term hot water storage. Doing so, however, would divert some amount of producer gas from the microturbine thereby reducing the amount of electricity that can be generated.

Being burned indoors, all of the chemical energy in the producer gas is assumed to be transferred to the home. This means that the 250 GJ additional need can be met by gasifying about:

250 GJ*(1000 MJ/GJ)*(1 kg/16.5 MJ) / 0.7 = 22 tons of additional residues

This leaves 552 – 22 = 530 tons for power, which can be converted to about 478,000 kWh for the year (about 4% less than Case 1). Since no additional capital is required, the marginal cost of excess heat is given by:

[(lost revenue from electricity sales) – (additional gas revenue)] / 250 GJ

For now, choose a competitive rate of $0.05/kWh for power that is to be sold to the grid. For the gas, choose a price that makes it competitive with LPG. In the city of Baicheng, LPG costs 36 Y per bottle, and lasts 20 days for a family of four (Mao, 1999). This is then 1.8 Y for a day's worth of cooking with LPG. With producer gas, a day's worth of cooking was found to require about 30 MJ. Priced equivalently with LPG, producer gas could be sold for 1.8 Y/30MJ*1000 MJ/GJ = 60 Y/GJ = $7.2/GJ. So that producer gas is more economically attractive, pick $5/GJ. The marginal cost is then:

[19,800 kWh*($0.05/kWh) – (250 GJ)*($5/GJ)]/ 250 GJ = ($990 – $1250)/250 GJ

= – $1/GJ (*profit*)

---

[9] Price quotation from Fisher Tank Company (1999)

With the selected sale prices, Case 2 actually turns a profit! Obviously, this is more auspicious than Case 1. From the perspective of an independent energy services provider, it may even be tempting to do away with the district heating system all together and just sell gas for heating all throughout the winter. The problem with this idea is that it replaces revenue that would have otherwise come from urban centers or rural industry with revenue from villagers who very well may not be able to afford it. Two other concerns with this option are the greater risk of CO-poisoning that comes from extended use of producer gas indoors and also CO_2 accumulation in the home (CO_2 is classified as an asphyxiant[10] by OSHA[11]). The indoor concentration CO_2 may achieve when used as described here can be estimated.

The month requiring the greatest heating above the average (see Appendix D) is January with 7.05/12.08 = 58% of the 250 GJ of additional heat. This would correspond to a daily household heat addition of 0.58*(2.50 GJ)/ (31 days/mo) = 47 MJ/day. Together with cooking gas combusted indoors this is 47 + 30 = 77 MJ/day. The producer gas' average molecular weight is 24.2 kg/kmol and its LHV is 4.95 MJ/kg. Therefore, 77 MJ/(4.95 MJ/kg)/(24.2 kg/kmol) = 0.64 kmol of producer gas is combusted each day on average in January. Referring to Table 1.1, there are (0.19 + 0.09 + 0.025) = 0.305 moles of carbon for every mole of producer gas, and so 0.305*0.64 kmol = 0.2 kmol of carbon dioxide[12] are added to the dwelling each day.

To determine the expected CO_2 concentration will require more information than is available, but a rough estimate may still be attempted. Jilin village dwellings typically have a floor area of 6x9 = 54 m^2. With an assumed ceiling height of about 2.5 m, the volume of air in a dwelling is about 135 m^3. At 1 atm and 15 °C, this corresponds to (1.01e5 Pa)*(135 m3)/(8.31 J/mol.K)/ (288 K) = 5.69 kmol of air. With an assumed household air exchange rate of ½ per

---

[10] Symptoms range from headaches and dizziness to coma.

[11] OSHA stands for the Occupational Safety & Health Administration of the U.S. Department of Labor.

hour (a well-sealed home), the air is replaced with outside air 12 times per day for a total air flow of 12*5.69 = 68 kmol/day. Spreading out the 0.2 kmol of CO_2 over 68 kmol of air we arrive at a concentration of 0.0029 or 2900 ppm. For reference, the OSHA recommended exposure limit for CO_2 is set at 5000 ppm (as a time-weighted average over the course of 8 hours).

Given the uncertainties in this calculation, such as with the selection of air exchange rate and neglecting the volume displaced by household objects, it might be risky to burn so much producer gas indoors without ventilation of combustion products. Meeting additional heat demand by burning producer gas indoors will likely only be safe if combustion products are vented, as with a gas furnace. Such a scenario involves additional cost and inefficiency and is discussed further in Section 4.4.2.

CASE 3: RECUPERATOR BYPASS

Another option for meeting above-average heat demand which would not require additional capital is recuperator bypass[13]. Using a bypass valve, the turbine exhaust can be partially re-directed outside the recuperator and then mixed back with the exhaust stream at the recuperator outlet to raise the exhaust temperature. This causes the microturbine to operate less efficiently, but allows for more thermal energy to be put into the district heating system as needed.

The effect of partial recuperator bypass can be simulated with the ASPEN model by decreasing the effectiveness of the recuperator. For instance, when the effectiveness is reduced from its nominal 86% to 73% (a 15% drop), the exhaust temperature is raised from 250 to 309 °C.

---

[12] Assumes a combustion efficiency of 100%: all carbon is oxidized to CO_2.

[13] Note that the first generation of microturbines now available do not have this feature. They are being targeted primarily for simple power generation. A growing interest in cogeneration may lead to designs

This corresponds to an additional 50 kW of thermal energy. Because more fuel is now required to achieve the same turbine inlet temperature, microturbine efficiency drops from 28.1% to 23.7%.

The 250 GJ of additional heat demand would occur mainly in December and January, and to a lesser extent in February. Therefore, if the microturbine were to be operated in partial bypass for 2.5 months continuously, the additional heat provided would be:

50 kW*(2.5mo)*(30d/mo)*(24hr/d)*(3600s/hr)*(10^-6 GJ/kJ) = 324 GJ/y

which is safely above the 250 GJ/yr needed. These operating conditions will be retained to allow for losses in distribution and possible variation in performance of heat exchange equipment which must operate under off-design conditions.

At 28.1% efficiency, the microturbine can produce 901 kWh for every ton of residues gasified. Now at 23.7%, the new energy conversion factor is 901*.237/.281 = 760 kWh/ton. Therefore, partial bypass operation for 2.5 months requires:

75 kW*(2.5mo)*(30 d/mo)*(24 hr/d)*(1 ton / 760 kWh) = 177 tons

Operation for the same period of time at 28% efficiency would require 150 tons. Total heating season power generation is then 270,000 kWh from 327 tons of straw. This leaves 552 – 327 = 225 tons for power generation for the rest of the year, amounting to another 203,000 kWh. At 75 kW output, this is 2707 hours of operation, or 2707 h/(365-150 days) = 12.6 hours per day over

---

with the recuperator bypass capability, an idea that was present at an earlier stage of development (Sieben, 1992).

the course of the non-heating season. Total annual production is then 270,000 + 203,000 kWh = 473,000 kWh, or 24,000 kWh less than Case 1.

The marginal cost of excess heat will have the same form as in Case 2 (the price of heat is chosen here to be \$2/GJ):

$$[(\text{lost revenue from electricity sales}) - (\text{heat revenue})] / 250 \text{ GJ}$$

$$= [24{,}000 \text{ kWh}*(\$0.05/\text{kWh}) - \$2/\text{GJ}*(250 \text{ GJ})] / 250 \text{ GJ}$$

$$= (\$1200 - \$500)/250 \text{ GJ} = \$2.8/\text{GJ}$$

Like Case 2, recuperator bypass is significantly more attractive than Case 1. A summary table comparing cases 1, 2, and 3 for the trigeneration option is presented below in Table 4.3:

Table 4.3 Comparison of Methods for Meeting Excess Heat Demand

Case	Additional residue req'd (tons)	Electricity production (kWh/yr)	Annual Capacity Factor (%)	Est'd marginal cost of extra heat (\$/GJ)
1. Storage	0	497,000	75.6	+ 43
2. Burning gas	22	478,000	72.8	– 1.0
3. Recuperator bypass	27	473,000	72.0	+ 2.8

In what follows, Case 3 has been selected for a more detailed analysis. It's economic performance will be comparable to that of Case 2 but does away with the concerns of CO_2 accumulation indoors and having an unattended producer gas flame firing for prolonged periods in a device not specifically designed for this purpose. Having settled on a means to achieve peak heating demand, it is now possible to describe and cost the district heating system.

4.4.1.2 THE DISTRICT HEATING SYSTEM

The general layout of the district heating system is shown in Figure 4.3. Exhaust from the microturbine enters a gas-to-liquid heat exchanger which produces hot water at about 85 °C.

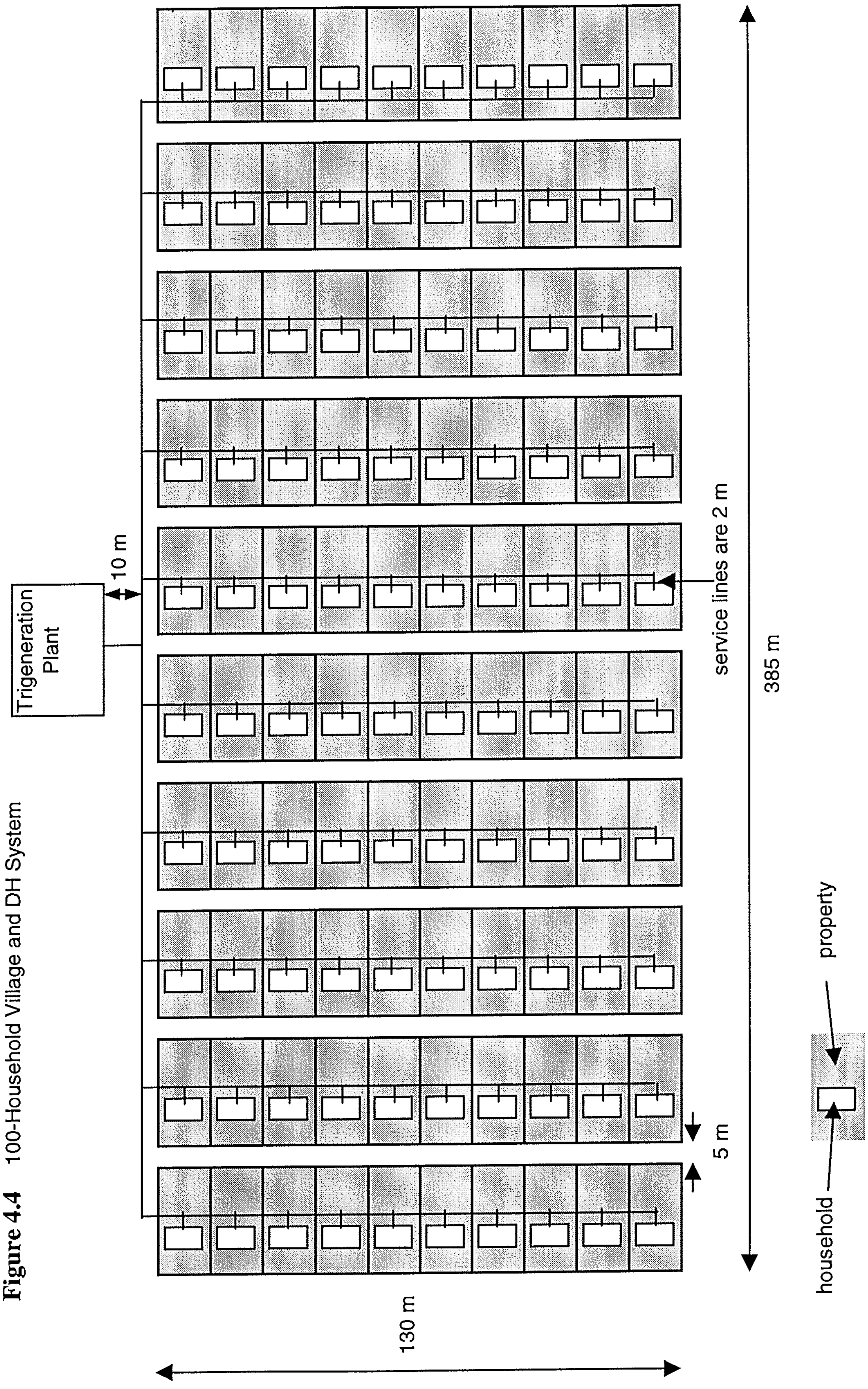
Water pumped through the heat exchanger subsequently enters a small storage tank which serves as a buffer for the system. Insulated piping distributes the hot water to each home where radiators extract an average of 1.2 kW of thermal energy. Used water leaves the homes a bit hotter than 50 °C, and a separate pipe returns it to the pump.

Because the most capital-intensive part of a district heating system is the piping (materials plus installation), density of homes to be served will play a key role in determining system cost. Moving low-quality heat over great distances is quite costly in general. Large, centralized combined heat and power plants typically run into this problem. Microturbines, however, are unique in that their small size allows them to be placed just a few meters outside of the village they serve. Furthermore, villages in Jilin are dense and orderly (see Figure 4.4) making district heating that much more economically viable.

An estimation of the amount of piping required for a 100 household village was made using a typical village layout[14] shown in Figure 4.4. The two general categories of pipe are trunk lines and service lines. The latter connect the former to homes. To be sure, there are a number of ways that pipes could be laid out and perform the same function. It turns out that if trunk lines are placed very close to the homes (as shown in Figure 4.4), the total cost is significantly reduced (primarily because the length of service lines required is reduced). With this configuration, a total of 200 meters of service lines and about 1590 meters of trunk lines are called for.

Pipe diameters, which depend on the flow rate to be accommodated, must be estimated as they strongly influence cost. One good method validated by experience in Sweden is to fix the maximum pressure drop per unit length at about 110 Pa/m (Geller, 1980). For the service lines, an inside diameter of 1.27 cm (0.5 inches) turns out to be more than adequate. Using the pipe

Figure 4.4 100-Household Village and DH System



flow friction factor chart made famous by L.F. Moody, this diameter with a flow of 0.01 kg/s[15] yields a trivial pressure drop of 8 Pa/m. Trunk lines will need to be larger, up to 2 inches to handle the full 1 kg/s flow. Most of the trunk lines, will however, be smaller. For average cost estimation purposes, a 2.54 cm (1 inch) diameter is representative.

Piping materials and installation costs can now be estimated using work done by Geller (1980) on hot water district heating systems. Geller provides a cost curve for pipe materials and installation which is a function of pipe inside diameter. For the diameters considered in this study, the curve can be used to estimate costs for steel and CPVC (chlorinated polyvinyl chloride) pipes with polyurethane foam insulation. In 1998 dollars, the one-way cost of 0.5 inch service lines will be about $22/m, while that of 1 inch trunk lines will be $30/m[16]. The cumulative cost along with the cost estimates for the other district heating system components are shown in Table E1 in Appendix E. Note two things: the predominance of the piping cost and the fact that this estimate is for the American context where materials and especially labor are quite costly. As later discussed, significant cost reductions can be expected for manufacturing in China.

In addition to allowing for a cost estimate, knowledge of pipe sizing, length, materials and so forth allows for an estimate of heat loss in the district heating system. Geller goes through calculations for the heat loss from insulated supply and return pipes for a hot water district heating system. The heat loss equation has the form:

$$Q = 2\pi L^*(T_f - T_g) / F$$

---

[14] Home, property, and street dimensions provided by Jia (1999).

[15] The total hot water flow rate is determined to be approximately 1 kg/s in Table B1 (Appendix B).

[16] Full cost per meter for supply and return pipes will therefore be $44/m and $60/m for service and trunk lines, respectively.

where L is the pipe length, T_f is the average water temperature, T_g is the annual average ground (surface) temperature, and F is a function of geometrical factors and thermal conductivities of the pipe wall, soil, and insulation. F is given by:

$$F = \frac{\ln \frac{r_3}{r_2}}{k_i} + \frac{\ln \frac{r_2}{r_1}}{k_p} + \frac{\ln\left(\frac{d}{r_3} + \sqrt{\left(\frac{d}{r_3}\right)^2 - 1}\right)}{k_g}$$

where r_1, r_2, r_3, and d are the distances from the center of the pipe to the inside surface of the pipe, the outside surface of the pipe, the outside surface of the insulation, and to the ground, respectively. The terms k_i, k_p, and k_g are the thermal conductivities of the insulation, pipe wall, and ground, respectively. Each term in F is a thermal resistance with the term for the insulation being the largest of all three. Note that no consideration has been given to fluid mechanics. This is purely a conduction heat transfer calculation which assumes the water is uniformly at the supply temperature right up to the wall of the pipe. This calculation will therefore give a *maximum* heat transfer rate.

To determine the appropriate insulation thickness, Geller uses marginal lifecycle cost analysis. More insulation is added until the marginal lifecycle cost of the insulation about equals the marginal lifecycle benefit of the avoided heat loss. Such a calculation requires a dollar value to be assigned to the heat. Geller's choice of \$12/GJ (1998 dollars) results in pipes with ample insulation and underlies both his heat loss and pipe cost curves. While the valuation of hot water here will be lower – \$4.50 - \$7.80/GJ for the trigeneration systems (see Appendix E) – heat loss will be about 1.5 times as great because of a larger temperature difference in the Jilin context (see next paragraph). Also considering that insulation is only about 20% of total CVPC pipe cost according to Geller, using his results should be reasonable for the present application. Therefore, insulation thicknesses of 6.6 and 7.6 cm will be used for the 1.27 and 2.54 cm diameter pipes, respectively.

Using the same geometry and materials (i.e. CVPC pipe and polyurethane foam insulation), Geller's results as applied to the Jilin context will need to be modified mainly on account of the temperatures selected. While Geller uses 73.3 °C for T_f and 11.67 °C for T_g, 84 °C and –7.4 °C are more accurate for Jilin. Geller's analysis was concerned with annual average heat losses, and so the annual average temperature was used[17]. Here, only heating-season losses are of interest, and so the heating-season average temperature of –7.4 °C is appropriate. Bearing in mind that heat loss is linearly proportional to temperature difference, these values will increase Geller's heat losses by a factor of (84+7.4)/(73.3-11.67) = 1.48. For 1.27 and 2.54 cm supply lines, heat losses are then estimated to be about 1.48*4 = 5.9 and 1.48*5 = 7.4 watts per meter, respectively, where 4 and 5 W/m are simply read off Geller's heat loss curve. Direct calculation[18] using the heat transfer equation above gives 6.0 and 7.1 W/m. Note that while the actual curve Geller presents has the added refinement of the effect of having two pipes (supply and return) buried together, the isolated pipe calculation is sufficiently close for our purposes here.

The calculated heat loss rates can be used to estimate the temperature drop expected by the household furthest from the plant. Using distances in Figure 4.4 and assuming each home is using 0.01 kg/s of hot water, appropriate flow rates are assigned to each stretch of piping. Using these flow rates with the heat loss rates above one finds that the furthest household experiences

---

[17] Because the ground surface temperature is close to the air temperature, the latter may be used for the former (Geller, 1980).

[18] Values used are 0.023, 1.3, and 0.138 W/m°C for ki, kg, and kp, respectively. For the 0.5-inch pipe, r1, r2, and r3 are 0.25, 0.375, 2.975 inches, respectively, using an insulation thickness of 2.6 inches (Geller, 1980). For the 1-inch pipe, r1, r2, and r3 are 0.5, 0.625, and 3.625 inches, respectively, using an insulation thickness of 3 inches (Geller, 1980).

about an 8 °C drop in delivery temperature from an original 85 °C to 77 °C. To extract an equivalent amount of heat from a 77 °C stream would require a somewhat larger radiator.

For a simple total system heat loss estimate, 6 W/m can be applied to the 200 m of service lines and 7.1 W/m to the 1600 m of trunk lines. Return pipes carrying about 55 °C water will have losses of roughly 4.8 W/m for service lines and 5.9 W/m for trunk lines (using the reduced insulation thicknesses given by Geller). The total system heat loss is then about 23 kW. For a 75 kW microturbine outputting 140 kW of hot water, a loss of approximately this size can be tolerated while still meeting the average village heat load of about 120 kW.

Cost estimates for the other components of the district heating system are shown in Table E1. Being less involved than estimates for the piping, their references are simply indicated in the table's notes and not described here. Before an economic analysis on the trigeneration system can be performed, both the gasifier and gas holder must be appropriately sized and costed.

4.4.1.3 GASIFIER AND GAS STORAGE CONSIDERATIONS

The gasifier for the trigeneration system must be able to accommodate the producer gas needs associated with cooking and power generation. Beginning with power generation, note that producer gas with a 5 MJ/m^3 lower heating value supplied at 1 m^3/hr would produce 0.389 kWe in a 28% efficient microturbine. Therefore, for a 75 kWe output, a gas flow of approximately 193 m^3/hr would be required.

Because the cooking load (about 6 m^3/day per household) is likely to be concentrated around particular times of day, it is valuable to turn to field experience in estimating gas flow rates. In Shandong Province, there are over 100 villages that have been equipped with corn stalk gasification systems for providing cooking gas, as previously mentioned. Specifications for one in particular, Tengzhai, are given by Dai et al (1998). Tengzhai has 216 households and a total of 800 people. The gasifier model selected (developed by the Shandong Energy Research Institute) is the XFF-2000, which can output 400 m^3/hr. On a per household basis, this is 1.85 m^3/hr of installed capacity. For our 100 household case, then, allowing for 185 m^3/hr is assumed to be adequate. A flowrate capacity of 380 m^3/hr, therefore, would cover both power and cooking gas needs.

A final concern when sizing gasifiers has to do with ability to meet partial loads. It is important to identify the lowest expected load and to see if the gasifier can be turned down this low. For reference, a gasifier turndown as low as 40% of full load will be used[19]. Applying this to a 400 m^3/hr gasifier, it will be assumed that 160 m^3/hr of quality producer gas can be generated. In terms of power production this is 62 kWe, which may be larger than desired or even possible at times. If grid power is very unreliable, a village may prefer having the microturbine operational for extended hours. In the face of a capacity factor that is limited by the amount of residues available, the microturbine may have to operate at significantly lower power output than maximum. Low load accommodation is one way in which gas storage can be useful.

The form of gas storage used currently in the Chinese gasification projects is the gas holder. The gas is held in a floating bell-shaped cap that is open at the bottom and sits in a tank of water (see Figure 4.5). As the amount of gas within the bell changes, the height of the bell varies under the action of a constant gravitational force thereby maintaining a constant supply pressure to the gas distribution system. Another nice feature of having a variable height gas holder is that its position and rate of change of position are good visual cues to operators who make sure loads are being met.

---

[19] 40% is the turndown advertised by BG Systems (1998).

With regard to how this type of gas storage can help to meet low loads, consider an example. If a part load of 50 kW is desired, a gas flow rate of only about 130 m^3/hr is needed. With the gasifier turned down to 40% output (160 m^3/hr) and 130 m^3/hr being used, there is a net accumulation rate of about 30 m^3/hr in the tank (i.e. the bell is rising). If the tank can hold 250 m^3, like that used in Tengzhai, the gasifier could operate up to about 8 hours in this fashion. After 8 hours, it could be shut down and 50 kW output could be maintained for another 8 hours by the stored gas. This suggests that a 250 m^3 gas holder in conjunction with a 400 m^3/hr gasifier, items that currently exist, should serve a 100 household village quite well. Economics for the gasifier are presented in the notes to Table E1 in Appendix E.

A special note needs to be made about gas storage given that it can be such a large expense. In the detailed cost breakdown for the Tengzhai gasification system, the tank alone turns out to be over one quarter of the total cost (which includes the gasifier, cleanup, pipeline network, household facilities, and installation). Part of the reason surely has to do with the fact that the design of this particular tank uses 16.7 tons of steel (Dai et al, 1998)! Because the gas holder operates at very low pressure (designed for 4000 Pa ~ 0.04 atm), using such a high-strength material is overkill. Furthermore, the material does not have to accommodate high temperatures since, as Sun Li (1998) says about the Shandong design, the gas is cooled to ambient temperature prior to entering the gas holder. Another idea, also shown in Figure 4.5, is to use an expandable, accordion-like chamber made of a durable plastic or fabric that is impermeable to producer gas constituents. A heavy cap riding up and down guide poles would provide the necessary pressure. It could be made of an inexpensive substance like concrete for example; anything with sufficient mass. Though cheaper designs may be possible, the Chinese design will be retained for the economics that follow. Now that gas storage, a gasifier and district heating system have been specified, an economic study of trigeneration in Jilin can be carried out.

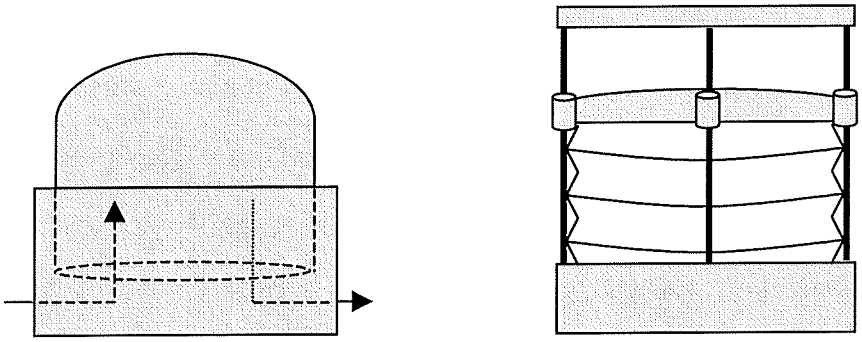


Figure 4.5 Gas Holder Design Schematics

4.4.1.4 ECONOMICS OF TRIGENERATION

As mentioned earlier, one of the benefits of an energy conversion system that does away with direct combustion of biomass or coal indoors is public health. Because it will turn out that the vast majority of power generated will be exported to the grid, the health of people in urban areas stands to improve as well. Every kWh generated with crop residues can displace a kWh of coal-derived power and its associated pollution[20], to say nothing of greenhouse gas emissions.

Capturing the substantial rural and urban health benefits of trigeneration systems warrants government intervention—because citizens should have the right to avoid the health damages associated with current energy systems. In the economic analysis of the trigeneration system presented here, it is assumed that this intervention takes the form of making available a low-interest loan (6%, instead of 12%, which would be a typical market rate) to finance the hot

---

[20] While it is true that emissions from producer gas combustion are very low because clean-up equipment is used (e.g. removing particulates and ammonia which readily oxidizes to NO_x), such equipment is intrinsic to the system. It *must* be used to protect the microturbine and other units. Clean-up technologies may also be used with coal plants, but they are only used when and if government regulations are created and enforced.

water and gas distribution piping systems for the village-scale trigeneration system—the key enabling infrastructure for the concept.

In principle, the amount of the subsidy provided by government could be up to the cost of the health damages avoided that is made possible by the trigeneration system. How much is avoiding pollution worth? Only the benefits of avoiding indoor air pollution are considered here. Although there are many uncertainties associated with the economic valuation of health impacts of air pollution, some progress has been made. An attempt to economically quantify the health impacts associated with environmental pollution has been included in a World Bank report that focuses on issues and challenges that China will face in the near future (Johnson, 1997). The cost of indoor air pollution health impacts for rural China, based on the principle of the "willingness to pay" to avoid adverse health impacts, is estimated in this World Bank report as being about $10.6 billion per year or $12 per year per "average" citizen living in rural areas. If a Jilin village were "average" for China, the benefit of avoided indoor air pollution for the 400-person village modeled here would be $4800 per year. The cost of the distribution infrastructure is estimated later in this section to be in the range $60,000 to $112,000. The corresponding annual savings to the village arising from having a 6% instead of a 12% loan for financing this infrastructure development (20-year term) would be in the range $2800 to $5200. Because the infrastructure cost will probably turn out to be closer to the lower than the higher estimate, the value of the health damage costs avoided would probably be greater than the annual loan subsidy. Thus the government subsidy for financing the infrastructure would appear to be justified when using the "willingness to pay" measure.

There is another sense in which the loan may be reasonable. Because open burning of unwanted crop residues has been escalating causing serious air pollution problems, recent legislation now makes this activity illegal in certain areas, such as near airports and highways. It is suspected, however, that this may be very difficult to enforce. The availability of a low-interest government loan for trigeneration infrastructure could be helpful in this situation. It may effectively encourage the development of energy conversion systems that make use of crop residues, consequently ending the open burning. For this analysis, it will be assumed that such a government loan is made possible and an interest rate of 6% is chosen.

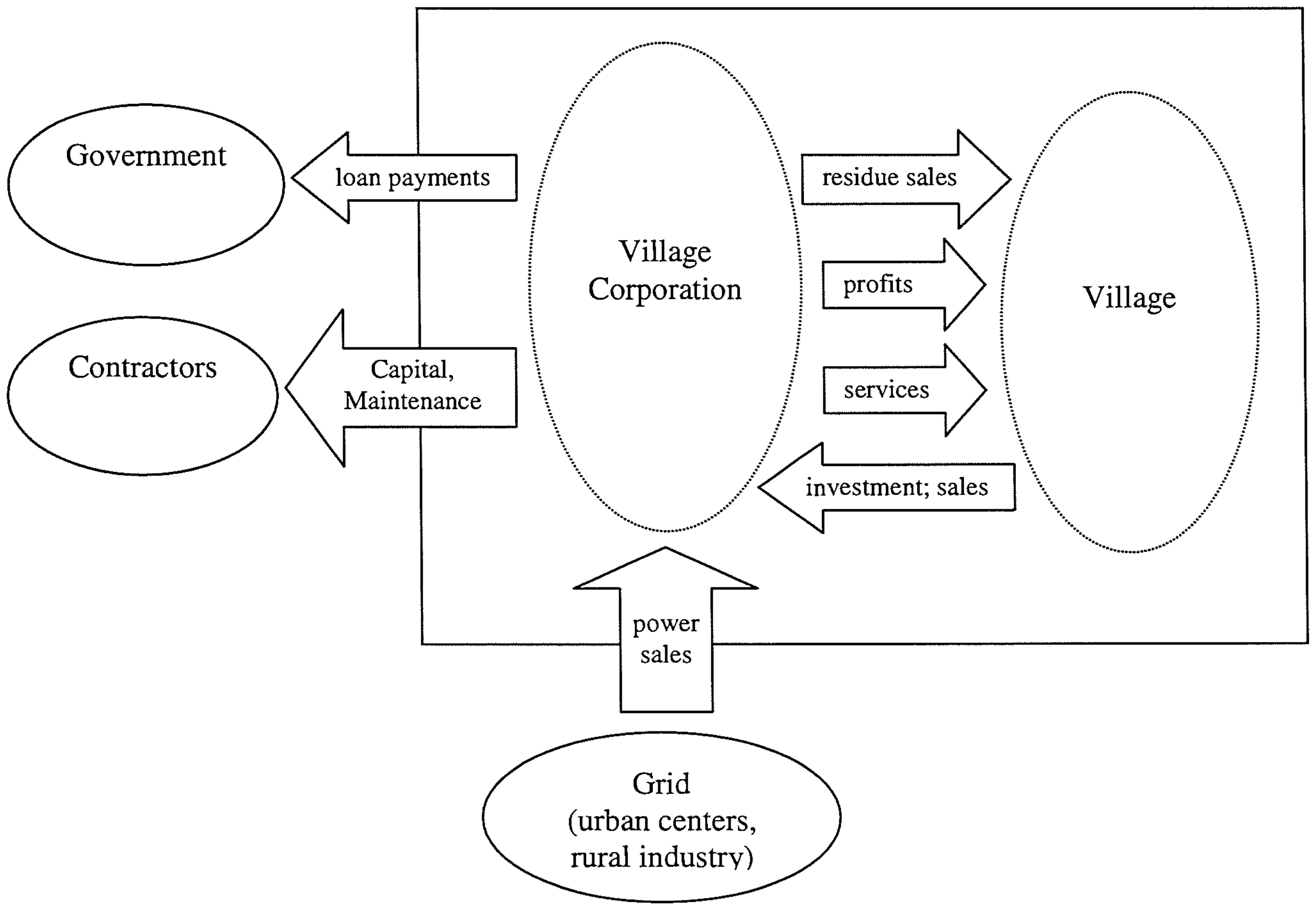
There are a number of ways in which the remaining costs may be covered. An independent power provider (IPP) for instance, may supply cooking gas, heat, and power to the village for an agreed upon period of time at a given price. Another possibility is the formation of a "village corporation" which can keep any generated income in the village.

THE VILLAGE CORPORATION

An interesting scenario to consider is one where a "village corporation" purchases and manages the trigeneration system in order to bring the most economic benefit to the village itself (as opposed to an outside third party). The investors (the villagers) provide as equity all the needed capital except the loan for infrastructure. See Figure 4.6 for a schematic which illustrates the village corporation concept.

The notion of having villagers put up the capital for the rest of the system may not be as implausible as it might first sound. According to the China Statistical Yearbook of 1998, the rural Jilin per capita net income (2186 Y) exceeded the per capita living expenditure by about 560 Y. Therefore, one year's pooled village savings adds up to about 560*4.1 people/hh*100 hh = 230,000 Y = $27,700. According to Table E2, the total initial investment needed is about $144,000 or roughly 5.2 years of village savings at the 1997 level.

Figure 4.6 The Village Corporation Concept



If a village corporation is created, market prices should be charged for the energy products so that resources are allocated efficiently. For gas, a price approaching that of LPG, \$6/GJ, is assumed. For heat, the price will be such as to cover the levelized cost of the district heating system (will vary between \$4-8/GJ). Power will be sold to village households at the common rural price of 0.8 Y/kWh. These three prices and average consumption rates give the result that each household will spend about 12-15% of its net income on these products. It is assumed that power produced in excess of household needs is exported to the grid and sold at about 0.4 Y/kWh (5 cents/kWh), which is half the rural price.

REMARK ON LABOR COST

A special note should be made with regard to the significance of the cost of labor because of the fact that it can quite easily "make or break" a small-scale plant. This is well illustrated by considering the trigeneration plant in an American context. Consider the scenario in which there are two shifts with two workers each, for a total of four full-time wages to be paid out each year. At a modest rate of \$15 per hour, this comes out to about 4 x \$30,000 = \$120,000 per year. Since 473,000 kWh are produced annually, labor alone would contribute a cost of \$0.25/kWh, thus rendering the plant an economic disaster in America.

The situation, for the time being at any rate, is very different in China. Cao et al (1998) give an example of a 159 kW rice hull gasification plant in which workers are paid an average monthly salary of 200 Yuan RMB, or about \$290 per year (\$1 = 8.3 Y), while management plus some fees totaled 12,910 Y (\$1,560) for the year. A planned corn stalk gasification and distribution system for a 110-household village is also described. Two workers each being paid 300 Y per month are accounted for. The Tengzhai village gasification and distribution pilot plant in Shandong province – a somewhat richer province than Jilin – is described in another report (Dai et al, 1998) as employing two workers at an annual salary of 4000 Y each (330 Y/month).

For the present analysis, therefore, a worker salary of 300 Y/month has been selected. In addition, 12,000 Y/yr will be allotted to management (e.g. of the village corporation), which involves overseeing operation of the plant, scheduling maintenance, and keeping records.

The number of workers required, of course, depends on the number of shifts and workers per shift that are needed. It is assumed here that during the five-month heating period, a full three shifts will be called for to provide heat day and night. Two shifts will be assumed for the remaining 7 months of the year. For plants described by Cao et al (1998) and Dai et al (1998) in which a gasification station and distribution network are involved, 2 workers are required per shift. Trigeneration has the additional complexity of a microturbine plus district heating system, and so an additional worker will be assumed to be needed for a total of 3 per shift. The total annual cost of workers is therefore 26,100 Y or $3,100 not counting weekends. Including weekends requires a scaling up by 7/5 to 36,500 Y or $4,400. Together with management, this sum is 48,500 Y or $5,800 per year.

With these assumptions, the contribution labor makes to the lifecycle levelized cost is $0.012/kWh. Although the cost of labor in the Chinese context may seem low to American eyes, it nevertheless turns out to be very significant to overall economics when one considers the reality of China's increasing wages and standard of living (see Figure 4.9 and Table 4.9).

HIGH-COST DISTRICT HEATING SYSTEM SCENARIO

To begin with, consider the economics of the trigeneration system with American pricing for the piping. Though it is far from realistic to assume that piping will be as expensive in China, this case will nonetheless serve as a useful reference case.

Table E1 in Appendix E summarizes the key economic features of this trigeneration system, and Table E2 lists the annual cash flows over the 20 year period of analysis. The trigeneration system is paid for with an initial equity capital investment of $144,000 plus a $112,000 government loan at 6% to cover gas and hot water piping infrastructure costs. For the heat revenue to cover the cost of the DH system requires a price of about $7.8/GJ. All together, household energy expenditures amount to 18.9% of net household income in this case. Note that the largest source of revenue is clearly the electricity sold to the grid. The village generates far more power than it can consume, and so most is exported to regions of higher electricity consumption (e.g. urban centers) or perhaps local industry spurred by the available power. Consequently, a large flow of revenues to rural areas is established. An internal rate of return (IRR) of 5.0% is calculated for this case, giving the village corporation a levelized net annual income of about $11,500. The village itself sees this revenue in addition to what it receives from selling crop residues to the corporation. Subtracting from this gross revenue what is paid to the corporation for heat, power and gas, a net village cost of about 450 Y per household is incurred (5% of average household annual income). The bottom line is that revenue from outside (the grid or local industry) is able to offset the majority of the cost associated with providing cooking gas, heat, and electricity to villagers.

LOW-COST DISTRICT HEATING SCENARIO

To estimate how the cost of components might drop if manufactured in China, it is helpful to refer to the work of Yang (1995) from the Energy and Resources Group at U.C. Berkeley. Yang studied the role integrated gasification combined cycle (IGCC) power plants may have in China. With information on the component-by-component costs of a Chinese steam power plant and a U.S. IGCC plant, Yang compared similar components and estimated sub-system costs of an IGCC plant manufactured in China. Some of Yang's results are presented below:

Table 4.4 Comparison of IGCC sub-system costs (Yang, 1995)

Sub-system	Capital investment, U.S. context ($/kW)	(Y/kW)	Conversion factors (Y/$)	Capital investment, China context (Y/kW)
coal supply and handling	26	220	2.9	75
coal grinding and slurry preparing	29	245	3.2	93
air separation plant	142	1200	4.2	596
gasification, gas cooling and cleaning	163	1380	5	815
acid gas removal and sulfur recovery	22	186	5	110
gas turbine generators	202	1710	4.4-8.6	889-1737
steam generation	81	684	3.1	251
steam turbine generators	94	794	4.4	414
BFW, condensate, makeup water	46	389	4.4	202
circulating water	34	287	1.1	38
electrical and control system	63	532	6.9	425
balance of plant	86	727	3.4	292
Sub-system Totals	988	8350		4200 – 5050

Notice that the conversion factor for most components is well below the exchange rate (then about 8.45 yuan per dollar). This means that marked cost reductions can be expected for those sub-systems that can be manufactured in China. The sub-system totals row in Table 4.4 points out that the cost of an IGCC plant would be about 50% less if maximal use were made of Chinese manufacturing. The average conversion factor is 3.96 (not counting the gas turbines for which a range is presented), which corresponds to a cost reduction of 53%. For some systems, like "circulating water," the reduction is 87%! Yang's findings show a trend: the less technologically sophisticated the system, the greater the cost reduction.

Because all of the components of the district heating system are towards the low end on the scale of technological sophistication, it would appear that cost reductions of at least 50% are conservative for the Chinese context. Reducing the capital cost of the hot water piping, heat recovery unit, storage tank, radiators, and distribution pump by 50% results in a total capital cost for the DH system of about $63,000. The low-interest government loan for infrastructure is lowered from $112,000 to about $60,000. The IRR increases from 5.0% to 8.4%, and village corporation levelized net annual income is $12,700. After selling their residues and paying for their energy consumption, each household makes a net profit equivalent to 0.8% of the average household's current net annual income (see Tables E3 and E4).

Given Yang's dramatic estimated cost reduction for the IGCC circulating water sub-system of 87%, it might be reasonable to reduce at least the piping component's cost more significantly. If 75% is applied to the piping and 50% to the other components, the district heating system capital cost is reduced to $37,000. Interestingly, this last result supports the rough estimate made by energy researchers in Jilin that hot water distribution, storage, and in-home utilization equipment would cost no more than the gas distribution system (Larson, 1998). With this 75%/50% combined cost reduction, there are some noteworthy changes to the trigeneration system's economic performance. Although most of the cost reduction comes from cheaper piping, which falls under the government loan, the capital needed up front is still lowered noticeably to $117,000 – about 4.2 years of estimated village savings. Holding household energy expenditures fixed at 14.3% of average household income, the internal rate of return is now 12.3% with a levelized net annual village corporation income of about $15,900. Subtracting the household energy bill from the $15,900 income and adding crop residue revenue, villagers make a net annual profit of 330 Y/hh, or 3.7% of the average household's current net income.

INDEPENDENT POWER PROVIDER

Consider the scenario now where instead of having a village corporation, an independent power provider (IPP) is responsible for providing the village with the trigeneration system. The IPP charges a particular rate for all services and receives all the profits. This option allows villagers to avoid having to make a large initial investment.

Using the costs from the 75%/50% case, again we have an IRR of 12.3% and a levelized net annual income of $15,900. For the villagers, there is no initial large investment to make. Instead, they simply spend about 14% of the average household's annual net income on power, gas and heat (or about 56% of a household's annual savings). Because they can sell their crop residues to the IPP, an additional 290 Y can be earned per household, which is a bit less than one quarter of a household's annual energy expenditure. The net annual cost of cooking gas, heat, and power is then only 11% of a household's net income (43% of the average household's 1997 savings).

In addition to negating the need for investments from the villagers, the IPP scenario may also make providing the required level of technical and managerial expertise easier. Experienced engineering firms from urban China may, for instance, be interested in being IPPs for rural China. If a firm chooses to serve a number of villages in a region at the same time, an efficient maintenance infrastructure could more easily be developed. Although the IPP option would not channel money from urban to rural areas, it nevertheless appears to be a valuable option to consider, in particular in the early stages of the trigeneration plant's development.

4.4.2 COOKING GAS AND POWER

The trigeneration system is one that tries to provide villagers with as many services as possible with the greatest efficiency possible. Because of the low cost of fuel and desire for low capital cost, however, efficiency may not be so important. Considered here is the trigeneration system without the district heating system. Efficiency is traded in for lower capital cost and greater system simplicity.

Without a hot water distribution system, the issue to resolve is household heating. To be sure, there are various ways producer gas can be used to heat a home. As mentioned earlier (see

Section 4.3.2), the Jilin Energy Research Institute is testing three ways with its gas system. The current thinking is that a household will be able to choose one of these three options and will be charged about 100 Y for each. For the present economic analysis then, it will be assumed that household heating is achieved at a cost of 100 Y per household using producer gas at an efficiency of 70%.

Tables E5 and E6 in Appendix E show the economic assumptions and results for this scenario. A low IRR of 5.9% is achieved with a levelized net income of about $8,700 per year. Revenues from the grid cover a large fraction of village energy costs. The average household spends 3% of its net annual income on gas for cooking and heating and power. Without the district heating system, the initial investment comes down to $100,000 which is about 3.6 years of village savings at the 1997 level. Note that a large quantity of crop residues, some 224 tons, must go to heating. After cooking needs are met, only 327 tons are left for power generation. This results in a low capacity factor of 45%. Economics stand to improve if the microturbine is re-sized. Now that the thermal output of the microturbine is no longer tied to the heating of homes, this may be done freely. If the microturbine were scaled down from 75 to 45 kWe[21], the capacity factor would increase to 75%.

To estimate the cost of a 45 kWe microturbine based on the price of a 75 kWe unit, we employ the cost scaling equation (Ulrich, 1984):

$$C_{45} = C_{75}\left(\frac{45}{75}\right)^{a}$$

where C_i is the price of a unit of size *i* and *a* is the scaling exponent. If a = 1, this is equivalent to the statement that 45 and 75 kWe units cost the same per kWe. However, since savings are likely

---

[21] Note that even a 45 kW microturbine would most likely be able to meet peak electrical loads (see Section 4.3.3).

to be largely in amount of materials used and not so much in manufacturing costs, this picture is unrealistic. Ulrich gives a table of typical scaling exponents for various devices. A 440 volt motor, for example, between the sizes of 0.75 and 15 kW has an exponent of 0.59. For an electrostatic precipitator, it is 0.68. A value of 0.5 will be chosen here in part due to the relative insensitivity in price of power electronics to small scale changes. If the 75 kWe unit costs \$350/kW, this gives a price of about \$450/kW for the 45 kWe unit.

The effects of moving to a 45 kWe microturbine are shown in Tables E7 and E8. Note that to be able to compare this system with the trigeneration system more easily, the price of gas is adjusted to keep the total household expenditure on gas and power at the same level: 14.3% of the net annual household income. With a smaller, less expensive prime mover that provides the same yearly output, the IRR increases to 8.1% and the levelized net annual income is \$9,500. Net revenues reduce villagers' energy costs to 2.2% of net income, and the initial investment is lowered to \$93,000 (3.4 years of village savings).

4.4.3 HOT WATER AND POWER

Currently, there is interest in the possibility of using corn stalks to generate hydrocarbon fuels via Fischer-Tropsch synthesis (Larson and Jin, 1999). The CO and H_2 in producer gas can provide the raw materials for the synthesis of a wide range of hydrocarbons. Products of the F-T process can include synthetic liquefied petroleum gas (LPG), the non-synthetic version of which is used in various parts of China for cooking. If F-T plants are realized and an inexpensive LPG is produced, then it would be worthwhile to consider another village-scale power plant configuration: one without the distribution of poisonous producer gas.

Begin with the assumption that the number and size[22] of F-T plants in Jilin is such that all rural cooking needs can be met. If 3.5 million households each require 30 MJ (LHV) of fluid fuel for their stoves each day, then the yearly cooking fuel energy demand is 38.3 x 10^6 GJ. On a HHV for LPG, this is 38.3 x 10^6 GJ / 0.92 = 41.6 x 10^6 GJ. The F-T plant geared towards synthetic LPG production described by Larson and Jin (1999) produces 0.155 GJ of electricity and 0.287 GJ of LPG for every GJ (HHV basis) of biomass it consumes. The entire province's yearly cooking demand, then, could be met by 41.6 x 10^6 / 0.287 / (18 GJ/ton) = 8.1 million tons. Since 22.7 million tons are available each year for cooking, heating, and power needs, this leaves 14.6 million tons for power and heat at the local level. For every 100 households, using the recuperator bypass technique, 327 tons would cover heating needs and generate 270,000 kWh of electricity. Scaled-up to all of Jilin, this would leave 14.6 – 11.4 = 3.2 million tons for local use the rest of the year. Every 100 household village would then be able to generate an additional 3.2 million tons / 35,000 'villages'*(901 kWh/ton) = 82,000 kWh for a total of 352,000 kWh per year. In addition to the LPG, the F-T plants would produce 8.1 million tons*(18 GJ/ton)*0.155 / 3600 = 6280 GWh per year = 1790 kWh per houshold per year. Table 4.5 presents a brief energy-accounting summary.

Table 4.5 Energy Accounting for F-T and Village Plants

	Tons consumed (millions)	LPG Produced (MJ/d/hh, LHV)	Power Produced (kWh/hh/d)	Domestic heat Produced (kW/hh, average)
F-T plants	8.1	30	4.9	0
Village plants	14.6	0	9.6	1.2

Table 4.5 is a testament to the size of the available biomass resource in Jilin Province. Enough synthetic LPG and hot water can be produced to meet all rural cooking and heating needs,

---

[22] Note that while the complexity of the process technologies required for an F-T plant prevent it from being applied at the village-scale, its scale could never become large by the standards of today's gas-to-liquids industry owing to corn stalk transportation logistics and costs (Larson and Jin, 1999).

respectively, and 14.5 kWh per rural household per day. For reference, in 1993 the average U.S. household daily electricity consumption was 27.3 kWh[23].

Consider now the economics of a village power plant that provides hot water for heating and power, but no cooking gas. Assume that F-T plants provide synthetic LPG for cooking and that it is sold for $7/GJ, a price approaching that of today's LPG. Employing the 50% district heating cost reduction described in section 4.4.1.4, economics still turn out to be dismal (see Tables E9 and E10 in Appendix E). Maintaining the 14.3% household income expenditure on energy, the IRR is found to actually be negative (- 4.8%). This is largely attributed to the fact that all revenue from LPG sales is redirected outside of the village to the F-T plant, a $7,000-stream of money leaving the village each year. Although the capacity factor is rather low at 53%, scaling down the microturbine would mean finding another way to meet heating needs. Although the initial investment is lower than the other options ($85,000 = 3.1 years of 1997 savings), the annual cost of energy products after profit distribution is high at 9.1% of net household income. The 75%/50% cost reduction for the district heating system helps somewhat, bringing the IRR up to 2.3%, but even so this option does not compare favorably with the others.

4.4.4 ECONOMIC SUMMARY TABLE

A number of different energy conversion systems that hinge on generation of gaseous fuel from biomass were described in the previous three sections. Economic results of each are summarized in Table 4.6 below.

---

[23] see ftp://ftp.eia.doe.gov/pub/consumption/residential/rx93cet1.pdf

Table 4.6 Economic summary of various energy conversion strategies

System	Electricity Generation kWh/year	Initial Capital Cost		Levelized Annual Profits		Levelized Village Profits		IRR
		$	Y	$	Y	$/hh/y	Y/hh/y	(%)
Trigeneration	473,000	122,000	1,010,000	12,700	105,000	8	69	8.4
(75%/50%)	473,000	117,000	971,000	15,900	132,000	40	330	12.3
No DH – 45 kWe	295,000	92,800	770,000	9,500	79,000	-24	-200	8.1
No Gas Distrib.	350,000	85,300	708,000	2,400	20,000	-98	-810	-4.8
(75%/50%)	350,000	80,000	664,000	5,000	42,000	-72	-600	2.3

Gross energy expenditures per household fixed at 14.3% of net household income, power sold to the grid at 5 cents/kWh, district heating systems at 50% of U.S. cost estimate (unless otherwise indicated)

Though it would require the largest initial capital investment, the trigeneration system produces at least one third more power than the other options, gives the greatest profits to villagers and has the highest IRRs. When the 75% cost reduction is applied to hot water piping, the trigeneration system's IRR markedly improves to 12.3%. The system with no district heating has significantly lower capital cost and power output accompanied by a mediocre IRR. The last option compares very unfavorably due to the fact that almost 50% of the villagers' energy expenditure is for LPG made elsewhere. This revenue stream leaves the village and goes to some third party. For the sensitivity analysis that follows, this last case will be discarded. Attention will be focused on trigeneration with both levels of district heating cost reduction and the system with no district heating at all.

4.4.5 ECONOMIC SENSITIVITY ANALYSIS

It is worthwhile to investigate how much economic feasibility of the systems described in Sections 4.4.1-3 depends on the sale price of electricity, cheap labor, and cheap biomass. Prices may fluctuate significantly, people may not work for peanuts for all time, and crop residues will go up in price as the demand for them gradually grows. In addition, the significance of the cost of the microturbine and in-home heating equipment will be investigated.

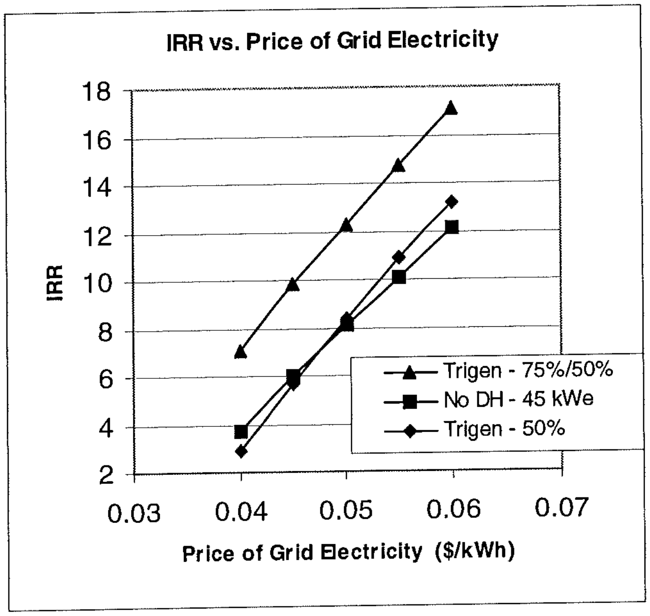


Figure 4.7

Figure 4.7 shows the variation of the IRR with price of electricity for the three alternatives considered. The two trigeneration systems are somewhat more sensitive than the No-DH case because revenue from sales to the grid constitutes a larger fraction of the total revenue (all receive the same amount from the villagers). This is clear by simply comparing the yearly kWh production for each case shown in Table 4.6. Therefore, the No-DH system may have a slight advantage over trigeneration when prices are low unless dramatic cost reduction can be expected for the district heating system. Table 4.7 presents sensitivities in terms of percentage change of the IRR. The economics of all systems are shown to be very sensitive to 1 cent/kWh changes (+/-20%) in the selling price of electricity.

There is a range of market prices for electricity in Jilin, with rural power being significantly more expensive. While city power can be as cheap as 3 to 4 cents/kWh, rural power is typically 6 to 10 cents/kWh (Larson, 1998; Liu, 1999). The food processing plants described in Cao et al (1998) pay 6 to 6.6 cents/kWh, the former being a plant in a city, the latter in a town. Figure 4.7 suggests that the systems discussed here would be able to compete quite well with rural power and to a lesser extent with some city power. If they could provide reliable, cheaper power to rural areas than is currently available, rural industrial development could be spurred.

Table 4.7 Sensitivity of IRR to Price of Electricity

Configuration	$0.04/kWh	$0.05/kWh	$0.06/kWh
Trigeneration	- 65%	0	+ 57%
(75%/50%)	- 42%	0	+ 39%
No DH – 45 kWe	- 54%	0	+ 49%

Revenue from village fixed at 14.3% of net household income

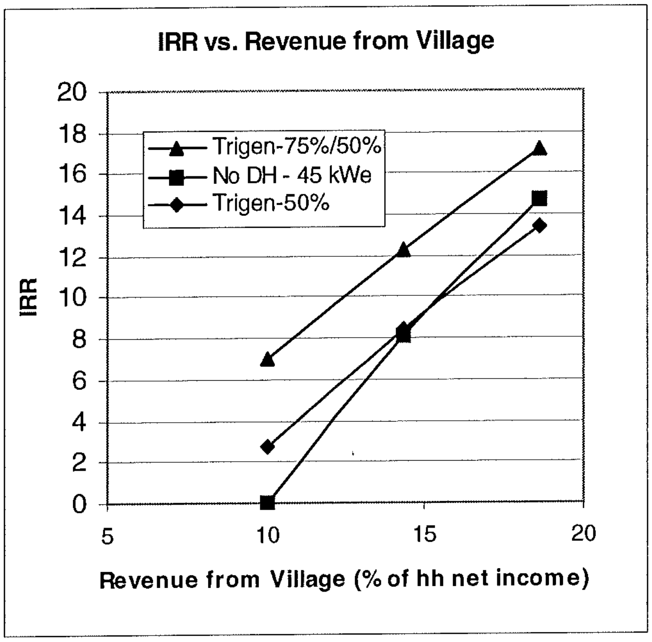


Figure 4.8

Because economics of the No-DH system have a somewhat lesser dependence on grid revenues, they correspondingly have a greater dependence on revenues from the village. This is clearly shown in Figure 4.8 and Table 4.8. Of course, in the village corporation scenario, sensitivity to village revenue is not a relevant point. The village corporation only uses prices for energy products to efficiently allocate resources, not to enhance its own profit.

Table 4.8 Sensitivity of IRR to Revenue from Village[a]

Configuration	10%	14.3%	18.6%
Trigeneration	-68%	0	+60%
(75%/50%)	-43%	0	+40%
No DH – 45 kWe	-100%	0	+81%

Price of electricity constant at 5 cents/kWh

[a] As a percentage of average net annual income

Considering the sensitivity of the three alternatives scenarios to the cost of labor and crop residues, only increases in these quantities will be considered. Wages are expected to only increase with time as China's economy continues to grow. The price of crop residues will surely increase as a market becomes established for it and supplies become scarce. Both 25% and 50% increases in the cost of each are considered here. These large cost increases naturally have large effects on the IRR as illustrated in Figures 4.9 and 4.10. As usual, the economic performance of the trigeneration system with the cheaper DH system is markedly better than the other options. The No-DH case turns out to be the most sensitive of the three to increases in both labor and residue costs. This behavior arises because while all three systems have the same labor and residue costs, the No-DH case, as mentioned earlier, generates significantly lower revenue from electricity.

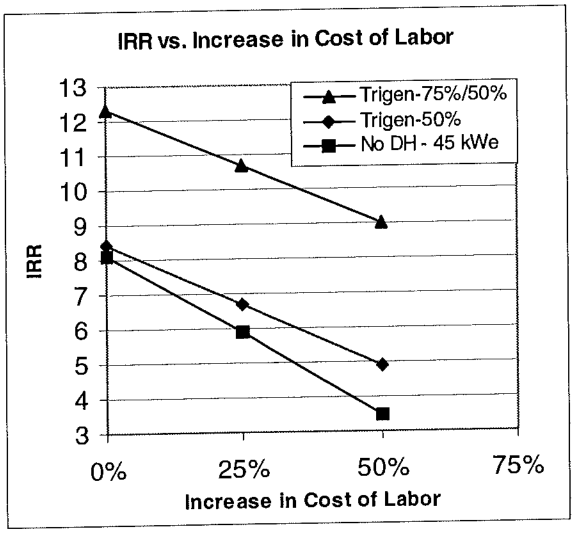


Figure 4.9

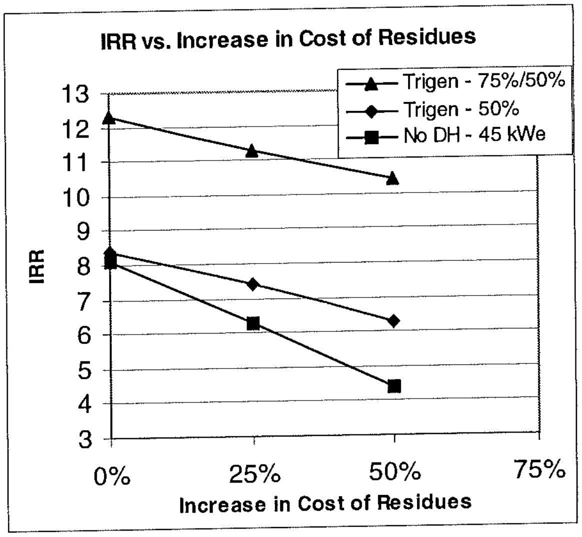


Figure 4.10

Note that for the village corporation scenario, increases in the price of crop residues would have no net effect on the economics. The additional villagers' revenue from crop residues would be balanced on the whole by lower profits from the village corporation.

Table 4.9 Sensitivity of IRR to Cost of Labor and Crop Residues

Configuration	Labor		Crop Residues	
	+ 25%	*+ 50%*	*+ 25%*	*+ 50%*
Trigeneration	-20%	-42%	-12%	-25%
(75%/50%)	-13%	-27%	-8%	-15%
No DH – 45 kWe	-27%	-57%	-22%	-46%

Revenue from village fixed at 14.3% of net household income, grid price set at 5 cents/kWh

Another quantity whose effect on the IRR should be examined is the cost of the microturbine. Thus far, only an American cost estimate from AlliedSignal for the year 2003 has been used. What if microturbines were manufactured in China? While domestic manufacture of megawatt-scale gas turbines is minimal in China, manufacture of microturbines would certainly be a lesser undertaking. The most sophisticated aspect of microturbines is their power electronics and controls. In Yang's cost reduction findings (section 4.4.1.3), the IGCC electrical and control subsystem would cost only 20% less to manufacture in China. A recent cost estimate for turbogenerators based on automotive turbochargers showed that the electrical subsystem (generator and power electronics) amounted to fully one-third the total manufacturing cost (Myers, 1997). Applying a 20% cost reduction to 1/3 of the microtubine's cost and a 50% reduction to the other 2/3 gives a cost of $210/kW (a reduction by 40%). Let this be the lower bound for the sensitivity analysis. For the 45 kWe microturbine used in the No-DH option (nominally at $450/kW), the lower bound will be taken as $270/kW.

Figure 4.11 shows IRR as a function of the cost of the microturbine. Significant improvements in overall economics are observed by changing the capital cost of this one component. As shown in Table 4.10, a 40% cost reduction increases the IRR between 30 and 40% of the original value depending on the plant. Clearly, there are incentives for determining what cost reductions may be achievable in the context of Chinese manufacturing.

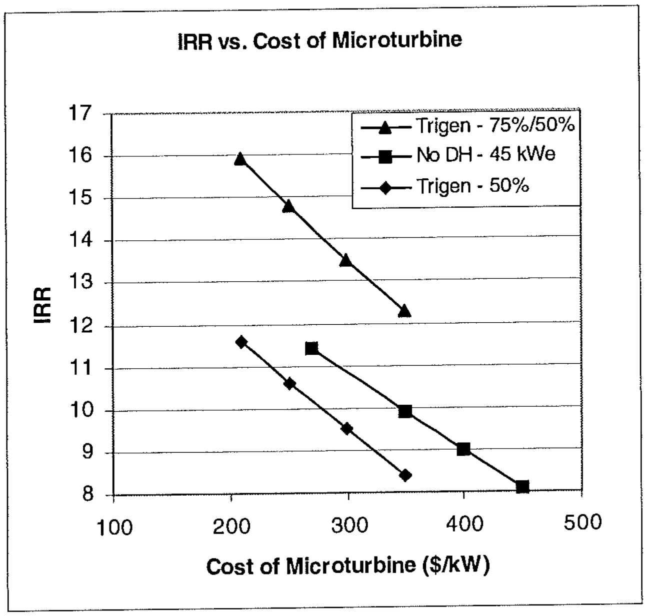


Figure 4.11

Table 4.10 Sensitivity of IRR to Cost of Microturbine

Configuration	- 20%	- 40% est. for manuf in China
Trigeneration	+ 18%	+ 38%
(75%/50%)	+ 14%	+ 29%
No DH – 45 kWe	+ 20%	+ 41%

The last quantity to be investigated here is the cost of the in-home heating equipment. The effect of three different costs of hot-water piping has already been discussed, but little has been said about in-home equipment like radiators, furnaces, piping, meters, etc. The cost of this hardware may play an economically significant role simply because of the quantity of units called for (one set per household). The cost of in-home producer gas cooking equipment has some precedent and so will not be considered here (see Notes for Table E1 in Appendix E).

For the two scenarios with district heating, the current cost accounting includes the equivalent of an $80, 1500-watt hot water radiator (Lorenz, 1996) and a 100 Y ($12) flow meter, the price of which is simply taken to be equal to that of the household gas meters in Dai et al (1998). The gas-heating scenario includes only the 100 Y estimate for heating equipment given by Jia (1999) for one of the three heating methods described in Section 4.3.2. While this seems surprisingly low, it should be pointed out that producer gas cooking stoves for the Tengzhai gas system are reported to only cost 40 Y each (Dai et al, 1998). Still, a home's gas heating arrangement can become significantly more involved than a stove, which is just a couple of gas burners mounted on a frame. Aspects such as the extent to which heat will be distributed or circulated within a home by mechanical means have the potential to escalate the base case cost dramatically. Therefore, investigation of large cost increases is merited.

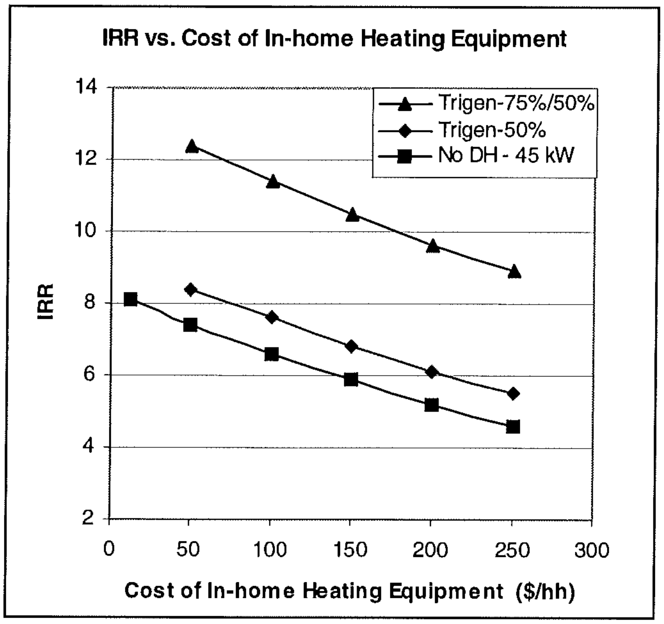


Figure 4.12

Figure 4.12 shows the change of IRR with in-home heating equipment cost. Moving from the $50/household level to $250/hh – a fivefold increase – the systems IRRs drop between 30-40%. With respect to increases from the $50/hh level, in-home heating equipment cost turns out to not be as significant a factor in system economics as the other parameters previously discussed in this section.

4.4.6 SOCIAL AND ADMINISTRATIVE CONSIDERATIONS

What has been presented thus far has been primarily a technical and economic investigation of what microturbine technology might be able to contribute to the people of rural Jilin Province. To be sure, these are only two aspects of a complex process that must come to fully integrate social and administrative considerations or be doomed to fail. This section by no means attempts to complete the design process, but rather seeks to identify a number of social considerations that would ultimately have to be addressed.

For any village energy system to succeed, it must be acceptable to the people who will use it. The existence of any customs that may produce significant conflicts with a proposed system must be known about. In Africa, for instance, many new technologies introduced to villages failed because they didn't fit in with existing social structure and practices (Lo, 1997). An example of this is a project in which household electrical lighting was provided that fully illuminated the rooms. In that particular culture, having the whole room illuminated was too revealing. Residents put cups over the light bulbs to dim them thereby wasting a significant fraction of the power provided. In the case of Jilin, it may be that villagers are very attached to sleeping on warm, kang-heated beds at night thereby requiring that any kind of indoor heating device effectively replicate this. A more fundamental consideration is that some people may not accept the reduced control over meeting their energy needs that accompanies a centralized system. Issues such as these need the full attention of planners if a village system is to be successful.

In addition to the social acceptability of a new technology is the question of how it will be used by villagers in practice as compared with the designer's conception of use patterns. A system designed to be able to meet a particular load may be in for trouble if villagers' energy consumption habits change significantly as a result of the presence of the new technology. For instance, having a clean, labor-free method for heating one's home may result in a greater consumption of heat than previously estimated. If in the case of Jilin the average heat demand is doubled from 1.2 kW (which would likely only be adequate for heating some fraction of a home) to 2.4 kW, for instance, the effect on overall economics would be significant. Assuming the trigeneration system with parameters in Table E1 is retained and that additional heating is met by burning producer gas indoors as described in Section 4.4.2, an additional 224 tons of residues would need to be gasified. This would reduce the fuel available for the microturbine from 551 tons/year to 327 tons/year thereby reducing its capacity factor from 72% to only 43%! Having an understanding with villagers that a variable price structure is needed to regulate consumption would be important for dealing with issues of this nature. The basic point is that a village energy system needs to be able to cope with unexpected behavior.

Another complex social issue that deserves attention is that of equity: how are the poorer farmers affected by the installation of a village energy system? Once crop residues have a market and therefore a cash value, could the poor farmers' access to residues be jeopardized in any way? The fact that there is, in reality, a distribution of household incomes has thus far been overlooked. To be sure, there will be very poor farmers who can not afford large investments in the village corporation for example. Therefore, when profits are redistributed, their share may not be able to cover their energy costs. One way to compensate for this would be for poor farmers to gather the residues from the fields of wealthier farmers who do not want to be bothered with this chore. By having their fields cleared, the wealthier farmers are provided with a service. For the poorer farmers, the result of this symbiotic relationship is that they would be able to sell a greater quantity of residues to the village corporation. To cover 100% of an average household's energy costs, a farmer would have to gather and sell the equivalent of 4 average households' available residues. However an energy system is implemented, care needs to be taken to ensure that people are at least not worse off as a result of the change.

Social concerns having been addressed, a further requirement is having sound administration of the village energy system's operation, maintenance, and accounting. Doing so within the context of a village corporation would likely be more challenging than with an experienced independent power provider (IPP). Village administration means having some form of village council. This is what has been done in the case of the Pura village energy system in India (Rajababapaiah et al, 1993). In Pura, administrative functions are carried out by the "village development society" which is composed of villagers that lead traditional community activities. The details of how such a body organizes itself and operates will depend on the culture.

4.4.7 CONCLUDING REMARKS

An energy conversion system which makes use of locally generated fuel to provide villages with power, heat and cooking gas has been described for the context of Jilin Province, China. It is clear that available crop residue resources are much larger than necessary to meet all current local energy needs. Because of this, there is the potential for considerable revenues to be generated from sale of excess power to areas of higher demand. A result of this is that not only can public health be improved in the rural areas by ending direct combustion of biomass indoors, urban public health can be improved as well by reducing dependence on coal-derived power.

Ultimately deciding how to finance and manage a gasification plant involves more issues than can be fully considered here. Whether the village corporation could come into being, for instance, would depend on such conditions as the willingness and ability of (1) villagers to invest and cooperate, and (2) a group to perform the necessary functions and accept the responsibilities of a village corporation.

As illustrated in the three examples considered in section 4.4.1.4, the economics of the trigeneration system are quite sensitive to the cost of the district heating system. Determining in actuality what cost can be achieved using Chinese manufacturing, labor, and materials would certainly be a worthwhile endeavor, one best carried out in China itself. The objective here has been to simply indicate what might be possible given the technologies and resources available.

4.5 IMPLICATIONS FOR CHINA IN GENERAL

Crop residue gasification has surprising potential for China because of the magnitude of the resource produced together with the fact that most of its population consists of rural villages[24]. That is to say, people live where the resources are. In 1995, the estimated total crop residue production was about 605 million tons, 355 million of which being available for fuel (Li et al, 1998). In terms of tons of coal equivalent (tce), the fuel resource is 178 million tce. If the 860 million rural people live in 4-person households each requiring 6 m^3 of cooking gas per day, about 200 million tons of residues would need to be gasified each year for cooking (0.95 tons/hh/year). If the remaining 150 million tons were used to generate electricity, 135,000 GWh could be produced[25]. At a capacity factor of 70%, this is equivalent to having 22 GW of installed capacity. In terms of 75 kW microturbines, this is about 300,000 units. According to the CIA's World Factbook, China has a total of about 250 GW installed generating capacity. Crop residue gasification and conversion could increase China's total power output by almost 10%! It should be noted, further, that this additional capacity would come with no net CO_2 emissions.

In addition to having a significant impact on China's power generating capability, widespread gasification of crop residues would also have dramatic public health benefits. As mentioned earlier, discontinuing direct combustion of biomass indoors will eliminate the unsafe concentrations of particulate matter blamed for high incidences of respiratory disease. Everything ranging from asthma attacks to chronic bronchitis and lung cancer could be markedly reduced for a large fraction of China's population[26]. To be sure, China has many incentives for finding a better way to use its crop residue resource.

Chapter 4 References

Anonymous. (1998). "Power and Heat from Biomass Gasification," BG Systems product literature.

Cao, J. (1998). "Evaluation of Biomass Energy Resources and Utilization Technology Prospect in Jilin Province," *Proceedings of Workshop on Small-Scale Power Generation from Biomass,* Working Group on Energy Strategies and Technologies, China Council for International Cooperation on Environment and Development, Changchun, China, 12-13 January, p. 16-25.

China Statistical Yearbook, (1998). State Statistical Bureau of the People's Republic of China.

Dai, L., Li, J., Overend, R., eds. (1998). *Biomass Energy Conversion Technologies in China: Development and Evaluation*, China Environmental Science Press, Beijing.

DeLaquil, P. (1998). "Small Scale Biomass Gasification Systems For Agricultural and Forest Product Industries," *Proceedings of Workshop on Small-Scale Power Generation from Biomass,* Working Group on Energy Strategies and Technologies, China Council for International Cooperation on Environment and Development, Changchun, China, 12-13 January, p.50-58.

Fisher Tank Company (1999). personal communication.

Florig, H. (1997). "China's Air Pollution Risks," *Environmental Science & Technology News*, vol 31, no. 6, p. 274-279.

Geller, H.S. (1980). "Thermal Distribution Systems and Residential District Heating," Princeton University, Center for Energy and Environmental Studies Report No. 97, August.

Jain, B.C. (1998). Ankur Scientific Energy Technologies, personal communication.

Jia, H.Q. (1999). Jilin Province Energy Research Institute, personal communication.

---

[24] About 860 million people live in rural areas (Dai et al, 1998) which is more than three times the entire U.S. population.

[25] Using the usual gasification efficiency of 70% and gas-to-electric thermal conversion efficiency of 28%.

[26] For China's significant smoking population, however, benefits may be marginal.

Jin, H. (1999). communication with Jilin Province Energy Research Institute.

Larson, E. and Jin, H. (1999). "A Preliminary Assessment of Biomass Conversion to Fischer-Tropsch Cooking Fuels for Rural China," *Proceedings of the Fourth Biomass Conference of the Americas*, Oakland, California, August 29-September 2, Overend and Chornet, eds., Elsevier Science Ltd., Oxford, vol 1, p. 855-863.

Larson, E. (1998). Communication with Jilin Province Energy Research Institute.

Li, J., Bai, J., Overend, R., eds. (1998). *Assessment of Biomass Resource Availability in China*, China Environmental Science Press, Beijing.

Liu, G.X. (1999). Professor, Jilin Agriculture University, personal communication.

Lo, M. (1997). "Social and Cultural Aspects of Renewable Energy in Africa," talk presented at Princeton University, Woodrow Wilson School STEP seminar, November 20.

Lorenz, C. (1996). "Design of a Community-Integrated Energy System," senior thesis, Department of Mechanical and Aerospace Engineering, Princeton University, May 6.

Mao, Y. (1999). "Economic and Institutional Analysis on the Baicheng Straw Gasification Project," Energy Working Group of the China Council for International Cooperation on Environment and Development (CCICED), Unirule Institute of Economics, Beijing, May, p. 8-17.

Miles, T.R., Miles, T.R. (Jr.), Baxter, L.L., Jenkins, B.M. and Oden, L.L. (1993). "Alkali Slagging Problems with Biomass Fuels," *Proceedings of the First Biomass Conference of the Americas*, vol 1, Aug 30-Sept 2, Burlington, Vermont, p. 406-421.

Mukunda, H.S. (1998). Indian Institute of Science, Bangalore, personal communication.

Mukunda, H.S. (1999). Indian Institute of Science, Bangalore, personal communication.

Myers, P.F. (1997). "Economics and Design Approaches for Small Commercial Turbogenerators," Paper No. 97-GT-364, American Society of Mechanical Engineers, New York.

Overend, R.P. (1998). "Small Power Systems for Rural Development," presented at the Workshop on Small-Scale Power Generation from Biomass, Working Group on Energy Strategies and Technologies, China Council for International Cooperation on Environment and Development, Changchun, China, January 12-13.

Overend, R.P. (1998). National Renewable Energy Laboratory, personal communication.

Rajabapaiah, P., Jayakumar, S. and Reddy, A.K.N. (1993) "Biogas Electricity – The Pura Village Case Study," in *Renewable Energy: Sources for Fuels and Electricity*, Johansson T.B., Kelly H., Reddy A.K.N, Williams R.H., eds, Island Press, Washington D.C.

Scott, D. (1999). Unifin International, personal communication.

Sieben, M. (1992). "Small Recuperated Gas Turbines for Power and Heat Generation," Master's thesis draft, Princeton University, Center for Energy and Environmental Studies, July.

Sun, L., Wang, Y.J. and An, Y.B. (1998). "Biomass Energy Conversion Technologies and Their Developing Environment in China," *Proceedings of Workshop on Small-Scale Power Generation from Biomass,* Working Group on Energy Strategies and Technologies, China Council for International Cooperation on Environment and Development, Changchun, China, 12-13 January, p. 59-68.

Sun, L. (1998). Deputy Director of the Shandong Energy Research Institute, personal communication.

Ulrich, G.D. (1984). *A Guide To Chemical Engineering Process Design and Economics*, John Wiley & Sons, New York.

Walker, E. and Hay, A. (1999). "Carbon monoxide poisoning is still an underrecognised problem," *British Medical Journal*, vol 319, October 23, p. 1082-1083.

Weinstein, C. (1999). AlliedSignal, personal communication.

Wu-Williams, A.H. et al. (1990). "Lung cancer among women in north-east China," *British Journal of Cancer*, vol 62, p. 982-987.

Xu, Z.Y. et al. (1989). "Smoking, Air Pollution, and the High Rates of Lung Cancer in Shenyang, China," *Journal of the National Cancer Institute*, vol 81, n 23, December 6, p. 1800-1806.

Yang, F. (1995). "IGCC and its Future Market Penetration in China," Master's Thesis, University of California at Berkeley, Energy and Resources Group.

5. CONCLUSIONS AND FUTURE WORK

With regard to the applicability of microturbines to biomass-derived gas, there is still work to be done. Of prime importance is establishing through experimental means the sensitivity of high-speed radial turbomachinery to the kind of particulate matter that can be expected from gasification of alkali-rich feedstocks. Hand in hand with this is the determination of what particulate levels and size distribution can be expected from a clean-up system using a fine filter that treats stalk-derived gas. Another issue is the catalytic combustor of the microturbine, which is necessary if an air/fuel co-compression scheme is chosen. Cost, life, and sensitivity to producer-gas contaminants have yet to be determined. As the microturbine evolves from a newcomer to the distributed power market to a familiar off-the-shelf alternative, some of these questions will be answered.

In identifying crop residue resources and considering a few different ways in which they can be utilized in Jilin villages, it is clear that gasification has great potential for meeting cooking fuel, heating, and rural electricity needs (as well as supplementing urban electricity needs and stimulating growth of rural industry). Based on the economic assumptions used here, internal rates of return (IRR) turn out to be relatively low except for the trigeneration case with hot water piping that has a 75%-lower cost than what was estimated for the U.S. context. The case with 50%-lower piping cost and the one with no district heating system join the 75%-lower case in achieving IRRs that exceed 12% when the selling price of electricity is greater than or equal to 0.06 $/kWh, as it is in a number of markets in China. The particular configuration selected will depend not only on factors like initial capital investment and IRR, but also on availability of cooking fuel alternatives and villagers' preferences. At the present time, the general need for a clean, easy-to-use cooking fuel would rule out the option with no gas distribution. Its high degree of safety, however, further motivates investigation of the possibility of Fischer-Tropsch synthesis plants that could produce synthetic liquefied petroleum gas (LPG) from crop residues.

There are certainly other issues that must be resolved to actualize any of the village-scale systems discussed here. Considerations such as a system's compatibility with existing social structure are critical to address, but beyond the scope of this treatment. Exporting significant quantities of power to the grid from small, distributed power plants – which economics of these systems utterly depend on in the absence of large rural consumers – may encounter institutional difficulties given that China's experience is limited primarily to large, centralized power plants. Still, the prospect of displacing on the order of a couple gigawatts of polluting, coal-derived power while simultaneously enhancing the living conditions of many people may prove sufficiently attractive to overcome these and other barriers.

APPENDIX A: ECONOMIC COMPARISON OF MICROTURBINES AND ICEs

Presented here is a simple economic comparison of microturbines and ICEs for power generation using producer gas. The context chosen is that of India, as an economic study of producer gas fueled diesel engines has already been done for this situation (Mukunda et al, 1993). A diesel engine derated by 20%, a spark-ignition engine derated by 50%, and a microturbine with no derating are compared as prime movers for an 80 kW output power plant with a 20-year analysis period. Wood is the fuel, which is available at a low price. The cost of labor, being in the Indian context, is distinctly low. All the pertinent economic and technical information and assumptions are presented in Table A1 with explanatory notes.

Using results from Table A1, the Figures A1, A2 and A3 present the distribution of levelized lifecycle costs (LLCs) for the diesel, spark-ignition, and microturbine plants, respectively. At 33% of the total cost of electricity (COE), diesel fuel turns out to be the most significant cost component for the diesel plant. This reveals how keenly sensitive to the price of diesel fuel such a system would be. In the case of the spark-ignition plant with no supplemental fuel needs, capital cost turns out to be nearly 60% of the COE. Also, the cost of wood plays a larger role than in the diesel plant. The distribution for the microturbine resembles that of the spark-ignition plant, but the significance of capital cost is somewhat less at 51%.

Comparing the LLCs shown in Table A1 reveals the significance of supplemental fuel dependence, the need for lubricating oil, and derating. The microturbine gives a COE that is significantly lower because it requires neither supplemental fuel nor lubricating oil and furthermore is not derated. The capital cost of the microturbine can actually reach $750/kW before it gives a COE equivalent to that of the diesel engine system. While the SI gas engine has no supplemental fossil fuel dependence, relative to the diesel case it has much greater capital cost and derating as well as lower efficiency. As a result it turns out to have a somewhat higher COE than the diesel plant.

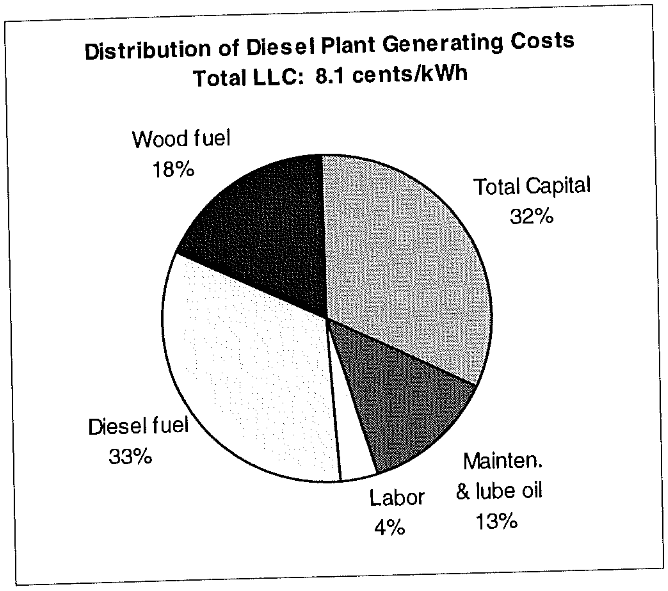


Figure A1

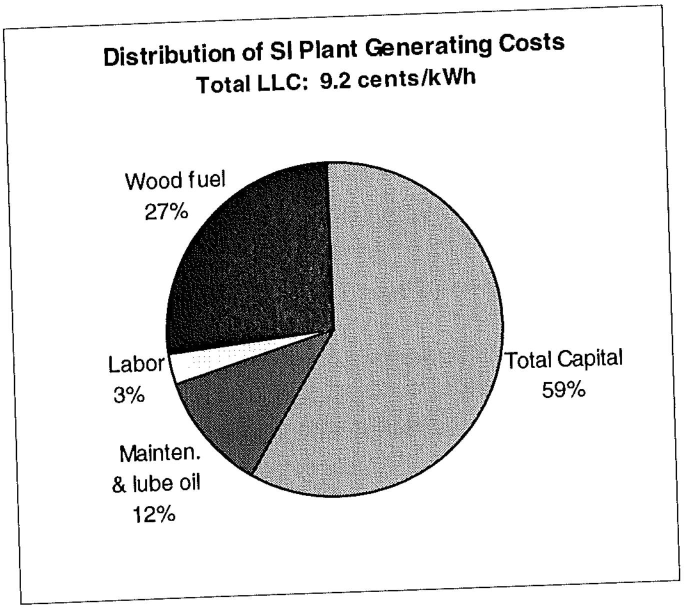


Figure A2

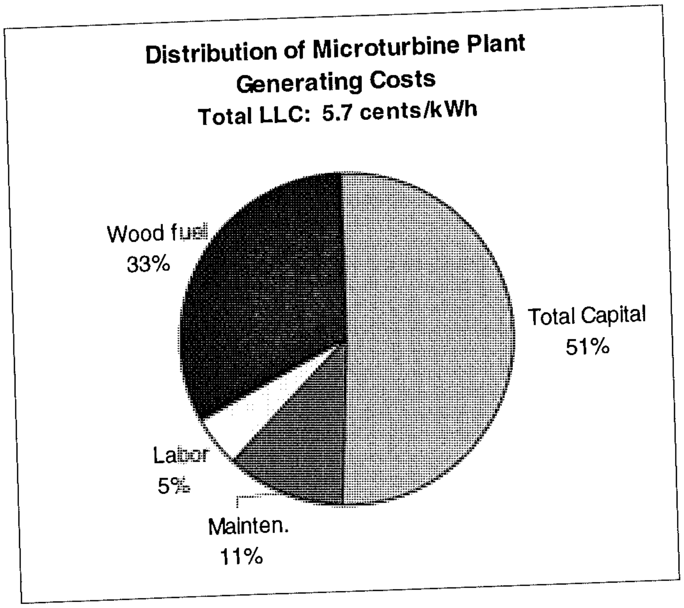


Figure A3

Table A1. Economics for Three 80 kW (actual output) Prime Movers

Actual Output (kW)	80		
Economic Parameters		**Fuel Parameters**	
Exchange Rate (Rs/1991$)	20	Biomass (MJ/kg)	17
GNP Deflator (98/91)	1.16	Diesel (MJ/kg):	45.5
Analysis Period (yrs)	20	Diesel, kg/lit:	0.85
Discount rate (%/yr)	0.120	1998$/lit:	0.32
Capital Recovery Factor	0.134		
Capacity factor (%)	0.65		
Annual kWh production:	456000		

	Diesel	Spark-Ignition	Microturbine
a Thermal Efficiency (LHV)	0.27	0.21	0.28
Deration	0.20	0.5	0
b Purchase (rated) size (kW)	100	160	80
c Genset Cost (1998$/kWrated)	181	362	350
(1998$/kWactual)	226	724	350
d Engine lifetime (years)	6	6	10
Replacements needed:	3	3	1
e Gasifier cold-gas efficiency	0.7	0.7	0.7
Gasifier lifetime (yrs)	6	6	6
Replacements needed:	3	3	3
Cleanup system lifetime (yrs)	10	10	10
Replacements needed:	1	1	1
Building lifetime (yrs)	40	40	40
Fuel, Oil Use and Cost			
f Diesel (kg/hr)	5.59	0	0
(MJ/hr)	255	0	0
Biomass (kg/kWh)	0.85	1.44	1.08
(kg/hr)	68	115	86.4
(MJ/hr)	1160	1960	1470
Diesel (1998 $/GJ):	8.4	0	0
Biomass (1998 $/GJ):	1.02	1.02	1.02
Lube oil use (g/kWh)	1.4	1.4	0
Lube oil, $/kg:	3.9	3.9	
Capital (1998 $)			
Gasifier	1160	1160	1160
g Cooling, cleaning	8690	8690	10300
Control system	11600	11600	11600
Engine gen-set	18100	57900	28000
Building	5790	5790	5790
Install., engr., contingencies (50%)	19800	39700	25500
TOTAL	65100	125000	82300
h **Maintenance** (1998 $/yr)	2500	2500	3000
Lube oil ($/yr)	2400	2400	0
Labor (1998$/hr)	0.23	0.23	0.23
Fuel			
Diesel (1998 $/hr)	2.13		
Biomass (1998 $/hr)	1.18	2.00	1.50
Levelized Lifecycle Costs (1998 cents/kWh)			
Capital for gasifier	0.06	0.06	0.06
Capital for cooling/cleaning system	0.34	0.34	0.40
Capital for control system	0.45	0.45	0.45
Capital for engine gen-set	1.01	3.22	1.09
Capital for building	0.17	0.17	0.17
Total Capital + inst, engr, conting's	2.61	5.41	2.92
i Total Salvage value	0.04	0.12	0.00
Maintenance & lube oil	1.08	1.08	0.66
Labor	0.29	0.29	0.29
Diesel fuel	2.67	0.00	0.00
Wood fuel	1.48	2.50	1.88
TOTAL (cents/kWh)	**8.08**	**9.16**	**5.74**

Notes for Table A1:

[Data in shaded cells comes or is derived from Mukunda et al (1993)]

[a] *diesel:* Data from BG Systems' product literature (1998) suggests a dual-fuel efficiency of about 27%. In practice, the efficiency will depend on the degree to which an engine (diesel or spark-ignition) is adapted to running on producer gas (Reed et al, 1988).
spark-ignition: Efficiency with producer gas is chosen to be 21%, which is a likely value based on Reed et al (1988).
microturbine: About 28% LHV is representative of AlliedSignal's microturbine (with 30% being their target).

[b] Because of derating, the actual size unit that must be purchased to produce 80 kW of power will be larger than 80 kW.

[c] AlliedSignal product literature (1998) estimates year 2003 installed capital cost at $350-450 kW for its 75 kW microturbine. As mentioned in Chapter 1, the spark-ignition engine is typically twice the cost of a comparably sized diesel engine. Note that "genset" refers to the engine-generator package.

[d] Mukunda et al (1993) give the diesel engine's life to be 25,000 reactor hours. In this analysis, that is equivalent to 4.4 years. Six years is chosen here with the implicit understanding that at least one major overhaul will be performed. The 10-year life for the microturbine is based on AlliedSignal's current estimate.

[e] The cold gas efficiency is the chemical enthalpy of the producer gas divided by the (lower) heating value of the raw fuel. Therefore, it does not take into account the producer gas' sensible enthalpy.

[f] For the diesel case, biomass and diesel fuel use were calculated such that their energetic sum gave an overall efficiency of 27%. A diesel engine running on 100% diesel fuel with 34% efficiency consumes 0.233 kg of fuel per kilowatt-hour output power. Producer gas here displaces 70% of this fuel consumption.

[g] For the microturbine case, the higher cost is attributed to an additional fine filter for enhanced particle removal. The cost is estimated at about $20/kW (see Section 3.3.1)

[h] Maintenance cost for the microturbine is based on AlliedSignal's 0.7 cents/kWh target which includes parts and labor at American rates. Currently they are able to guarantee no more than 1 cent/kWh at this early stage. For the diesel engine, a maintenance cost of 10% of the initial capital cost per year is used while 5% is applied with the gasifier, controls, clean-up system and building (Mukunda et al, 1993). For the spark-ignition engine, maintenance costs were taken to be the same as those for the diesel engine on a dollar – not percentage – basis. This is done partly out of simplicity and partly because an SI engine rated at 160 kW which only produces 80 kW will not experience as much wear and tear. Therefore, a full 10% annual maintenance cost may be excessive.

[i] Salvage values based on a linear depreciation of capital.

APPENDIX B: HEAT RECOVERY UNIT PRESSURE DROP CALCULATION

To estimate the pressure drop that may be experienced by microturbine exhaust flowing through a heat recovery unit, heat exchanger design calculations were performed using standard techniques found in Kays and London (1964). Table B1 summarizes some of the key features and results. The scale is appropriate for a 75 kWe microturbine.

Table B1. Heat Recovery Heat Exchanger Parameters and Results

Gas Side		~ air
mass flow	kg/s	0.771
inlet temp	°C	250
outlet temp	°C	74
Water Side		water
mass flow	kg/s	1.0
inlet temp	°C	50
outlet temp	°C	83
kW to water	kW	138

Heat Exchanger		crossflow
Surface		11.32-737-SR
Material		stainless steel
Dimensions	in	20x18x8
Overall Heat Transfer Coeff.	W/m^2K	46.13
Effectiveness	%	88
Gas-side Pressure Drop (%)		0.83

In the Jilin Province context, hot water (~85 °C) for district heating will be called for. Therefore a gas-to-liquid heat exchanger surface consisting of flat tubes with straight fins was chosen. It provides much more surface area on the gas side (where most of the thermal resistance is) than on the water side. A concern to be taken into account in the design of a lower-temperature heat exchanger in which the gas contains water vapor is condensation within the flow passages. This can contribute to corrosion, partial blockage of flow passages, and performance deterioration. The microturbine exhaust is about 2 molar percent water, which means its partial pressure is about 0.02 atm. As long as the exhaust temperature does not get too close to the dew point temperature of 18 °C, condensation will not be an issue. At 74 °C, we observe that in fact the exhaust temperature at the heat exchanger exit is indeed a safe one.

Recent experience in Sweden with microturbine cogeneration (Carnö et al, 1998) provides a good check on the realism of the amount of heat estimated to be recoverable in Table B1. The Swedish utility Vattenfall has a 38 kW-microturbine demonstration plant in Gothenburg, Sweden. From a recuperator exhaust stream of 0.25 Nm^3/s (0.32 kg/s) at 245 °C, 70 kW of heat is transferred to a water stream with an inlet temperature of 55 °C. Therefore, about 220 kW are transferred per kg/s of airflow. Scaled up to the mass flow in Table B1, this corresponds to about 170 kW, suggesting that the calculated value of 138 kW is perhaps a conservative one.

References

Kays, W.M. and London, A.L. (1964). *Compact Heat Exchangers*, 2nd ed., McGraw-Hill Book Co., New York.

Carnö, J., Cavani A. and Liinanki, L. (1998). "Micro Gas Turbine for Combined Heat and Power in Distributed Generation," Paper No. 98-GT-309, American Society of Mechanical Engineers, New York.

APPENDIX C: HOUSEHOLD HEAT LOSS ESTIMATE

The wintertime heat loss of a Jilin household is here estimated in a simple way to show that the gas demand suggested for heating in Section 4.3.2 is actually quite low. A second objective is to show the significance of adding insulation.

The heat loss calculation will only consider: (1) natural convective and conduction heat transfer through the walls and ceiling and (2) air exchange with the environment. No contributions from the wind, floor, or windows will be considered. Therefore, it is safe to say that the results will likely be lower than what is experienced in reality.

The general equation for convection heat transfer from an object with surface area A to a fluid is

$$Q = h\,A\,(T_w - T_o),$$

where Q is the heat transfer rate, h is the average heat transfer coefficient, T_w is the temperature of the surface and T_o is the ambient fluid temperature. The objective is to determine h, which embodies all the relevant fluid mechanical, thermal, and geometrical parameters. The value h takes will depend strongly on the wind, but for the purposes of this estimate, a typical indoor (i.e. no wind) coefficient of 8 $W/m^2\,{}^{\circ}C$ will be used for both inside and outside surfaces (Socolow, 1978). Just to reinforce the assertion that this calculation will yield a relatively low heat loss, note that the value 8 $W/m^2\,{}^{\circ}C$ is some 3.5 times smaller than that which would arise with a 5 meter-per-second wind (Socolow, 1978).

Conduction through the walls and ceiling will be treated as a simple one-dimensional problem. For a homogeneous solid of length L with fixed temperatures at the ends (T_1 and T_2) and cross-sectional area A, heat conducted through it is given by

$$Q = k/L\, A\, (T_1 - T_2).$$

This expression is valid for one-dimensional heat transfer. In the case of a wall, this means conduction through the faces and not up through the edges. For this analysis, thermal conductivities of 0.722 and 0.935 W/m°C are used for brick walls and the concrete ceiling respectively.

Convection inside and outside a wall or ceiling and conduction through it are related by the fact that these processes are connected in series. The heat flow calculated for each of these three problems must be equal. By dividing the term $A\,(T_i - T_o)$ by the sum of thermal resistances (L/k for conduction, 1/h for convection), the resulting heat flow can be readily determined.

In addition to heat losses through the walls and ceiling, air exchange losses (mass transfer) are also considered. Any home will have leaks through which significant amounts of heat can be lost. The rate at which a home's internal volume of heated air will be lost to the environment is called the air exchange rate and is expressed here in terms of "home volumes" of air per hour. A home's air exchange rate will depend on how well sealed it is, the wind, and also on the indoor-outdoor temperature difference which buoyancy is proportional to. Values measured in New Jersey townhouses ranged from 0.25 to 2.5 per hour, and up to nearly 1 per hour on a cold, windless day (Socolow, 1978). For this analysis, a rate of 1 per hour will be assumed. This corresponds to a heat loss equal to this mass flow of air multiplied by its specific heat and the indoor-outdoor temperature difference.

Calculations use a home with a floor area of 6x9 = 54 m^2 (Jia, 1999) and an assumed height of 2.4 meters as shown in Figure C.1. The wall and ceiling thicknesses are nominally taken to be 10 cm, but this dimension will not be very significant when insulation of some kind is added.

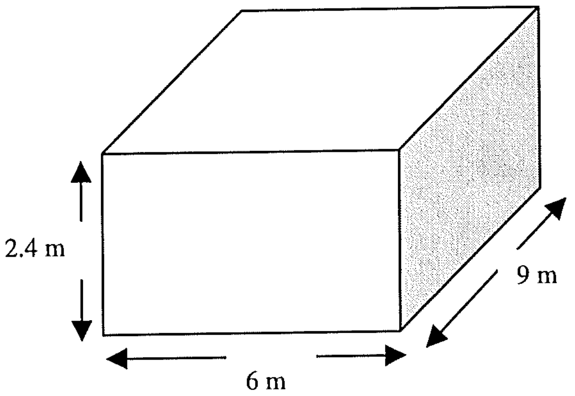


Figure C1 Model Jilin home

Results for several different indoor temperatures are shown in Table C1, with and without insulation. All calculations use 18.6 °F (-7.4 °C) for the ambient temperature, which is the average winter temperature in Jilin. Notice that the largest heat loss calculated (no insulation, 60 °F indoors) is a factor of 7 greater than the baseline heat load selected in Section 4.3.2 of 1.2 kW per household. Of course, if only one particular region in the home was to be heated, losses from that region alone would be noticeably lower.

Adding 6 centimeters of insulating material that has the same thermal conductivity as corrugated cardboard (presumably an inexpensive material) appears to be an effective measure for reducing heat loss. With an indoor temperature of 60 °F (15.6 °C), the heat loss drops by over 60% when this form of insulation is added to the walls and ceiling. If the home is further made more air tight such that the air exchange rate drops to 1/2 per hour, the heat loss would be nearly 70% less. Reducing heat loss from windows (not considered here) would be the next important step to take. Retrofits to a home can certainly bring marked reduction in heat requirements as discussed by Socolow et al (1978)[1].

Table C1. Household heat loss calculation results

T_o = 18.6 °F (-7.4 °C)	Indoor Temperature °F (°C)	Heat loss through walls and ceiling (W)	Heat loss through air exchange[a] (W)	Total heat loss (W)
no insulation	60 (15.6)	7770	950	8720
	50 (10)	5900	720	6620
	40 (4.4)	4020	490	4510
insulation[b] (6 cm)	60 (15.6)	2230	950	3180
	50 (10)	1690	720	2410
	40 (4.4)	1150	490	1640

[a] air exchange rate taken to be 1 per hour
[b] using the thermal conductivity of corrugated cardboard, k = 0.064 W/m°C

References

Holman, J.P. (1990). *Heat Transfer,* 7th ed., McGraw-Hill Publishing Co., New York.

Socolow, R.H. ed. (1978). *Saving Energy in the Home: Princeton's Experiments at Twin Rivers,* Ballinger Publishing Co., Cambridge, MA.

---

[1] Retrofits to a New Jersey townhouse reduced its heat requirement by 2/3.

APPENDIX D: ESTIMATING ABOVE-AVERAGE HEAT DEMAND

Outlined here is the method used to estimate village heat demand in excess of that which the microturbine's exhaust can supply at design-point operation. Design point for the microturbine is considered to be 75 kWe power output at 28% efficiency with recoverable heat adequate for the average heating-season heat demand of a 100-household village.

With only average monthly temperatures for the city Changchun in Jilin Province, the magnitude of the amount of excess heat needed may be roughly estimated. Of course, this method does not give information on daily peak heating needs, but this is not too serious an issue for a microturbine with recuperator bypass functionality (described in section 4.4.1.1). Different heat outputs can be readily achieved while maintaining full power output by (1) increasing the fuel/air ratio and (2) changing the amount of turbine exhaust that flows through the recuperator. Because recuperator bypass can significantly lower the microturbine's efficiency, it will be necessary to estimate how much bypass operation will be required. To do so requires an estimate for the amount of excess heat needed. This prerequisite step is performed here.

Following Ross and Williams (1989), the heat needed by a home can be expressed as:

$$Q = L\,(T_i - T_o) - I - S$$

where

L = thermal lossiness of the home (includes conductive and air infiltration lossiness)
T_i (T_o) = indoor (outdoor) temperature
I = internal heat sources (people, appliances, etc.)
S = heat from sunlight entering through windows

Incorporating I, S, and LT_i into a new term, LT_{trig}, the expression can be simplified to:

$$Q = L\,(T_{trig} - T_o)$$

where T_{trig} is a reference temperature called the "trigger" temperature. If T_o is greater than or equal to T_{trig}, then no heating is needed. The value of T_{trig} for Jilin can be estimated because the heating season is known to be five months long and average monthly temperatures are available.

Refer to Table D1 for monthly average temperatures in Changchun, Jilin Province, for 1990 – 1997. The heating season will be taken as the five coldest months: November through March. Using neighboring months' average temperatures (October: 7.6 °C, April: 8.1 °C), we estimate the trigger temperature to be approximately 8 °C. This value will be used in defining "heating degree months."

Table D1 Monthly Average Temperatures in Changchun, Jilin Province

Year	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Avg**
1990	21.8	15.6	10.6	-0.1	-10	-16.9	-6.7	2.5	7.5	15.1	20.3	22.6	6.9
1991	23.6	15.7	7.4	-1.8	-12	-15.7	-11	3.3	7.8	15.6	19.8	21.8	6.2
1992	21.4	14.6	7.9	-5	-11.4	-11.7	-8.6	0	8.2	14.8	18.7	23.2	6.0
1993	21.2	15.8	6.6	-4.4	-12.2	-14.3	-8.5	0.6	6.9	16.1	19.5	22.8	5.8
1994	23.3	15.8	7.7	-0.3	-11.7	-16.1	-10.2	-3.4	10.3	15.1	23.1	24.9	6.5
1995	21.8	15.2	8.8	-1.2	-10.4	-11.4	-7.7	-3.4	7.2	12.9	21.4	22.1	6.3
1996	21	15.2	6.2	-5	-10.5	-13.7	-9.4	-1.9	7.7	16.7	21.8	22.6	5.9
1997	23	14.7	5.2	-1	-8.4	-15.5	-9.3	-0.1	9.5	14.8	22.4	25	6.7
Avg	22.1	15.3	7.6	**-2.4**	**-10.8**	**-14.4**	**-8.9**	**-0.3**	8.1	15.1	20.9	23.1	6.3

Source: China Statistical Yearbook, 1998

For a given month, it will be assumed that the heating needs are proportional to the number of "heating degree months" for that month, defined as $T_{trig} - T_{avg}$, where T_{avg} is the average monthly temperature. The larger the number of heating degree months, the colder it is and therefore the greater the heat demand.

The microturbine is sized to be able to meet the average heat load which can be expressed in terms of heating degree months. First the total heating degree months for the five month heating season is determined:

Nov: 8 – (-2.4) = 10.4
Dec: 8 – (-10.8) = 18.8
Jan: 8 – (-14.4) = 22.4
Feb: 8 – (-8.9) = 16.9
Mar: 8 – (-0.3) = 8.3
Total: 76.8 heating degree months

The average number of heating degree months per month is therefore 76.8 / 5 = 15.36. This quantity will correspond to the heat load that the microturbine can supply at its design point. Any heating degree months greater than 15.36 correspond to heating needs in excess of what the microturbine can provide. This situation occurs in December, January, and February with 3.44, 7.04, and 1.54 excess degree months, respectively, for total of 12.02. As a fraction of the total heat demand which is proportional to 76.8, the above-average heat demand is therefore 12.02 / 76.8*100 = 15.7%.

References

Ross, M.H. and Williams, R.H. (1981). *Our Energy: Regaining Control*, McGraw-Hill Book Company, New York.

APPENDIX E: ECONOMIC TABLES FOR SECTION 4.4

CONTENTS

Table E1. TRIGENERATION ECONOMIC DATA: High-cost DH

Economic parameters			
Analysis Period	years	20	
Discount rate	%/yr	5	a
Capital Recovery Factor		0.08	
Infrastructure discount rate	%/yr	6	
Infrastructure CRF		0.087	
Turbogenerator			
Rated capacity	kWe	75	
Capital cost (installed)	$/kW	350	b
Microturbine efficiency (LHV)	%	28	
Turbogenerator life	years	10	
# of replacements		1	
Maintenance	%/yr	8	c
Capacity factor		0.72	
Power gen., kWh/yr		473000	
Gasifier, clean-up and BOP			
Capital cost (installed)	$	25000	d
Gasifier output	m^3/hr	400	
Gasifier efficiency		0.7	
Gasifier lifetime	years	6	
# of replacements		3	
Cleanup system lifetime	years	6	
# of replacements		3	
Power requirements	kWh/year	9160	e
Maintenance	%/yr	5	
Gas Supply System (100 households)			f
Storage tank	Y	120000	
	$	14500	
Distribution system	Y	57200	
	$	6900	
Builiding	Y	63000	
	$	7590	
Other (includes installation)	Y	63800	
	$	7690	
Maintenance	%/yr	2.4	
District Heating System			
Chinese cost factor		1	
piping (installed)	$	105000	
heat recovery unit	$	7800	g
40,000 liter storage	$	2700	h
radiators	$/hh	80	i
	$	8000	
distribution pump	$	300	j
meters	Y/hh	100	k
	$	1200	
Total	$	125000	
Maintenance	%/yr	2.4	l
Power requirements	kWh/year	300	m

kWh per ton of stalks (des. pt)		901	n
(recup bypass)		761	
m^3 of gas per kg		2.3	
kWhth per ton of stalks		3210	
Stalk consumption for:			
power (des. pt)	tons/yr	374	
power (rec byp)	tons/yr	177	
cooking	tons/yr	95	
TOTAL consumption	**tons/yr**	**647**	
Annual resource	tons/yr	647	

Labor			o
Workers		10	
	Y/mo/emp	300	
	Y/yr total	36000	
	$/yr total	4340	
Management	Y/yr	12000	
	$/yr	1450	
Prices			
Corn stalks	Y/t	45.0	p
	$/t	5.4	
	$/GJ	0.33	
Cooking gas sale price	Y/m^3	0.249	
	$/m^3	0.030	
	$/GJ	6.00	
Heat sale price	$/GJ	7.80	
Electricity sale price			
village	$/kWh	0.096	
grid	$/kWh	0.05	
Capital Costs			
Gasifier, Cleanup, and BOP	$	25000	
Microturbine	$	26300	
Cooking gas system	$	36600	
Heat supply system	$	125000	
Total Investment	$	213000	
Total Present Value	$	**272000**	
Levelized Lifecycle Costs and Revenues			
Power Generating Capital	$/kWh	0.019	
Cook + Heat Capital	$/kWh	0.008	
infrastructure @ i=6%	$/kWh	0.021	
Fuel for power	$/kWh	0.006	
Fuel for cooking gas	$/kWh	0.001	
Labor & mgmt.	$/kWh	0.012	
Maint (power gen)	$/kWh	0.007	
Maint (cook+heat)	$/kWh	0.008	
Parasitic power	$/kWh	0.002	
Engineering and contingencies	$/kWh	0.007	
Total generating cost	$/kWh	**0.092**	
Cooking gas revenue	$/year	6570	
	$/kWh	**0.014**	
Heat supply revenue	$/year	11700	
	$/kWh	**0.0247**	
Electricity revenue			
from residential use	$/year	2100	
	$/kWh	**0.004**	
from grid	$/year	22600	
	$/kWh	**0.048**	
Gasifier + Cleanup salvage val.	$	504	q
(present value)	$/kWh	**0.0011**	
Net cost of electricity	$/kWh	**0.0**	
	Y/kWh	0.0	

Per cap net income	Y/yr	2186
Per hh net income	Y/yr	8963
Cost of gas per hh	**Y/yr**	**545**
Cost of heat per hh	**Y/yr**	**971**
Cost of power per hh	**Y/yr**	**174**
Total cost as % of hh income	%	18.9

Notes for Table E1. Trigeneration Economic Data Table: High-cost DH

[a] A discount rate of 6.5% makes the levelized lifecycle cost of electricity zero, i.e. 6.5% is the internal rate of return.

[b] AlliedSignal 1998 product literature estimates an installed cost of 350-450 $/kW for their 75 kW model in the year 2003. Labor involved in installation is likely to be less expensive in a Chinese context. For simplicity, the lower bound of this estimate was chosen.

[c] When fueled with producer gas, 10%/year has been used for reciprocating ICEs (see section 1.4.1) which are expected to have much greater maintenance needs. For the microturbine, only a moderate decrease to 8%/year is chosen to allow for unknowns like catalyst replacement.

[d] Data from the Shandong gasifier system is presented below (Dai et al, 1998):

Gasifier, cleanup and BOP (400 m^3/hr capacity)	Yuan	$
gasifier + cleanup	90,000	10,843
hay cutter	1000	120
water pump	300	36
installation	6500	783
others	2200	265
TOTAL	100,000	12,048

According to Dr. Jain of Ankur (1998), the capital cost of a 100 kWe gasifier system using a diesel engine does not exceed \$600/kW$_e$ in India. Less a diesel engine at about \$200/kW, this gives a total capital cost of \$40,000. Such a system includes the state-of-the-art, low-tar gasifier BG Systems uses (see section 4.2). For the analysis here, an intermediate capital cost of \$25,000 is used to allow for a better gasifier and clean-up than used in Shandong.

[e] To operate the same scale gasification system in Tengzhai village, Shandong, it was found that 8 kWh/day of electricity was required (Dai et al, 1998). Since 1300 m^3/day were generated, a flat power requirement of 6.2×10^{-3} kWh/m^3 is assumed.

[f] Gas supply system costs here are taken from estimates for a system planned for a 110-family village in Jilin performed by Cao et al (1998):

Component	Yuan	$
storage tank (100 m^3)	120,000	14,500
pipeline network	57,200	6,900
support equipment	40,700	4,900
building	63,000	7,600
installation plus other facilities	23,100	2,800
TOTAL	304,000	36,600

Compare with the more detailed actual costs shown below for the gas system set up in 1996 for Tengzhai, a 216-household village (Dai et al, 1998). In spite of the fact that the Tengzhai system serves twice as many people, its cost is curiously comparable. This would tend to support the idea that the Jilin estimates are conservative ones.

	Component	Yuan	$
gasification station (select components)	storage tank (250 m^3)	105,000	12,700
	land and building	54,000	6,500
	installation	6,500	780
pipeline network	gas pipes	57,000	6,870
	spare parts	7,700	930
	water holders	2,300	280
	labor	9,200	1,100
indoor facilities	stove	40 x 216 = 8,640	1,000
	gas meter	100 x 216 = 21,600	2,600
	final filter	30 x 216 = 6,480	780
	tube and spares	40 x 216 = 8,640	1,000
TOTAL		287,000	34,600

[g] The heat recovery unit is an air-to-water heat exchanger. Unifin International, a leader in heat transfer equipment, designs heat recovery units for microturbines sized between 28 and 150 kWe. The heat exchanger itself is expected to cost the end-user about $7,800 (Unifin, 1999).

[h] Water storage tank estimate from Trigen Corporation (Larson, 1998)

[i] Lorenz (1996) reports a cost for 10 household radiators of $785 (European manufacturer). Each has about a 1500 watt capacity when using 70 °C hot water that is rejected at 55 °C.

[j] Estimate from Trigen Corporation (Larson, 1998).

[k] The cost of a gas meter in the Tengzhai village gasification project (Dai et al, 1998) is borrowed for the water meter as an approximation.

[l] For simplicity, the maintenance cost rate is being borrowed from that of the gas system.

[m] The pumping work for water distribution used here is enough for a 65% efficient pump to circulate 1 kg/s through a length of pipe equivalent to the roundtrip distance (616 m) to the furthest home. Each meter is taken to have a 110 Pa pressure drop. To allow for greater pressure drops (village growth, contamination of pipes), a 100,000 Pa pressure drop is allowed for. The sale price of power for the pump is assumed to be 0.8 Y/kWh.

[n] The value 901 kWh per ton of stalks assumes (1) a corn stalk lower heating value of 16.5 MJ/kg, (2) 70% of this chemical enthalpy is in the producer gas (i.e. gasifier has a cold-gas efficiency of 70%), and (3) the thermal to electric conversion efficiency is 28%.

[o] See Section 4.4.1.4. For three shifts over a 5 month period and two shifts over a 7 month period in which weekends are covered and each shift has three people, a total of 10 workers are required.

[p] Cao et al (1998) report that about 5 tons of corn stalks are available for fuel per hectare. Therefore, an area of about 110 ha (1.1 km^2) would be adequate for the systems being considered. Cao et al (1998) give a growth cost of 30 Y/ton, a loading and unloading cost of 10 Y/ton, and a transportation cost of 2 Y/ton.km for a total of 42 Y/ton.km. An area of 1.1 km^2 is contained within a circle of radius 0.6 km. A cost of 45 Y/ton is chosen to accommodate more significant distances.

[q] At the end of the 20 year period of analysis, the gasification system will still have some salvage value. A linear depreciation is assumed.

Table E2. Trigen High-cost DH Yearly Cash Flow ($)

Period	years	20
IRR	%	**5.0**
CRF		0.08

Prices	$	Yuan	
grid power	0.05	0.42	per kWh
residential power	0.096	0.8	per kWh
gas	6.00	50	per GJ
hot water	7.80	65	per GJ

Replacements	At the end of Year #	Investment	Payment on gov't loan	Operating cost	Total cost	Power revenue (grid)	Power revenue (village)	Gas revenue	Heat revenue	Total revenue	Net' Income	Total pres. value
	0	144000										-144000
	1		9760	17400	27200	22600	2100	6570	11700	42900	15700	-129000
	2		9760	17400	27200	22600	2100	6570	11700	42900	15700	-114000
	3		9760	17400	27200	22600	2100	6570	11700	42900	15700	-101000
	4		9760	17400	27200	22600	2100	6570	11700	42900	15700	-87700
	5		9760	17400	27200	22600	2100	6570	11700	42900	15700	-75400
gasifier	6	25000	9760	17400	52200	22600	2100	6570	11700	42900	-9260	-82300
	7		9760	17400	27200	22600	2100	6570	11700	42900	15700	-71100
	8		9760	17400	27200	22600	2100	6570	11700	42900	15700	-60400
	9		9760	17400	27200	22600	2100	6570	11700	42900	15700	-50300
microturbine	10	26300	9760	17400	53437	22600	2100	6570	11700	42900	-10500	-56700
	11		9760	17400	27200	22600	2100	6570	11700	42900	15700	-47500
gasifier	12	25000	9760	17400	52187	22600	2100	6570	11700	42900	-9260	-52700
	13		9760	17400	27200	22600	2100	6570	11700	42900	15700	-44300
	14		9760	17400	27200	22600	2100	6570	11700	42900	15700	-36300
	15		9760	17400	27200	22600	2100	6570	11700	42900	15700	-28800
	16		9760	17400	27200	22600	2100	6570	11700	42900	15700	-21500
	17		9760	17400	27200	22600	2100	6570	11700	42900	15700	-14600
gasifier	18	25000	9760	17400	52187	22600	2100	6570	11700	42900	-9260	-18500
	19		9760	17400	27200	22600	2100	6570	11700	42900	15700	-12200
salvage	20	-16700	9760	17400	10500	22600	2100	6570	11700	42900	32400	**0**

Farmers' revenue from residues:

$	3510

Levelized net annual income:

$	11500
plus stalks	15000
$/hh	150
Y/hh	1250
% of hh inc	13.9

Village's net annual income*:

$	-5360
$/hh	-54
Y/hh	-445
% of hh inc	-5.0

*defined as the levelized net annual income plus residue sales less what villagers pay for the services

Table E3. TRIGENERATION ECONOMIC DATA: Low-cost DH

Economic parameters		
Analysis Period	years	20
Discount rate	%/yr	8.4
Capital Recovery Factor		0.1
Infrastructure discount rate	%/yr	6
Infrastructure CRF		0.087
Turbogenerator		
Rated capacity	kWe	75
Capital cost (installed)	$/kW	350
Microturbine efficiency (LHV)	%	28
Turbogenerator life	years	10
# of replacements		1
Maintenance	%/yr	8
Capacity factor		0.72
Power gen., kWh/yr		473000
Gasifier, clean-up and BOP		
Capital cost (installed)	$	25000
Gasifier output	m^3/hr	400
Gasifier efficiency		0.7
Gasifier lifetime	years	6
# of replacements		3
Cleanup system lifetime	years	6
# of replacements		3
Power requirements	kWh/year	9160
Maintenance	%/yr	5
Gas Supply System (100 households)		
Storage tank	Y	120000
	$	14500
Distribution system	Y	57200
	$	6900
Builiding	Y	63000
	$	7590
Other (includes installation)	Y	63800
	$	7690
Maintenance	%/yr	2.4
District Heating System		
Chinese cost factor	0.5	0.5
piping (installed)	$	52500
heat recovery unit	$	3900
40,000 liter storage	$	1350
radiators	$/hh	40
	$	4000
distribution pump	$	150
meters	Y/hh	100
	$	1200
Total	$	63100
Maintenance	%/yr	2.4
Power requirements	kWh/year	300

kWh per ton of stalks (des. pt)	901	
(recup bypass)	761	
m^3 of gas per kg	2.3	
kWhth per ton of stalks	3210	
Stalk consumption for:		
power (des. pt)	tons/yr	374
power (rec byp)	tons/yr	177
cooking	tons/yr	95
TOTAL consumption	**tons/yr**	647
Annual resource	tons/yr	**647**

Labor		
Employees		10
	Y/mo/emp	300
	Y/yr total	36000
	$/yr total	4340
Management	Y/yr	12000
	$/yr	1450
Prices		
Corn stalks	Y/t	45
	$/t	5.4
	$/GJ	0.33
Cooking gas sale price	Y/m^3	0.249
	$/m^3	0.030
	$/GJ	6.00
Heat sale price	$/GJ	4.50
Electricity sale price		
village	$/kWh	0.096
grid	$/kWh	0.05
Capital Costs		
Gasifier, Cleanup, and BOP	$	25000
Microturbine	$	26300
Cooking gas system	$	36600
Heat supply system	$	63100
Total Investment	$	151000
Total Present Value	$	**194000**
Levelized Lifecycle Costs and Revenues		
Power Generating Capital	$/kWh	0.021
Cook + Heat Capital	$/kWh	0.009
infrastructure @ i=6%	$/kWh	0.011
Fuel for power	$/kWh	0.006
Fuel for cooking gas	$/kWh	0.001
Labor & mgmt.	$/kWh	0.012
Maint (power gen)	$/kWh	0.007
Maint (cook+heat)	$/kWh	0.005
Parasitic power	$/kWh	0.002
Engineering and contingencie:	$/kWh	0.007
Total generating cost	$/kWh	**0.081**
Cooking gas revenue	$/year	6570
	$/kWh	**0.014**
Heat supply revenue	$/year	6750
	$/kWh	**0.0143**
Electricity revenue		
from residential use	$/year	2100
	$/kWh	**0.004**
from grid	$/year	22600
	$/kWh	**0.048**
Gasifier + Cleanup salvage va	$	350
(present value)	$/kWh	**0.0007**
Net cost of electricity	$/kWh	**0.0**
	Y/kWh	0.0

Per cap net income	Y/yr	2186
Per hh net income	Y/yr	8963
Cost of gas per hh	**Y/yr**	**545**
Cost of heat per hh	**Y/yr**	**560**
Cost of power per hh	**Y/yr**	**174**
Total cost as % of hh income	%	14.3

Table E4. Trigen Low-cost DH Yearly Cash Flow ($)

Period	years	20
IRR	%	**8.4**
CRF		0.105

Prices			
	$	Yuan	
grid power	0.05	0.42	per kWh
residential power	0.096	0.8	per kWh
gas	6.00	50	per GJ
hot water	4.50	37	per GJ

Replacements	At the end of Year #	Investment	Payment on gov't loan	Operating cost	Total cost	Power revenue (grid)	Power revenue (village)	Gas revenue	Heat revenue	Total revenue	Net Income	Total pres. value
	0	122000										-122000
	1		5180	15900	21100	22600	2100	6570	6750	38000	16900	-106000
	2		5180	15900	21100	22600	2100	6570	6750	38000	16900	-91900
	3		5180	15900	21100	22600	2100	6570	6750	38000	16900	-78600
	4		5180	15900	21100	22600	2100	6570	6750	38000	16900	-66400
	5		5180	15900	21100	22600	2100	6570	6750	38000	16900	-55100
gasifier	6	25000	5180	15900	46100	22600	2100	6570	6750	38000	-8140	-60200
	7		5180	15900	21100	22600	2100	6570	6750	38000	16900	-50600
	8		5180	15900	21100	22600	2100	6570	6750	38000	16900	-41700
	9		5180	15900	21100	22600	2100	6570	6750	38000	16900	-33500
microturbine	10	26300	5180	15900	47400	22600	2100	6570	6750	38000	-9390	-37700
	11		5180	15900	21100	22600	2100	6570	6750	38000	16900	-30800
gasifier	12	25000	5180	15900	46100	22600	2100	6570	6750	38000	-8140	-33900
	13		5180	15900	21100	22600	2100	6570	6750	38000	16900	-27900
	14		5180	15900	21100	22600	2100	6570	6750	38000	16900	-22500
	15		5180	15900	21100	22600	2100	6570	6750	38000	16900	-17400
	16		5180	15900	21100	22600	2100	6570	6750	38000	16900	-12800
	17		5180	15900	21100	22600	2100	6570	6750	38000	16900	-8460
gasifier	18	25000	5180	15900	46100	22600	2100	6570	6750	38000	-8140	-10400
	19		5180	15900	21100	22600	2100	6570	6750	38000	16900	-6720
salvage	20	-16700	5180	15900	4460	22600	2100	6570	6750	38000	33500	0

Farmers' revenue from residues:

$	3508

Levelized net annual income:

$	12700
plus stalks	16300
$/hh	163
Y/hh	1350
% of hh inc	15.1

Village's net annual income*:

$	832
$/hh	8
Y/hh	69
% of hh inc	0.8

*defined as the levelized net annual income plus residue sales less what villagers pay for the services

Table E5. GAS AND POWER ECONOMIC DATA: 75 KW CASE

Economic parameters		
Analysis Period	years	20
Discount rate	%/yr	5.9
Capital Recovery Factor		0.087
Infrastructure discount rate	%/yr	6.0
Infrastructure CRF		0.087

Turbogenerator		
Rated capacity	kWe	75
Capital cost (installed)	$/kW	350
Microturbine efficiency (LHV)	%	28
Turbogenerator life	years	10.0
# of replacements		1.0
Maintenance	%/yr	8
Capacity factor		0.45
Power gen., kWh/yr		29500

Gasifier, clean-up and BOP		
Capital cost (installed)	$	25000
Gasifier output	m^3/hr	400
Gasifier efficiency		0.7
Gasifier lifetime	years	6.0
# of replacements		3.0
Cleanup system lifetime	years	6.0
# of replacements		3.0
Power requirements	kWh/year	9160
Maintenance	%/yr	5

Gas Supply System (100 households)		
Storage tank	Y	120000
	$	14500
Distribution system	Y	57200
	$	6890
Builiding	Y	63000
	$	7590
Other (includes installation)	Y	63800
	$	7690
Maintenance	%/yr	2.4

Home heating		
in-home heating equipment	Y/hh	100
	$/hh	12
total cost	$	1200
Heating efficiency	%	70

Labor		
Employees		10
	Y/mo/emp	300
	Y/yr total	36000
	$/yr total	4340
Management	Y/yr	12000
	$/yr	1450

Prices		
Corn stalks	Y/t	45.0
	$/t	5.4
	$/GJ	0.33
Cooking gas sale price	Y/m^3	0.150
	$/m^3	0.018
	$/GJ	3.62
Electricity sale price		
village	$/kWh	0.096
grid	$/kWh	0.05

Capital Costs		
Gasifier, Cleanup, and BOP	$	25000
Microturbine	$	26300
Cooking gas system	$	36600
Home heating	$	1200
Total Investment	$	89100
Total Present Value	$	**143000**

Levelized Lifecycle Costs and Revenues		
Power Generating Capital	$/kWh	0.031
Cook + Heat Capital	$/kWh	0.009
infrastructure @ i=6%	$/kWh	0.002
Fuel for power	$/kWh	0.010
Fuel for cooking gas	$/kWh	0.002
Fuel for heating	$/kWh	0.004
Labor & mgmt.	$/kWh	0.020
Maint (power gen)	$/kWh	0.011
Maint (cook+heat)	$/kWh	0.003
Parasitic power	$/kWh	0.003
Engineering and contingencies	$/kWh	0.005
Total generating cost	$/kWh	**0.100**
Cooking gas revenue	$/year	3960
	$/kWh	**0.013**
Heat supply revenue	$/year	9380
	$/kWh	**0.0318**
Electricity revenue		
from residential use	$/year	2100
	$/kWh	**0.007**
from grid	$/year	13700
	$/kWh	**0.046**
Gasifier + Cleanup salvage val.	$	456
(present value)	$/kWh	**0.0015**
Net cost of electricity	$/kWh	**0.0**
	Y/kWh	0.0

kWh per ton of stalks (des. pt)		901	
m^3 of gas per kg		2.3	
kWhth per ton of stalks		3208	
Stalk consumption for:			
power (des. pt)	tons/yr		327
heating	tons/yr		224
cooking	tons/yr		95
TOTAL consumption	**tons/yr**		**647**
Annual resource	tons/yr		**647**

Per cap net income	Y/yr	2186
Per hh net income	Y/yr	8963
Cost of gas per hh	**Y/yr**	**329**
Cost of heat per hh	**Y/yr**	**779**
Cost of power per hh	**Y/yr**	**174**
Total cost as % of hh income	%	14.3

Table E6. Gas and Power 75 Yearly Cash Flow ($)

Period	years	20
IRR	%	**5.9**
CRF		0.087

Prices	$	Yuan	
grid power	0.05	0.42	per kWh
residential power	0.096	0.8	per kWh
gas	3.62	30.0	per GJ

Replacements:	At the end of Year #	Investment	Payment on gov't loan	Operating cost	Total cost	Power revenue (grid)	Power revenue (village)	Gas revenue	Heat revenue	Total revenue	Net Income	Total pres. value
	0	100000										-100000
	1		600	15600	16200	13700	2100	3960	9380	29100	12900	-87800
	2		600	15600	16200	13700	2100	3960	9380	29100	12900	-76400
	3		600	15600	16200	13700	2100	3960	9380	29100	12900	-65500
	4		600	15600	16200	13700	2100	3960	9380	29100	12900	-55300
	5		600	15600	16200	13700	2100	3960	9380	29100	12900	-45600
gasifier	6	25000	600	15600	41200	13700	2100	3960	9380	29100	-12100	-54200
	7		600	15600	16200	13700	2100	3960	9380	29100	12900	-45600
	8		600	15600	16200	13700	2100	3960	9380	29100	12900	-37500
	9		600	15600	16200	13700	2100	3960	9380	29100	12900	-29800
microturbine	10	26300	600	15600	42500	13700	2100	3960	9380	29100	-13400	-37300
	11		600	15600	16200	13700	2100	3960	9380	29100	12900	-30500
gasifier	12	25000	600	15600	41200	13700	2100	3960	9380	29100	-12100	-36600
	13		600	15600	16200	13700	2100	3960	9380	29100	12900	-30500
	14		600	15600	16200	13700	2100	3960	9380	29100	12900	-24700
	15		600	15600	16200	13700	2100	3960	9380	29100	12900	-19300
	16		600	15600	16200	13700	2100	3960	9380	29100	12900	-14200
	17		600	15600	16200	13700	2100	3960	9380	29100	12900	-9300
gasifier	18	25000	600	15600	41200	13700	2100	3960	9380	29100	-12100	-13600
	19		600	15600	16200	13700	2100	3960	9380	29100	12900	-9300
salvage	20	-16700	600	15600	-450	13700	2100	3960	9380	29100	29550	0

Farmers' revenue from residues:

$	3510

Levelized net annual income:

$	8670
plus stalks	12200
$/hh	122
Y/hh	1010
% of hh inc	11.3

Village's net annual income*:

$	-3270
$/hh	-33
Y/hh	-271
% of hh inc	-3.0

*defined as the levelized net annual income plus residue sales less what villagers pay for the services

Table E7. GAS AND POWER ECONOMIC DATA: 45 KW CASE

Economic parameters		
Analysis Period	years	20
Discount rate	%/yr	8.1
Capital Recovery Factor		0.103
Infrastructure discount rate	%/yr	6.0
Infrastructure CRF		0.087

Turbogenerator		
Rated capacity	kWe	45
Capital cost (installed)	$/kW	450
Microturbine efficiency (LHV)	%	0.28
Turbogenerator life	years	10.0
# of replacements		1.0
Maintenance	%/yr	8
Capacity factor		0.75
Power gen., kWh/yr		295000

Gasifier, clean-up and BOP		
Capital cost (installed)	$	25000
Gasifier output	m^3/hr	400
Gasifier efficiency		0.7
Gasifier lifetime	years	6.0
# of replacements		3.0
Cleanup system lifetime	years	6.0
# of replacements		3.0
Power requirements	kWh/year	9160
Maintenance	%/yr	5

Gas Supply System (100 households)		
Storage tank	Y	120000
	$	14500
Distribution system	Y	57200
	$	6890
Builiding	Y	63000
	$	7590
Other (includes installation)	Y	63800
	$	7690
Maintenance	%/yr	2.4

Home heating		
in-home heating equipment	Y/hh	100
	$/hh	12
total cost	$	1200
Heating efficiency	%	70

kWh per ton of stalks (des. pt)	901	
m^3 of gas per kg	2.3	
kWhth per ton of stalks	3208	
Stalk consumption for:		
power (des. pt)	tons/yr	327
heating	tons/yr	224
cooking	tons/yr	95
TOTAL consumption	**tons/yr**	**647**
Annual resource	tons/yr	647

Labor		
Employees		10
	Y/mo/emp	300
	Y/yr total	36000
	$/yr total	4340
Management	Y/yr	12000
	$/yr	1450

Prices		
Corn stalks	Y/t	45.0
	$/t	5.4
	$/GJ	0.33
Cooking gas sale price	Y/m^3	0.150
	$/m^3	0.018
	$/GJ	3.62
Electricity sale price		
village	$/kWh	0.096
grid	$/kWh	0.05

Capital Costs		
Gasifier, Cleanup, and BOP	$	25000
Microturbine	$	20300
Cooking gas system	$	36600
Home heating	$	1200
Total Investment	$	83100
Total Present Value	$	**124000**

Levelized Lifecycle Costs and Revenues		
Power Generating Capital	$/kWh	0.030
Cook + Heat Capital	$/kWh	0.011
infrastructure @ i=6%	$/kWh	0.002
Fuel for power	$/kWh	0.010
Fuel for cooking gas	$/kWh	0.002
Fuel for heating	$/kWh	0.004
Labor & mgmt.	$/kWh	0.020
Maint (power gen)	$/kWh	0.010
Maint (cook+heat)	$/kWh	0.003
Parasitic power	$/kWh	0.003
Engineering and contingencies	$/kWh	0.006
Total generating cost	$/kWh	**0.100**
Cooking gas revenue	$/year	3960
	$/kWh	**0.013**
Heat supply revenue	$/year	9380
	$/kWh	**0.0318**
Electricity revenue		
from residential use	$/year	2100
	$/kWh	**0.007**
from grid	$/year	13700
	$/kWh	**0.046**
Gasifier + Cleanup salvage val.	$	360
(present value)	$/kWh	**0.0012**
Net cost of electricity	$/kWh	**0.0**
	Y/kWh	0.0

Per cap net income	Y/yr	2186
Per hh net income	Y/yr	8963
Cost of gas per hh	**Y/yr**	**329**
Cost of heat per hh	**Y/yr**	**779**
Cost of power per hh	**Y/yr**	**174**
Total cost as % of hh income	%	14.3

Table E8. Gas and Power 45 Yearly Cash Flow ($)

Period	years	20
IRR	%	**8.1**
CRF		0.103

Prices			
	$	Yuan	
grid power	0.05	0.42	per kWh
residential power	0.096	0.8	per kWh
gas	3.62	30.0	per GJ

Replacements	At the end of Year #	Investment	Payment on gov't loan	Operating cost	Total cost	Power revenue (grid)	Power revenue (village)	Gas revenue	Heat revenue	Total revenue	Net Income	Total pres. value
	0	92800										-92800
	1		600	15100	15700	13700	2100	3960	9380	29100	13400	-80400
	2		600	15100	15700	13700	2100	3960	9380	29100	13400	-69000
	3		600	15100	15700	13700	2100	3960	9380	29100	13400	-58400
	4		600	15100	15700	13700	2100	3960	9380	29100	13400	-48600
	5		600	15100	15700	13700	2100	3960	9380	29100	13400	-39600
gasifier	6	25000	600	15100	40700	13700	2100	3960	9380	29100	-11600	-46900
	7		600	15100	15700	13700	2100	3960	9380	29100	13400	-39100
	8		600	15100	15700	13700	2100	3960	9380	29100	13400	-32000
	9		600	15100	15700	13700	2100	3960	9380	29100	13400	-25300
microturbine	10	20300	600	15100	36000	13700	2100	3960	9380	29100	-6900	-28500
	11		600	15100	15700	13700	2100	3960	9380	29100	13400	-22800
gasifier	12	25000	600	15100	40700	13700	2100	3960	9380	29100	-11700	-27400
	13		600	15100	15700	13700	2100	3960	9380	29100	13400	-22500
	14		600	15100	15700	13700	2100	3960	9380	29100	13400	-18100
	15		600	15100	15700	13700	2100	3960	9380	29100	13400	-13900
	16		600	15100	15700	13700	2100	3960	9380	29100	13400	-10100
	17		600	15100	15700	13700	2100	3960	9380	29100	13400	-6500
gasifier	18	25000	600	15100	40700	13700	2100	3960	9380	29100	-11700	-9400
	19		600	15100	15700	13700	2100	3960	9380	29100	13400	-6300
salvage	20	-16700	600	15100	-1000	13700	2100	3960	9380	29100	30000	**0**

Farmers' revenue from residues:

$	3510

Levelized net annual income:

$	9520
plus stalks	13000
$/hh	130
Y/hh	1080
% of hh inc	12.1

Village's net annual income*:

$	-2420
$/hh	-24.2
Y/hh	-201
% of hh inc	-2.2

*defined as the levelized net annual income plus residue sales less what villagers pay for the services

Table E9. HEAT AND POWER ECONOMIC DATA: Low-cost DH (50%)

Economic parameters		
Analysis Period	years	20
Discount rate	%/yr	-4.8
Capital Recovery Factor		0.029
Infrastructure discount rate	%/yr	6.0
Infrastructure CRF		0.087

Turbogenerator		
Rated capacity	kWe	75
Capital cost (installed)	$/kW	350
Microturbine efficiency (LHV)	%	28
Turbogenerator life	years	10.0
# of replacements		1.0
Maintenance	%/yr	8
Capacity factor		0.53
Power gen., kWh/yr		350000

Gasifier, clean-up and BOP		
Capital cost (installed)	$	25000
Gasifier output	m^3/hr	400
Gasifier efficiency		0.7
Gasifier lifetime	years	6.0
# of replacements		3.0
Cleanup system lifetime	years	6.0
# of replacements		3.0
Power requirements	kWh/year	9160
Maintenance	%/yr	5

LPG utilization equipment		
Stoves	Y/hh	40
	$/hh	5
total	$	480

District Heating System			
Chinese cost factor		0.5	0.5
piping (installed)	$		52500
heat recovery unit	$		3900
40,000 liter storage	$		1350
radiators	$/hh		40
	$		4000
distribution pump	$		150
meters	Y/hh		100
	$		1200
Total	$		63100
Maintenance	%/yr		2.4
Power requirements	kWh/year		300

kWh per ton of stalks (des. pt)	901	
(recup bypass)	761	
m^3 of gas per kg	2.3	
kWhth per ton of stalks	3208	
Stalk consumption for:		
F-T plants	tons/yr	231
power (des. pt)	tons/yr	238
power (rec byp)	tons/yr	177
TOTAL consumption	**tons/yr**	**647**
Annual resource	tons/yr	**647**

Labor		
Employees		10
	Y/mo/emp	300
	Y/yr total	36000
	$/yr total	4340
Management	Y/yr	12000
	$/yr	1450

Prices		
Corn stalks	Y/t	45.0
	$/t	5.4
	$/GJ	0.33
LPG sale price	$/GJ	7.00
Heat sale price	$/GJ	4.20
Electricity sale price		
village	$/kWh	0.096
grid	$/kWh	0.05

Capital Costs		
Gasifier, Cleanup, and BOP	$	25000
Microturbine	$	26300
LPG utilization equipment	$	480
Heat supply system	$	63100
Total Investment	$	115000
Total Present Value	$	**297000**

Levelized Lifecycle Costs and Revenues		
Power Generating Capital	$/kWh	0.019
Cook + Heat Capital	$/kWh	0.001
infrastructure @ i=6%	$/kWh	0.013
Fuel for power	$/kWh	0.006
Labor & mgmt.	$/kWh	0.017
Maint (power gen)	$/kWh	0.010
Maint (cook+heat)	$/kWh	0.004
Parasitic power	$/kWh	0.003
Engineering and contingencies	$/kWh	0.002
Total generating cost	$/kWh	**0.075**
Heat supply revenue	$/year	6300
	$/kWh	**0.0180**
Electricity revenue		
from residential use	$/year	2100
	$/kWh	**0.006**
from grid	$/year	16400
	$/kWh	**0.047**
Gasifier + Cleanup salvage val.	$	1280
(present value)	$/kWh	**0.0037**

Net cost of electricity	$/kWh	**0.0**
	Y/kWh	0.0

Per cap net income	Y/yr	2186
Per hh net income	Y/yr	8963
Cost of LPG per hh	**Y/yr**	**585**
Cost of heat per hh	**Y/yr**	**523**
Cost of power per hh	**Y/yr**	**174**
Total cost as % of hh income	%	14.3

Table E10. Heat and Power Yearly Cash Flow ($)

	low-cost DH (50%)	
Period	years	20
IRR	per year	**-4.8**
CRF		0.029

Prices	$	Yuan	
grid power	0.05	0.42	per kWh
residential power	0.096	0.8	per kWh
LPG	7.00	58.0	per GJ
hot water	4.20	35.0	per GJ

Replacements	At the end of Year #	Investment	Payment on gov't loan	Operating cost	Total cost	Power revenue (grid)	Power revenue (village)	Heat revenue	Total revenue	Net Income	Total pres. value
	0	85300									-85300
	1		4580	13800	18400	16400	2100	6300	24800	6390	-78600
	2		4580	13800	18400	16400	2100	6300	24800	6390	-71500
	3		4580	13800	18400	16400	2100	6300	24800	6390	-64100
	4		4580	13800	18400	16400	2100	6300	24800	6390	-56400
	5		4580	13800	18400	16400	2100	6300	24800	6390	-48200
gasifier	6	25000	4580	13800	43400	16400	2100	6300	24800	-18600	-73200
	7		4580	13800	18400	16400	2100	6300	24800	6390	-64200
	8		4580	13800	18400	16400	2100	6300	24800	6390	-54700
	9		4580	13800	18400	16400	2100	6300	24800	6390	-44800
microturbine	10	26300	4580	13800	44700	16400	2100	6300	24800	-19900	-77300
	11		4580	13800	18400	16400	2100	6300	24800	6390	-66300
gasifier	12	25000	4580	13800	43400	16400	2100	6300	24800	-18600	-99900
	13		4580	13800	18400	16400	2100	6300	24800	6390	-87800
	14		4580	13800	18400	16400	2100	6300	24800	6390	-75100
	15		4580	13800	18400	16400	2100	6300	24800	6390	-61700
	16		4580	13800	18400	16400	2100	6300	24800	6390	-47600
	17		4580	13800	18400	16400	2100	6300	24800	6390	-32900
gasifier	18	25000	4580	13800	43400	16400	2100	6300	24800	-18600	-78100
	19		4580	13800	18400	16400	2100	6300	24800	6390	-61800
salvage	20	-16700	4580	13800	1730	16400	2100	6300	24800	23100	0

Farmers' revenue from residues:

$	2250	local
$	980	from F-T
$	3230	

LPG expenditure:

$/year	7050

Levelized net annual income:

$	2440
plus stalks	5670
$/hh	57
Y/hh	471
% of hh inc	5.3

Village's net annual income*:

$	-9780
$/hh	-98
Y/hh	-812
% of hh inc	-9.1

*defined as the levelized net annual income plus residue sales less what villagers pay for the services