

Trigeneration in a northern Chinese village using crop residues

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Gasification of crop residues can provide modern energy carriers to rural areas at potentially attractive costs along with substantial environmental benefits. Such possibilities are illustrated here by modeling a village-scale “trigeneration system” for a hypothetical village in northern China to provide clean cooking fuel, hot water for heating, and electricity. The electricity and hot water would be provided by a microturbine operated in the combined heat and power mode. The cooking fuel and hot water would be distributed by underground pipes to individual houses in the village. Overall system economics would be most favorable when the microturbine is operated as a baseload power-generating unit. Because of low village electricity demand levels, this mode of operation requires selling most of the generated electricity into the electric grid. Prospective generating costs would be sufficiently low to make this option attractive as a source of grid electricity, but policies are needed that allow such village generators to sell their electricity into the grid at prices that reflect its value.

1. Introduction

The quality of life can be improved markedly in rural areas of developing countries by the introduction of modern, clean energy carriers (e.g., fluid fuels and electricity) to serve cooking, heating, lighting, and other basic needs and to support local industrial activities [Reddy et al., 1997]. This paper summarizes the findings of a recent study exploring the prospects for providing such energy carriers to a rural village in Jilin province, China: clean gas for cooking, hot water for heating, and electricity [Henderick, 2000]. These clean energy services would be provided via a “trigeneration” system that involves gasification of crop residues (mainly corn stalks) in a centralized village gasifier. Some of the gas so generated would be distributed via PVC pipes to households for cooking purposes; the rest would be burned in a microturbine for combined heat and power (CHP). The heat would be generated as hot water via heat recovery from turbine exhaust heat and distributed via a district heating (DH) network to houses in the village. Some of the generated electricity would be used to serve village needs; surplus electricity would be sold to the electricity grid.

As will be shown, the proposed trigeneration system has the potential for providing clean, modern energy carriers at attractive costs, and there are plausible strategies by which even the poorest households in the village would be able to afford the full range of energy services provided. The environmental/human health benefits offered provide compelling additional reasons for considering this option.

2. The environmental/human health impacts context

Direct burning of biomass or coal has been the dominant means of providing cooking and heating energy services

in rural areas. The indoor air pollution arising from these activities can lead to serious respiratory diseases [Smith et al., 1994]. Pollution involving particles small enough to lodge themselves deep in the lungs reaches dangerous levels inside houses. Products of incomplete combustion such as carcinogenic hydrocarbons and carbon monoxide are other dangerous air pollutants. Even when combustion products from cooking and heating systems are vented, health risks are still present^[1]. In China, respiratory disease due in large part to air pollution from biomass and coal-burning is a leading public health problem [Florig, 1997]. A recent World Bank report on environmental challenges facing China estimated, on the basis of the principle of the “willingness to pay” to avoid adverse health impacts of air pollution, that the cost of indoor air pollution in rural China amounts to \$10-11 billion per year [Johnson, 1997].

A new environmental concern in China is outdoor air pollution from burning crop residues in the fields. Traditionally, crop residues were well utilized for heating, cooking, and other purposes in low-income villages. But with rising incomes, growing numbers of farmers are no longer willing to gather crop residues from the fields and store them for use throughout the year, preferring instead to buy coal briquettes or LPG as need arises. As a result, excess crop residues that dry out too quickly to decay for incorporation into the soils are burned off in the fields to avoid insect infestation problems. The resulting air pollution is severe – often causing the closing of airports near harvest time. The quantity of residues that are burned off in Chinese fields is uncertain, but 100 million tonnes (Mt) per year is regarded as a conservative estimate [Sun et al., 1998]. Air pollution from residue-burning has become so severe that in 1999 the Chinese government banned

Table 1. Estimated average daily energy needs for a rural household^[1] in Jilin province

Fuel	Cooking	Cooking + heating ^[2]
Crop residues	74 MJ or 4.5 kg	290 MJ or 17.5 kg
Producer gas	30 MJ or 6 m ³ (2.6 kg of residue input) ^[3]	100 MJ or 20 m ³ (8.7 kg of residue input) ^[3]

Notes

1. For a four-person household
2. During the heating season
3. Residues required for gasification. Relevant energy parameters (LHV basis): heating value of crop residues = 16.5 MJ/kg; energy density of producer gas = 5 MJ/Nm³, and coal-gas efficiency = 70%.

the field burning of residues near airports, railroads and highways^[2]. This ban will be difficult to enforce unless alternative productive uses of the excess residues can be found.

In several Chinese provinces efforts are under way to use residues and centralized village-scale gasifiers to generate a cooking gas that is distributed by pipes to households [Dai and Sun, 1998]. This use of crop residues provides a convenient cooking gas and virtually eliminates the indoor air pollution problem caused by direct burning of biomass or coal for cooking^[3]. However, this strategy would actually exacerbate the problem of field burning of residues if all households were to shift to residue-derived gas for cooking, because residue requirements for cooking with gas are not much more than half the residue requirements for cooking via direct residue-burning (see Table 1). Partly for this reason, activities have recently been initiated in China aimed at exploring the prospects for CHP using crop residues produced in excess of cooking needs^[4].

3. Gasification technology for biomass feedstocks

The key process for converting solid biomass into a form versatile enough to provide multiple energy products is thermochemical gasification. The focus here is on gas derived from biomass via partial oxidation in air at atmospheric pressure. The fuel gas so generated, called "producer gas", typically has a heating value 10-15% of that of natural gas^[5]. After appropriate gas-cleaning, producer gas can be used as a cooking gas, in applications calling for heat, or as fuel for power or CHP applications.

Many biomass gasifier designs exist, but the most promising today for village-scale trigeneration applications is the downdraft gasifier. Though it is not a new technology, it is only in recent years that downdraft gasifiers (primarily of Indian origin) have been able to provide gas of quality adequate for small reciprocating internal combustion engine (ICE) applications (see Section 4), for which gas quality requirements are far tougher than for cooking or heating purposes. The critical gas quality issues for reciprocating ICEs relate to tars and particulates.

Experts estimate that the tar level in producer gas should be less than 30-50 mg/Nm³ for reciprocating ICEs [Milne et al., 1998] to avoid problems associated with tar condensation on critical engine parts. The most appropriate method for achieving such tar levels depends on the

type of biomass feedstock.

For wood chips, the tar problem is more or less solved with at least one and perhaps two Indian gasifiers.

One Indian gasifier (Imbert type) cracks tars catalytically using as catalyst the charcoal by-product of gasification. If operated properly, the gasifier maintains the charcoal bed in the reduction zone at a thickness appropriate for the biomass feedstock. The thickness must be enough to give sufficient residence time for tars that escape the combustion zone to be cracked by the charcoal bed. For designs tailored appropriately to the woody feedstock, the tar level in the producer gas is reportedly ~5 mg/Nm³ before gas clean-up [Anonymous, 1998], so that no further tar removal is needed. The primary function of subsequent water scrubbing and filtration gas clean-up steps is gas cooling and particulate removal [DeLaquil, 1998].

An alternative Indian downdraft gasifier (open top or stratified type) cracks tars thermally with long gasifier residence times. This "thermal" tar cracking has led to measured tar levels of about 100 mg/Nm³ at the gasifier outlet and 20 ± 10 mg/Nm³ after cleaning that involves water scrubbing and sand-bed filtration [Mukunda et al., 1994]. Discharging the tar-laden cleaning water to the environment could pose significant water pollution problems, since the tars contain phenols and other toxic substances. However, the tar-contaminated water can be cleaned using the charcoal by-product of the gasifier (which has a strong affinity for tars), so that the cleaning water can be recirculated along with make-up water as needed.

Low bulk-density crop residues cannot be used in the Imbert-type gasifiers that crack tars catalytically using charcoal: residues will not flow through the throat constriction and the required high temperatures cannot be realized. Open top (stratified) gasifiers are needed instead, and even for these, tar levels in the gas exiting the gasifier can be much higher (~1 g/Nm³) than for wood chips – because the low bulk density limits the temperatures that can be maintained.

One Indian open-top gasifier suitable for use with crop residues uses a water scrubber plus a sawdust filter for tar removal. The charcoal by-product of gasification is used to clean the tars out of the water; the tar-laden charcoal has a good heat value and can be pressed into briquettes that might be used for boiler fuel or other suitable purposes. The tar-laden sawdust in the filter has to be

replaced every 100 hours or so but can be returned to the gasifier as a supplement to the crop residue feedstock. For this gasifier, the tar level in the cleaned gas is 10-15 mg/Nm³ [DeLaquil, 2000].

4. Reciprocating internal combustion engines

The only prime mover commercially available for power generation from producer gas is the reciprocating ICE. ICEs for stationary power applications are mechanically similar to their automotive counterparts but must be designed to last significantly longer. Though a widely used technology, the ICE is mechanically complicated, having many moving parts (e.g., pistons, valves, belts, pumps).

When operating reciprocating ICEs on producer gas, the gas must be relatively free of tars and particulates (see Section 3). Also, maintaining a clean lubricating oil supply is critical to the realization of adequate performance and system life; this requires having a lubricating oil tank, distribution system, filter, and pump, as well as a satisfactory scheme for disposing of dirty oil. A water cooling system is also often needed to keep the engine from being overheated and damaged. In addition, attention must be given to supplementary fuel requirements and power output derating.

The most common commercial units use diesel engines in which the primary producer gas fuel is supplemented by diesel "pilot oil" for ignition purposes.^[6] Producer gas can typically displace about 70% of the engine's normal diesel fuel consumption.

The maximum output of a reciprocating ICE will be lower with producer gas fueling than its rating with a conventional liquid fossil fuel. Derating arises because the ICE burns one fixed volume of fuel-air mixture at a time, and the energy content of a stoichiometric fuel-air mixture of producer gas is less than for liquid fossil fuels [Reed and Das, 1988]. Supplementing the gas with some diesel pilot oil partially alleviates this problem by enhancing the heating value of the fuel mixture relative to pure producer gas. Field units have shown maximum power output can decrease from 10 to 40%, depending on the amount of pilot oil used [Stassen, 1995].

Supplementary fossil fuel requirements can be avoided by using a spark-ignited engine, the firing of which does not require pilot oil. However, derating is higher for spark-ignited than for diesel engines – typically 50% [Stassen, 1995], due in part to the absence of a high energy-content pilot oil. Another drawback of industrial spark-ignited engines is that they are significantly more expensive than diesel engines, costing about twice as much for the same power output [McKeon, 1998]. Thus, despite the pilot oil savings benefit offered by the spark-ignited producer gas engine generator set, the overall electricity generation cost tends to be higher than for a diesel dual-fuel unit (see Table 2).

5. Microturbines

A new option for small-scale power generation is the "microturbine". Although there has been extensive military and aerospace experience with variants of the technology,

microturbines have only recently become available for commercial power generation. Capstone Turbine Corporation (www.capstoneturbine.com), which made the first commercial offering and sale in late 1998 with its 30-kW unit, now offers commercial units for CHP applications, for use with "sour" (H₂S-contaminated) natural gas, and in special packages for the oil and gas industry. Honeywell (formerly Allied Signal Power Systems) expects to ship in 2000 the first 2,000 to 3,000 of its 75-kW microturbines to small businesses [Golden, 2000]. Honeywell projects that its current production capacity of 10,000 units/year will be reached in 2001. Both Capstone and Honeywell have agreements with domestic and international distributors. Other microturbine companies in the US include NREC and Elliott. Also, a microturbine has been developed and demonstrated in Sweden for CHP by Vattenfall, the Swedish utility [Carnö et al., 1998], and the London-based Turbo Genset Company (www.turbogenset.com/home.html) has developed and offers a 45-kW microturbine genset.

A simple schematic of a microturbine is shown in Figure 1. Air from the atmosphere: (1) is compressed by a centrifugal compressor, (2) is heated in the recuperator by heat transfer from the expander exhaust, (3) is heated further as a result of fuel combustion in the combustor, (4) expands through the radial expander generating mechanical power that drives the compressor and generator, (5) flows through the recuperator to transfer heat to the compressor outlet stream, and (6) is ultimately exhausted to the atmosphere. The compressor, expander and generator core (permanent magnet) are all on the same shaft. The compressor's impeller and the expander's rotor (the rotating components) are each a single stage and consist of a single piece of metal. The blades of the expander are uncooled. Some microturbines have only one moving part (the shaft with attached components). Some that employ air bearings do not even require gear-boxes and lubricating oil. Such simplicity is in stark contrast to the complexity of the microturbine's more familiar multi-megawatt gas turbine cousins.

It is worthwhile to consider microturbines for producer gas applications for a number of reasons. Like SI reciprocating ICEs, microturbines do not require pilot oil. This and the absence of lubricating oil requirements for some designs make it possible to reduce to very low levels dependence on consumables produced in centralized facilities. Moreover, as is discussed below, derating for operation on producer gas would not be required if air and fuel are co-compressed. Expected benefits of design simplicity include few failure modes, low maintenance requirements, and low capital costs under mass production conditions. As a result of all these features, total electricity generation costs are expected to be significantly less than for power generation based on reciprocating ICEs (see Table 2).

A California-based company (FlexEnergy), with support from the US Department of Energy and State of California, is working to modify and demonstrate microturbine technology for biomass-derived producer-gas

Table 2. Electricity cost with alternative engines: diesel and crop-residue-derived producer gas options^[1]

System type	Diesel engine		Spark-ignition engine	Micro-turbine
	Diesel only	Dual-fuel ^[2]		
Engine-generator set				
Equipment lifetime ^[3] (years)	6	6	6	10
Rated power output (kW)	80	100	160	80
Derated power output ^[4] (kW)	80	80	80	80
Thermal efficiency, LHV ^[5] (%)	34	27	21	28
Installed equipment cost (IEC) ^[6] (\$/kW _{rated})	181	181	362	350
IEC (\$/kW _{derated})	181	226	724	350
PV of IEC + costs of replacement units ^[7] (\$/kW _{derated})	330	413	1320	463
Total system (including building + gasifier + gas clean-up^[8])				
Total initial cost ^[9] (\$/kW _{derated})	243	680	1280	850
PV of initial cost + costs of replacement units ^[10] (\$/kW _{derated})	392	960	1970	1070
Operating costs				
Diesel fuel ^[11] (\$/hr at full power output)	5.48	1.65	0	0
Crop residues ^[12] (\$/hr at full power output)	0	0.39	0.66	0.50
Lubricating oil ^[13] (\$/hr at full power output)	0.21	0.42	0.42	0
Labor ^[14] (\$/hr during operation at full power output)	0.12	0.23	0.23	0.23
System maintenance ^[15] (\$/yr)	1500	2800	2800	3300
Levelized lifecycle electricity generation cost (¢/kWh)				
Total capital cost	0.92	2.26	4.63	2.51
Diesel fuel	6.85	2.06	0	0
Crop residues	0	0.49	0.83	0.62
Lubricating oil	0.26	0.53	0.53	0
Maintenance	0.34	0.62	0.62	0.73
Labor	0.16	0.33	0.33	0.33
Total (¢/kWh)	8.5	6.3	6.9	4.2

Notes

- All costs are in 1998 US dollars. All systems are designed for an electrical output capacity of 80 kW_e and operation at 65% average capacity factor, so that annual electricity generation is 456,000 kWh. Costs are calculated for a 12% real discount rate and a system lifetime of 20 years, so that the capital recovery factor is 0.134.
- "Dual fuel" refers to operation on producer gas plus pilot oil. It is assumed that producer gas displaces 70% of the diesel fuel required for standard operation on diesel fuel only.
- It is assumed that reciprocating internal combustion engines (ICEs) have 6-year (34,000 h) lifetimes. The 10-year (57,000 h) lifetime for the microturbine is an estimate by Honeywell.
- Compared with operation on diesel fuel, a diesel engine operated on producer gas + pilot oil is typically derated 20%; for spark-ignited engines operated on producer gas, a 50% derating relative to operation on gasoline is typical; it is expected that there will be no derating penalty for microturbines operated on producer gas using an air/fuel co-compression scheme [Henderick, 2000].
- The assumed efficiencies (producer gas to electricity) for ICEs converted to run on producer gas (21% and 27% for spark and diesel engines, respectively) are representative [Reed et al., 1988]. For the microturbine, 28% is representative of Honeywell's 75 kW_e model (their target is 30%). The overall conversion efficiency (crop residues to electricity) is obtained by multiplying these efficiencies by the 70% gasifier efficiency.
- The installed equipment cost (IEC) for the diesel engine is from Mukunda et al. [1993]. The spark-ignition engine is assumed to be an industrial gas engine, for which the IEC is typically twice that of a diesel [McKeon, 1998]. Honeywell product literature (1998) estimates the year 2003 IEC at \$350-450/kW_e for its 75 kW microturbine.
- The present value (PV) of the lifecycle capital investment includes the IEC plus future replacements during the 20-year lifecycle, less equipment salvage value.
- Based on Mukunda et al. [1993], capital costs for gasification and gas clean-up are assumed to be \$1,160 for the gasifier, \$8,700 for the cooling and cleaning system, \$11,600 for a control system, and \$5,800 for a building (\$1,740 if diesel only). For the microturbine, an additional fine filtration cleaning unit costing \$20/kW is assumed.
- The total installed cost includes a 20% increment over the IEC to allow for engineering and contingencies.
- Over the 20-year lifecycle, the gasifier is replaced three times (6-year life), and the clean-up and control systems are replaced once (10-year life), while the building requires no replacement [Mukunda et al., 1993].
- The diesel fuel price is assumed to be \$0.25/liter.
- For rural Jilin province in China, the cost of gathering corn stalks from the field and delivering them to the "trigeneration" facility modeled here is estimated to be 45 yuan RMB/t (\$0.33/GJ), based on data for the province in Cao et al. [1998].
- On the basis of Mukunda et al. [1993] lubricating oil requirements are assumed to be 1.36 g/kWh for dual-fuel engines; for spark-ignition engines the same value is assumed, and half this rate is assumed for conventional diesel engines; microturbines require no lubricating oil. Also, on the basis of Mukunda et al. [1993] the lubricating oil cost is assumed to be \$3.5/l (\$3.87/kg).
- On the basis of Mukunda et al. [1993] for rural India, during the 65% of the time the engine is assumed to be operating at full output, labor costs are \$0.23/hr (4 rupees/hr) for 2 workers for dual-fuel systems – assumed to be the same for spark-ignition engines and microturbines. Labor costs at half this rate are assumed for conventional diesel engines. In addition, it is assumed that these labor costs rates are applicable for 14 hours a week during downtime, for maintenance, preparation, etc.
- On the basis of Mukunda et al. [1993] annual maintenance costs are estimated as fixed percentages of installed building and equipment costs (not including engineering and contingencies) for the diesel, dual-fuel, and microturbine cases. The assumed percentage for diesel and dual-fuel engines is 10%; that for microturbines is assumed to be 8%. The assumed percentage for the building, gasifier, and gas clean-up is 5%; for the control system the assumed percentage is 2%. It is assumed that the maintenance costs for the spark-ignition engine case are the same as for the dual-fuel engine case.

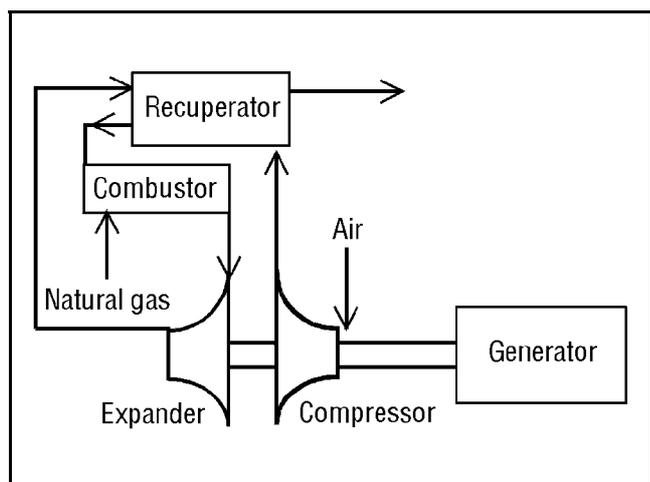


Figure 1. Recuperated microturbine fueled with natural gas

Table 3. Crop residue resources and utilization in Jilin province

Village use	Million tonnes	Tonnes per household ^[1]
Fuel (cooking + heating)	20.9	6.0
Fodder	6.8	1.9
Fertilizer	3.3	0.9
Surplus	1.7	0.5
Processing	0.4	0.1
Total exploitable crop residues	33.2	9.5

Source: Cao et al. [1998].

Note

1. There are 3.5 million households in rural Jilin province.

applications. The modifications will include using the compressor to compress a premixed combination of producer gas and air (to avoid the expense and energy penalties of a separate fuel gas compressor) and providing a catalytic combustor (because of the low heating value of the fuel gas/air mixture). With such modifications it is expected that there would be no power derating compared with operation on high-energy-density fossil fuels [Prabhu and Tiangco, 1999], the prospects for which have been confirmed by independent modeling [Henderick, 2000]. A feasibility study of the concept carried out for the Electric Power Research Institute (EPRI) was completed in early 1998 under the guidance of an Advisory Board made up of EPRI and other industrial experts. This report, along with the results of successful autoignition tests on the air/fuel gas mixture, led the Advisory Board to conclude unanimously that there was a high probability that the planned demonstration project would be able to meet its goals. The technology – called the “Flex-Microturbine” – is expected to undergo proof-of-concept testing to demonstrate operation on producer gas derived from coal and biomass some time in 2001. The technology could be offered commercially before 2005 if demonstration efforts are successful.

Producer gas quality issues for microturbines are simi-

lar to but not exactly the same as for reciprocating ICEs. If the tar level is low enough for reciprocating ICE engines (see Section 3), it will probably be low enough for microturbines. The reason for this judgment is that in both cases gasifier product gases are cooled to ambient temperatures for cleaning. After gas clean-up, the producer gas is always exposed to increasingly high temperatures before it is burned in a microturbine, so that the potential for tar condensation is reduced. In contrast, for some diesel engines (e.g., turbocharged aftercooled diesels) there are swings in the gas temperature that can lead to tar condensation on some engine parts. Another gas-quality concern for microturbines is the alkali content of the gas and its potential for turbine blade damage. This could be a serious problem if the producer gas had to be cleaned while hot. But because the gas is cooled to ambient temperatures for clean-up, the alkalis will be fully condensed on particulates, which are then removed in fine filters. Fine filter operation should not be problematic if tars in the gas (which might clog the filters and necessitate their frequent changing) can be kept to low levels via the approaches discussed in Section 3. A final possible gas-quality concern relates to effects of contaminants in the gas on catalytic combustor performance. Sulfur, for example, is known to poison catalysts but fortunately is present only in small amounts in biomass relative to coal; moreover, to the extent that there might be sulfur in the raw producer gas, its presence has been shown to be largely removable by recirculated scrubber water [Sharan et al., 1997]. In summary, it does not appear that gas-quality concerns will inhibit the adaptation of microturbines to operation on biomass-derived producer gas, although field experience is needed to confirm this judgment.

6. Residue supplies and village energy demands in Jilin province

Jilin, one of the largest grain-producing provinces in China (with corn the principal crop), produces large quantities of corn stalks and other crop residues. In 1996, Jilin generated 41.5 Mt of such residues, 33.2 Mt of which are considered recoverable for various applications [Cao et al., 1998]. At present about half of the residues generated are used for cooking and heating (see Table 3).

Because the proposed trigeneration system would meet both of these needs, a strategy that would gasify such residues for trigeneration applications should be acceptable. Here it is assumed that the residues traditionally used for cooking and heating as well as surplus residues are available for conversion.

The trigeneration system is sized to satisfy all cooking and heating needs. The point of departure for determining the appropriate system capacity therefore is understanding energy demand levels for cooking and heating. Energy demand levels in relation to the corresponding inputs of crop residues needed to satisfy cooking and heating needs via the burning of either crop residues or producer gas derived from crop residues are indicated in Table 1. Analysts at the Jilin Province Energy Research Institute estimate that when residues are used directly, each

four-person household (HH) consumes 4-5 kg of residues per day for cooking and 15-20 kg per day in the winter for both cooking and heating [Larson, 1998a]. If instead demands were met with residue-derived producer gas, some 30 MJ (6 Nm³) for cooking and 100 MJ (20 Nm³) for cooking plus heating in winter and somewhat more than half as much residue inputs would be adequate to support the same useful energy demand levels [Cao et al., 1998].

There is enough experience to be confident that 6Nm³ per day is a reasonable estimate of the gas required for cooking with producer gas^[7]. The demand estimate is more uncertain for heating with producer gas, as there has been very little experience with so providing space heating needs. Preliminary experiments are being conducted in Jilin with three simple heating technologies [Jia, 1999], but little is yet known about how a family would use gas for heating in practice. Important considerations that should be taken into account in heat demand estimation are prospects for and potential impacts on energy demand of introducing in homes heat-saving technologies such as adding insulation to walls and ceilings and double-paned windows^[8]. In the present study, it is assumed that average HH heat demand over the five-month heating season is 100 MJ per day (15 GJ per year) or 1.2 kW of thermal power transferred to the home – i.e., heat equivalent to the chemical enthalpy in the 20 Nm³ per day estimated for cooking plus heating.

According to Jilin Province Energy Research Institute analysts, average HH electricity consumption is 0.6 kWh per day. Put into more familiar terms, this is equivalent to 100W for 6 hours. Total village power needs per HH are about double this rate during the spring (irrigation) and fall (crop processing). Therefore, it is assumed here that during these times of agricultural activity, the total village consumption rate is 1.2 kWh/day/HH. Of course over the lifetime of the trigeneration system it is very likely that electricity consumption rates would rise substantially as incomes rise. However, as will be shown, the trigeneration system could easily accommodate prospective electricity demand growth.

7. Trigeneration plant configuration

Here a detailed design is presented for a producer gas-fired, microturbine-based trigeneration system for a prototypical 100-HH Jilin village (4.1 persons/HH, on average) that would use all crop residues potentially available for energy (6.5 tonnes/HH/yr – see Table 3). The system would convert residues into producer gas that would be used to provide all village requirements for cooking fuel, heat, and electricity. Electricity produced in excess of village demand would be sold to the electricity grid (see Figure 2a).

Residues would be gathered from fields and stored near the conversion facility. When needed, residues would be chopped to the appropriate size and gasified in a down-draft gasifier (producing 400 Nm³/hr). The producer gas generated would be cleaned and subsequently fed to a gas holder (250 Nm³ capacity) that maintains a constant gas

pressure^[9]. The gas would be available for both the cooking gas distribution system and the microturbine CHP system, as indicated in Figure 2a. Heat would be recovered from the microturbine exhaust in the form of hot water that would be piped to homes. As shown in Figure 2b, this system converts about 46% of the energy content of the residues into usable energy forms.

Meeting cooking gas needs requires 0.95t of stalks per HH annually, which leaves 5.5t/HH for CHP. It is assumed that the microturbine is sized to meet the average village winter heat demand (100×[1.2 kW/HH] = 120 kW). Because the estimated heat loss in piping hot water to homes is 20 kW (see Section 8), the required heat output rate is 140 kW, which implies that the appropriate microturbine capacity is 75 kW_e.

A 75 kW_e microturbine operated 16 hours each day would generate 1200 kWh of electricity, an order of magnitude more than the peak daily demand of the village, so that most of the produced electricity would be available in the near term for sale to the electricity grid and over the long term for support of future village industrial activity that might be developed.

Selling the excess power to the electricity grid is technically feasible at present in Jilin, because all villages in the Jilin corn belt are already grid-connected [Larson, 1998a]. Although power provided to Chinese villages is apparently not adequate or reliable [Sun et al., 1998], being grid-connected is very desirable because it would make it feasible for these small-scale residue-fueled power plants to be operated as baseload units to the extent that residues are available. Generating capacity utilization could be improved and total electricity generating costs per kWh could be reduced thereby to levels far below what would be feasible if only local electricity demand could be served by these power-generating units.

Sizing the microturbine to meet the average winter heat demand implies that a means other than operating the microturbine at its design point is needed to meet the peak heat demand during the coldest days of the winter. It would not be desirable instead to size the microturbine to meet the peak heat demand with the microturbine operated at its design point, because doing so would reduce the system capacity factor (because the total residue supply is fixed) and thereby increase the electricity generating cost per kWh. How best might the peak heat demand be met?

One attractive possibility for meeting above-average heat demand at extraordinarily low incremental capital cost would be to employ a microturbine with recuperator by-pass capability, which would make it possible for the microturbine to meet the peak demand via operation during the dead of winter in an off-design mode. With an appropriate by-pass valve, the turbine exhaust could be partially re-directed outside the recuperator and then mixed back with the exhaust stream at the recuperator outlet to raise the temperature of the turbine exhaust. This would cause the microturbine to operate at lower electrical efficiency but would make it possible to put more thermal energy into the DH system during peak heat demand

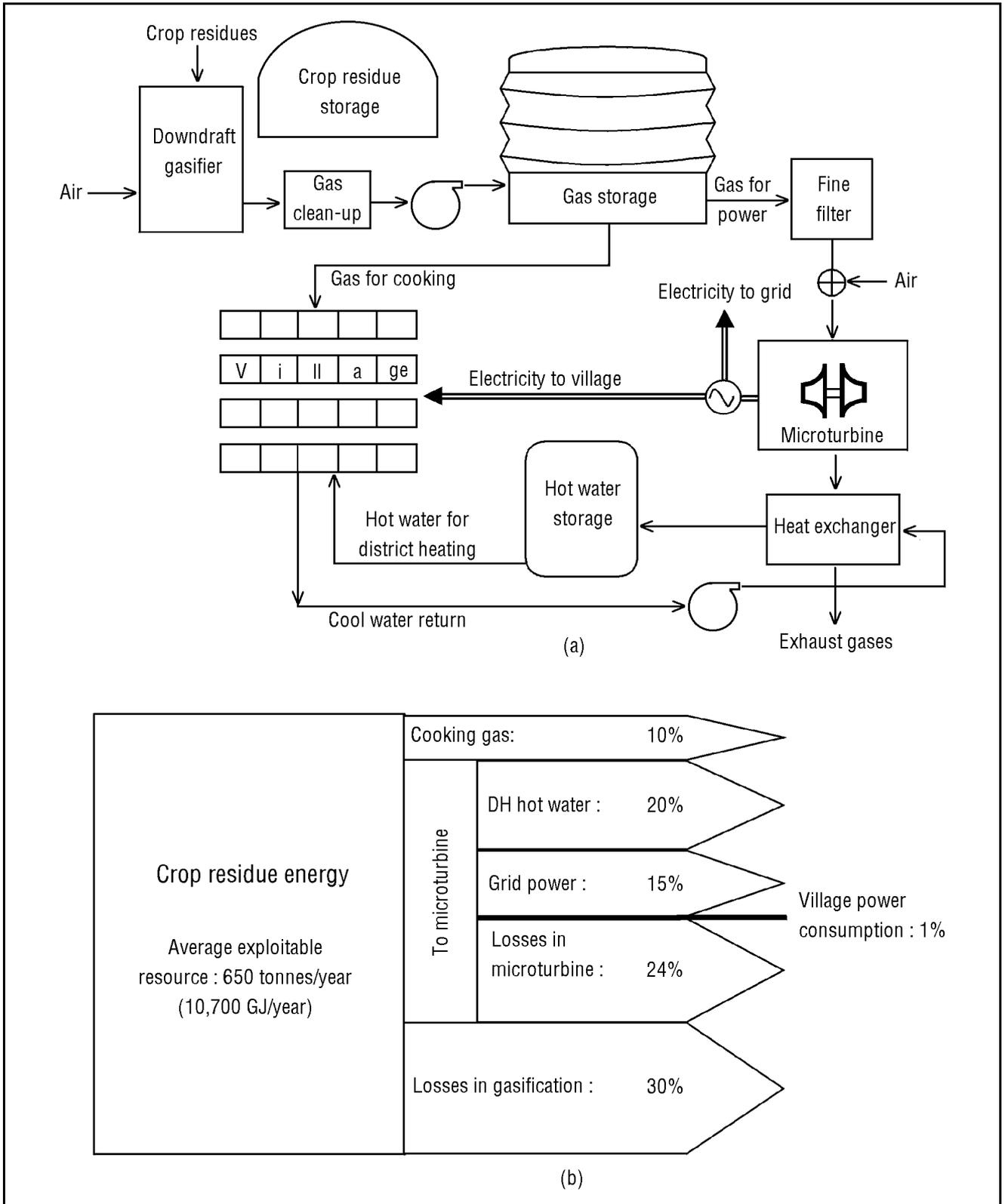


Figure 2(a). Trigeneration system and (b). Energy conversion flowchart

periods without requiring additional equipment, such as an auxiliary water heater (although an auxiliary heater might still be desirable as a back-up).

To see how this might work, consider that the demand for heat in excess of the microturbine's capacity at design point operation is about 250 GJ per heating season – mainly in December and January and to a lesser extent in

February [Henderick, 2000]. Using the flowsheet simulator ASPEN Plus, the effect of partial recuperator by-pass has been simulated by decreasing the effectiveness of the recuperator [Henderick, 2000]. When the effectiveness is reduced from its nominal 86% to 73%, the turbine exhaust temperature increases from 250 to 309°C, which leads to the production of an additional 50 kW of thermal energy.

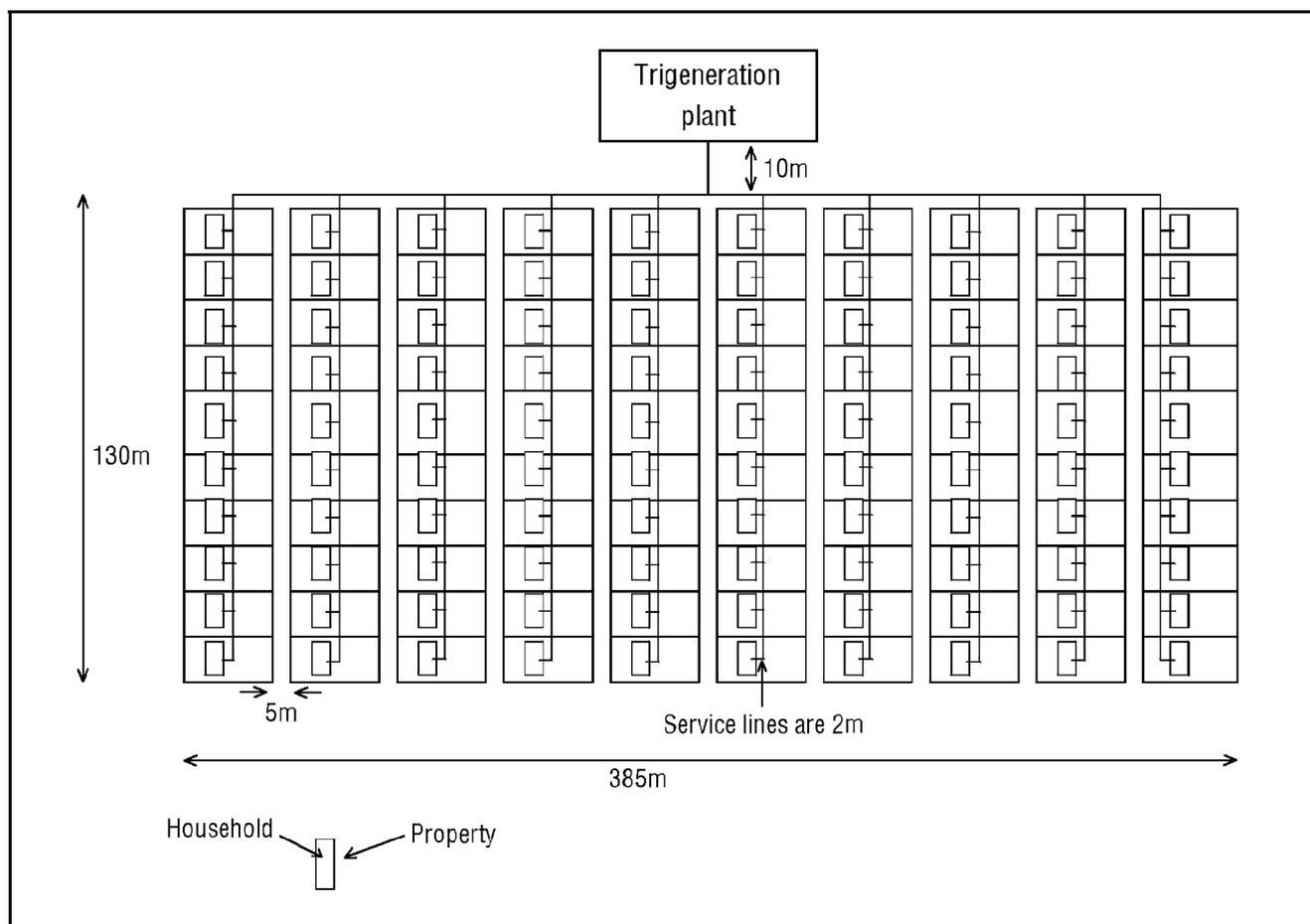


Figure 3. District heating piping system for the 100-household village

When the microturbine is operated in the by-pass mode, more fuel must be burned to realize the same turbine inlet temperature, so that the electrical efficiency of the microturbine drops from 28% to 24%. Here it is assumed that the microturbine is operated in partial by-pass for 2.5 months continuously, when the additional heat provided would be:

$$50 \text{ kW} \times (2.5\text{mo/yr}) \times (30\text{d/mo}) \times (24\text{hr/d}) \times (3600\text{s/hr}) \times (10^{-6}\text{GJ/kJ}) = 324 \text{ GJ/yr,}$$

which is well above the needed 250 GJ/year. These operating conditions are assumed to allow for losses in distribution and possible variation in performance of heat exchange equipment when the system is operated under off-design conditions.

8. The district heating system

Figure 2 shows how DH fits into the system. Hot water at 85°C is produced via gas-to-liquid heat exchange from the turbine exhaust. Water pumped through the heat exchanger subsequently enters a small storage tank that serves as a buffer. Hot water is distributed via insulated pipes to homes where radiators extract, on average, 1.2 kW of thermal power per home. The heat-depleted water leaves homes at about 50°C and is returned to the central conversion unit in separate pipes.

The most capital-intensive part of a DH system is piping (materials plus installation), reflecting the inherent high cost of transporting low-quality heat over long dis-

tances. Although DH costs can be prohibitively high for large CHP plants, the problem is more manageable for microturbines, which can be located near users. Also, Jilin villages tend to be dense and orderly, further reducing DH costs.

The amount of piping required for a 100-household village was estimated for the model village layout^[10] shown in Figure 3. (Each line in the figure represents a supply pipe and a return pipe laid side by side.) Two general pipe categories are trunk lines and service lines: the latter connect the former to homes. There are numerous ways that pipes could be laid out and perform the same function. Here it is assumed that trunk lines are placed close to the homes so that service lines are short – a relatively low-cost configuration, for which a total of about 200m of service lines and 1590m of trunk lines is required.

Pipe diameters, which depend on the flow rate to be accommodated, strongly influence cost. One good method for estimating pipe diameter 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) is more than adequate; using Moody's pipe flow friction factor chart, this diameter with a flow of 0.01 kg/s^[11] yields a pressure drop of 8 Pa/m. Trunk lines must be larger, up to 5cm, to handle the full 1 kg/s flow; however, most of the trunk lines will be smaller than this maximum; for average cost estimation purposes, a 2.54-cm (1-inch)

Table 4. Alternative DH system scenarios

	Base case	High-cost case	Low-cost case
Capital costs for DH systems (1998 \$)			
Piping ^[1] (installed)	52,500	105,000	26,300
Heat recovery unit for microturbine ^[2]	3,900	7,800	3,900
Hot water storage tank ^[3]	1,350	2,700	1,350
Distribution pump ^[3]	150	300	150
In-home equipment ^[4]	5,200	9,200	5,200
Installation ^[5] (not including piping)	970	1,740	970
IEC for DH system	64,070	126,740	37,870
Total initial cost for DH system ^[6]	76,900	152,000	45,500
Total initial cost for trigeneration system	182,000	258,000	151,000
Equity component ^[7]	123,00	146,000	118,000
Debt component ^[8]	59,000	112,000	33,000
Internal rate of return (%/yr)	9.6	0.0	13.5
Average net cash flow to village corporation or IPP ^[9] (\$/yr)	13,900	7,800	16,800
Villagers' income, village corporation scenario ^[10] (\$/yr)	17,400	11,300	20,300
Villagers' expenditure on energy ^[11] (\$/yr)	17,200	17,200	17,200

Notes

1. See Section 8.
2. The heat recovery unit is an air-to-water heat exchanger. Unifin International, a heat transfer equipment manufacturer, designs heat recovery units for microturbines at capacities between 28 and 150 kW_e. The heat exchanger is expected to cost the end-user about \$7,800 [Scott, 1999].
3. Water storage tank and pump estimates from Trigen Corporation [Larson, 1998c].
4. In-home equipment includes a hot water radiator (assumed to cost \$80, for a 1.5 kW unit [Lorenz, 1996]) and a water meter (assumed to cost 100 yuan RMB or \$12, the same as the cost for a gas meter in the Tengzhai village gasification project [Dai and Lu, 1998]).
5. Installation of components aside from piping and in-home equipment is 2.5% of equipment cost, following experience with the Tengzhai village gasification system [Dai and Lu, 1998]. Since in-home equipment installation is likely to be more labor-intensive in its installation (one set for each household), the installation is assumed to be 16% of the equipment cost, the same as that documented for the piping component of the cost for the Tengzhai village gasification project.
6. IEC plus 20% for engineering and contingencies. Does not include future replacements.
7. Total initial cost less initial cost for piping of gas and hot water – the part of the total initial cost to be financed by equity investment.
8. The total initial cost for piping of gas and hot water – the part of the total initial cost to be financed by a government loan at 6% interest.
9. Average net cash flow to the corporation is the levelized value of the total annual revenues less the total operating costs (which include periodic replacement of equipment).
10. Average net cash flow to the corporation plus \$3500 from crop residue sales to the corporation.
11. Total annual expenditures on cooking gas, heat, and electricity in the village.

diameter is representative.

Capital cost estimates for the DH system (see Table 4) are dominated by piping costs, which include costs for pipe insulation and installation. Piping cost estimates are based on a DH piping cost model of Geller [1980], who developed a cost curve for materials plus installation as a function of inside pipe diameter appropriate for US conditions. The Geller model predicts one-way pipe costs of \$22/m and \$30/m (1998 \$) for 0.5-inch service lines and 1-inch trunk lines, respectively^[12]. As discussed in the next section, while these cost estimates are useful benchmarks, they are probably too high for DH piping in China.

The heat losses from the insulated water pipes in the DH system can be represented by:

$$Q = 2\pi L \times (T_f - T_g) \times F,$$

where L is the pipe length, T_f is the average water tem-

perature, T_g is the average ground (surface) temperature, and F is a function of geometrical factors and thermal conductivities of pipe walls, soil, and insulation. Because the piping costs estimated here are for the same materials and insulation levels as in the Geller model, the pipe heat losses for the Jilin village will be different from those estimated by Geller for US conditions. In Geller's model T_f = 73.3°C and T_g = 11.7°C for the supply pipes. More appropriate parameters for the present analysis are T_f = 84°C and T_g = - 7.4°C (the average outdoor temperature during the Jilin heating season). These adjustments lead to a heat loss rate that is a factor of (84+7.4)/(73.3-11.67) = 1.48 higher than that estimated by Geller for US conditions. This implies a total heat loss rate for the Jilin village of about 20 kW when return pipes as well as supply pipes are taken into account [Henderick, 2000]. Thus

Table 5. Trigeneration economic parameters

Project lifetime (yr)	20	Microturbine^[5] – 75 kW	
Interest rate for piping investment ^[1] (%/yr)	6	IEC (\$)	26,250
Crop residues consumed (tonnes/yr)	650	Total initial cost (\$)	31,500
		LHV efficiency (%)	28
Gasification station^[2]		System life (yr)	10
Installed equipment cost (IEC) (\$)	25,000	Maintenance (% of IEC/yr)	8
Total initial cost (\$)	30,000	Capacity factor (%)	72
System lifetime (yr)	6	Power generated (kWh/yr)	473,000
Maintenance (% of IEC/yr)	5		
Power requirements (kWh/yr)	9,000	Prices^[6] and revenues^[7]	
		Crop residue price (\$/GJ)	0.33
Gas distribution system^[3]		Cooking gas price (\$/GJ)	6
Pipeline investment (\$)	6,900	Revenue (\$/yr)	6,600
Storage tank investment (\$)	14,500	Heat price (\$/GJ)	5
Building investment (\$)	7,600	Revenue (\$/yr)	7,500
Other (including installation) (\$)	7,700	Price of electricity purchased in the village (\$/kWh)	0.096
IEC (\$)	36,700	Revenue (\$/yr)	3,200
Total initial cost (\$)	44,000	Price of electricity sold into the grid (\$/kWh)	0.05
Maintenance (% of IEC/yr)	2.4	Revenue (\$/yr)	22,000
Labor^[4]			
Salaries for workers (\$/yr)	4,300		
Management (\$/yr)	1,400		

Notes

1. For the low-interest government loan for financing the piping for gas and the DH system (see Section 9).
2. The IEC for a Chinese gasification station (gasifier, clean-up, plus balance of plant) with 400 m³/hr capacity is reported as \$12,000 [Dai and Lu, 1998]. A commercial, state-of-the-art, low-tar Indian system including a 100 kW_e diesel engine does not exceed \$600/kW_e in India [Larson, 1998b]; subtracting \$200/kW_e for the diesel engine, this gives an equipment cost of \$40,000. For the analysis here, an intermediate cost of \$25,000 is assumed. Lifetime and maintenance estimates are from Mukunda et al. [1993], and power requirements are estimated from data in Dai and Lu [1998]. The total initial cost is the IEC plus 20% for engineering and contingencies.
3. Gas distribution system costs are taken from estimates for a system planned for a 110-family village in Jilin performed by Cao et al. [1998]. The total initial cost is the IEC plus 20% for engineering and contingencies.
4. See Box B. For three 3-person shifts over a 5-month period and two shifts over a 7-month period in which weekends are covered, a total of 10 workers are required.
5. See Table 2 notes.
6. Cao et al. [1998] report that about 5t/ha/y of corn stalks are available for fuel, so that an area of 130 ha (1.3 km²) would be adequate for the systems being considered. Cao et al. [1998] estimate residue costs amounting to 30 Y/t for crop growth, a loading and unloading cost of 10 Y/t, and a transportation cost of 2 Y/t-km, corresponding to a total cost of 42 Y/t-km. The required growing area is contained within a circle of radius 0.64 km. Here a total cost of 45 Y/t (\$5.4/t or \$0.33/GJ) is assumed. See Section 9 for discussion of the prices assumed for energy products.
7. See Sections 6 and 9.

the microturbine heat output must be approximately 140 kW in order to deliver 120 kW of heat to the houses.

9. Economics of trigeneration

The economics of trigeneration are examined using an internal rate of return (IRR) analysis. Investment cost parameters for the DH sub-system are presented in Table 4; other relevant cost parameters are presented in Table 5.

The total capital investment required for the system is divided into two parts: a key enabling infrastructure component (the installed equipment cost [IEC] for gas and water piping) and the rest of the required capital. It is

assumed that the infrastructure component is financed by a low-interest (6%) government loan. The rationale for assuming that piping is financed by a low-interest loan is that: (1) this infrastructure is key to realization of the very substantial environmental and public health benefits that the trigeneration concept can provide, and (2) simple calculations show that the cost of the subsidy is likely to be less than the value of the public health/environmental benefits provided by the system (see Box 1)^[13].

Three alternative levels of capital cost are considered for the DH system (see Table 4). Alternative DH cost levels are considered because DH costs calculated for US

Box 1. Do the public health/environmental benefits of crop-residue trigeneration justify government assistance for enabling infrastructure development?

The gas and water pipelines for the trigeneration system represent costly infrastructure that enables substantial public health and environmental benefits: (1) the virtual elimination of indoor air pollution that would otherwise be associated with direct burning of biomass or coal for cooking and heating; (2) the elimination of outdoor air pollution that would otherwise result from burning crop residues in the field; and (3) reductions in outdoor air pollution that would otherwise be produced by coal-fired power displaced by crop-residue-based trigeneration power; (4) climate change mitigation benefits associated with providing electricity with zero net GHG emissions, since crop residues are a renewable resource.

It is beyond the scope of this study to estimate the full economic value of such benefits. However, as noted in Section 2, eliminating the adverse health impacts of indoor pollution (which could largely be accomplished with the proposed trigeneration system) would be worth \$10-\$11 billion/yr for rural China [Johnson, 1997], or \$12/yr per "average" citizen living in rural areas. If a Jilin village were "average" for China, the benefit of eliminating indoor air pollution for the 400-person village modeled here would thus be \$4800/yr. The total public health/environmental benefit could well be considerably higher.

The Chinese government might consider encouraging crop residue-based trigeneration technology by facilitating investment in the needed infrastructure, as a strategy both to capture such public benefits and as a mechanism to facilitate enforcement of the government's ban on field burning of crop residues.

The gas and water pipelines for the trigeneration system require an initial investment of \$33,000, \$59,000, or \$112,000, for the low-cost, base case, and high-cost DH scenarios, respectively (see Table 4), accounting for 1/5 to 2/5 of the total initial required investment. If the government were to provide a subsidized loan at 6% for this investment as an alternative to a commercial loan at a 12% market rate of interest, the subsidy to villagers would be \$1500, \$2800, or \$5300 per year levelized over the 20-year project life, for these same scenarios. Since in all cases the subsidy is probably less than the public health/environmental benefits, the infrastructure-facilitating subsidy would seem to be justified.

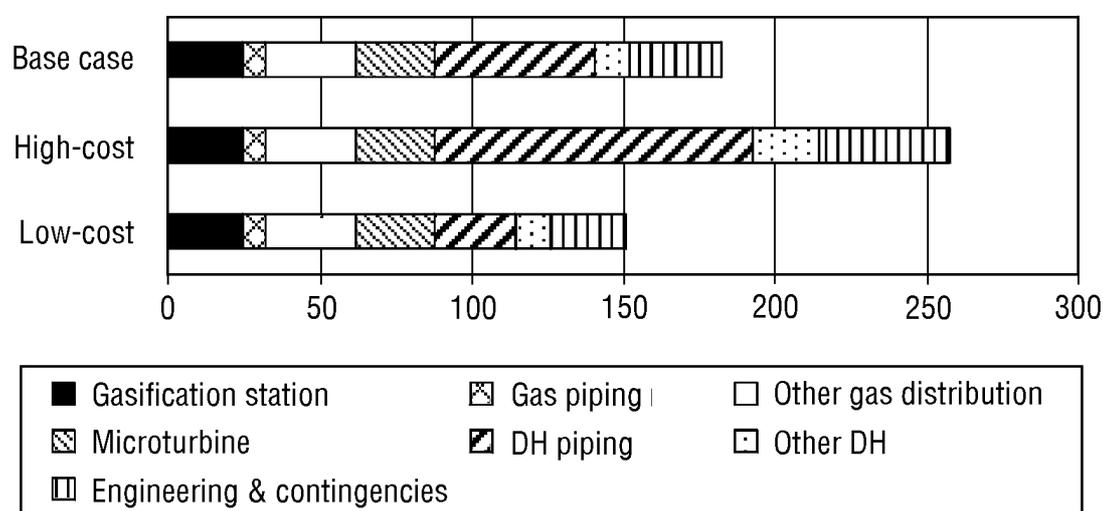


Figure 4. Total initial cost by component for the village trigeneration system (10^3 1998 \$)

conditions are high (accounting for more than two-fifths of the total trigeneration investment cost) but probably grossly exaggerate what DH costs would be in the Chinese context; therefore DH costs calculated for US conditions represent the high-cost case in the present analysis. Insights regarding the potential for lower DH costs in China can be gleaned from Yang [1995], who examined the potential for cost reduction if Chinese manufacture of components for a coal integrated gasification combined cycle (IGCC) power plant were maximized instead of simply

importing IGCC technology. Yang gathered highly disaggregated cost estimates for both a US coal IGCC plant and a Chinese coal steam-electric plant. Yang estimated potential cost savings for the IGCC plant on a component-by-component basis. He found that the less technologically sophisticated the component, the greater the potential cost reduction. For example, although he estimated a potential cost reduction of only 20% for an "electrical and control" sub-system, his estimated cost reduction for the "circulating water" sub-system was 87%!

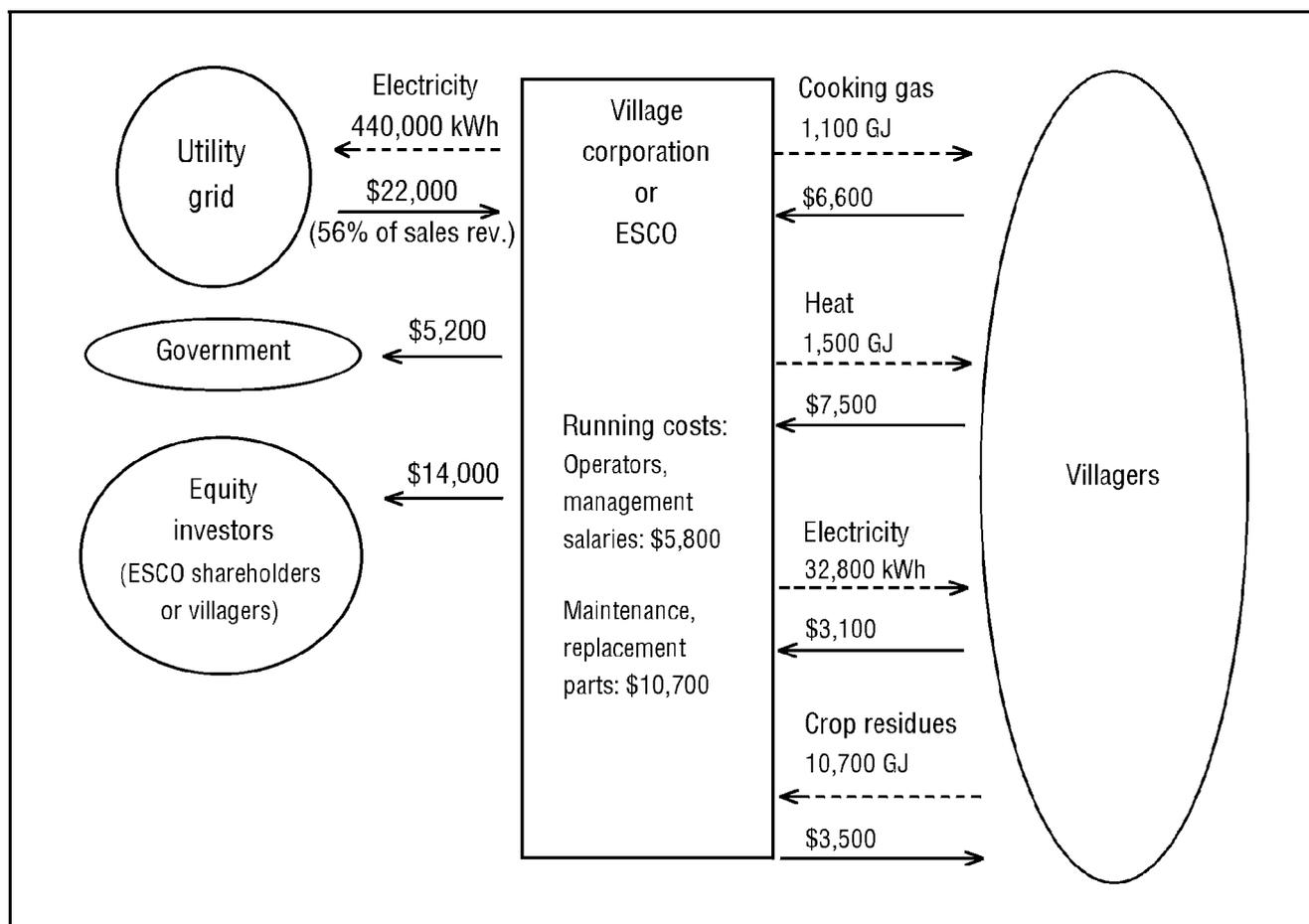


Figure 5. Annual energy and levelized cash flows for the trigeneration system (base case)

He estimated an average potential cost reduction of about 50% for an IGCC plant when maximum use is made of opportunities for Chinese manufacture.

Because all DH system components are technologically relatively unsophisticated, a cost reduction of at least 50% relative to the cost estimated for US conditions would be conservative for the Chinese situation.

Therefore a 50% cost reduction below the US-context estimates for DH system components is assumed for the base case. A low-cost case is also considered for which water piping costs are one-half of those for the base case but all other DH component costs are the same as for the base case; this case is motivated by Yang's findings for the coal IGCC plant that the "circulating water" subsystem would cost 87% less in China than in the US.

Initial capital requirements and their distribution by component for the three scenarios are summarized in Table 4 and Figure 4. For the base case, the total initial capital cost is \$182,000 or \$1,800/HH. For the high- and low-cost cases the required investments are \$2,600/HH and \$1,500/HH, respectively. It is assumed that the water and gas piping (accounting for one-third of the total initial cost in the base case) is financed by a 6%-interest loan from the government and that the rest of the required investment is provided as equity capital by the corporation that owns and manages the trigeneration system.

For this system, villagers sell their residues to this corporation for \$0.33/GJ (see Note 6, Table 5) and purchase

cooking fuel, heat in the form of hot water, and electricity from the corporation. Electricity produced in excess of village needs is sold to the electricity grid. Prices for energy products of the system are key determinants of the internal rate of return on investment. The assumed cooking gas price is \$6/GJ, somewhat less than the LPG price in rural areas, to provide an incentive for villagers to purchase producer gas instead of LPG. The assumed \$5/GJ price for heat from the DH system is somewhat less than for gas, to discourage burning extra producer gas in stoves for heating. The price at which villagers purchase electricity is assumed to be 0.8 Y/kWh (\$0.096/kWh) [Larson, 1998a], the price they would otherwise pay for grid electricity^[14]. The price for electricity sold to the grid is set sufficiently low (\$0.05/kWh [about 0.4 Y/kWh]) to persuade the grid operator to buy it. Figure 5 shows annual energy and revenue flows for the assumed prices and village energy consumption rates.

The internal rate of return on investment is 9.6%, 0%, and 13.5%, for the base case, high-cost case, and low-cost case, respectively (see Table 4). Except for the high-cost case, these are attractive returns.

Trigeneration economics might be improved if the system were to serve new demands for hot water that the DH system makes possible. In the present analysis it is assumed that hot water is used only during the 5-month heating season but in fact could be used throughout the year at near-zero incremental cost on the production side

– e.g., for providing daily hot showers. For example, providing domestic hot water at the average rate for US single-family HHs (-0.19 kW/capita [Ritschard et al., 1992]) would create an “off-season” hot water demand in the village two-thirds as great as the heating season demand for hot water.

It is helpful to think about the meaning of the prospective economics in the context of two alternative business arrangements for owning and managing the corporation: (1) a “village corporation” and (2) an independent energy service company (ESCO).

Consideration of investment requirements in relation to the savings rate suggests that the village corporation concept is plausible. Average 1998 net per capita income in rural Jilin was 2384Y, which exceeded per capita living expenditures by 912Y, corresponding to a 38% savings rate [NBS, 1999]^[15]. Thus the total equity capital investment required for the base case (\$123,000 [see Table 4] or 1.02 million Y) corresponds to less than 3 years of savings for the village at the 1998 savings rate for rural Jilin province. Under the village corporation scenario, the income to the villagers associated with the trigeneration project would be the sum of the average net cash flow to the corporation plus the income villagers would earn from selling residues to the corporation. As shown in Table 4, this income would be approximately the same as total expenditures on clean energy in the base case. In other words, in exchange for less than three years of savings, villagers would get “free clean energy” for the 20-year life of the project. For the high-cost case, income would cover two-thirds of energy expenses, and for the low-cost case, income would be about one and a quarter times energy expenses.

An alternative to the village corporation would be for an ESCO to provide the needed equity capital and be responsible for providing trigeneration services to the village. The ESCO option might make providing the required levels of technical and managerial expertise easier. Experienced engineering firms from urban China might, for instance, be interested in becoming ESCOs for rural China. Such firms might seek to serve a number of villages in a region at the same time, thereby facilitating the development of an efficient maintenance infrastructure. This option would allow villagers to avoid having to make large initial equity outlays, although corporate profits would not flow to the villagers, and therefore they would have to pay more for the energy services provided. For the base case, expenditure on energy less income earned from selling crop residues to the ESCO would amount to 12% of HH income at average income levels for rural Jilin in 1998. Although the ESCO option, in contrast to the village corporation option, would not channel economic resources from urban to rural areas, it nevertheless might be a useful option to consider, especially in the early stages of the evolution of the trigeneration concept.

10. Social and cultural issues

Successful deployment of a new technology such as the trigeneration system proposed here must be not only tech-

nically sound and economically attractive, but also it must be acceptable both socially and culturally. In short, the new technology has to be desirable to those who would use it, and its attractions have to be far greater than its drawbacks, in order to justify disrupting the status quo by its adoption.

There has been some preliminary work in this area for China. Analysts at the Energy Research Institute of the Shandong Academy of Sciences conducted a socioeconomic study of the social implications of the village-scale crop residue gasification demonstration project for providing cooking gas to Tengzhai village in Huantai county in Shandong province, which went into operation in May 1996 [Dai, Liu, and Lu, 1998]. They found that with the producer-gas cooking system, cooking time for housewives was reduced from 3 to 1.5 hours per day. In a survey of 30 randomly selected households (out of 216 in the village) the researchers found that this technology was regarded as being as good as or better than coal or LPG (the major technologies displaced) with regard to price, convenience, reliability of supply, environmental impact, and working intensity of housewives (all the issues investigated in the survey) by 97.5% or more of all households surveyed for each issue. Moreover, because all households in the sample thought it was a good idea to go the next step and build a straw-gas-fired power plant with the surplus straw, the analysts made the recommendation “to build a pilot project of gas-fired power generation at proper place and time”.

To the authors’ knowledge, public attitudes toward DH have not been much explored for villages, although for most of the major cities of northern China DH systems are already in place, under construction, or being planned, as part of a national policy to discourage direct use of coal for heating buildings and to mitigate the associated pollution problems^[16]. Issues that might arise are that: (1) villagers accustomed to sleeping on warm, *kang*-heated beds might be reluctant to shift to a new space heating system based on hot water circulation and radiators, and (2) some might be reluctant to accept the reduced level of control over meeting their energy needs associated with a centralized DH system. These do not seem to be insuperable concerns, however, and might well be more than offset by the prospect of lifestyle improvement such as the option of having hot showers every day.

Equity considerations are also important. How would the poorest households fare under a trigeneration scheme? Could they afford to pay for the clean energy carriers provided? Once crop residues acquire a market value, would the poor farmers’ access to residues they have used for cooking and heating be jeopardized? If a village corporation were formed, the poorest households might not be able to participate as investors and thus would not be able to enjoy the “average HH” benefits described in Section 9. Despite such concerns there appear to be plausible strategies under which even the poorest HHs could enjoy the full modern energy benefits offered by the trigeneration concept. These strategies are associated with the fact that *crop-residue-based energy systems provide an*

Box 2. The cost of labor

The labor price is a key parameter in determining the economic viability of this technology. For a 159 kW rice hull gasification plant discussed in Cao et al. [1998] a worker is paid 200 yuan (\$24) per month (\$1 = 8.3 Y), while management plus some fees totaled 12,910 Y (\$1,560) annually. Cao et al. [1998] also discuss a planned corn-stalk gasification and distribution system for a 110-household village, for which two workers are employed, each paid 300 Y/mo. A residue gasification and distribution pilot plant at Tengzhai village, Shandong province, employs two workers, each earning 330 Y/mo [Dai and Lu, 1998].

Here it is assumed that a worker's salary is 300 Y/mo, and that 12,000 Y/yr is needed for corporate management (overseeing plant operation, scheduling maintenance, and keeping records). It is assumed that three shifts are needed during the five-month heating season, but only two shifts are needed during the rest of the year. Because the trigeneration system would be more complex than the gasification/distribution systems considered above, it is assumed that three workers are employed per shift. The total annual cost of workers is therefore 36,500 Y (\$4,400), which includes salaries for weekend workers.

Charging the total annual labor cost (including management) of 48,500 Y (\$5,800) against only power generation yields \$0.01/kWh. In contrast, if the same technology were deployed in the US, where the price of labor might be \$15 per hour, the labor cost for this system (excluding management) with only one worker per shift would amount to a prohibitively high \$0.28/kWh. This simple calculation shows that this small-scale technology will have very limited market opportunities in industrialized countries.

opportunity for the poor to have their labor monetized for gathering residues from the fields and delivering them to the trigeneration plant for processing – an opportunity that does not exist for fossil energy systems. Today, crop residues are being burned in the field because the richer farmers are reluctant to gather them and use them directly for heating and cooking. With a trigeneration system in place, poor households could provide the service of removing crop residues from the fields of rich households, thereby helping them comply with the ban on field-burning of residues. To cover 100% of an average HH's energy costs under the trigeneration scheme, a poor farmer would have to gather and sell the equivalent of 4.6 average HHs' available residues.

Not only does the village corporation concept have to be financially viable, but also there has to be within the village the administrative capacity for carrying out the energy system's operation, maintenance, and accounting tasks – which, at least initially, might be more challenging than if an experienced ESCO were to perform such functions. A village corporation might be evolved in the context of an existing village administrative body. A model from abroad that might be considered is administration via a village council, as was pursued for a village-scale biogas energy system in Pura village in India [Rajabapaiah et al., 1993]. In Pura, administrative functions are carried out by a “village development society” made up of villagers who lead traditional community activities. How such a body might organize itself and operate, of course, depends on the local culture.

11. Implications for China generally

Gasification of residues has a large potential for meeting energy/developmental needs with clean energy carriers in rural areas of China, partly because, as the present analysis has shown, costs are prospectively attractive, and the residues are available near the villages where some 860

million people live [Dai, Zhang, and Li, 1998]. In addition, the residue resource is huge: in 1995, the estimated total crop residue production was about 605 Mt, 355 Mt of which were available for energy purposes [Li et al., 1998]. If rural people live in 4-person HHs on average, each requiring 6 Nm³ of cooking gas per day, about 200 Mt/yr of residues would be adequate to meet the cooking needs of the entire rural population (0.95 t/HH/yr). If the remaining 150 Mt were used to generate electricity, some 135 TWh/yr could be produced using microturbines^[17] – equivalent to 15% of total thermal power generation (mostly from coal) in China in 1997 [NBS, 1999]^[18]. Moreover, for those parts of China where winters are severe, hot water could be provided for space heating via CHP and DH as a co-product with electricity, without having to burn extra fuel.

Assuming a 70% average capacity factor, the power generating capacity associated with surplus residues amounts to 22 GW_e, which is 20% greater than the capacity that is being planned for the Three Gorges hydroelectric power project. And whereas the electricity generated at Three Gorges will have to be transmitted long distances to most customers, this crop-residue-based electricity would be provided in about 300,000 units (assuming an average microturbine capacity of 75 kW_e) that would be located close to rural electric loads. Although initially most of the electricity generated this way might be exported to urban centers, in the longer term it could provide a basis for attracting industry to rural areas.

Such potential energy benefits complement the environmental/public health benefits offered by the trigeneration concept: virtual elimination of the indoor air pollution associated with cooking/heating with biomass or coal burned directly, elimination of the air pollution associated with field burning of crop residues, and the reduction in local and regional air pollution emissions and GHG emissions associated with displacing coal in power generation.

12. Policy issues

The most important policy issues relate to the need for: (1) strong environmental policies framed in ways that make technological strategies such as crop-residue-based trigeneration attractive options for meeting environmental objectives, (2) projects to demonstrate the technologies involved, (3) grid access for distributed generators, (4) strategies for “buying down” technology costs during the initial deployment period, and (5) strategies for overcoming the high transaction costs associated with small-scale energy technologies under widespread deployment conditions.

Environmental policies aimed at fully internalizing adverse environmental/health costs in energy prices are highly desirable for advancing inherently clean technologies. Where full internalization of costs is not politically practical (which is often the case), a second-best strategy would be for government to provide appropriate financial incentives for the inherently clean energy technologies – e.g., the government might provide low-interest loans for enabling infrastructure development (see Box 1).

Technological demonstration projects are needed to prove the viability of both residue gasification for power generation applications (because commercial producer gas technologies for power applications are based largely on wood rather than crop residues – see Section 3), and operation of microturbines on producer gas (see Section 5). These activities might proceed in parallel – demonstrating crop-residue gasification with commercially available dual-fuel diesel engine generator sets, as is currently being planned under a UNDP-sponsored project in China^[19], at the same time microturbine technology is being demonstrated on producer gas. Although efforts to demonstrate microturbine technology on producer gas are being made in the US (see Section 5), demonstrations are also needed in China and other developing countries, because there will be few applications of this labor-intensive technology in industrialized countries (see Box 2). New mechanisms are needed for carrying out such demonstrations in an international context, whereby both multilateral and bilateral financial resources can be readily channeled to such projects. One proposed mechanism is the creation under the auspices of the Global Environment Facility of a demonstration support facility that would provide a framework for such demonstration projects organized by international industrial joint ventures – industrial collaborations that offer considerable promise as agents of technology transfer and technological innovation relating to sustainable energy strategies [PCAST, 1999].

Policies that make it possible for small-scale generators to sell electricity to the electricity grid at competitive rates are also needed to make the technology economically viable. The requirement of grid access is key to commercial success not only for small-scale biopower technologies but also for a wide range of other new technologies that offer the potential for providing electricity in much cleaner and often more energy-efficient ways than is fea-

sible with conventional central-station power systems [PCAST, 1999]. The on-going world trend toward market liberalization and competition in electricity generation will be helpful in this regard [PCAST, 1999].

Such grid access policies would only be helpful once the biopower technologies are fully established in the market. Consideration also has to be given to the fact that when any new technology is first introduced, its cost will tend to be higher than for the established technology it would replace, until a sufficient number of the new plants has been built to “buy down the cost” of the new technology along its learning curve to prospective market-clearing price levels [PCAST, 1999]. One mechanism for doing this in a competitive electricity market would be to require each electricity provider to include in its portfolio of electricity supplies a small but growing fraction provided by biopower or other renewable energy supplies during a transitional period as the new renewable energy industries are being launched in the market. Power generators could either produce this renewable electricity themselves or purchase renewable energy credits that are sold in a credit trading market. Experiments with this mechanism are being conducted in various US states (where it is called a Renewable Portfolio Standard) and in Europe (where it is called Green Certificate Markets). The concept has not yet been adopted in developing countries, but in January 2000 China’s State Development Planning Commission and the Energy Strategies and Technologies Working Group of the China Council for International Cooperation on Environment and Development convened and co-hosted a workshop in Beijing to discuss its potential application to China^[20]. At the time of this writing, the concept was being considered seriously in China as an option for assisting the commercialization of renewables.

A final consideration relates to the fact that transaction costs per project can often be prohibitively high for small-scale technologies unless ways can be found to spread these costs over a large number of projects. This might be accomplished, for example, if an ESCO were to have responsibility for a large number of trigeneration projects in a region. Alternatively, under the village corporation mode of organizing trigeneration projects, an ESCO might provide to a large number of village corporations both maintenance services and various other managerial services that village corporations might want to purchase. Mechanisms for so engaging ESCOs are needed that are consistent with on-going trends toward energy market liberalization. This might be achieved by means of, for example, concessions that are awarded by governments on a competitive basis for providing rural energy services. In a concession, the concessionaire is granted exclusive right to provide these energy services in exchange for the *obligation to serve* all customers in the region. Concessions offer the advantage of being able to greatly reduce transaction costs in serving large numbers of small customers compared with other mechanisms. Competitively awarded

rural energy concessions have recently been introduced in Argentina in conjunction with adoption of broad energy market reforms [Reddy et al., 1997].

13. Concluding remarks

Village-scale trigeneration based on gasification of crop residues and use of microturbines for CHP offers major promise in advancing multiple economic and environmental goals for rural development simultaneously. Not all the required technologies are on the market today but all could be in five years time or less. The main obstacles are institutional rather than technological. But even on the institutional front there are promising options for overcoming the challenges.

China has a major opportunity to become a world leader in crop-residue-based trigeneration technology because: (1) its residues are abundant, (2) severe rural indoor/outdoor air pollution has become a powerful driver for exploring technological innovations aimed at making better use of crop residues, (3) China has already taken the first steps to evolve the technologies needed for trigeneration, (4) the high level of electric grid access already available in rural areas makes it easier to achieve favorable economics for the technology more quickly in China than elsewhere. If the technology could become well established in Chinese markets over the next decade, China would become well-positioned to then export the technology to the many other developing countries that are blessed with abundant, low-cost crop residues. ■

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Notes

1. For instance, in cold northeastern provinces such as Jilin, the traditional method for home heating involves kang, large brick-lined furnaces built under the house. Crop residues such as corn stalks or alternative solid fuels are piled in and set to smolder through the winter months. Although products of combustion are vented outdoors, there are potential indoor air pollution problems from leaks. This is suggested by studies done in northeastern industrial cities which found that lung cancer risk increases with the number of years of kang use [Xu et al., 1989; Wu-Williams et al., 1990]. Another concern is chronic, low-level CO poisoning, the symptoms of which mimic those of other illnesses, causing frequent misdiagnosis [Walker et al., 1999].
2. As reported by the Xinhua Beijing News Agency, May 25, 1999. Critical areas are within a 15 km radius of airports and within a 4km swath along railroads and highways.
3. Although air pollution levels from producer gas cooking are low, there is a residual risk of CO poisoning or even accidental deaths as a result of gas leaks. This risk can be mitigated by "odorizing" the cooking gas to facilitate leak detection. Cooking gas with some residual tars might be adequately odorized by the aromatics in the tars, but an odorant might have to be added to an especially clean cooking gas.
4. Such as the UNDP project "Modernized Biomass Energy in China: Jilin" aimed at demonstrating crop residue-fueled CHP using currently available gasifier and reciprocating engine technologies. For more information about this project contact Susan McDade (susan.mcdade@undp.org).
5. The primary combustibles in cleaned producer gas are CO and H₂ (together typically 35-40% by volume) as well as a small amount of CH₄. Diatomic nitrogen from air (the oxidant for gasification) makes up about half of the components in producer gas by volume.
6. Producer gas/air mixtures do not auto-ignite under the brief high temperatures and pressures associated with diesel engine compression.
7. For example, see the discussion of the cooking gas system for Tengzhai village in Shandong Province [Dai and Lu, 1998]. There is also a demonstration cooking gas system in operation in the town of Shijiapu in Jilin province.

8. Energy-saving retrofits to a New Jersey townhouse, for example, were shown to reduce its heat requirement by two-thirds [Socolow et al., 1978].
9. For a discussion of the sizing of the gasifier and gas holder see Henderick [2000].
10. Household dimensions and village layout description supplied by the Jilin Province Energy Research Institute [Jin, 1999].
11. The total system water flow rate is about 1kg/s for the 100-household village.
12. The full cost for supply plus return pipes is therefore \$44/m and \$60/m of supply pipes, for service and trunk lines, respectively.
13. In addition to the public health/environmental benefits, this trigeneration technology also offers public benefits associated with the small-scale, distributed nature of the power system [Hoff et al., 1996] that are not taken into account in the present analysis. One especially important "distributed benefit" offered is that wide use of small, crop-residue-fired power plants that sell baseload electricity to electricity grids would greatly improve the capacity factors of these grids and thereby the economic efficiency of grid utilization; moreover, the much higher power flows on the rural grid with these distributed generation systems in place would provide a substantial revenue base to help pay for upgrading the grid to make it more reliable.
14. There is a range of electricity prices in Jilin province. Although city power can be as cheap as 3 to 4¢/kWh, rural power prices range from 6 to 10 ¢/kWh, and rural prices at the high end of this range are common [Larson, 1998a; Liu, 1999].
15. The national average savings rate for rural HHs in China was 26% in 1998 [NBS, 1999].
16. Controlling emissions from coal burning is much easier at large centralized coal boilers than in small distributed burners.
17. For an overall 19.6% efficiency in converting crop residues into electricity, based on a gasification efficiency of 70% and gas-to-electric thermal conversion efficiency of 28%.
18. Long before the full potential of crop residues for power generation would be realized, advanced technologies far more efficient than the microturbine would become available if biopower technology were to provide the basis for a growth industry. One such option is a solid oxide fuel cell/microturbine hybrid operated on producer gas that could be provided by the same kind of gasifier considered in the present study. A preliminary analysis of this technology indicates that a 46.5% LHV efficiency (biomass to electricity) could be realized at a scale of 200 kW_e [Kartha, Kreutz, and Williams, 1997]. With this technology potential power generation from crop residues would be 320 TWh/yr, equivalent to 35% of thermal power generation in China in 1997.
19. See Note 4.
20. See, for example, Berry and Jaccard [2000].

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