10 January 1998

Small-Scale Gasification-Based Biomass Power Generation

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Prepared for the
Biomass Workshop
Changchun, Jilin Province, China
12-13 January 1998

Introduction

Gasifying biomass to produce a combustible gas provides the possibility for much more efficient overall conversion of a given biomass resource into electric power than is possible with traditional combustion-based technologies. In particular, gasified biomass can be used to power internal combustion engines (ICEs), gas turbines, and fuel cells, all of which are able to produce electricity at considerably higher efficiency than boiler/steam-turbine systems of comparable size. In addition, ICEs, gas turbines, or fuel cells coupled with biomass gasifiers have the potential for considerably lower capital investment requirements than comparably-sized boiler/steam turbine systems. In the size range below 5 MW_e, spark-ignition or compression-ignition engines are the technologies of choice today for gasification-based power generation from biomass (Fig. 1). Fuel cells and micro-gas turbines coupled with biomass gasifiers will offer considerably higher efficiencies at small scales compared to internal combustion engines [Williams, 1998], but such advanced technologies are still under development. This paper presents an overview of technology and economics of biomass-gasifier/internal combustion engine technology, with some discussion of applications in the context of Jilin Province.

Historical Perspective on Biomass-Gasifier/Internal Combustion Engine (BiG/ICE) Systems

Gasified wood-charcoal was widely used as a civilian fuel in Europe during the Second World War [Anonymous, 1979], running several hundred thousand vehicles and powering industrial machinery [National Research Council, 1983]. The development of inexpensive petroleum supplies after the war led to essentially total abandonment of BiG/ICE technology until the first oil price shock of the 1970s. Crash attempts were then made worldwide to resurrect and install BiG/ICE systems for stationary power supply, especially in remote areas of developing countries [Foley and Barnard, 1982]. Most such efforts failed, however, primarily because lignocellulosic biomass was the preferred feedstock, rather than charcoal.[1] Significant amounts of tar can be produced during gasification of raw biomass. Condensation of tars on downstream equipment causes system operating problems. Such problems were encountered in many of the gasifier-engine systems installed in the 1970s and 1980s (e.g., see Coovattanachai, *et al.* [1982]; Kumar, *et al.* [1985]; Zijp and Stassen [1984]). Tar and other problems [Stassen and Knoef,

[1] A substantial fraction of the energy content of the original raw biomass is lost in the process of converting it to charcoal, particularly using charcoal conversion technologies that are commonly found worldwide today. When gasifiers were resurrected in the 1970s, these energy losses were generally considered unacceptable from a resource supply standpoint. Hence the emphasis on lignocellulosic feedstocks. Similar concerns with over-utilization of the biomass supply during the Second World War led Sweden to ban charcoal use in gasifiers toward the end of the war.

1995], coupled with a resumption of low oil prices and an emphasis on centralized power generation for rural electrification in developing countries, led to a second abandonment of efforts to commercially establish BiG/ICE technology by the end of the 1980s.

Research efforts continued, however, and led to the identification of gasifier and gas cleanup system designs for eliminating tar and other technical problems. The process of transferring these research findings into commercial products in the 1990s coincided with the growing recognition among developing country governments and multilateral lending agencies of the financial and environmental shortcomings of business-as-usual expansion of centralized public-sector electricity supply to rural areas. Private power generation and renewable energy implementation began to be strongly encouraged by many governments around the world. Today, interest has again revived worldwide in BiG/ICE technology for small-scale stationary power generation. Unlike with the previous resurrection efforts, BiG/ICE systems are now being offered commercially, with warranties and performance guarantees, by a growing number of companies worldwide [e.g., see Anonymous, 1997 and Turnbull *et al.*, 1996].

BiG/ICE Technology

A typical BiG/ICE power generating system includes three basic elements: a gasifier, gas cooling/cleaning, and the engine/generator (Fig. 2):

Gasification: The thermochemical processes of gasification include pyrolysis (devolatilization) and char conversion.[2] During pyrolysis, the volatile components of the feedstock vaporize at temperatures between about 300°C and 600°C, leaving behind fixed carbon (char) and ash [Milne, 1979; Antal, 1983]. Biomass is high in volatile matter (typically 70-90%) in contrast to coal, so pyrolysis plays a large role in biomass gasification. Products of pyrolysis include carbon dioxide, carbon monoxide, hydrogen, methane, water vapor and complex organic compounds (tars and oils) that condense at high temperatures and can be difficult to decompose ("crack") into lighter permanent gases. In some gasifiers, the tars and oils constitute an important energy component of the product gas. A relatively small amount of char remains after pyrolysis, some of which burns to provide heat for pyrolysis of additional biomass and gasification of the uncombusted char. Since biomass chars react 10 to 30 times more rapidly than coal chars [Graboski, 1982], biomass gasifiers can typically operate at lower temperatures than coal gasifiers while achieving the same char conversion.

The intended use of the gas and the particular feedstock to be gasified influence the design and operation of the gasifier and auxiliary equipment. Cost economies of scale usually permit large-scale systems to be more technologically sophisticated. Figure 3 shows several of the most prominent gasifier designs, and Fig. 4 shows the general range of applicability of each design.

The simplest gasifier design is the updraft reactor (Fig. 3a), named according to the direction of airflow through a packed-bed of reacting biomass. Air is injected at the bottom and biomass enters at the top, from which point it successively undergoes drying, pyrolysis, char gasification and char combustion. The combustion releases heat and carbon dioxide that drive gasification and pyrolysis as the combustion products travel up through the bed. Updraft gasifiers have high energy conversion efficiencies due to the efficient counter-current heat exchange

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[2] A variety of names are associated with gasified biomass. "Producer gas" derives from the first "gas producers" that were developed in the 1800s for gasifying coal [Rambush, 1923]. Because of the low heating value of such gas (4 to 6 MJ/Nm^3, or 10% to 15% of the heating value of natural gas), its name is "poor gas" in French. Coal-derived producer gas was widely used in the 19th and early 20th centuries in urban areas (and continues to be used in some areas today) for domestic cooking, heating, and public lighting, which led to its being labeled "town gas". The use of gasified biomass in vehicles in Europe during World War II resulted in the name "suction gas," because engine suction is used to draw the required air for gasification into the reactor.

between the rising gases and descending solids. Condensing of pyrolysis tars from updraft gasifiers is problematic in applications where the producer gas must be cooled before it can be used, e.g. in internal combustion engines. Successfully removing tars from the gas before use can significantly penalize overall efficiency, since tars constitute an important fraction of the energy output of the gasifier. Thus, in practical operations, the use of updraft gasifiers has been limited to direct heating applications where no gas cooling is required, such as for producing a fuel that is burned in a "close-coupled" boiler or kiln.

Downdraft gasifiers produce an order of magnitude less tar [Brown, *et al.*, 1987]. The design shown in Fig. 3b was the dominant design used during World War II. In this design, the combustion zone is fixed at the point of air injection, and product gas is drawn out from below. Pyrolysis occurs above and continues within the combustion zone. All pyrolysis products are forced to pass through the hot char gasification zone, where a significant fraction of tar is cracked. In actual field experience in the 1970s and 1980s, it proved extremely difficult to reduce tar to acceptable levels efficiently and cost-effectively, particularly at small scales [Parikh, *et al.*, 1988]. Fairly elaborate and costly gas cleaning systems were recommended for applications where a cool, tar-free gas was needed [Reed and Das, 1988].

A number of researchers have contributed to developing an understanding of the science of what was previously the ill-defined art of gasification[Groeneveld, 1980; Reed and Markson, 1982; Shrinivasa and Mukunda, 1983; Kaupp, 1984; Susanto, 1984; Parikh *et al.*, 1988; Reed and Das, 1988; Mukunda *et al.*, 1984, 1993, 1994a, 1994b; Sasidharan *et al.*, 1995]. Such work led to the identification of specifications for modified downdraft gasifier designs and gas cleaning systems that enable acceptable tar levels to be achieved under commercial operating conditions [Mukunda *et al.*, 1994b]. One such design is the open-top reactor (Fig. 5). The most obvious differences between this design and the traditional downdraft gasifier (Fig. 3b) are the open top and the lack of a flow restriction at the "throat," but many differences in details that were identified through theoretical and experimental research, including an understanding of required fuel physical and chemical characteristics, have contributed to the development of this design [Mukunda *et al.*, 1993].

For larger-scale applications, various fluidized bed designs derived from coal gasifiers and combustors are used. The bubbling-bed (Fig. 3c) was the first fluidized-bed gasifier design developed. The circulating fluidized-bed (CFB) (Fig. 3d), is an increasingly popular commercial variant. In a fluidized bed, an inert material (like sand) constitutes the bed into which biomass fuel is continuously fed. Air, oxygen and/or steam are injected from below to keep the bed fluidized. Turbulence leads to excellent heat and mass transfer, producing relatively uniform temperatures throughout and overall faster reactions than in updraft or downdraft reactors. The higher reaction rates lead to higher throughput capabilities per unit volume, and hence lower capital costs per unit of capacity. Fluidized-beds are generally more expensive than fixed-beds at smaller scales due to the high costs for blowers, continuous feed systems, control systems and other instrumentation [Larson *et al.*, 1989]. Indirectly-heated gasifiers, designed specifically to take advantage of the higher reactivity of biomass compared to coal, are also being developed [Wyman, *et al.*, 1993; Katofsky, 1993]. In these designs, biomass is heated by an inert heat-carrying material such as sand (Fig. 3e) or through a heat exchanger (Fig. 3f). The indirect designs rely on the high reactivity of biomass feedstocks to compensate for the generally lower operating temperatures that can be achieved using indirect heating. A primary attraction of the indirect design is that it produces a much higher energy content product gas than air-blown gasifiers, since there is no nitrogen dilution.

Gas Cooling/Cleaning: Gas from the gasifier must be cleaned to avoid contaminant deposition and erosion or corrosion damage to the engine. The gas must also be cooled to increase its density for injection into the engine cylinders. Properly designed and operated, the best commercial gasifiers available today minimize tar production, such that a direct-contact water quench followed by a filtration system for particulate removal can be used [Anonymous, 1997; Mukunda *et al.*, 1994a]. Careful design of the scrubber and filter are critical to ensuring adequate gas cooling and cleaning, as well as ease of maintenance and operation of the cooling/filter system.

Engine/Generator: Gasified biomass can fuel either compression ignition (diesel) engines or spark ignition (gasoline) engines. Diesel engines are favored because of their higher efficiency, greater durability and reliability, simpler maintenance, and because diesel fuel is readily available in most developing countries. Producer gas can replace 65-85% of the diesel fuel requirements of an engine—some diesel fuel is needed to assist ignition. Commercial diesel engines require only minor modifications to the air intake system so that engine suction draws both air and fuel gas simultaneously. Decreasing air flow with a control valve permits the fuel-air ratio to be adjusted.

Crop Residues for Big/ICE Systems in Jilin Province

A wide variety of biomass feedstocks can be used to fuel BiG/ICE systems, but the physical and chemical characteristics (size, texture, moisture content, fixed carbon content, etc.) of the feedstock are important in determining performance. In general, a BiG/ICE technology supplier sets feedstock specifications that must be met to insure successful operation, since a gasifier's design and operation varies with the feedstock being used. Commercial BiG/ICE systems are available today that will operate on wood chips, maize cobs, cotton stalks, rice hulls, soy husks, coconut shells, palm nut shells, sawdust, and other fuels. Residue fuels, which are available today in most regions of the world, are an attractive fuel source for BiG/ICE systems because of their generally low cost.

Maize production is a major residue generating activity in Jilin Province: an estimated 9 million tonnes of residues are available annually for non-field use.[3] Figure 6 shows a rough estimate of the annual quantity of maize residues that would be needed to fuel BiG/ICE power plants of up to 500 kW_e capacity. Also shown is the estimated area of maize that must be harvested annually to provide these residues, assuming a maize yield of 6 tonnes/ha and a ratio of dry residues to primary maize production of 1:1, and that one-third of the residues must remain on the land to provide organic matter and nutrients. To operate a 200 kW_e system with a 65% capacity factor would require residues from about 300 ha of maize production. The total tonnage of ecologically-recoverable maize residues in Jilin province would support an installed BiG/ICE generating capacity of some 1500 MW_e.

Energy Crops for BiG/ICE Systems

In addition to residue fuels, biomass can be grown specifically for energy purposes. Such fuel will generally be more costly than residues, but much greater quantities can be generated from a given land area, and lands not well suited for crop production (marginal or degraded lands) might be suitable for growing energy crops. Woody crops, which can be harvested as needed and stored more easily after harvesting than herbaceous crops, might supplement seasonal residue fuels, or replace them entirely in the longer term.

It is often assumed that large plantations (tens of thousands of hectares) of energy crops are needed in order to produce dedicated biomass energy competitively. However, an alternative small-scale biomass supply system, "farm forestry," might be ideally suited to providing biomass to supplement or replace residue fuels in rural applications where large blocks of land cannot be dedicated to energy crop production. Farm forestry is increasingly being implemented in Brazil (see box), and similar activities have been reported elsewhere.

[3] Based on maize production of 13.5 million tonnes/year (as reported in transparencies prepared by Ralph Overend for this workshop), a residue-to-maize ratio of 1:1, and a requirement that ⅓ of residues are left on the field for maintenance of nutrients and organic matter status.

BOX: Farm Forestry in Brazil

In a typical farm-forestry program in Brazil, a forestry company provides the material inputs and technical know-how for establishing trees on a farmer's land (1 to 50 hectares of trees per farm) and contracts with the farmer to buy some or all of the first harvest for an agreed upon price that incorporates repayment for the initial inputs and services. The inputs include saplings (typically some species of eucalyptus in Brazil), fertilizers (applied at planting), herbicides (applied at some point after planting), and pesticides. The company samples the farmer's soil and provides inputs "tuned" to that farmer's soil.

Under programs ongoing in Brazil, biomass yields reported for small-farm plantings are not much below those reported for large-scale plantations owned and operated by forestry companies. This success is attributed to a combination of sophisticated material inputs and careful (typically-manual) tending by the farmer. Yields can be expected to increase as both farmers and their contracting companies learn improved methods and approaches (most programs in Brazil started less than a decade ago.) Yield reductions are often offset by substantially lower costs to companies for establishing farm forests. Limited survey data indicate that the per hectare cost for farmer-contracted land is substantially less than half the cost for company-owned land [Larson and Williams, 1995]. Limited data also suggest that delivered costs for biomass are not much different between farm-forests and large-scale plantations.

Farm forestry is growing rapidly in Brazil, with encouragement from the private sector; from federal, state and local governments; and from farmers. Several hundred thousand hectares have been established in less than a decade. This compares favorably with the estimated 6 to 7 million hectares of large-scale plantations established in Brazil since the 1960s. Farmer-owned plantations account for as much as 20 percent of some forestry companies' total planted area, and some companies have a goal of raising this fraction to 50 percent or more.

The overall results of the small-farm forestry programs in Brazil have been minimal changes in land ownership and use patterns (large forestry companies are not buying out small farmers), while local wood supplies at reasonable costs have increased, and farmers (including formerly subsistence farmers) have gained a revenue source.

Regardless of the scale at which dedicated biomass energy crops are produced, they are likely to be more costly to use in BiG/ICE applications than residue fuels. Costs will vary with local soil, climate, labor costs, and other factors. Some indication of costs can be derived from an extensive assessment of expected productivities and costs for plantation-grown biomass undertaken for the nine states (covering 155 million hectares) that comprise the semi-arid region of Northeast Brazil [Carpentieri, *et al.*, 1993]. Large areas of the Northeast have been identified that are suitable and potentially available for energy crop production (Fig. 7). The total estimated biomass production potential is substantial: it is estimated to be sufficient to generate 20 to 40 times the current electricity consumed in the Northeast region. Average projected plantation yields vary from region to region within the Northeast, and costs vary accordingly (Fig. 8). About one-third of the potential biomass production has delivered costs below $1.2/GJ in 1988 US$ (Fig. 9)--about $1.6/GJ in 1997 US$. An additional fifty percent of the potential regional plantation-biomass supply would have an average delivered cost of $1.3/GJ (1988$) or $1.7/GJ (1997$).

Local assessment in Jilin Province is needed to estimate what local costs might be for production and delivery of dedicated energy crops. The growing season is shorter in Jilin than in Northeast Brazil, which will tend to lower yields, but higher rainfall may be a compensating factor. Differences in labor costs between Jilin and NE Brazil could also be important.

The higher cost associated with plantation biomass provides a strong incentive for pursuing higher efficiency in converting the biomass to electricity. Higher efficiency also reduces the land requirements for providing each kWh of electricity. Figure 10 shows land area requirements for small biomass power generating systems. Area is shown as a function of power plant capacity up to 500 kW_e, for assumed plantation yields of 5, 10, and 15 dry tonnes per hectare per year. Curves are shown for conversion efficiencies representing the performance of BiG/ICE technology and for a technology that might have twice this efficiency.

Costs for BiG/ICE Systems

The overall economics of BiG/ICE technology are illustrated here in terms of the lifecycle cost of power generation.

Mukunda *et al.* [1993] provide one detailed estimate of capital and operating costs for BiG/ICE technology at a scale of 96 kW_e. This particular system utilizes the gasifier designed at the Indian Institute of Science (Bangalore) and now being pursued for commercialization by an Indian-Swiss joint venture company [Anonymous, 1996]. Mukunda *et al.* project a total first cost for an installed system (in 1997 US$) to be about $460/$kW_e$, but key components of such a system (for example, the gasifier and the engine) require replacement at regular intervals. Over a 25-year investment period, the present value of total installed equipment costs (including replacement of the gasifier and engine every 6 years and the cleanup and control systems every 10 years) is an estimated $800/kW (using a 12% discount rate).

Another BiG/ICE system is offered commercially by EnergyWorks through a joint venture with Ankur Scientific, an Indian gasifier manufacturer [Anonymous, 1997]. DeLaquil [1998] estimates an installed cost of about $1200/$kW_e$ for such a system today. This estimate includes manufacture of the system in a developing country, such as India or Indonesia, but it is for a newly commercial technology. It is conceivable that costs would fall in the future (perhaps as low as the estimate by Mukunda, *et al.*) once demand grows such that high production volume is achieved. In any case, the assumed capital investment has relatively little impact on the overall economics of BiG/ICE power generation, as illustrated below. Fuel costs are more critical.

Fuel consumption is estimated by Mukunda *et al.* at full load to be 1.3 kg/kWh of biomass (with 15% moisture content) and 0.1 liters/kWh of diesel fuel (representing a displacement of 70% of the full diesel consumption in diesel-only operation). DeLaquil estimates biomass and diesel consumption at 1 kg/kWh (20% moisture content) and 0.1 liters/kWh.

Table 1 shows the calculated cost of electricity generation for a 96 kW_e BIG/ICE system, assuming a capital cost of $800/$kW_e$, an internal rate of return to the investor of 12%, a capacity factor of 65%, operating labor costs representing a rural Indian context, diesel fuel costing $0.26/liter ($6.7/GJ), and biomass costing $20/tonne with 15% moisture content ($1/GJ). With these assumptions, the total cost of power generation is 7.4 ¢/kWh. One-third of the total cost is for diesel fuel; one-quarter is for biomass fuel (Fig. 11). Generating costs compare very favorably with stand-alone diesel power generation at the same scale, even at relatively low diesel fuel prices (Fig. 12).

The analyses in Table 1 and Fig. 12 assume a capacity factor of 65%. Capacity factors in the 25-50% range might be more representative of power demands in a rural village at a relatively early stage of electrification. At lower capacity factors, the cost of power increases substantially (Fig. 13). However, to reduce power costs at the early stages of electricity demand development in rural areas, one strategy might be to export baseload electricity to urban demand centers [Kartha *et al.*, 1997]. Low power demands in rural areas lead to high costs for power delivered to such regions over the central electricity grid from power plants located near urban centers, because transmission line capacity is vastly underutilized in such situations [Sinha and Kandpal, 1991]. Nevertheless, it may be economically feasible to transmit power from, rather than to, the rural area until local demand grows, since transmission lines could then be utilized with high capacity factors. It is noteworthy that remote hydroelectric sites and mine-mouth coal-fired power plants provide power to urban centers under such arrangements.

As noted earlier, power generating costs are not especially sensitive to capital costs—a capital cost of $1200/$kW_e$ instead of $800/$kW_e$ increases per-kWh generating costs by about 15% at a 65% capacity factor. However, the cost of fuel, both diesel and biomass, has a large impact on total cost. Even at the low end of diesel fuel costs, diesel fuel still accounts for one-third of the total cost of power (Fig. 11). With the diesel cost fixed at $0.26/liter, Fig. 14 shows power generating cost for a range of biomass costs, from zero (negative fuel costs are conceivable in some situations, e.g., where disposal costs can be avoided) to $2/GJ, which might be a high-end estimate of the costs of dedicated energy crop production in Jilin Province.

At the high end of the biomass cost range shown in Fig. 14, power generating costs exceed 10 ¢/kWh. More efficient technologies are desirable, especially for use with such higher-cost biomass. Such technologies could become available in the future. One such technology is a hybrid system involving gasification to power a fuel cell and recuperated gas turbine. Capital costs for such a system are projected to be modestly higher than costs for BiG/ICE today, while efficiencies[4] above 40% (at least double the BiG/ICE) are projected at a scale of 200 kW_e [Kartha *et al.*, 1997]. This efficiency corresponds to a biomass consumption of about 0.5 kg/kWh (15% moisture content). With such high efficiency systems (that also require no diesel fuel), the cost of electricity generation would be under 6 ¢/kWh with biomass costing $2/GJ and assuming a capital cost of $1200/$kW_e$ (Fig.15).

Institutional and Infrastructure Issues

While advanced technologies, such as gasifier/fuel cell systems, promise improved economics for small-scale biomass power generation in the future with dedicated biomass energy crops as fuel, the economic analysis above indicates that BiG/ICE systems that are commercially-available today can be competitive for rural power generation today in a variety of situations. In particular, where low-cost biomass residue fuels are available, BiG/ICE technology would appear to be very competitive with stand-alone diesel generation.

To maximize the potential economic benefits of introducing BiG/ICE, some important institutional and infrastructure development challenges must be addressed. Successfully addressing such issues using technology available today (BiG/ICE) will greatly facilitate the introduction of advanced technologies in the future (e.g., gasifier-fuel cell systems) that promise still greater benefits for rural development.

One challenge is to put into place production and delivery infrastructures for residue fuels. Where conditions are especially favorable, dedicated energy crop production systems might also start to be developed.

Another challenge is developing a diversified electric load with an isolated (non-grid-connected) system in order to achieve high system capacity factors and thereby lower the cost of generated power. If a BiG/ICE system were able to connect to the grid, then the possibility exists for exporting power to urban demand centers until such time as local power demands can be expanded and diversified. Institutional arrangements for allowing small-scale power supply to the utility grid would need to be worked out. Revenue collection systems would also need to be put in place.

The introduction of BiG/ICE systems would also provide opportunities to develop technology transfer and certification mechanisms, as well as for the development of a rural-focussed independent power producer industry and associated technology marketing, maintenance, and operator training infrastructures.

Potential Rural Development Benefits

Small-scale gasification-based biomass power generation is a potentially attractive strategy for sustainable electricity supply in rural areas. Gasifier/internal combustion engine systems are commercially available today, and advanced systems under development promise still better economics in the longer-term.

[4] Efficiency is defined here as the fraction of the higher heating value of biomass converted to electricity.

Biomass-derived power could contribute to rural development in a number of ways. In addition to direct employment in fuel gathering, delivery, and power plant operation, the economically competitive electricity that could be produced by such systems could draw other employment- and income-generating activities into rural areas, especially energy-intensive industries that offer well-paid jobs. Until sufficiently-high levels of electricity demand develop locally, biomass-derived power might be economically exported to urban demand centers to achieve the high plant capacity factors that lead to lower generating costs. Privatized biomass-power generation and the industrial activities it attracts might provide a tax base to help finance rural infrastructure building that would serve to attract additional economic activities. Such tax revenues could also be used to subsidize the provision of basic human needs to communities that remain outside of the cash economy. Building on an initial residue fuel supply, production of dedicated energy crops in the longer term might be a strategy for restoring marginal or degraded lands to more productive use.

References

Anonymous. *Generator Gas: The Swedish Experience from 1939-1945*, SERI/SP-33-140, Solar Energy Research Institute, Golden, Colorado, 1979. (Translation from Swedish of, *GENGAS*, prepared by Swedish Academy of Engineering, Stockholm, 1950.)

Anonymous, "Biomass Gasification for Power Generation," NETPRO Renewable Energy marketing brochure, Bangalore, India. 1996.

Anonymous, "BG Systems for Power and Heat from Biomass Gasification," EnergyWorks L.L.C. marketing brochure (in English and Indonesian), Landover, Maryland, USA, 1997.

M.J. Antal, Jr. , "Biomass Pyrolysis, a Review of the Literature, Part 2: Lignocellulose Pyrolysis, *Advances in Solar Energy*, 2:175-255, 1983.

M.G. Brown, E.G. Baker, and L.K. Mudge, "Evaluation of Processes for Removal of Particulates, Tars, and Oils from Biomass Gasifier Product Gases, *Energy from Biomass and Wastes X*, D. Klass (ed), Elsevier Applied Science, London, 1987, pp. 655-77.

A.E. Carpentieri, E.D. Larson, and J. Woods, "Future Biomass-Based Electricity Supply in Northeast Brazil," *Biomass and Bioenergy*, 4(3), 1993, pp. 149-173.

A.E. Carpentieri, E.D. Larson, and J. Woods, "Prospects for Sustainable, Utility-Scale, Biomass-Based Electricity Supply in Northeast Brazil," PU/CEES Report No. 270, Center for Energy and Environmental Studies, Princeton University, Princeton, New Jersey, 1992.

N. Coovattanachai, W. Chongchareon, and C. Kooptamond, "The Feasibility of Producer Gas in Electricity Generation," *Reg. J. Energy Heat Mass Transfer*, 4(4), 1982.

P. DeLaquil, "Small Scale Biomass Gasification Systems for Agricultural and Forest Product Industries," prepared for the Biomass Workshop, Changchun, Jilin Province, China, 12-13 January 1998.

G. Foley and G. Barnard, *Biomass Gasification in Developing Countries*, Earthscan Technical Report No. 1, London, 1982.

M.S. Graboski, "Comparison of Coal and Wood as Feedstocks for Methanol Manufacture," *Proceedings Biomass-to-Methanol Specialists' Workshop* (SERI/CP-234-1590), T.B. Reed and M. Graboski (eds), Solar Energy Research Institute, Golden, Colorado, 1982, pp. 41-59.

M.J. Groeneveld, "The Co-Current Moving Bed Gasifier," Ph.D. thesis, Twente University, Twente, The Netherlands, 1980.

S. Kartha, T.G. Kreutz, and R.H. Williams, "Small-Scale Biomass Fuel Cell/Gas Turbine Power Systems for Rural Areas," *Proceedings of the Third Biomass Conference of the Americas*, Elsevier Science, Inc., Tarrytown, New York, 1997.

R.E. Katofsky, *Fluid Fuels from Biomass*, MSE thesis, Mechanical and Aerospace Engineering Dept., Princeton University, Princeton, New Jersey, 1993.

A. Kaupp, *Gasification of Rice Hulls: Theory and Praxis*, German Appropriate Technology Exchange, Eschborn, Germany, 1984.

S. Kumar, M.A. Date, R.N.Pandya,, S.R. Patel, K.C. Shah, V. Damour, and B.C. Jain,"Design and Development of a Biomass Based Small Gasifier-Engine System Suitable for Irrigational Needs in Remote Areas of Developing Countries," *Energy from Biomass and Wastes*, D. Klass (ed), Institute of Gas Technology, Chicago, 1985.

E.D. Larson, "Technology for Electricity and Fuels from Biomass," *Annual Review of Energy and the Environment*, Vol. 18, 1993, pp. 567-630.

E.D. Larson, P. Svenningsson, I. and Bjerle, "Biomass gasification for gas turbine power generation," *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications*, Lund Univ. Press, Lund, Sweden, 1989, pp. 697-739.

E.D. Larson and R.H. Williams, "Biomass Plantation Energy Systems and Sustainable Development," chapter 9 in *Energy as an Instrument for Socio-Economic Development*, Goldemberg and Johansson (eds), United Nations Development Program, New York, New York, 1995, pp. 91-106.

T. Milne, "Pyrolysis: the Thermal Behavior of Biomass Below 600°C," in *Survey of Biomass Gasification*, Vol. II, Solar Energy Research Institute, Golden, Colorado, 1979, pp. 95-131.

H.S. Mukunda, P.J. Paul, U. Shrinivasa, and N.K.S. Rajan, "Combustion of Wooden Spheres—Experiments and Model Analysis," presented at the 20th International Combustion Symposium, The Combustion Institute, 1984, pp. 1619-1628.

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

H.S. Mukunda, S. Dasappa, P.J. Paul, N.K.S. Rajan, and U. Shrinivasa, "Gasifiers and Combustors for Biomass—Technology and Field Studies," *Energy for Sustainable Development*, I(3), September 1994a, pp. 27-38.

H.S. Mukunda, P.J. Paul, S. Dasappa, U., Shrinivasa, and H. Sharan, "Results of an Indo-Swiss Programme for Qualification and Testing of a 300-kW IISc-Dasag Gasifier," *Energy for Sustainable Development*, I(4), November 1994b, pp. 46-49.

National Research Council, *Producer Gas: Another Fuel for Motor Transport*, National Academy Press, Washington, DC, 1983.

P.P. Parikh, A.G. Bhave, D.V. Kapse, A. Ketkar, A.P. Bhagwat,"Design and Development of a Wood Gasifier for IC Engine Applications--New Approach for Minimization of Tar," *Research in Thermochemical Biomass Conversion*, T. Bridgwater and J. Kuester (eds), Elsevier Applied Science, London, 1988, pp. 1071-87.

N.E. Rambush, *Modern Gas Producers*, Benn, London, 1923.

T.B. Reed, A. and Das, *Handbook of Biomass Downdraft Gasifier Engine Systems*, Solar Energy Research Institute, Golden, Colorado, 1988.

T.B. Reed and M. Markson, "Biomass Gasification Reaction Velocities," in *Fundamentals of Thermochemical Biomass Conversion*, Overend, Milne, and Mudge (eds.), Elsevier Applied Science, New York, 1982, pp. 951-965.

P. Sasidharan, K.P. Murali, and K. Sasidharan, "Design and Development of a Ceramic-Based Biomass Gasifier—an R&D Study from India," *Energy for Sustainable Development*, II(4), November 1995, pp. 49-52.

U. Shrinivasa, and H.S. Mukunda, "Wood Gas Generators for Small Power Requirements," *Current Science*, 52(23), Dec. 5:1094-1098, 1983.

C.S. Sinha and T.C. Kandpal, "Decentralized versus Grid Electricity for Rural India: the Economic Factors," *Energy Policy*, 19, pp. 441-448.

H.E.M. Stassen and H.A.M. Knoef, "UNDP/World Bank Small-Scale Gasifier Monitoring Programme – Final Findings," *Energy for Sustainable Development*, II(1), May 1995, pp. 41-48.

H. Susanto, "Moving Bed Gasifier with Internal Recycle and Separate Combustion of Pyrolysis Gas," Ph.D. thesis, Institut Teknologi, Bandung, Indonesia, 1984.

J.H. Turnbull, S. Hulkkonen, and R. Dracker, "Development of Small Modular Biomass Power Systems." *Proceedings of Bioenergy '96*, Southeastern Regional Biomass Program, Nashville, Tennessee, 1996, pp. 605-611.

R.H. Williams, paper on biomass-gasifier fuel cell/gas turbine power system presented at this workshop, Jan. 1998.

C.E. Wyman, R.L. Bain, N.D. Hinman, D.J. and Stevens, "Ethanol and Methanol from Cellulosic Materials," in T.B. Johansson, H. Kelly, A.K.N. Reddy, R.H. Williams, and L. Burnham (eds), *Renewable Energy: Sources for Fuels and Electricity*. Island Press, Washington, 1993.

T. Zijp and H.E.M. Stassen, *Operating Experience with Producer Gas Plants in Tanzanian Villages*, Dept. of Chemical Engineering, Twente University of Technology, Enschede, The Netherlands, 1984.

Table 1. Performance and costs for a 96 kW_e BiG/ICE system, based on Mukunda, *et al.* [1993].

Performance Parameters	
Installed Electric Capacity (kW)	96
Capacity factor (%)	65
Annual kWh production	546,624
Specific fuel use	
Diesel (kg/hr): 70% of 0.28 kg/kWh replaced	8.06
(MJ/hr)	367
Biomass (kg/kWh), 15% moisture content	1.1
(kg/hr)	106
(MJ/hr)	1795
Lubricating oil use (grams/kWh)	1.36
Costs – 1997 US$ (a)	
Capital investment, $/kW (b)	800
Maintenance, $/year (c)	2511
Lube oil, $/year (d)	2624
Labor, $/operating hour (e)	0.23
Fuel, $/operating hour (f)	
Diesel	2.4
Biomass	2.1
Lifecycle Costs, 1997 US cents per kWh (g)	
Capital	1.8
Maintenance and lube oil	0.9
Operating labor	0.2
Diesel fuel	2.5
Biomass fuel	1.9
TOTAL (cents/kWh)	7.4

Notes:

(a) Costs given by Mukunda *et al.* [1993] are converted from 1991 Indian Rupees at 20 Rs/US$ and then from 1991 US$ to 1997 US$ using the Gross Domestic Product deflator for the USA (1.15 in 1997 relative to 1991).

(b) A 25-year analysis period is considered. A 12% discount rate is assumed to calculate the present value of future replacement units that must be purchased over this period. The gasifier and engine-generator are assumed to be replaced at 6-year intervals. The cooling/cleaning and control systems are replaced at 10-year intervals. The building does not require replacement.

(c) Annual maintenance cost is estimated as 5% of the first cost of the gasifier and building plus 10% of the first cost of the engine-generator set.

(d) Lubricating oil is assumed to cost $3/liter.

(e) Operating labor is assessed at 4 Rs/operating hour (1991 Rs).

(f) Diesel fuel is priced at $0.26/liter (1997$), or $6.65/GJ. Biomass is $20 per tonne (1997$) containing 15% moisture, or $1/GJ.

(g) This is the revenue required to achieve a 12% internal rate of return on a 25-year investment.

Figure Captions

Fig. 1. Scales of application for prime mover technologies in combination with biomass gasification. Gas engine refers to spark-ignited internal combustion engine. IGCC refers to integrated gasifier-gas turbine/steam turbine combined cycle. Source: TPS, Inc., Nyköping, Sweden.

Fig. 2. Typical equipment layout for a biomass-gasifier/internal combustion engine power generating system.

Fig. 3. Alternative designs for biomass gasification: (a) updraft fixed-bed, (b) downdraft fixed-bed, (c) bubbling fluidized bed, (d) circulating fluidized bed, and (e,f) indirectly-heated fluid beds. Source: Larson, 1993.

Fig. 4. Scales of application for alternative biomass gasifier designs. Source: TPS, Inc., Nyköping, Sweden.

Fig. 5. Two variants of the open-core downdraft biomass gasifier [Mukunda, *et al.*, 1993].

Fig. 6. Approximate maize residue requirements (and associated maize growing area) for biomass-gasifier/internal combustion engine power generation up to 500 kW_e in size.

Fig. 7. Regions in Northeast Brazil identified as suitable and potentially available for biomass energy crop production [Carpentieri, *et al.*, 1993]. The inset shows the location of the Northeast region relative to the Amazon jungle.

Fig. 8. Estimated delivered cost of eucalyptus that would be grown for energy in Northeast Brazil as a function of yield [Carpentieri *et al.*, 1992]. The average yield in each of the nine states of the Northeast are indicated, as are average yields by bioclimatic region.

Fig. 9. Estimated potential cost-supply curve for biomass energy from plantations in Northeast Brazil [Carpentieri *et al.*, 1992].

Fig. 10. Approximate planted area for energy crop production required to fuel gasifier-engine systems up to 500 kW_e in size. Area requirements are shown for BiG/ICE technology and for future technology with double the efficiency of BiG/ICE systems. For each technology, the area is shown for crop yields of 5, 10, and 15 dry tonnes per hectare per year.

Fig. 11. Distribution of power generating cost for a 100-kW_e scale BiG/GT system.

Fig. 12. Cost comparison between 100-kW_e scale BiG/ICE and stand-alone diesel-only power generating systems as a function of diesel fuel cost.

Fig. 13. Calculated electricity generating cost for 100 kW_e BiG/ICE systems as a function of system capacity factor. Results are shown for two levels of initial capital investment. See Table 1 for additional details.

Fig. 14. Calculated electricity generating cost for a 100 kW_e BiG/ICE system as a function of assumed biomass fuel cost. Results are shown for two levels of initial capital investment. See Table 1 for additional details.

Fig. 15. Calculated electricity generating cost for small-scale biomass power systems as a function of the biomass required per kWh generated, assuming two different capital investment levels and two different biomass fuel costs. (For simplicity, diesel fuel consumption is assumed to be zero.) The shaded boxes along the x-axis indicate the biomass utilization range that can be expected for presently-available BiG/ICE systems and for future systems coupling gasification with fuel cells.

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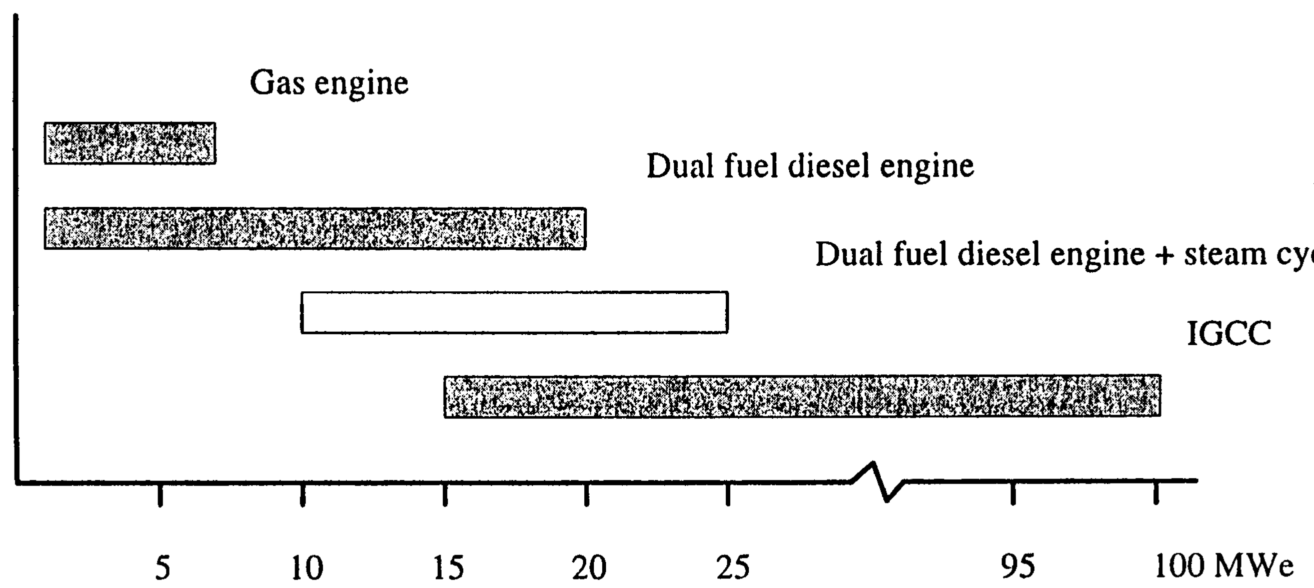
Technology Options with Gasification

- Internal combustion engines, gas turbines, fuel cells are candidate technologies.
- Biomass-Gasifier/IC Engines (BiG/ICE) are near-term technology of choice below 5 MW_e



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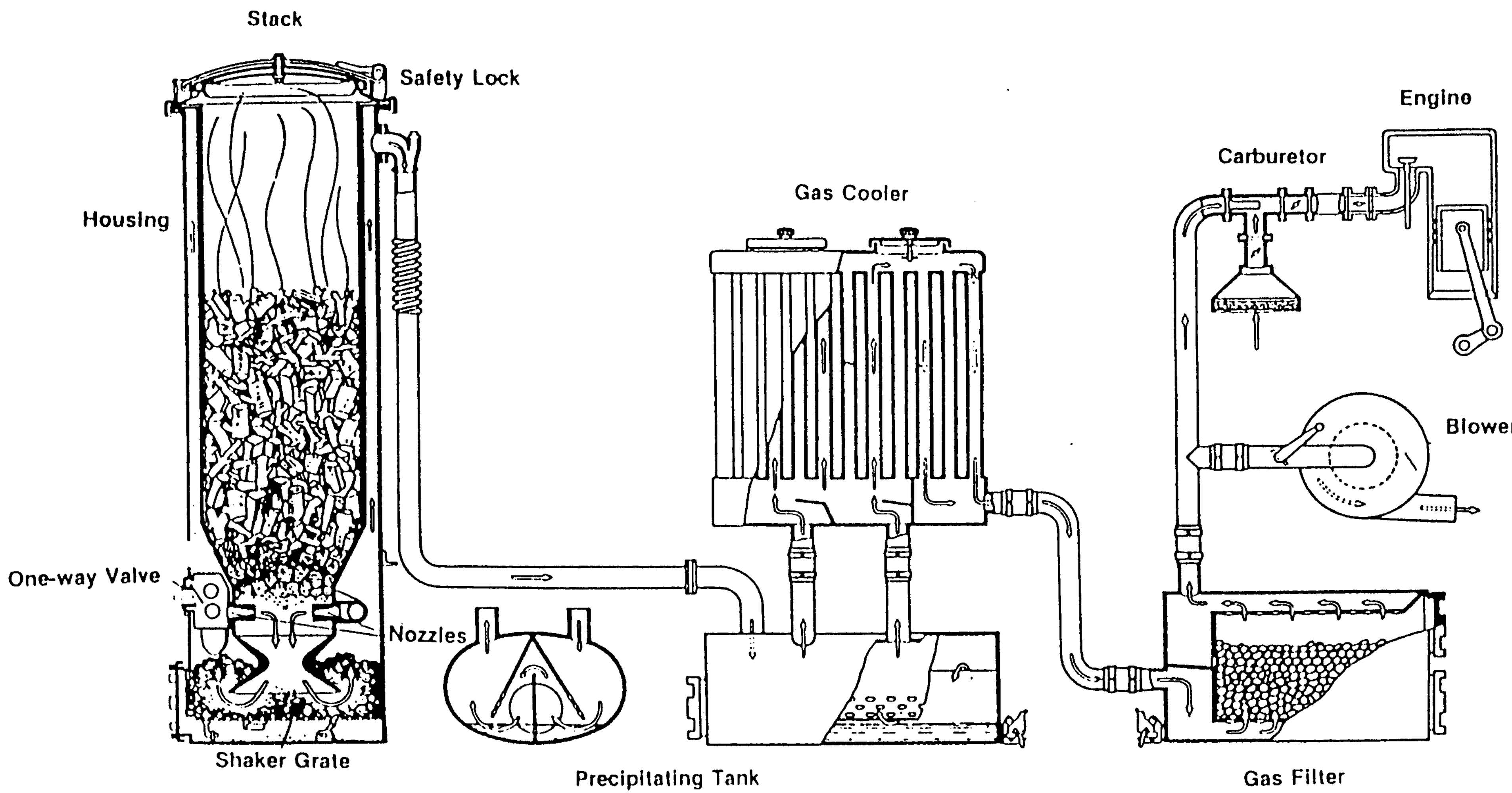
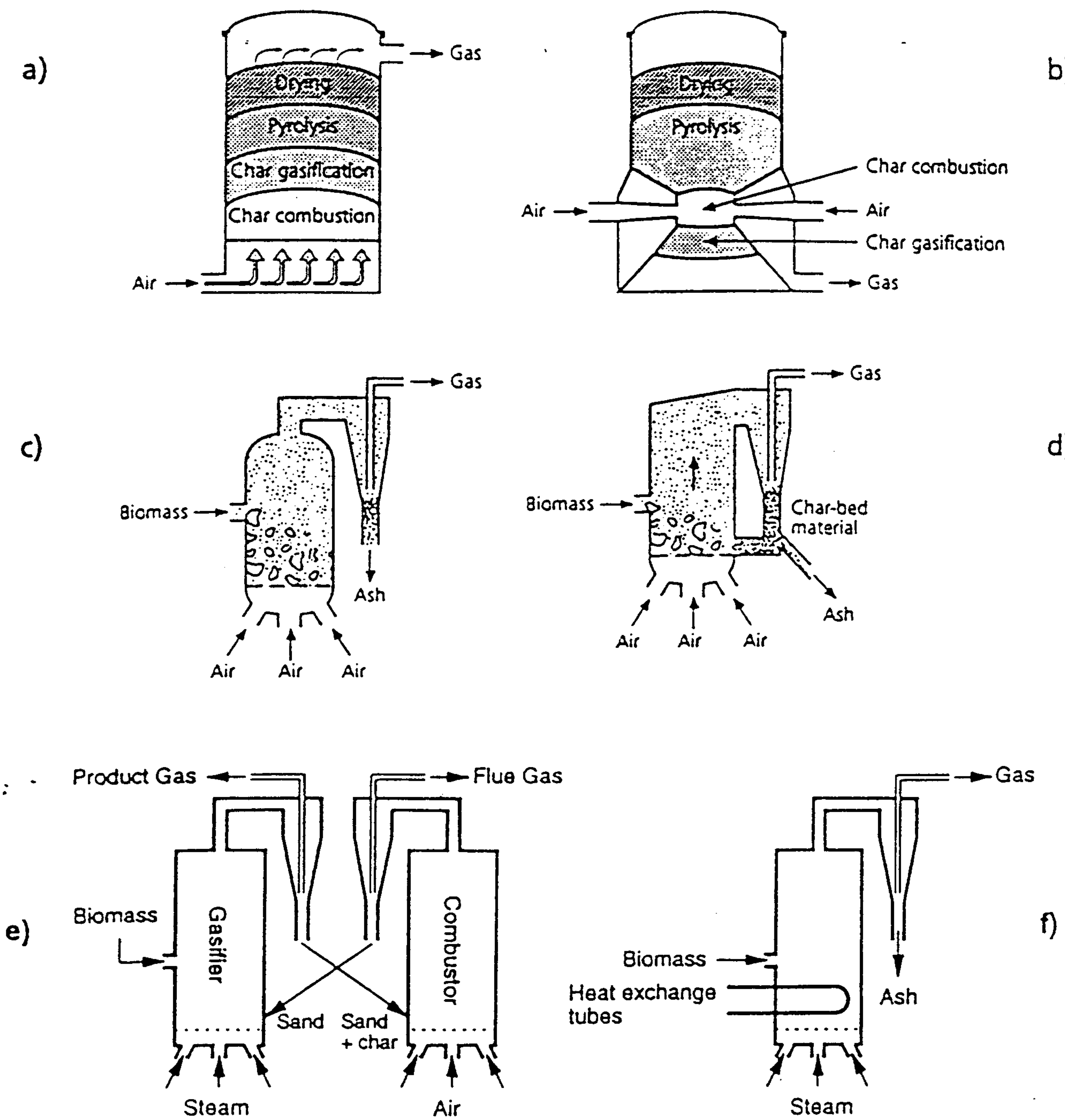
Basic Layout of a BiG/ICE System



Alternative Gasifier Designs



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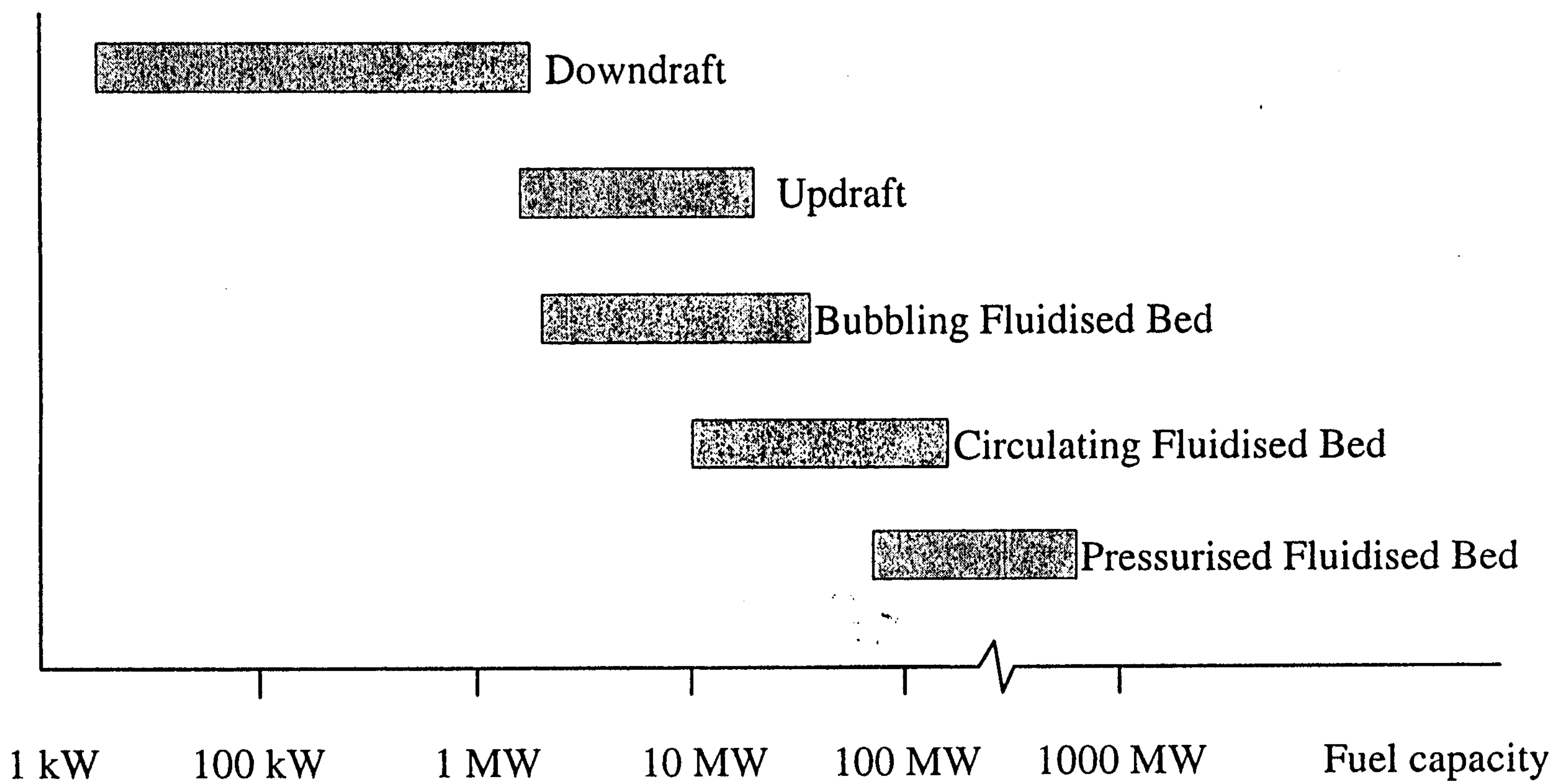
Preferred Gasification Technologies at Different Scales



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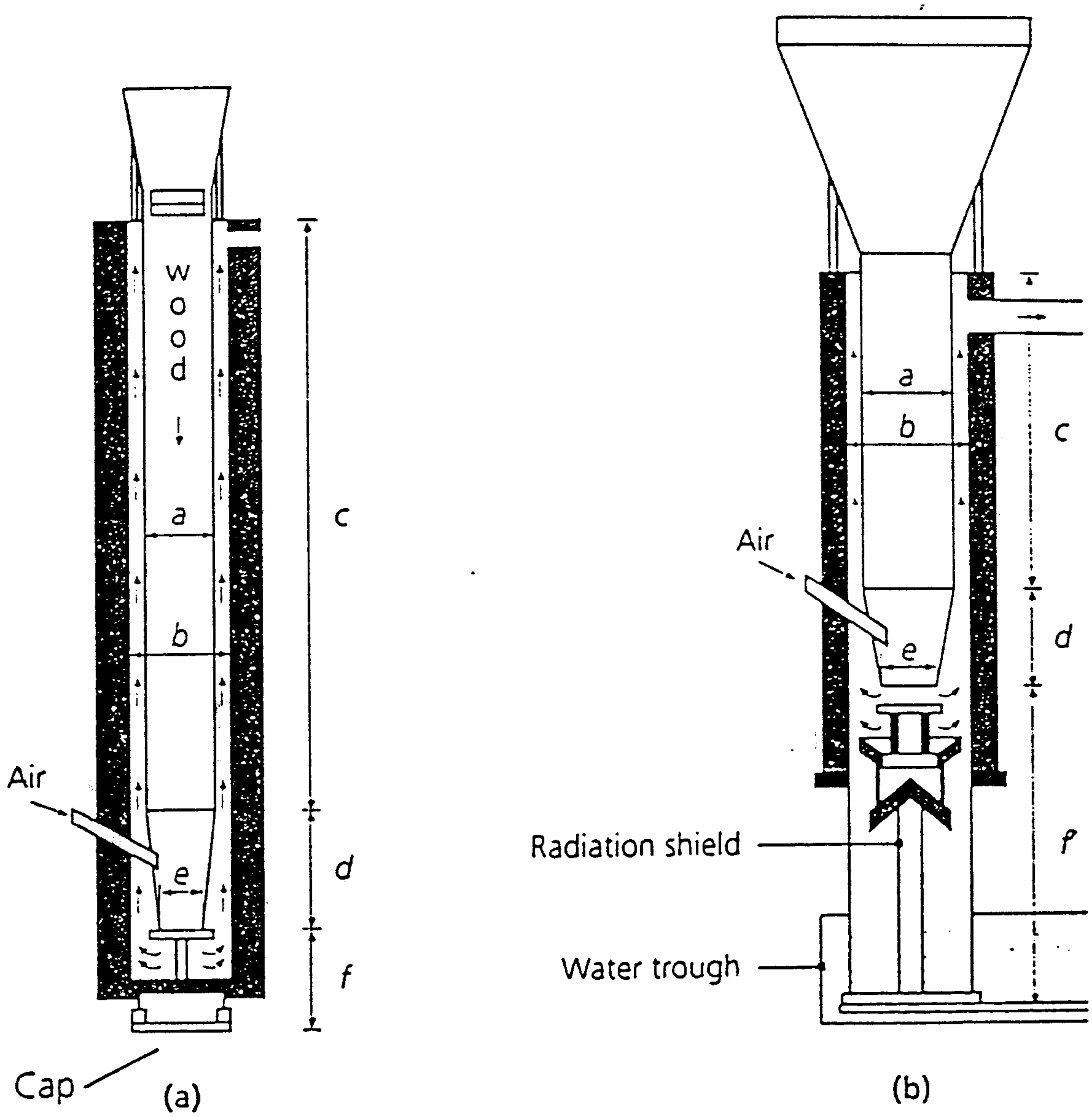
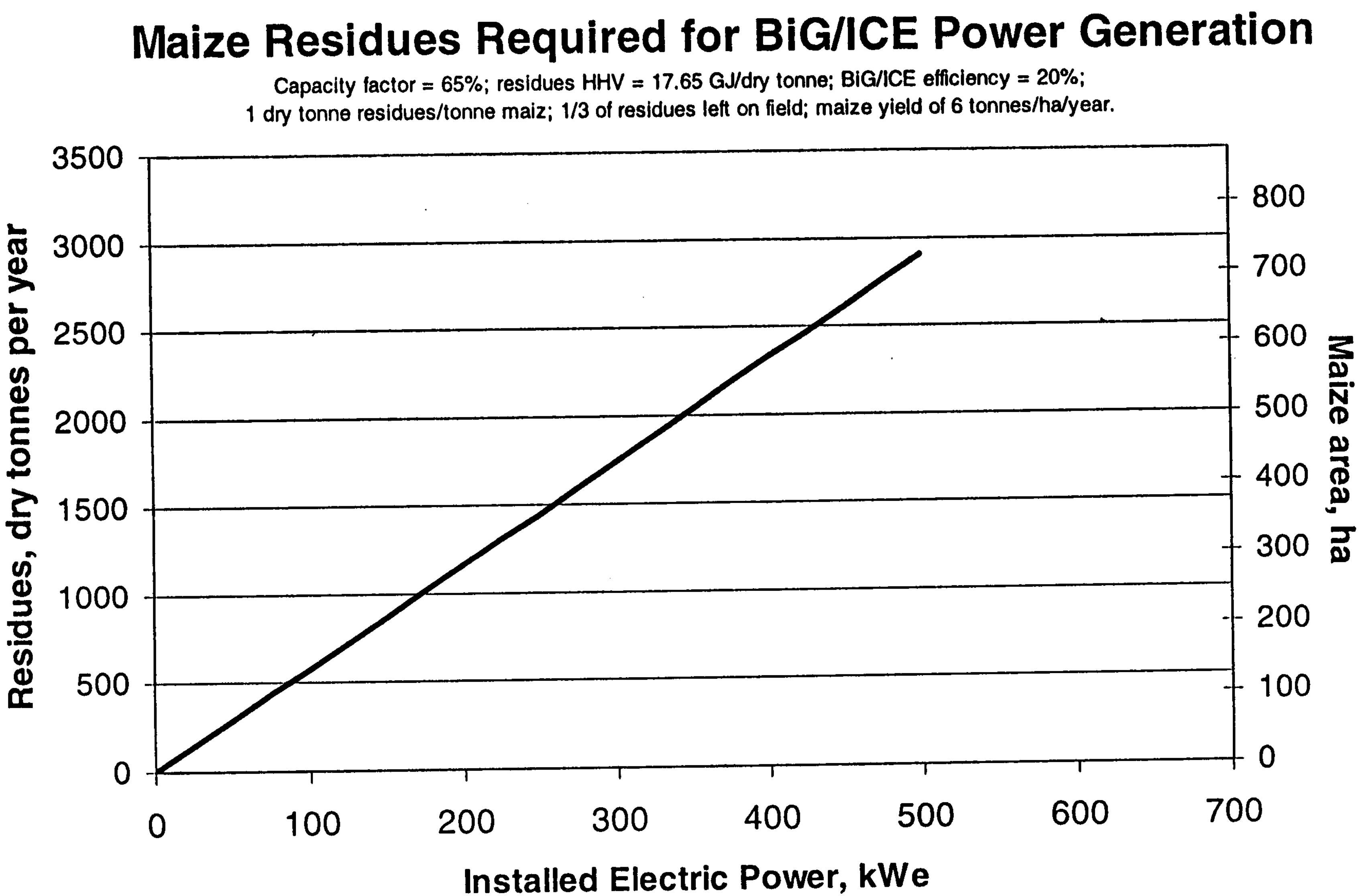
Open-Top Gasifier Designs (modified downdraft)



Capacity kilowatts	a	b	c	d	e	f	f'
	dimensions in millimeters						
3.7	150	180	1,200	250	80	500	250
20	230	300	1,650	350	145	600	300
100	350	450	2,800	500	250	850	500



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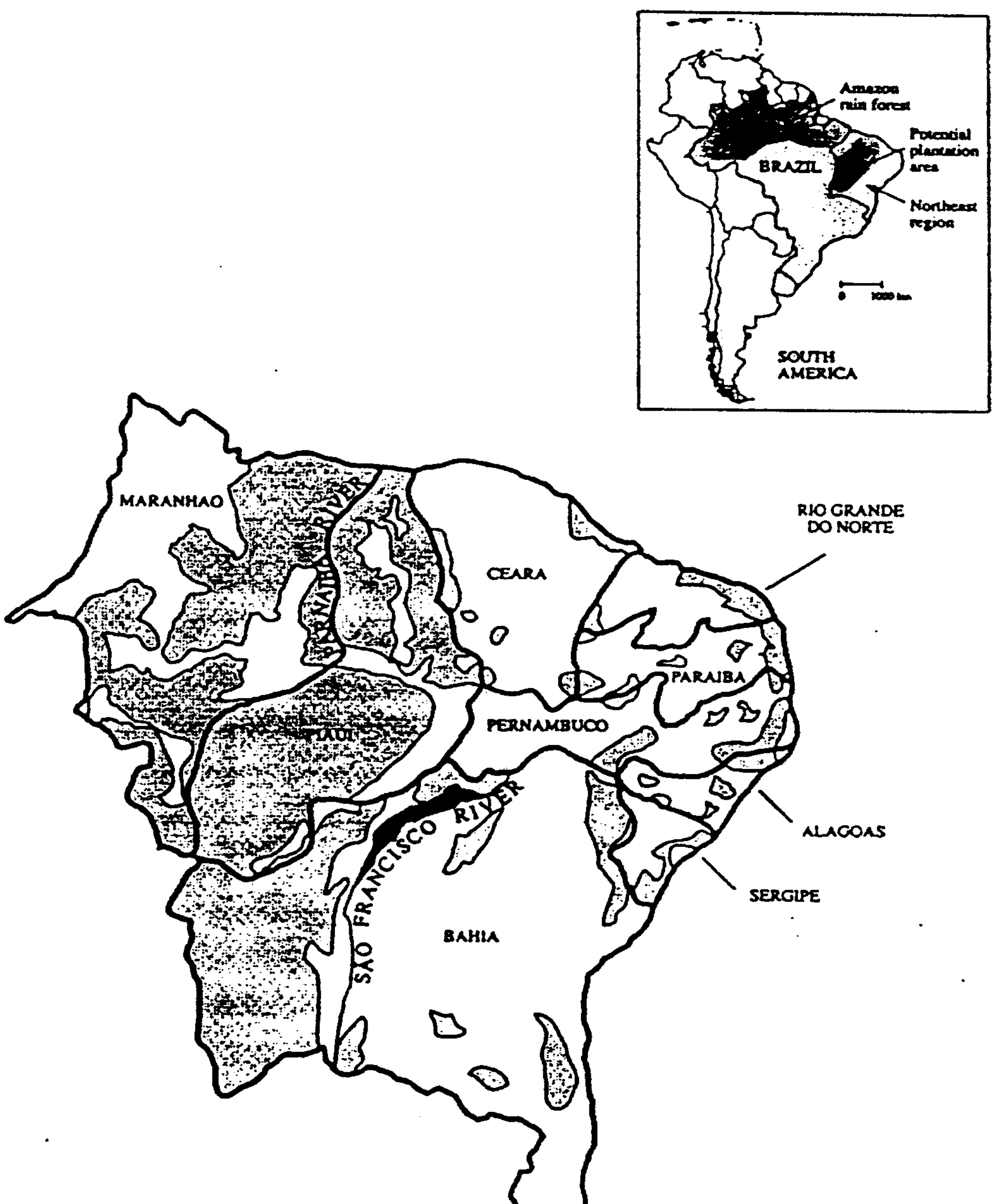
Costs for Short-Rotation Tree Plantations?

Northeast Brazil Assessment



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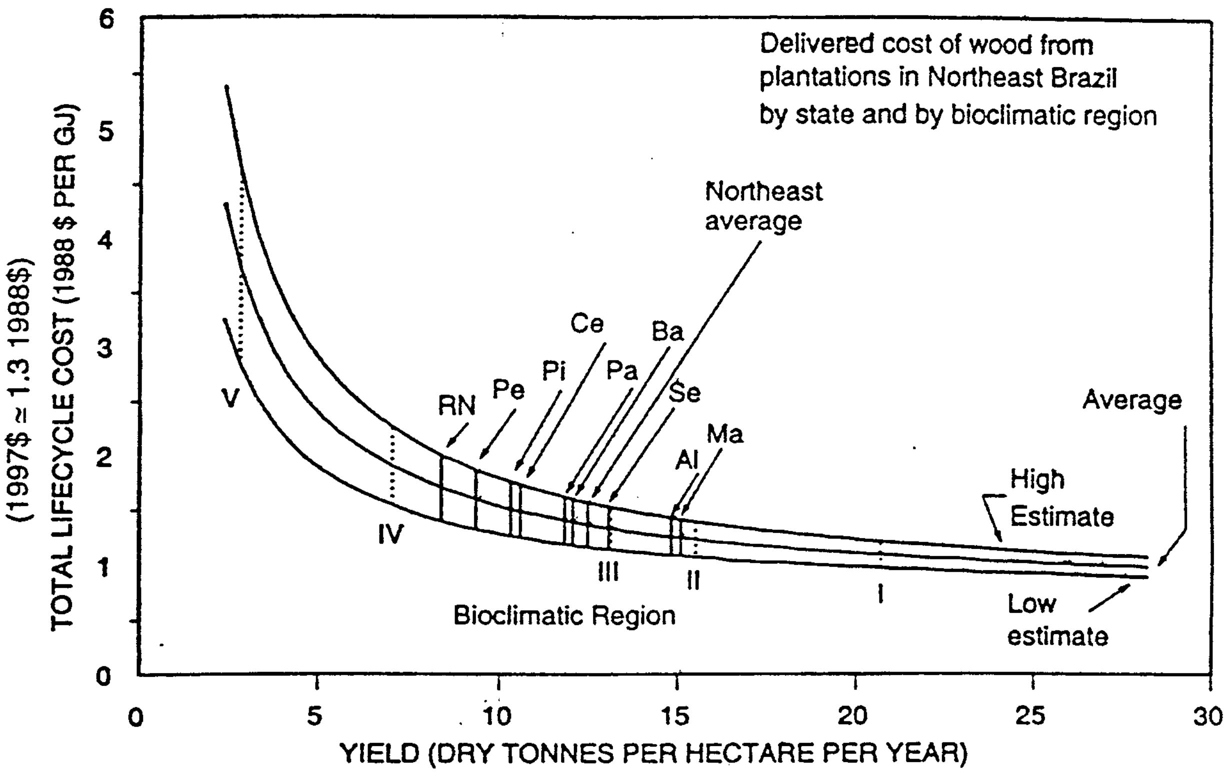

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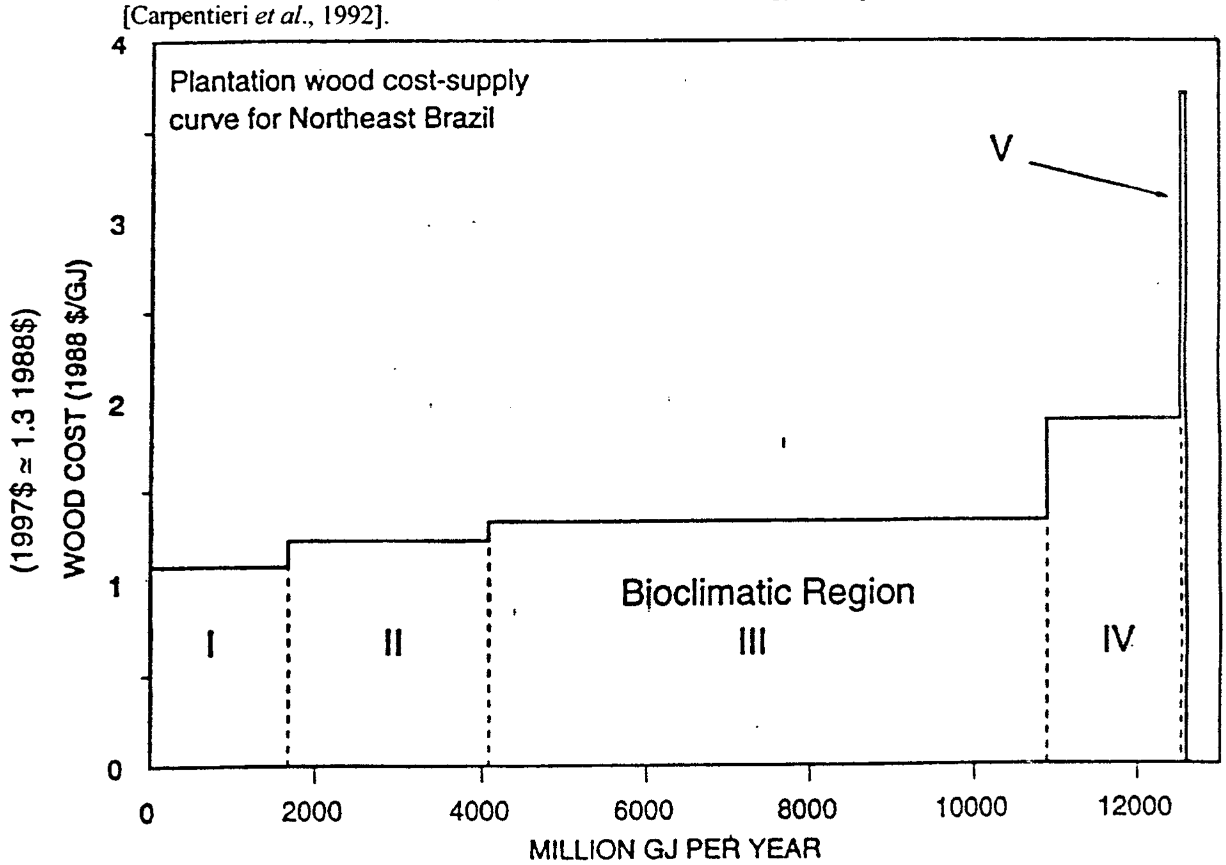

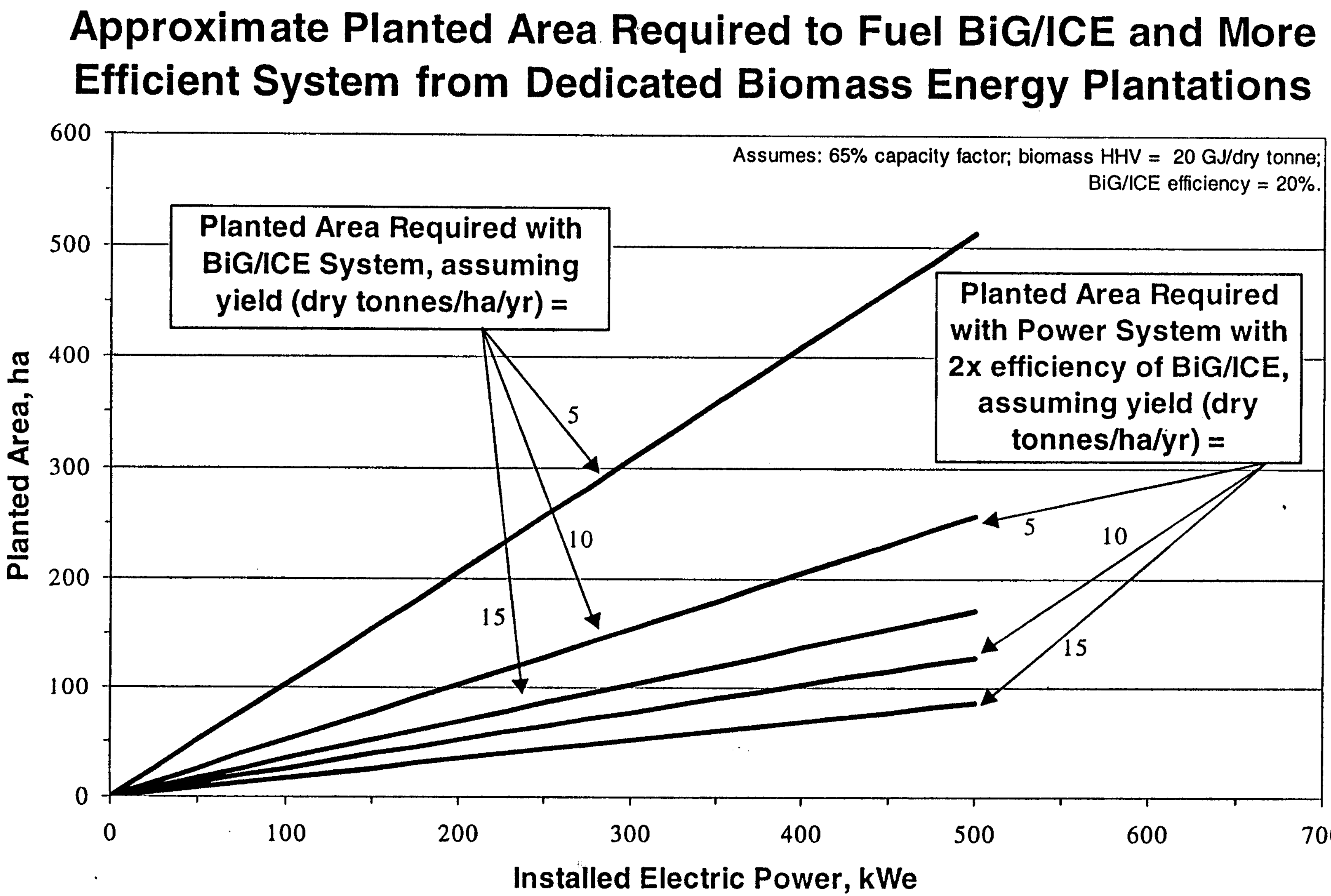

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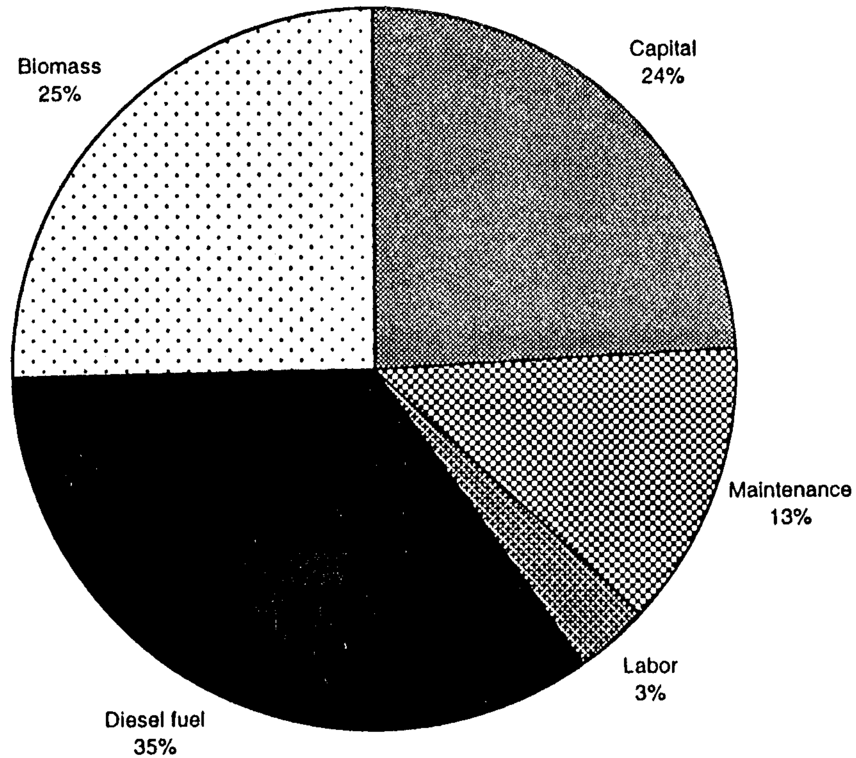
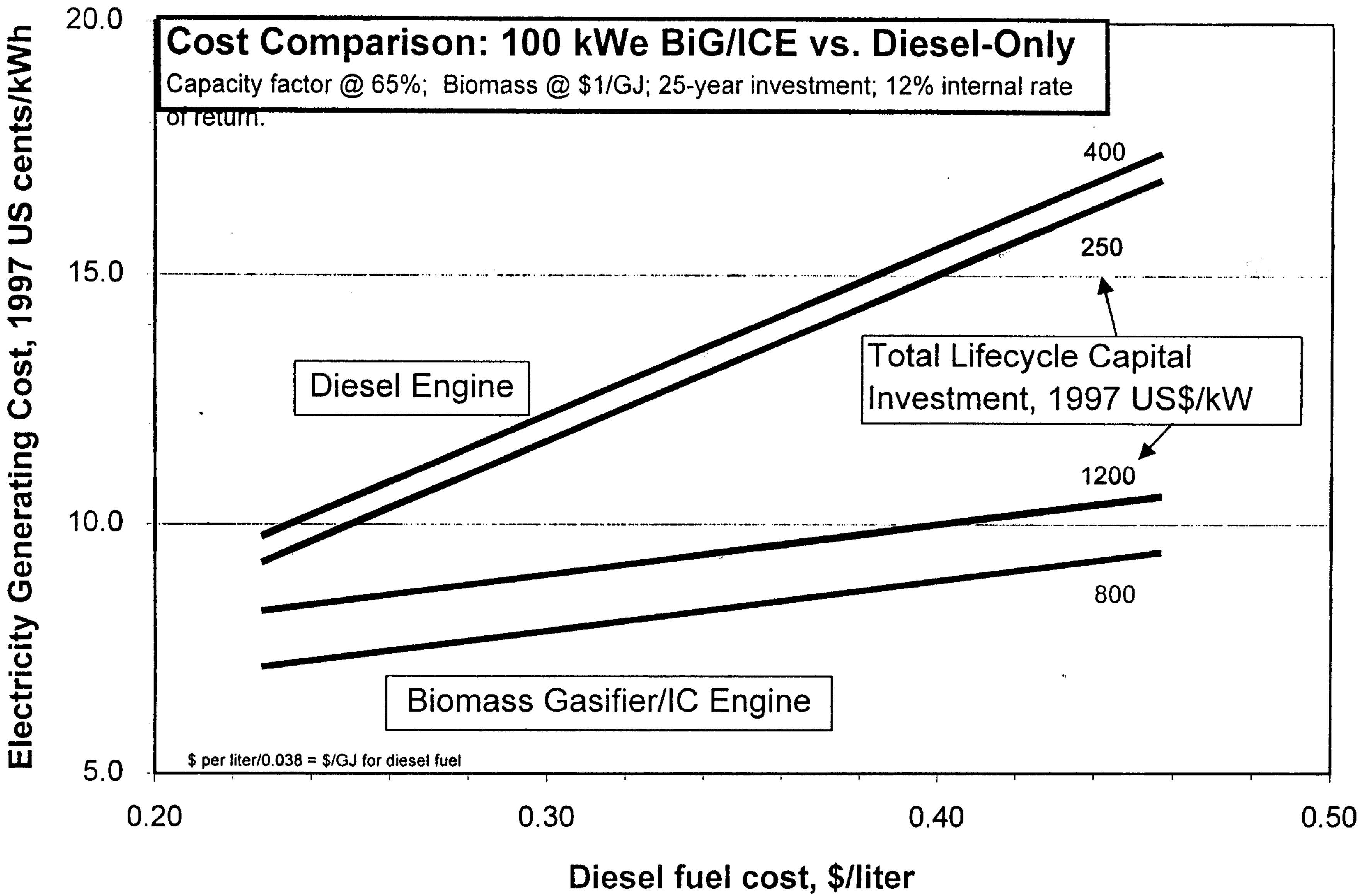
Distribution of BiG/ICE Generating Costs

Total = 7.4 cents/kWh



Assumptions: $800/kW, 65% capacity factor, 12% return on investment,
$0.26/lit and 0.08 g/kWh diesel, $1/GJ and 18.7 MJ/kWh biomass

Fig. 11. Distribution of power generating cost for a 100-kW$_e$ scale BiG/GT system.



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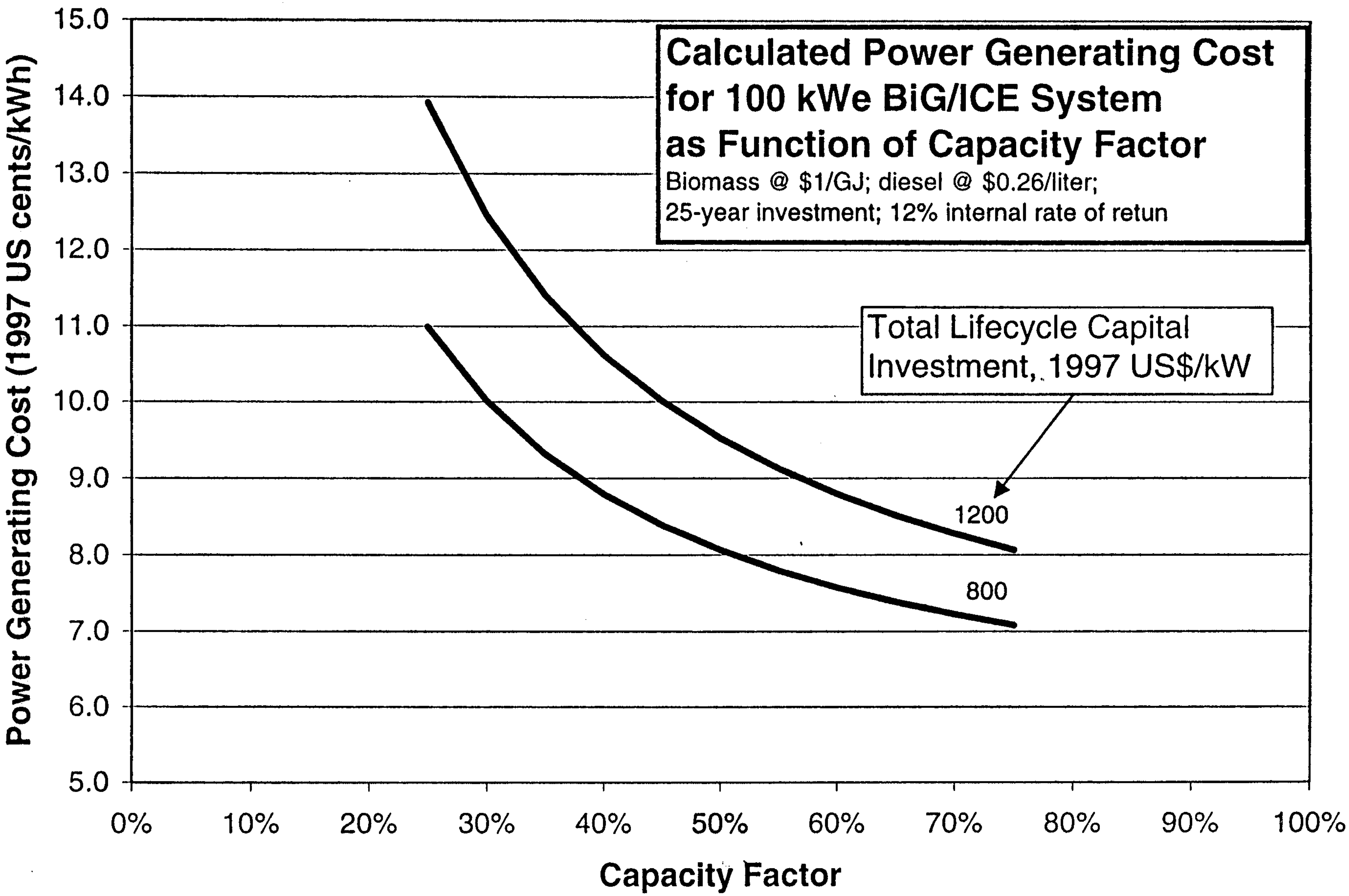

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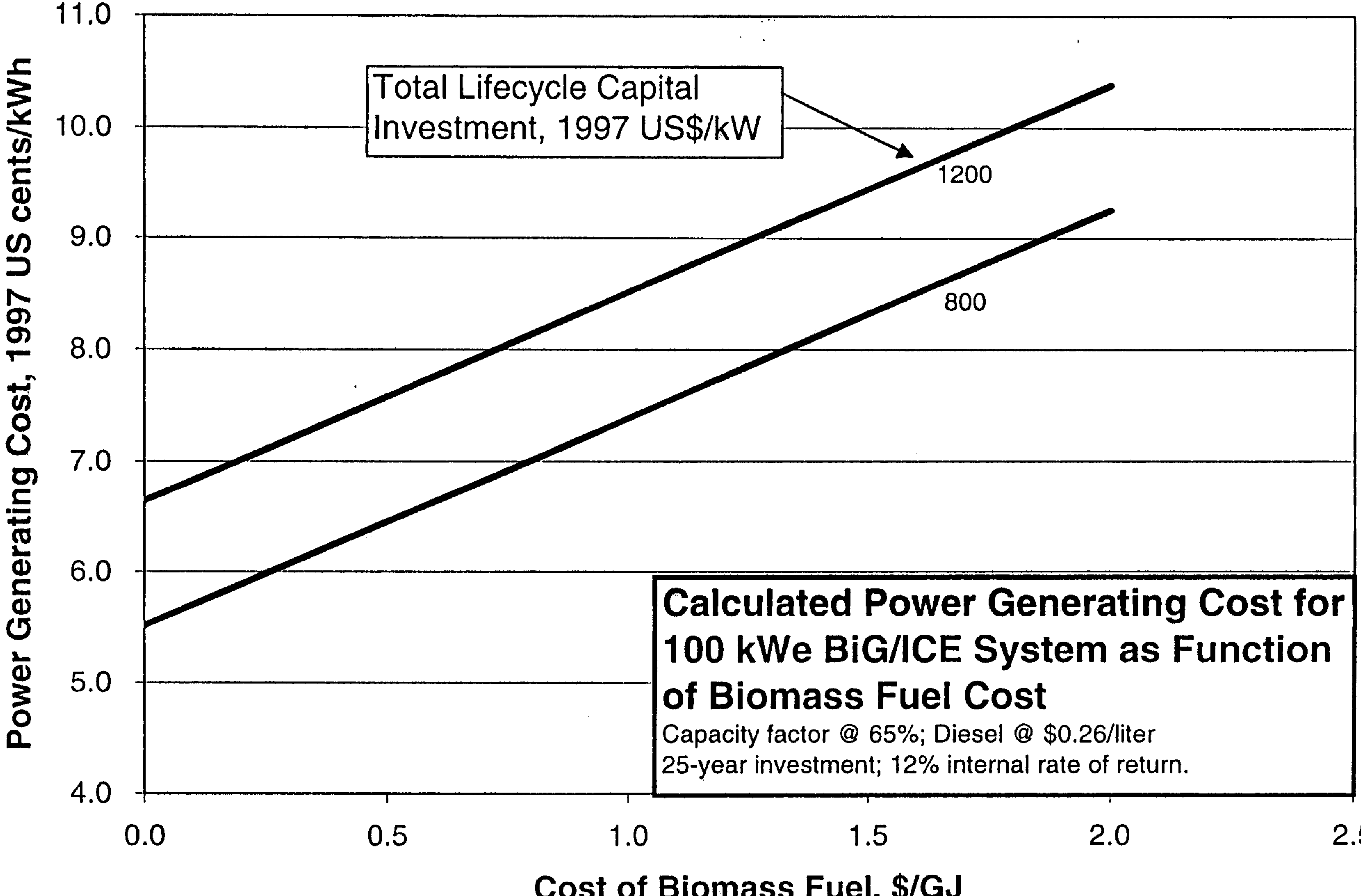

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