A Cost-Neutral Strategy for Maximal Use of Renewable Energy Sources and Energy Efficiency for Manaus, Brazil

Ashok Gadgil, Lawrence Berkeley National Laboratory
Gilberto Jannuzzi, Ennio Silva, and Maria-Lucia Leonardi, NEPAM-Environmental Research Center, University of Campinas, Brazil

We report results from a recently completed project to assess the maximum feasible cost-neutral reduction in the environmental impacts of energy demand growth in the city of Manaus located in the heart of the Amazonian rainforest. The city's energy demand has grown rapidly as a result of its on-going industrial (and population) expansion based on a ''free-trade zone'' policy. On the other hand, the large adverse environmental impact of the recent energy supply project (the Balbina hydroelectric dam) for Manaus has also been well documented. Since Manaus is located in the heart of the Amazonian rainforest (1000 km of rainforest in all directions!), it is an attractive location to explore the extent to which modern renewable and energy efficiency technologies can move it towards energy sustainability—or at least significantly reduce or delay the next expansion of its conventional energy supply project—without increasing the net present value (NPV) of the energy scenario. Our results, based only on collection and analysis of existing data, show that on a technical fix basis (i.e., without political support for broader policy changes for reducing conventional energy use), about a quarter of conventional energy consumption for the year 2002 can be cost-neutrally replaced with efficiency and renewables.

INTRODUCTION

This paper describes the results from a project (Jannuzzi et al. 1996) to develop a maximally renewable and energy-efficient cost-neutral (''MREECN'') energy scenario for Manaus. The objective of the project was to evaluate the magnitude of cost-neutral reductions in the conventional energy use (and its rapid growth) in a city in the heart of the Amazonian rainforest. The project, initiated in August 1994 and completed in February 1996, comprised collection and analysis of existing data, and meetings and interviews with experts from the energy production and end-use sectors. The MREECN energy scenario incorporates maximal use of energy-efficiency and renewable sources of energy, consistent with the constraint of ''cost-neutrality.'' By this constraint we mean that the net present value (NPV) of the total investments and expenses of this energy scenario over a horizon of 10 years will equal the NPV of total investments and expenses of supplying energy to Manaus according to a ''business as usual'' scenario over the same period. The time-horizon of 10 years was selected somewhat arbitrarily based on discussions with ELETROBRAS* planners. The MREECN energy scenario incorporates our best current estimates of available opportunities and options for reducing or delaying the environmental impact of rapid growth of energy services in Manaus at zero incremental cost, on a purely technical basis (without broader policy action requiring political support from outside the energy sector).

With interest sparked by the present results, ELETROBRAS has commissioned a follow-up project coordinated by Gilberto Jannuzzi, which is co-funded by UNDP and PROCEL (The National Electricity Conservation Program), to collect primary data on electricity end-uses for the residential, commercial and industrial sectors in Manaus. This additional work, to be completed in mid 1996, will strengthen detailed design of DSM and energy-efficiency programs in Manaus. USAID has also expressed an interest in financing implementation projects in Manaus jointly with ELETROBRAS and ELETRONORTE based on the data and analysis developed in this work.

We developed the MREECN scenario with the following steps. First we constructed an energy balance for the city of Manaus. Then we evaluated the potential of renewable energy sources and of energy efficiency in the city's energy economy. Based on this information, we constructed two scenarios: a business as usual (''Base-Case'') scenario, and an Energy Efficiency (or ''EE'') scenario in which cost-effective energy efficiency measures are implemented and some of the savings are captured. In the next step of scenario development, these savings were assumed invested in renewable energy source development. This investment leads to some additional displacement of conventional energy supply, and corresponding additional savings. These savings

*ELETROBRAS is the largest electricity generating utility in Brazil, and is also the holding company for other regional utilities. It houses many of the important national electricity and energy planning centers including PROCEL, which specifically focuses on end-use efficiency.

are again invested in more efficiency and renewables, and the calculations are repeated. The calculations quickly converge to a new scenario, the Maximally Renewable and Energy Efficient Cost Neutral (MREECN) scenario. Ideally the investment sequence in efficiency and renewables would be based on supply curves of conserved energy for efficiency, and of producing energy from the renewables (after taking into account the ''lumpiness'' of some of these investment options). However, in this effort, we have neither adequate and accurate data, nor the time to develop a rigorously optimized MREECN scenario. What we present is a first cut, although supported with existing data, but also relying on our judgment and educated guesswork.

Characterization of Manaus

Manaus is situated on the confluence of two enormous rivers, Rio Negro and the Amazon. The city of Manaus has an area of about 12,000 km^2 and a population of 1.2 million (1991). During the ''rubber boom'' of the late last century Manaus was a very wealthy city; its wealth rapidly declined with the end of rubber monopoly in 1940s. In 1967, Manaus was declared a free trade zone, ''*Zona Franca de Manaus-ZFM,*'' with special fiscal incentives for industrial assembly plants. This dramatically revitalized Manaus economy with a concurrent rapid grown in population (about 6.5% annually). Manaus contributes very substantially to the gross domestic product of the state (1990 US dollars 5.8 billion in 1991), and per capita GDP (US$ 2,900 in 1990).

The emerging industrial sector in Manaus is international in character, highly competitive and specialized. The industries show increasing domination of electrical and electronic manufacturing. The tourism industry is also gaining importance.

Environmental degradation is not an issue of significant public concern in Manaus. In terms of the large environmental impacts of energy production and utilization, there is an ecological sensitiveness concerning only the Balbina hydroelectric project, which flooded 2,300 sq. km. of virgin rainforest for about 150 MW of installed capacity in the late 1980s. Although the construction of the Balbina plant allowed the continued economic expansion of Manaus, it also continues to cause serious environmental impacts, which have even compromised the operation of the plant itself. The present thermal power plants have no environmental controls on their stack emissions. The environmental impacts of the continued expansion of energy demand in Manaus are, however, not a topic of public discussion and debate locally or regionally.

The rest of this text comprises 4 parts. (1) Energy supply and demand, (2) Assessment of options for alternate energy scenarios, (3) Energy scenarios, (4) Discussion. The development of the scenarios and the assessment of feasible investments in renewable energy and energy efficiency were necessarily iterative. However, in the interest of space, we have presented the results sequentially, thus some of the scenario results appear in the section on the assessment of energy efficiency potential in Manaus, before the section on development of the scenarios. We request you bear with this inconvenient artifact.

ENERGY SUPPLY AND DEMAND

The state of Amazonas consumes less than 1% of Brazil's delivered energy, and accounts for about 1.5% of Brazil's GDP. Approximately 87% of electricity consumption and 95% of oil products consumption in the state of Amazonas occurs in the city of Manaus. Most of the energy demand is met with production from one oil refinery, and one hydroelectric and three oil-fired thermal power plants. The overall energy consumption in Manaus has been increasing at a higher rate than that for the country as a whole.

Structure of Energy Production and Supply

We expended significant effort to construct a consistent energy balance for Manaus (Table 1). The most recent data across all the sectors were for the year 1992 for which the table is shown. In that relatively dry year, hydroelectric generation represented only about 30% of the electricity produced for the city. In the following year with normal rainfall, this value returned to the usual fraction of about 60%, and has remained stable since then.

In the energy balance (Table 1), energy use by consumption sector is shown in rows, and energy supply by various sources is shown in columns. The bottom of each column shows the quantity of energy from that source imported into Manaus.

Transport, industrial and residential sectors dominate consumption, and diesel oil, fuel oil and electricity are the main forms of energy supply. The fuel consumed to produce electricity is highly significant; it is responsible for about 50% of the equivalent primary energy consumed. The use of firewood as an energy source remains insignificant in the city.

In rest of this section, we focus on electricity consumption and supply for three reasons: (1) it is rising rapidly, (2) it has potentially very large environmental impacts, and (3) it presents many opportunities for improved efficiencies of use and of substitution with renewable energy sources.

The two immediately notable features of the electricity use in Manaus are (1) a higher average residential consumption compared to the national average and (2) a high level of

Table 1. *Manaus Energy Balance for 1992*
(Units are 1000 Tons of Oil Equivalent, TOE)

Thousands of TOE*	Electricity[1]	Gasoline[2]	Diesel Oil	Alcohol	Fuel Oil[2]*	LPG[2]*	Hydro-electric[3]	Fuel-wood[4]	Consumption Sector Totals
Residential	46	0	0		0	42		0	88
Commercial	23	1	1		0	0		0	25
Public sector	8	2	3		0	0		0	13
Industrial	36	1	25		8	2		32	104
Transport	0	57	112	30	6	0		0	205
Others	13	1	136		62	3		0	215
Sub-totals	126	62	277	30	76	47		32	650
T&D losses	40								40
Electricity generation	−166	0	122		222	0	167	0	345
Energy Source Totals		62	399	30	298	47	167	32	1,035

Sources: ELETRONORTE, PetroBras and authors' estimates.
Note 1: in terms of secondary energy (1 MWh = 0.09 toe)
Note 2: estimated
Note 3: in terms of primary energy (1 MWh = 0.29 toe);
Note 4: estimated assuming a 1.9% annual growth rate during 83-92.
Note 5: The first column, electricity, and the seventh column, hydroelectricity, need special mention. In the first column, the energy content of electricity is shown at the secondary energy conversion rate (i.e., equal to the resistance heat produced with the electricity). In that column, the total electricity generation (thermal plus hydroelectric) shows up as a negative number in the second cell from the bottom, since it is a source, not a sink. Note that in the row for electricity generation, we have entries for fuel consumption (diesel and fuel oil) by the fossil-oil burning power plants. In the column titled hydroelectricity, the energy content of electricity is shown at the primary energy conversion rate (i.e., equal to the heat content of the fuel that would have to be burnt to produce that much electricity in a power plant). This treatment is consistent with standard practice.

technical and commercial losses. These losses comprise commercial losses (i.e., clandestine connections and theft of electricity), and technical losses (i.e., resistive losses in transmission and distribution), and have grown from 15% of sales in 1985 to 25% of sales in 1995.

The peak (i.e., the maximum) demand of Manaus electricity system has increased at a rate of 9.5% per year since the 80's, reaching 314.5 MW in 1990, and 363 MW in 1994. The load factor has fluctuated between 61% and 68% during that period, although in 1995 it rose to 85%. The increase of the load factor in Manaus in recent years is the direct result of a jump in the industrial growth in that area, as result of governmental economic policy. The electrical and electronic industries located in Manaus dominate the national market. The recent boom in the sales of consumer electronics in the country has fueled rapid expansion of these industries in Manaus. On the other hand, the local electrical capacity has been almost stagnant, with no initiatives until this year for demand side management (DSM). Thus the reserve system capacity has been slowly eroded.

Options under Consideration for Increasing Electricity Supply. Owing to the rapid growth in the industrial demand, particularly in 1995, the electrical system is already facing capacity problems from early 1996. (Tavares 1996). This has drawn the attention of ELETROBRAS and ELETRONORTE officials, who are implementing emergency measures for the Manaus system during this year, including end-use efficiency programs with the assistance of some of the co-authors of this paper.

Four options are being currently considered by the utilities for new electricity supply for Manaus (1) a new hydroelectric dam and hydropower plant at Cachoeira Porteira, (2) the use of natural gas from Urucu and Jurua fields for electricity generation with gas turbines, (3) establishing a transmission interconnection with Guri (Venezuela), and (4) establishing a transmission interconnection to Tucuruí Power Plant. These supply options are all mutually exclusive and each has a high initial cost and a significant environmental impact. Owing to the (uncertain) lead time needed for the political decision on option selection, and then an additional lead time (about 10 more years) on its engineering implementation, none of the options can be expected to be on-line within the time horizon of this study (i.e., within 10 years).

Although the use of local natural gas resources (from Urucu and Jurua) appears to have the strongest technical recommendations, developmental considerations for other parts of the region favor other choices. Thus it is unclear at the present which one will be selected. Owing to the large lead time for whichever option gets chosen, we assume in our energy scenario development that conventional supply (in the form of a smaller sized oil-fired power plant, common to this region) would be implemented by the utilities as an interim measure for Manaus.

Structure of Electricity Consumption

Of the electricity consumers in Manaus, 91% are residential, 7.5% commercial, and less than 0.7% industrial. The residential sector is responsible for 36% of the total electricity consumption, the commerce and service sector for 18%, and the industrial sector for 32%. The rest (14%) of the electricity is consumed for diverse uses such as supply to rural consumers, street lighting, power plant self consumption, water works, etc. (ELETRONORTE 1992). A significant percentage of residential consumers (estimated 16%, Dutra 1994) have irregular connections to the electric grid[1]. The industrial bulk consumption of electricity (i.e., the high voltage consumption segment), has grown rapidly at about 6.2% per year from 1982 to 1993, compared to the rate of increase of only 1.5% for consumption by small and medium industries with low voltage consumption. The number of high voltage consumers represent less than 5% of the number of industrial consumers, but account for 60% of the total industrial electricity consumption.

The use of air conditioning is widespread in residential, commercial, and public buildings. Regrettably, the architecture of these buildings and of new construction (900,000 sq. m. of new building construction permits were issued in 1990 alone, SPEM 1994) shows little regard for climate-sensitive design. New buildings are predominantly of designs suited for cooler climates of Europe, North America or Southern Brazil. Thus we expect air conditioning demand to continue to rise rapidly in the future.

Only 15 industries account for 50% of the industrial electricity consumption of Manaus. Of these, 3 are considered power-intensive: an oil refinery, a cement plant and a steel plant. Although the energy consumption in the industrial sector is increasing, a small reduction in the energy intensity is noticeable. It means that less electrical energy (kWh) is being consumed for each US$ of goods produced. This seems to be a result of the ongoing intense restructuring of the industrial sector in the ZFM, owing to the increasing presence of high-technology industries (e.g., electronics) of relatively lower energy intensity.

ANALYSIS OF OPTIONS FOR DEVELOPING ALTERNATE ENERGY SCENARIOS

In this section, we describe the assessment of renewable energy sources and energy efficiency potential for the Manaus region for the MREECN scenario development. In this and subsequent sections, we use the term ''short-term'' to refer to the period within the scenario horizon (i.e., 10 years), and ''long term'' to mean a period of several decades.

Assessment of Renewable Energy Sources in Manaus

The renewable energy sources investigated for the Manaus region are the following.

(a) Solar Thermal Energy: low temperature thermal for solar hot water production (this would replace current electric resistance heating in residential and commercial sectors); (b) Solar Photovoltaic Electricity (possible mostly on the rooftops in the city); (c) Biomass for the production of fuels (solid, liquid and gas) and electricity; (d) Wind energy for water pumping and electricity production; and (e) Hydro Energy: electricity production.

Our estimates of the long and short term potentials of these sources are summarized below. Wherever background data for these calculations were not available, we have had to make best estimates based on our judgment and discussions with various experts, for the likely magnitude of the missing data values. Thus, the estimates below have accuracy of only the first significant digit.

Solar Water Heating. Presently hot water is produced in residences and hotels almost exclusively with electric resistance heating. This is obviously a wasteful use of electrical energy, some of which could be profitably replaced with solar water heating. Owing to the industrially dominated loads on the Manaus system, water heating load appears to be off-peak.

For the residential sector, we estimated the long term potential for substituting electric water heating with solar water heating using the following assumptions. (1) households consuming more than 200 kWh/month would be able to replace 50% of their electricity use for water heating with solar energy. (2) households using 200 kWh or less per month would be able to replace 25% of their electricity use for water heating with solar energy. The long term annual potential for electricity savings for domestic water heating are then 6,300 toe[2]. The estimate of short term potential assumes that only the households consuming more than 200 kWh/month would reduce their electricity consumption for water heating by 25%. This results in a short-term annual potential for electricity savings of 2,500 toe.

For the commercial sector, we estimated the long term potential assuming that the present electricity use for water heating can be reduced by 50%, or 2,000 toe/year. The estimate of the short term potential assumes a 25% reduction in the present level, or 1000 toe/year. Lastly, we estimate that the potential for solar water heating in the industrial and public sectors is insignificant.

From the utility perspective, the cost of conserving electricity using solar hot water systems assuming incentives and price structure identical to those for Campinas (Madureira 1995; CPFL 1995) is US$ 20 / MWh.

Solar Photovoltaic (PV) Electricity. For estimating the long term potential of solar PV electricity, we assumed that 0.3 % of the surface area of the municipality of Manaus (i.e. 3,500 ha, which equals the area currently under agricultural cultivation around Manaus) would be devoted to solar PV electricity production. We assumed solar PV conversion efficiency of 10%, and daily insolation of 18 MJ / sq. m. This results in annual electricity production equivalent to 1.85 million toe.

The production cost of PV electricity is estimated to be US$ 160 / MWh, based on utility bulk purchase of PV systems in the international market, and practical experience both internationally (Weinburg & Williams 1990) and in the Sao Paulo region (CESP 1985) which has insolation similar to that of Manaus.

Biomass Energy via Ethanol for Liquid Fuels. We estimate the maximum technical potential for ethanol production assuming that an area equal to the present agriculture area (3,500 ha) is used for cassava plantation for ethanol. This will annually produce 8,200 toe of ethanol. The short term potential for economically feasible local production is considered negligible owing to the currently low international price of oil, the long lead time required for commercial ethanol production under the conditions in Manaus, and the unlikely availability of government subsidies for new producers of biomass based ethanol.

Biomass Energy via Fuelwood for Electricity. A regulation currently protects a 20 km green belt surrounding the present city of Manaus. However, this by itself is not seen as a serious constraint, since enough degraded lands exist in the vicinity of Manaus which could be used for biomass plantation. Although rainforest soils are nutrient poor, and clear-cutting typically washes away the rich forest detritus leaving only bare degraded land, selective harvesting and other forestry strategies could keep the fuelwood plantation viable. However, larger issues (for example see Fearnside 1995 and the extensive references cited therein) relating to the likely adverse environmental impact of commercial production of fuelwood around Manaus raise serious doubts regarding the advisability of this option. We nevertheless present the technical potential below.

For estimating the maximum technical potential of fuelwood production, we assume that 20,000 sq. km. of degraded land area around Manaus is gradually converted to commercial fuelwood production, with a harvesting cycle of 20 years. The harvested wood fuels a 500 MW thermal power plant annually producing 3000 GWh of electricity. In the short term we estimate that a 80 MW capacity wood fired electricity plant could deliver 480 GWh/year of electrical energy. Assuming a conversion factor of 0.29 toe/MWh (in primary energy) this gives 850,000 toe for the maximum technical annual potential and 140,000 toe for the short term annual potential. The production of cost of electricity from fuelwood is estimated by Brazilian electric utilities (Poole, Ortega & Moreira 1990) to be US$ 40 / MWh for power plants of this size.

Biogas for Energy. The maximum technical potential is based on the present rural bovine population in the Manaus municipal region. This leads to a production equivalent of 1,600 toe/year; the short term potential assumes that 25% of this can be economically and technically produced.

Vegetable Oils for Liquid Fuels. The maximum technical potential for vegetable oil production is estimated assuming arbitrarily that an area equal to the total present agricultural land area (3,500 ha) is used for vegetable oil production for liquid fuels for energy. This leads to a production potential of 15,000 toe/year. For the short term it is assumed that only 10% of this amount can be economically and technically produced. There are serious technical problems in implementing commercial agroforestry over large areas of the Amazon rainforest. These problems will have to successfully addressed by any program planning to use biomass for energy (either through vegetable-oil or direct biomass for fuel). See Fearnside (1988) for a discussion of problems facing a 16,000 sq. km agroforestry investment at Jari in the northern region of the Amazon.

Wind Energy. The potential for wind energy in Manaus is negligible from technical and economic viewpoints.

Hydroelectric. The potential for mini-hydro power is negligible. The hydroelectric dam and power plant at Cachoeira Porteira will produce electricity at an estimated cost of US$ 30–35/MWh (including the cost of transmission facilities to Manaus). This project is located 480 km from Manaus and will initially have a capacity of 700 MW with a future planned expansion of another 700 MW in a second phase. Setting up the hydroelectric plant would submerge a portion of the virgin rainforest in the reservoir, as happened at the Balbina hydroelectric power plant in the last decade. However, the utilities note that the submergence to power ratio (i.e., the ratio of forest area submerged / installed MW) for this project will be about ten times smaller than the corresponding ratio for Balbina (about 15 sq. km / MW). Given the difficulty of removing the standing timber from even the close-by Balbina forest before its flooding, it seems certain the 2000 sq. km. standing rain forest in the region of the reservoir of Cachoeira will almost certainly be flooded and left to rot. Owing to its long lead-time and political uncertainty, we have not included this project in our renewables assessment within the 10-year planning horizon.

Table 2 summarizes the potential of supplying energy and power from the various renewable energy sources in Manaus region, in terms of the technical potential and short-term (i.e., over a ten-year horizon).

Table 2. *Potentials of Various Renewable Energy Source Near Manaus*

Energy Source	Max. Technical Potential (1000s of toe/year)	Short Term (10 yr.) Potential (1000s of toe/year)	Cost (for the short term) US$/toe
Solar Hot Water			
residential	6.3	2.5	138 *
commercial	2	1	69 *
industrial	—	—	
public sector	—	—	
Solar Electricity			
photovoltaic	520		190 **
Ethanol production			
through Biomass	8	neg.	260 ***
Electricity through fuelwood			
wood plantation	851	139	138 +
Biogas	1.6	0.4	250 ++
Vegetable oils			
for liquid fuels	1.5	1.5	400 +++
Wind Energy	—	—	

* assuming the same costs for solar hot water as in Sao Paulo region, US$ 20/MWh (commercial sector) and 40 US$/MWh (residential sector). Costs estimated from the electric utility perspective. (Madureira 1995; CPFL 1995)

** assuming the same PV electricity costs as for Sao Paulo region, US$ 160/MWh (CESP 1985; Weinburg & Williams 1990).

*** assuming US$ 500/m^3 alcohol production costs in the region (this is 20% higher than Sao Paulo production costs, Authors' estimates), and $1m^3 = 0.52$ toe.

\+ assuming electricity from fuelwood at 40 US$/MWh, and 1 MWh = 0.29 toe (Poole 1990)

++ based on a study carried out by the Sao Paulo Electricity Company -CESP for biogas production costs (Bertasso 1994).

+++ authors' estimates

Assessment of Energy Efficiency Potential in Manaus Over 10 Years

We present our assessment of the energy efficiency potentials in the residential, commercial and industrial sectors of Manaus over the 10 year time horizon of this planning study. These are our best estimates based on the 18 months of effort reported here. Subsequent deeper surveys, collection of primary data and reanalysis (currently underway) will doubtless lead to some revisions in these estimates.

Tables 3–5 show the savings potential of electricity efficiency measures in the city under both scenarios. The costs of conserved energy in the energy efficiency (''EE'') scenario are based on corresponding costs in other parts of Brazil (Jannuzzi 1993) and assume a discount rate of 12% (utility perspective). For the more aggressive MREECN scenario, we assume spending more effort (and money) for achieving higher saturation, and also implementing the efficiency measures in some of those marginal end-use situations where no implementation took place in the EE scenario. Both these effects will raise the amount of energy saved,

Table 3. Electricity Consumption (GWh) and Demand (Peak MW) Actual for 1992, and Projections for 2002 for Manaus

Consumption (GWh)	Year	Residential	Commercial	Industrial	TOTAL
Actual	1992	574	347	432	1354
ELETRONORTE Scenario	2002	1081	666	1276	3488
Base Case	2002	1082	606	1201	2889
EE Scenario	2002	998	514	995	2507
MREECN Scenario	2002	976	495	983	2453
Demand (MW)					
Actual	1992	79	109	117	305
ELETRONORTE Scenario	2002	na	na	na	695
Base Case	2002	153	204	325	686
EE Scenario	2002	130	178	270	578
MREECN Scenario	2002	112	151	243	506

but also raise the CCE. Without the availability of detailed supply curves of conserved energy across the implementation distribution for each separate efficiency measure, we have had to work from our judgment in guessing how much higher investments (and CCE) for MREECN will produce how much more savings. The CCE numbers in the tables under the MREECN column reflect our judgment, rather than hard engineering-economic analysis. The annual energy savings estimated in the EE and MREECN scenarios depend on the efficiency increase in each of the newly implemented end-use technologies, and their respective annual hours of use, as well as on the saturation of the implementation of respective efficiency improvements.

The other sectors (public sector, transportation, self-consumption by the oil refinery and thermal power plants etc.) were not studied so far, and are not reported here.

ENERGY SCENARIOS FOR MANAUS

The development model for the country's North region relies on the creation of the Free-Trade Zone of Manaus. Some experts have questioned the long-term viability of this model, and its mid and long-term socio-economic feasibility. These matters obviously affect any consideration of the future energy demand in Manaus. However, as the most likely scenario, we assumed that for the period 1992–2002, there will be no significant changes in the current development model for the region. This assumption also has the unanimous support of the experts participating in this analysis. Furthermore, we do not address in this paper the issues relating to the social, economic, and environmental consequences of the ZFM creation and operation.

The structure of energy consumption in Manaus is strongly influenced by the existence of the Free-Trade Zone (which determines the local economy, the population features, demand for services, etc.). Therefore any significant change in the ZFM status would imply a significant change in the city's structure of energy consumption, and modify substantially the structure of future energy scenarios from those presented here. Furthermore, as can be expected, the ZFM is very sensitive to outside events and decisions (e.g., import and export politics of various countries, fiscal incentives, customs duties and quotas, growth or decline in economic

Table 4. *Residential Sector: Average Costs and Potential of Energy Conservation*

End-Use Measure	CCE US$/kWh		GWh saved in 2002	
	EE	MREECN	EE	MREECN
Replace incandescents with CFLs	0.02	0.04	2.61	3.13
Use efficient motors for fans	0.03	0.06	0.94	1.50
Efficient Air Conditioners	0.08	0.16	32.78	43.71
Electronic Ballasts for fluorescent lamps	0.06	0.10	3.35	3.73
Efficient Single-door Refrigerators	0.07	0.12	24.20	28.23
Efficient Two-door Refrigerators	0.07	0.12	7.38	8.60
Efficient Freezers	0.07	0.12	6.53	8.71
Insulation for Water Heaters	0.10	0.15	1.94	2.99
Other	0.10	0.18	4.70	5.16

Table 5. *Commercial Sector: Average Costs and Potential of Energy Conservation*

End Use Measure	CCE US$/kWh		GWh saved in 2002	
	EE	MREECN	EE	MREECN
Lighting	0.03	0.04	28	32
Air Conditioners	0.09	0.13	35	46
Refrigeration	0.07	0.09	20	26
Other	0.10	0.15	6	7

activity various parts of the world). Thus our energy demand projections for Manaus are to be taken with this caveat.

Energy Consumption and Peak Demand under various Energy Scenarios

Continuing to focus on electricity, we first construct two scenarios for Manaus, each with a time horizon of 10 years, and projecting the peak demand (MW) and the annual electrical energy consumption (GWh). The energy demand components of the two scenarios were based on our examination of the structure and rates of growth of different end-uses of energy in Manaus. Our assumed rate of economic growth for Manaus up to the period 2002 appears to agree well with that used by ELETRONORTE in its projections (as far as could be estimated from an examination of their various documents). However, our business-as-usual (here called the ''Base Case'') scenario predicts a somewhat smaller peak demand (MW) and consumption (GWh) than theirs.

The Base Case scenario assumes a background rate of energy efficiency improvements consistent with historical trends. It assumes no use of renewables, nor any plans to accelerate the implementation of energy efficiency in Manaus. Then we constructed an alternate electricity scenario which assumes accelerated implementation of cost-effective energy efficiency measures (those for which CCE is below the current production cost of electricity). We call this scenario the EE scenario. We then estimated the societal costs (in terms of the net present value of energy supply investments, including investments for efficiency for EE scenario, and operating costs) over the period 1992–2002 for the Base Case and EE scenarios. The MREECN (maximum renewable and energy-efficient cost neutral) scenario represents the case where the capital stream of investments and operating costs in the MREECN scenario has the same NPV as that for the Base Case scenario. Since renewable energy supply options remain somewhat more expensive than conventional ones in Manaus, the cost-neutrality constraint on an MREECN scenario meant in reality that the savings achieved from accelerated implementation of energy efficiency were

Table 6. *Industrial Sector: Average Costs and Potential of Energy Conservation*

	CCE US$/kWh		GWh saved in 2002	
End Use Measure	EE	MREECN	EE	MREECN
Motors	0.03	0.06	156	161
Process heating	0.08	0.16	16	19
Direct heating	0.09	0.18	27	28
Lighting	0.04	0.08	7	8
Other	0.08	0.16	0	0

Table 7. *The Electricity Capacity and Consumption Growth Under the Scenarios 1992–2002*

	Inst. Capacity, MW			Annual Consumption, GWh			Peak Demand, MW		
Year	MREECN	EE	Base Case	MREECN	EE	Base Case	MREECN	EE	Base Case
1992	610	575	575	1354	1354	1354	305	305	305
1993	610	575	575	1464	1469	1507	325	332	343
1994	610	575	575	1575	1584	1661	345	359	381
1995	610	575	575	1686	1700	1814	365	387	419
1996	610	605	705	1796	1815	1968	385	414	457
1997	610	605	705	1907	1930	2121	406	441	496
1998	610	605	705	2018	2046	2275	426	468	534
1999	610	605	705	2128	2161	2428	446	496	572
2000	610	605	705	2239	2276	2582	466	523	610
2001	610	605	705	2349	2392	2735	486	550	648
2002	610	605	705	2460	2507	2889	506	578	686

invested to pay for the cost differential between the renewable and conventional energy supply options. After we have fully invested in the renewable potential for environmentally acceptable investments, we invest the remaining capital in efficiency measures beyond those that are currently cost effective. Hence the penetration of efficiency measures in MREECN scenario is above the market-driven saturation assumed in the EE scenario (making the aggregates of efficiency measures in MREECN more expensive than those in the EE case (tables 3–5)). Table 6 summarizes and compares our base case and EE and MREECN scenarios projections, by sector, to those of ELETRONORTE for the year 2002.

Feasibility of Investments in Renewable Energy Sources in Manaus

Although hydro-power has a large technical potential, there is great environmental concern regarding (and even strong opposition to) the construction of large hydroelectric plants in Amazonia region, due to first the prediction and later the

Table 8. *Stream of Yearly Expenses (Capital and O&M) for Each Scenario (In millions of undiscounted 1992 US$)*

	Conventional Elect. Production			Energy Efficiency		Wood-fired Plant	Solar Thermal	Solar PV
Year	Base Case	EE	MREECN	EE	MREECN	MREECN	MREECN	MREECN
1992	156	156	142	0	0	10	0	0
1993	173	169	153	2	4	10	0.9	0.08
1994	191	182	165	4	8	10	1.8	0.16
1995	209	195	176	6	13	10	2.7	0.24
1996	213	209	186	8	17	11	3.6	0.32
1997	231	220	197	11	21	11	4.5	0.40
1998	246	233	209	13	25	11	5.4	0.48
1999	264	246	220	15	29	11	6.3	0.56
2000	276	259	232	17	34	11	7.2	0.64
2001	294	273	243	19	38	11	8.1	0.72
2002	312	285	255	21	42	11	9.0	0.80
NPV#	1,286	1,226	1,102	49	97	64*	21**	2+

Notes: # NPV is of course in discounted dollars, all other rows in this table are not.
assuming production, transmission and distribution costs of:
* = 83 US$/MWh,
** = 90 US$/MWh and
+ = 160 US$/MWh

unfortunate confirmation of the large environmental damage caused by the construction of hydroelectric power plant at Balbina (e.g., Fearnside 1989). Besides, the lead time for constructing a large hydro-power dam puts it outside the 10 year horizon of this exercise. Therefore, the constructions of hydro-electric plants have not been considered in the MREECN scenario. Both options of installing power transmission lines to Manaus entail similar distances and costs. Between them, the option of a transmission line from Tucuruí is generally favored by the Expert Advisory Committee for this project (primarily comprising Brazilian power and environmental experts), for potentially bringing more benefits to the country and to Brazil's North Region.

Establishing a large wood plantation and its sustainable harvesting and use for electricity production presents the largest technical potential for renewable electricity generation for Manaus. However this technology is not yet mature, and must be therefore introduced on a small scale and then expanded in scope as its technical, environmental and economic feasibility is monitored and proven. These issues are still considered open questions. Furthermore, several rainforest experts who have examined the impact of modern civilization on Amazonian rainforest suggest that while fuelwood plantations may be initially established on degraded lands, low environmental awareness and the lax regulatory enforcement will quickly lead to tracts of virgin rainforests being converted to fuelwood plantations for commercial gain, resulting in more harm than good from this technology. With these reservations, the MREECN scenario makes only a modest investment in wood-fired thermal power plant. It is straightforward to construct alternate MREECN scenarios

Table 9. *Scenario Results Year 2002: Summary Table*

Electricity Demand (GWh)	Base Case	EE	MREECN
Electricity Production (GWh):			
Conventional Production	2889	2507	2217
Firewood plant	—	—	138
Solar Water heating	—	—	100
Solar Photovoltaic	—	—	5
Conserved with Energy efficiency	—	382	429
Total GWh supplied to Manaus	2889	2889	2889
Total Electricity Production Costs Millions of 1992 dollars, NPV over 1992–2002	**Base Case**	**EE**	**MREECN**
Conventional Production	1286	1226	1102
Firewood	—	—	64
Solar Water heating	—	—	21
Solar Photovoltaic	—	—	2
Energy Efficiency	—	49	97
Total Scenario Costs 1992 US dollars, NPV over 1992–2002	1286	1275	1286

with all investments only in non-fuelwood options and without any fuelwood-fired electricity production.

One of the large energy supply problems in Manaus is the river-based import of liquid fuels over a long distance. However, the potential of liquid and gas renewable-fuel production (i.e., ethanol production from sugar-cane and cassava, bio-diesel from dendê oil, and biogas from agricultural residues), is insignificantly small in the short-term.

Evolution of Installed Electrical Capacity under the three scenarios

Table 7 shows the required growth of the installed electrical capacity during 1992–2002 to meet the city's energy demand under the Base Case, Energy-efficiency (EE) and maximum renewable energy-efficient and cost neutral (MREECN) scenarios. The NPV of energy supply costs (i.e., investments and operating costs) during 1992–2002 was calculated for the Base Case and EE scenarios with a discount rate of 12%. In this calculation of NPV, all generation investments were assumed to have a lifespan of 30 years, and were assumed to depreciate linearly. The NPV of energy costs for the period 1992–2002 for the Base Case scenario would be US$ 1.286 billion (1992 US$) and for the EE scenario US$ 1.226 billion. However, the EE scenario also requires a stream of investments for energy efficiency measures. These have an NPV of US$ 49 million. Thus the EE scenario represents savings with an NPV of US$ 11 million over the period 1992–2002. The MREECN scenario has the same NPV as the Base Case, with investments worth (NPV) US$ 97 million in energy efficiency, US$ 64 million in electricity production from the wood power-plant, US$ 21 million solar thermal energy and US$ 1.85 million in solar photovoltaic.

The Base Case scenario assumes the installation of a new oil fired 130 MW power plant operating initially with a load factor of 0.5 and producing electricity at 0.12 US$/kWh (including T&D costs). The load factor is assumed to increase to 0.8 in 2002. The EE scenario requires a smaller investment in power generation: a new oil fired 30 MW power plant operating with a load factor of 0.3 until 1997 and increasing to 0.5 in 2002, with electricity costs at 0.12 US$/kWh (including T&D).

Annual Investment and O&M Streams for the Three Scenarios

The investment and operation and maintenance (O&M) costs streams in undiscounted millions of 1992 US$ for the three scenarios are shown in Table 8. Note that we delay significant investments in solar PV in the hope that better efficiencies or prices may be available in the future. There are no investments in renewables in the Base Case and EE scenarios, so those columns are absent under the renewable headings.

DISCUSSION

The main results (energy and total NPV costs) for the three scenarios are displayed in Table 9. At this first estimate, we believe that about 25% of the total conventional electrical energy for Manaus in the year 2002 can be replaced cost-neutrally with a combination of efficiency and renewables. Our estimates and assumptions are conservative owing to the sparseness of data. With more accurate and detailed survey data that is presently being collected and analyzed, we suspect that larger savings could be identified and highlighted for the policy makers.

Furthermore, this study focused on the actions that the electric utility can take primarily with its own initiative. We have not attempted to quantify additional (and almost certainly, significant) energy savings achievable with actions that require local political support, such as promulgation and enforcement of building energy codes, improved public transport systems, performance standards for motor vehicles, refrigerators and air conditioners and chillers.

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ENDNOTES

1. An unmetered connection by 16% of the Manaus residential customers can be regarded as a conservative estimate. Many of the research team members conducting the survey believe that 20% would be a more realistic estimate.

2. We assumed for Manaus that 15% of the electricity use in households consuming >200 kWh is used for water heating and 8% of the electricity use in households consuming >200 kWh is used for water heating For reference, in the temperate city of Sao Paulo about 30% of the average household electricity consumption is spent in water heating. The lower values were chosen for Manaus due to its tropical climate and higher saturation of air conditioning amongst households using >200 kWh. We assumed that 50% of electricity used for water heating for households using >200 kWh/month could be replaced with solar systems and the corresponding figure would be 25% for households using >200 kWh/month. The reason for this difference is attributed to differing housing types and economic conditions amongst the two categories of households. In 1992, 66,700 TOE was consumed by the >200 kWh households and 82,000 Toe by the >200 kWh. Note that the insolation in Manaus is about the same as that in the temperate city of Campinas near Sao Paulo. The cost of conserved electricity with domestic solar hot water in Campinas is 60 US$/MWh from the consumer's perspective, and 20 US$/MWh from the utility perspective (these estimates result from authors' studies of the economics of domestic solar hot water in Campinas (Madureira, 1995). ''ERRATUM: Tables currently numbered 3, 4, 5, and 6 should be renumbered 6, 3, 4, and 5 respectively.''

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