Design of Optimal Power Cogeneration for North-east Sri Lanka based on Stand-alone Renewable Energy Systems

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ABSTRACT

This paper presents an optimal model to satisfy electricity needs of North-east Sri Lanka (NE-SL). With the absence of indigenous fossil fuel and large-scale hydrologic resources, NE-SL depends on the import of fossil fuel for electricity generation, causing economic and environmental hardships. This paper explores a sustainable power generation using a mix of renewable energy resources.

KEYWORDS: Renewable energy, sustainable economy, Sri Lanka, power generation

1. INTRODUCTION

In **Northern and Eastern Sri Lanka (NE-SL)**, electricity is not available in most of the places due to the civil war. There is practically no electricity production and distribution system available or planned. Since Sri Lanka, as a whole, is suffering from power-shortage, it will be not possible for her to supply electricity to NE-SL, by the time the civil war comes to an end. An alternative generation and distribution system should, therefore, be designed to supply electricity to NE-SL.

The need for electric power may be analyzed by a fairly intensive and deep study, which invariably requires life cycle analysis of the society in terms of energy use and conservation, industrial and household development, population and industry distribution, export and import of electricity, etc. In contemporary NE-SL, however, the very basics in a societal infrastructure such as industry, highways and education system, are either non-existent or in primitive form. And due to the on-going war in this region, important data for electricity power sector decision-making (such as income and purchasing power of the population, planned transportation and highway infrastructure, environmentally sensitive areas, meteorological data, etc.) are either not available or inadequate.

The objective of this paper is to demonstrate that to achieve a sustainable electricity generation for NE-SL, in addition to utilizing the abundant intermittent resources NE-SL has, namely solar and wind, biomass production must be given utmost priority. The scope of this paper is limited to design of a mixture of power plants in the cogeneration system, not involving the other aspects of electricity sector such as transmission and distribution. Limitation of this work: due to the ongoing civil war in the region, there is no recent data available about energy production and consumption in this region; the data used in this paper is from 1994 to 1996.

2. NEEDS AND REQUIREMENTS FOR SUSTAINABLE POWER SUPPLY

The long-term life cycle scenarios for energy to the planet Earth points to massive utilization of solar power, or its derivatives as hydro-, wind- or biomass power (Weinberg, 1990). Power from tidal waves, geothermal and ocean thermal power is insignificant as far as NE-SL is concerned. Each type of energy has its own economy, life cycle and complications. Direct solar power and wind power is complicated by its diluted form and its variation with time and location. However, some of these variations are predictable and may be used in optimal predictive control of cogeneration systems (Asbjornsen, 1984). Example of such cogeneration system is a combination of solar, wind and biomass power. The power generating systems interconnected by the power grid is an existing technology. But incorporating intermittent power supplies (like solar, wind) to the grid requires careful planning. Nuclear power or hydropower systems acting as the base-load supplier of the utilities, try to even out any fluctuations or failures in the intermittent power supplies, if the intermittent power supplies are connected to the grid. With absence of fossil fuels, hydropower or nuclear power, a sustainable cogeneration system for NE-SL has to use biomass as buffer in incorporating intermittent power supplies. The other option is to include energy storage in the cogeneration system. The energy storage will store energy when the generated electricity from intermittent supply is in excess and it will contribute electricity to the grid when demand exceeds supply. However, studies show that energy storage systems are generally expensive (Friberg, 1993).

2.1 Basic Needs Analysis

The total system needs may be formulated as a combined need for electric power by the society and a need for global environmental protection, formulated as follows:
- There is a need for electric power, fairly distributed, to the society population
- There is a need to replace fossil fuel as energy source for industrial and domestic electric power generation on economic and environmental perspective.

2.2 Basic Requirements Definition

The system needs lead to requirements, which are consequences partly of the needs, partly of the customer and user situation, and partly of conceptual solutions. The definition of system requirements is an iterative process, which expands in detail, as the system baseline concept is designed (Asbjornsen, 1991). At the present level of details, and the present system analysis, a set of requirements may be defined fairly simply:
- The cost of electric power generation and distribution in NE-SL shall be within the price range for customers and users in the rest Sri Lanka

- Compared to the rest of Sri Lanka, the power generation system designed for NE-SL shall have the same or better, reliability, availability and fair distribution of electric power. Cogeneration system should also meet the customers' power requirement at any time
- The power generation system shall have none or minimal harmful pollution effects, on the air, soil or water environment, or on the social environment.

There are some other requirements too, due to the varying nature of the intermittent energy sources, and due to the economic requirement on conversion technology:
- In case of intermittent primary energy source is used, energy back-up shall be provided by the system
- Existing technology for energy conversion shall be utilized to a degree, which is the most feasible economically
- The economy of scale shall be utilized optimally in terms of size and capacity of units, modularization and standardization, distribution and centralization

3. SYSTEM INTEGRATION

Some thoughts are given below on integrating generators into the electric grid, by considering the technology's social and environmental effects.

3.1 System Response to Customers' Power Requirements

Changes in customers' power requirements will automatically be taken care of by the demand management system through control of the turbines in the power generation systems. The optimal strategy will be to let the solar power generation run at its maximum capacity at any time. This capacity will change during the day and go to zero when the sun sets. It is also optimal to let the wind power run at its maximum capacity, which will also change with the intensity of the wind. The remaining power requirement will be taken care of by the biomass and fossil fuel power generation systems. As long as the system is designed to tackle all possible situations, as described, the customer will see the power generation system as totally reliable. The key issue in the whole system is to match capacities of the total cogeneration system to the customers' power requirements and to the availability of the energy sources, solar radiation, and wind speed.

Because of the intermittent nature of solar and wind power, when incorporating these generators into the grid, the total plant capacity must always exceed the maximum expected demand by a large margin (penalty for intermittence), in-order to increase system reliability. In NE-SL, where wind and solar power will be contributing most of the time, thermal plants that have higher operating fuel costs but cheaper to build become more attractive (such as natural gas plant), because the reduced operating time will make fuel costs less important. There is a limitation on the extent to which the intermittent sources like solar and wind contribute to the total power generation. As the percentage of power generation of wind and solar increases, there is steady decline in value, because adding intermittent sources reduce the reliability. Contribution from wind energy ranging from 0% to 50% of overall installed capacity is feasible before operational losses become prohibitive (Grubb and Meyer, 1994).

3.2 Smaller the Better

For a developing country like NE-SL, which does not have any large-scale hydrologic resource for electricity generation, the selection of optimum power plant mix should be based

on small, affordable power generators. Reliability of the power generation and distribution system will be increased if large number of small generators, scattered throughout the nation, is used rather than few large plants. By using a large number of smaller plants, the potential danger of over building or commissioning less cost effective large plants could be avoided. Small plants can be added quickly as they are needed and even disassembled and moved if loads decline; the economics of the larger plants depend heavily on long-term forecasts (Johannson et al, 1993; Kelly and Weinberg, 1994).

In case of biomass-generated electricity, power plants are modest in scale (less than 100MW) to assist collection and transportation of dispersed biomass supplies (Williams and Larson, 1994). If the small generators are scattered throughout the region, a number of other benefits emerges: heavy pollution of a region (congestion) is avoided; employment (less rural exodus) and community participation (awareness) is also increased in distributed power generation. Ideally, each region should become self-sufficient in electricity generation; if the demand exceeds its supply, the utility in that region imports electricity from the neighboring utilities, and similarly, the excess capacity is also sold to the neighboring utilities (Johannson et al, 1993; Kelly and Weinberg, 1994).

3.3 Participatory Development

For a sustainable cogeneration system to succeed, the participation of the community becomes essential. Take for example, production of electricity from residues form paddy: today rice husk is normally sold at the rice mills, for insignificant price for trivial use. Now, the rice mill is expected to sell the husk to the utility. The mill management will certainly hesitate to sell if high expenses are incurred in doing so (transportation). However the question is, even if the extra expenses incurred are negligible, whether the management will be willing to sell. The answer to this question depends on the participation of the management in the community's affairs. This 'bottom up' approach where grass roots organize, assist and take responsibilities, and solve (save energy) the energy problem will certainly promote the efficient supply of electricity to the whole nation.

4. ESTIMATING ELECTRICITY DEMAND OF NE-SL BY 2010

Since no energy-macroeconomics data for NE-SL is available, the basic assumption made here is that, the energy needs of her population will be the same as the needs of the rest of Sri Lanka. Sri Lanka, with a population of 18 million, today has a per capita electricity consumption of 168 kWh (CIA, 1996). The electricity needs of the NE-SL with a population of 3 million, is therefore 504 GWh per year.

In recent years, total firewood consumption in Sri Lanka has been around 5 million tons per year. Of this value, industries consumed approx. 1.05 million tons (Hall et al, 1994). It is reported that the only half of the firewood supply is obtained in a sustainable way (such as forest regeneration, rubber re-plantation cycle etc) (Munasinghe and Meier, 1993). Therefore decline in the natural forest area in Sri Lanka is inevitable. The natural forest area has fallen to 24% in 1980 from 44% in 1955. Surely NE-SL wants to keep its very limited natural forests therefore the amount of energy obtained in Sri Lanka through firewood supply has to be compensated for through electricity supply. Since firewood is generally the most economic biomass fuel for industrial heating (if used by efficient combustion), only the portion of firewood (ca. 4 million tons) consumed for domestic purposes has to be substituted

by electricity. For NE-SL this is equivalent to 0.7 million tons. Therefore additional electricity needed to compensate for use of firewood is 355 GWh.

In 1986, Sri Lanka consumed 154.2 thousand tons (kt) of Kerosene, which is solely used for domestic lighting and cooking and 129.0 kt of Fuel oil for industrial use and electricity generation. A portion of fuel oil used for electricity generation is assumed to be 50%. This portion of fuel oil and the amount of kerosene used (totaling 218.7 kt) could be substituted by electricity. Assuming again consumption is proportional to population, this will be equivalent to 130 GWh. The total electricity needed today is therefore approximately 989 GWh.

By 2010, the energy needs of the population are expected to be three folded (assuming 8% rate of increase in the standard of living (ca. 6.9%) and population growth (ca. 1.2%)) (CIA, 1996). The total electricity needs per year will then be 2967 GWh. With these data, general performance requirements for the cogeneration system could be set up as shown on Table-1.

Functional Requirement	The cogeneration system should be able to supply 2967 GWh of electricity per year.
Operational Requirement	The cogeneration system should be able to support quickly varying demands; should be able to deliver peak power of 564 MW.
Physical Requirement	The system should be smaller, distributed throughout the nation. Building materials and construction, operation and scrapping conform to international and local standards.

Table-1: General requirements of the cogeneration system for the year 2010.

5. ENERGY RESOURCES IN NE-SL

By 2010, relevant power generation technologies to NE-SL will be solar, wind, biomass, coal and natural gas.

5.1 Biomass

Energy from biomass is divided into two general categories 1) agricultural crops and residue, wood and wood waste, animal waste, aquatic plants and 2) plantation biomass:

5.1.1 Crop residues

Sugarcane cultivation is a well-established industry in NE-SL. In 1995, NE-SL produced 1.2 million tons of sugarcane (FAOSTAT, 1995). Each ton of sugarcane produce about 0.43 ton of bagasse and leaves. BIG/ISTIG power plant produces 677 kWh of electricity per ton bagasse (Williams and Larson, 1994). If production is assumed to grow at 3.3% (corresponding to Sri Lankas current growth in agricultural production) and all the residues from the sugar industry are used for electricity production, they could produce 568 GWh of electricity by 2010. This is about 19% of the anticipated electricity needs of NE-SL. Residues from the pulp industry, sawdust and bark from de-barking and chipping of logs, could also be used as biomass energy source to the power plant; It is therefore possible for a collateral generation of electricity - pulp - sugar production, especially suited for Eastern Sri Lanka.

In NE-SL, agriculture is and will be the main source of income. In 1995, Sri Lanka produced 2.2 million tons of rice (FAOSTAT, 1995). Before the civil war broke out, NE-SL used to produce about 33% of the total rice production in Sri Lanka (TEEDOR, 1992). Each ton of

rice produced is accompanied by 2.25 tons of residues in terms of paddy straws and rice husks. With the same rate of growth in production (3.3%), and assuming NE-SL will be able to produce 33% of total production, the residues will have an energy equivalent of 900 GWh of electricity which is about 30% of the electricity needed by year 2010 (paddy rice is a C_3 plant, which has about 50% energy contents of a C_4 plant such as sugarcane). In NE-SL, Groundnut, Maize, Soybean, Cowpea are also cultivated. Substantial amounts of energy can be generated from residues of these crops.

In summary, the large amounts of crop residues that are normally not fully utilized could be used to generate more than 49% of electricity needs.

5.1.2 Plantation biomass

One of the tropical legumes, *Leucaena leucocephala* ("Ipil-Ipil") has already been successfully planted in Sri Lanka. In NE-SL, experimental *Casuarina* plantation gave promising results (TEEDOR, 1994; TEEDOR, 1995). Plantation biomass energy is a solid option for electricity production in NE-SL. For plantation biomass to be successful plantation wood should be cheaper than the wood purchased on the open market and its cost of energy should be lower than that of conventional energy systems. Also, energy crops should not have long-term environmental, ecological damages. So far no serious study has been done on the economics of harnessing energy crops in Sri Lanka or NE-SL.

5.2 Solar and Wind

The utilization of solar energy (Photovoltaic or solar thermal) is a major option to satisfy the energy needs of NE-SL. NE-SL, being a tropical country receives annual average solar insulation of 200 W/m^2. The solar power system is renewable, it answers all the serious global as well as local environmental issues such as, zero emission of Green House Gases (GHG) and no solid waste. Wind power generation offers many benefits too such as, environmentally friendly (no gaseous emissions), rapid modular addition of capacity, wide range of capacities (from few kW to hundreds of MW), easy to integrate with existing power grid, coexistence with other use of land, no fuel needed and economically competitive (NRC, 1991). NE-SL confines to a region where the wind energy is attractive for power generation with average wind speeds over 5 m/s, giving an average generation of over 33% of rated power (Twidell and Weir, 1986).

6. ESTIMATING THE COSTS OF ENERGY PRODUCTION

There are a huge number of parameters involved in the equations for calculating costs of energy production. In this section, only a very limited set of parameters is considered. However, the parameters taken into consideration are the most important ones, thus the model developed in this section and in the following section 7, can be considered as representative.

6.1 Estimated Energy Costs in the Year 2010

Fixed annual cost (FAC) of the total installed cost:
$$FAC = ICC \times CRF$$
Where *ICC* is the total installed capital cost and *CRF* is the capital recovery factor.

CRF is equal to:

$$\frac{r}{1-(1+r)^{-n}}$$

Where r represents the interest rate and n is the lifetime in years.

The cost of electricity (COE) is then,

$$COE = \frac{(FAC + OMC)}{P_r \times CF \times 8766} \text{ \$/kWh}$$

Where P_r is the rated capacity, OMC is the Operational and Maintenance (O&M) costs per year, and CF is the average capacity factor and $8,766$ is the number of hours per year (365.25×24).

Table-2 presents values for the parameters involved in the calculations for costs of energy production. All values are given in 1994-US\$. The capital recovery factor (0.0888) is for 8% interest rate and a 30-year plant life. All taxes and insurance costs are neglected.

	Biomass (Heaps and Hill, 1996)	Solar (De Laquil, 1994)	Wind (Cavallo et al, 1994)	Coal (Johannson, 1994)
System rating (MW)	111	200	500	109
Installed capital cost ($ /kW)	974	3200	850	1122
Variable O&M costs ($ /kWh)	0.0009	0.0065	0.008	0.0010
Fixed O&M costs ($ /kW-year)	34.2	-	-	48.0
Fuel costs ($ /GJ)	2.43	-	-	2.00
CF	0.75	0.59	0.33	0.75
Efficiency	0.43	-	-	0.42

Table-2: Parameter values for calculating costs of energy production

Table-3 summarizes the electricity generation costs for different technologies:

	Wind	Biomass	Coal	Solar
Capital (fixed)	2.60	1.32	1.52	5.50
Fuel	-	1.18	1.71	-
Operation & Maintenance	0.80	0.61	0.83	0.65
Total	3.40	3.11	4.06	6.15

Table-3: Electricity generation costs for different technologies (US cents / kWh).

6.2 Environmental Costs Associated with Electricity Generation

It is important to note that the costs of energy given in Table-3 represent only a part of the costs the society has to pay for electricity generation. The costs of electricity generation can be divided into two, namely the direct or internal costs that are borne by the generating company (capital costs and recurrent or operating costs) and the external costs ('externalities') such as the costs associated with environmental damage due to electricity production (Hill et al, 1995). Environmental externalities are becoming the most important external costs in electricity generation. There are various economic methods available to

internalize (incorporate into the total cost of energy) environmental externalities. In this paper, internalization values based on US and German studies are used as presented in (Seshadri, 1978).

Estimation for air emissions from a coal-fired power plant is given below, in Table-4 (Munasinghe and Meier, 1993). Also given are the values to monetize emissions (Fritsche, 1994).

	Emission (kg per kWh)	Value \$/kg	Environmental cost \$/kWh
SO_2	0.00640	4.060	0.0260
CO_2	0.32000	0.013	0.0042
NO_X	0.00370	1.640	0.0061
Particulate	0.00050	2.380	0.0012
HC	0.00004	0.680	0.0000
Solid ashes	NA	NA	NA
Limestone	NA	NA	NA
Total			0.0375

Table-4: Environmental costs due to coal-fired power generation.

7. DESIGN OF OPTIMAL POWER COGENERATION

Computer modeling and simulations are done to find the optimal mix of power plants in the cogeneration system; most of these computer models are based on linear programming formulation, and the question is to find out *"the mix of different types of plants that will satisfy the power demand with minimum costs"*.

The objective function: Minimize S = "The cost of power generation by different plants" subject to constraints:

      1. The total generation should meet the demand
      2. Each plant's generation cannot exceed its physical limitation.

In mathematical notation (simplified):

Minimize:
$$\{S\} = \sum x_k \cdot c_k \quad [\$ / \text{year}],$$

Subject to:

Constraint 1:
$$\sum x_k \geq \eta$$

Constraint 2:
$$x_k \leq X_k \cdot CF_k$$

Where x, c, η, X, and CF are the generation of a specific plant per year, the Coefficient of Energy (COE) of the specific plant type, the peak power of that plant, and the average capacity factor (CF), respectively.

7.1 Basic Assumptions

Two basic assumptions are given below:

1. In order to prevent over-relying on the intermittent solar and wind energy systems, penetration of intermittent power supplies is limited to 33%, if wind power alone is used.

If wind and solar power are used (with the assumption that, owing to subsidy solar power costs are now equal to wind power's) then 40% penetration of these two combined, is chosen.

2. Biomass: Contribution from biomass is taken to be 1468 GWh /year or 170 MW, which is 49% of the total electricity needed.

7.2 Typical Solutions for Cogeneration System

Depending on whether solar power is subsided or not, two solutions are proposed:

Case - A: Environmental damages are neglected and there is no form of subsidy to solar power: In this case, a mix of wind farm(s) of 186 MW and biomass power plants totaling to 170 MW could act as the base-load power supplier. Fossil fuel-fired power plants (coal and natural gas) providing 303 MW of power act as the intermediate and peak suppliers. Solar power is too expensive to consider under any category. Total rated power of the plants put together amounts to 659 MW. So there is a reasonable margin (17%) to take care of the intermittent nature of wind energy and also to increase the reliability of the cogeneration system.

Case - B: If environmental costs are included in production costs and if there is enough subsidy available to include solar power then the cogeneration mix becomes: intermittent solar and wind could contribute 226 MW together (40% penetration) to the base load with the addition of 170 MW biomass power plants. Fossil fuel power should provide 281 MW. The ratio of Solar/Wind depends on the subsidy available for solar power generation and meteorological-statistical data. Total rated power of the plants put together amounts to 677 MW. Here too, a reasonable margin (20%) is available to improve the reliability.
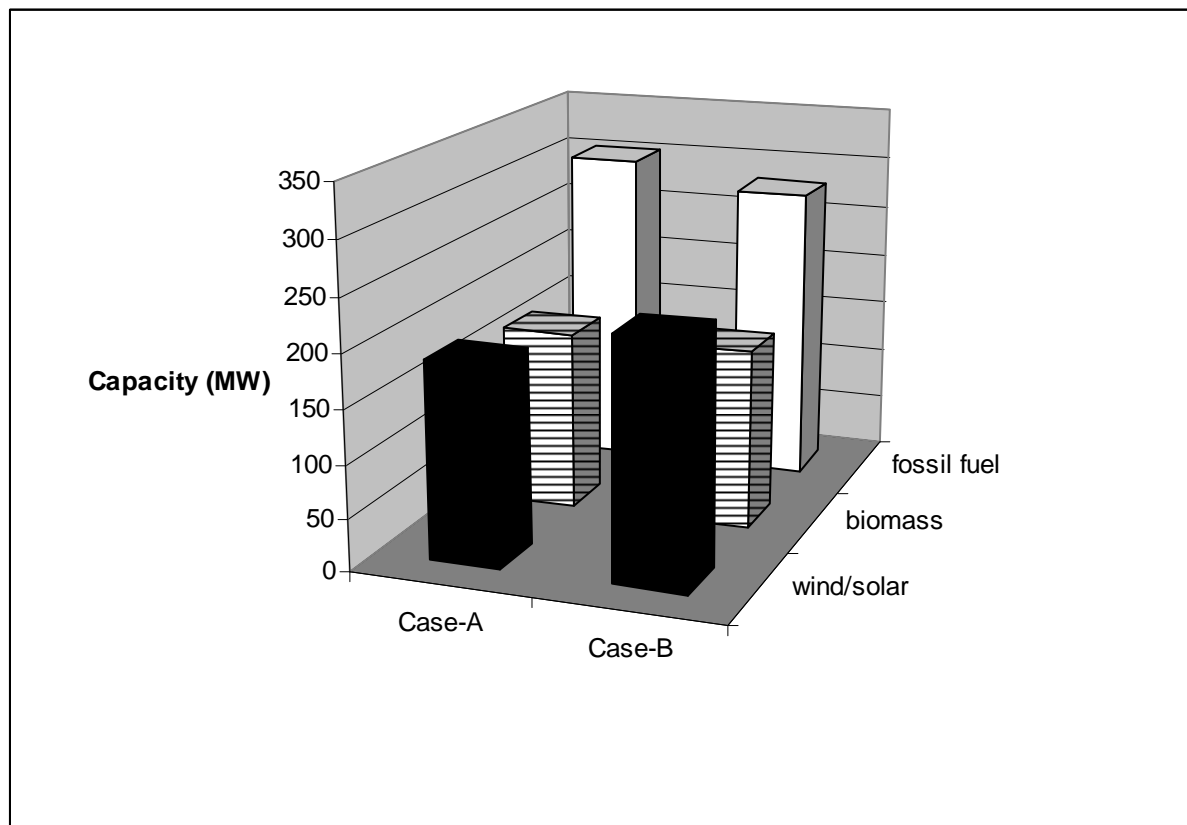
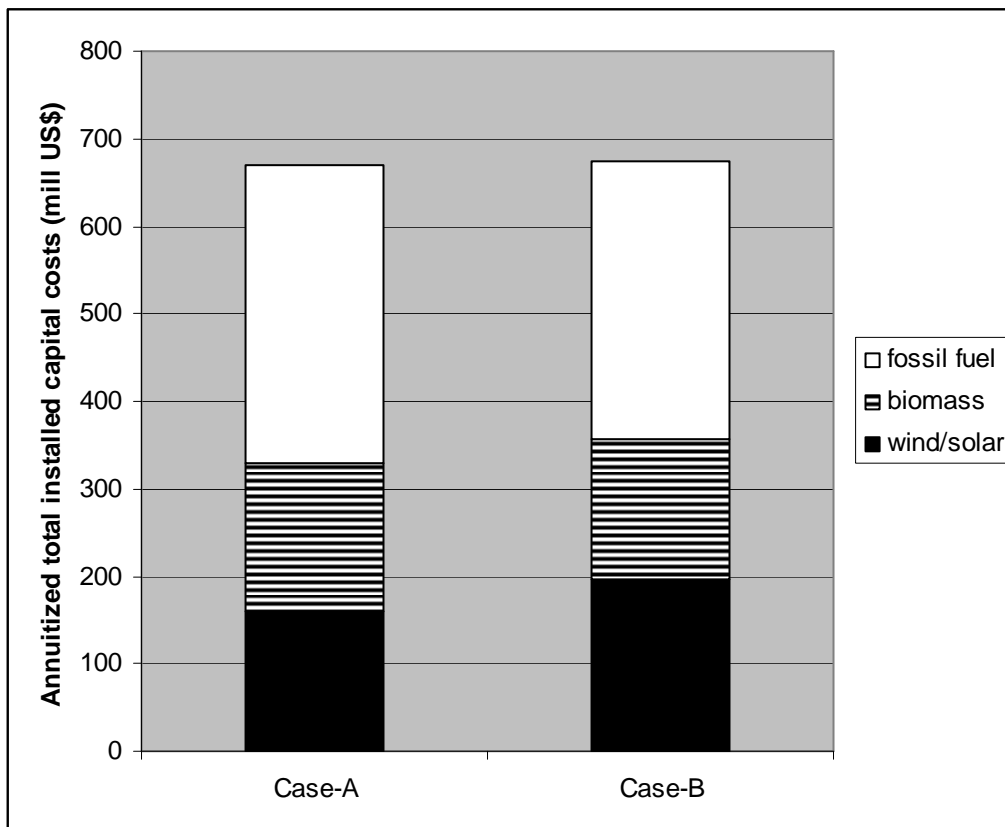Figure-1: Suggestion for an optimal mix of power plants.

Figure-2: Cost of the cogeneration system.

Figures- 1 and 2 shows optimal mix of plants in terms of capacity and costs respectively. In Figure-2, coal power replaces fossil fuel power (coal and natural gas) for simplicity. Also, the reduced capital cost of solar power (in Case - B) is assumed to be equal to that of wind power.

8. DISCUSSION AND CONCLUSION

In the typical cogeneration system for NE-SL, the contribution of fossil fuel-fired power is too high: when considering peak rate, it is 53% in case-A, and 50% in case-B (Figure 1). The growing demand for fossil fuel resulting in the rising price of oil, together with the serious environmental damages due to fossil fuel burning indicates that NE-SL should investigate the use of more sustainable resources for her electricity generation. Though intermittent energy resources solar and wind is abundant, their percentage of contribution cannot go beyond certain limit. Therefore the only way out is to engage large-scale plantation biomass energy.

In case-B, fossil fuel contributes to 281 MW of electricity generation. This is equivalent to 6.1 million tons of wood. Assuming that one hectare of biomass plantation yields 25 tons of wood, a total area of 109 thousand hectare (5.4% of total area of NE-SL) of biomass plantation is needed for complete sustainable electricity generation.

Normally, unproductive or degraded land (unsuitable for field crops) is allocated for plantation thereby avoiding land for food versus fuel conflict. Plantation biomass species like Ipil-Ipil and Casuarina has rapid growth, even on degraded land. In Tamil Nadu, South India,

biomass plantation yields an optimal value of 55 dry tons of wood per hectare per year (Seshadri, 1978). Also, Ipil-Ipil and Casuarina requires minimal management and care. Ipil-Ipil has the ability to fix nitrogen from atmosphere and thus has the 'self-fertilizing' ability too (a by product of Ipil-Ipil, high-protein seeds and leaves could be used as animal feed and green fertilizer).

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