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A New Approach towards Carbon-Constrained Energy Sector Planning: A Case Study for Lakshadweep Islands, India

Santanu Bandyopadhyay*, Nishith B. Desai, Adwit Kashyap

Department of Energy Science and Engineering, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
santanub@iitb.ac.in

Non-renewable energy sources dominate the requirement of world's energy. In recent years, there is a rise in electricity generation from renewable energy sources (i.e., solar photovoltaic, solar thermal, wind, biomass, etc.). These sources are fluctuating in nature and capital intensive. With increase in global energy demand, there is a need for power generation system planning, which has an optimum mix between non-renewable and renewable energy sources. In this paper, a Pinch Analysis based approach is proposed to determine the cost-optimum overall energy mix. Applicability of the proposed methodology is demonstrated through an illustrative case study of Lakshadweep Islands, India. The approach in the case study has the added benefits of reducing the dependency of Lakshadweep's economy on external fossil fuel sources, as well as reducing the burden of subsidy on electricity borne by the government. The policy implications for subsidy are also studied in this paper.

1. Introduction

Two of the most important challenges for the world today are global warming and climate change. This is primarily attributed to the use of non-renewable energy sources for different applications, mainly power generation. Reduction of green-house gas emissions in power generation can be achieved through generating electrical energy from renewable energy sources (i.e., solar photovoltaic, solar thermal, wind, biomass, etc.). From an environmental point of view, it is desirable to maximize use of renewable energy sources. However, these technologies are usually more capital intensive as compared to conventional fossil fuel based technologies. In recent years, electricity generated from some renewable based technologies, has reached grid-parity. It is desirable to know the minimum amount of low or zero-carbon energy sources required to meet national or regional carbon emission limits. Pinch Analysis can be applied to planning power system with reduced green house gas emissions.
Pinch Analysis, a branch of process integration, helps in analyzing and developing efficient processes. In recent years, it has found a multitude of new areas of applications, which includes production planning (Singhvi et al., 2004), financial management (Zhelev, 2005), carbon constrained energy sector planning (Tan and Foo, 2007), carbon capture and storage (Tan et al., 2009), isolated power systems (Bandyopadhyay, 2011), integration of batch processes (Morrison et al., 2012), etc. Emission targeting in a chemical process plant, using Pinch Analysis, has been developed by Linnhoff and Dhole (1993). Energy sector planning subject to carbon emission constraints is a relatively new application of Pinch Analysis. Carbon constrained energy sector planning, using Pinch Analysis, has been presented by Tan and Foo (2007). Foo et al. (2008) have targeted the minimum requirement of low-carbon emission energy sources using the technique of cascade analysis, originally developed for targeting the minimum freshwater resource in water Pinch Analysis. Krishna Priya and Bandyopadhyay (2013) have studied emission constrained power system planning using Pinch Analysis and have discussed the case study of Indian electricity sector. Francisco et al. (2014) have used the carbon sources diagram for targeting low as well as zero-carbon energy sources for carbon-constrained energy planning.

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In this paper, the problem of managing different energy sources (both non-renewable and renewable) for energy requirement of a locality is studied using Pinch Analysis. A Pinch Analysis based methodology is proposed in this paper to determine the cost optimal mix of various electricity generation options for an isolated region. Applicability of the proposed methodology is demonstrated through an illustrative case study of Lakshadweep Islands, India. Government of India, provide significant subsidy to supply electrical energy in these islands. The policy implications for subsidy are also studied in this paper.

2. Problem Statement

In isolated regions, such as different islands, electricity is typically generated through diesel based captive power plants. Diesel has to be imported from the main land or from large port near-by. Cost of electricity generated through such diesel based captive power plants is extremely high. To make it affordable to the people of the island, significant economic subsidy is provided. Import of diesel also increases the risk of energy security of this region. It is important to use locally available resources to generate electricity and thereby reduce the dependency on the diesel import, reduce the economic subsidy on electricity generation, and improve the energy security of the region. Locally available resources are typically renewable and hence reduction of green house gas emission is an added advantage. Techniques of Pinch Analysis are applied to address this problem. In the proposed methodology following analogies are adopted: the energy potentials of renewable energy sources as flows from internal sources (kWh), unutilized renewable energy sources as waste, non-renewable energy source as resource, and per-unit cost of energy (Rs./kWh or $/kWh) as quality. The general problem is defined in the following paragraph.

There are N_s internal energy sources (locally available renewable energy sources) in the system, with every source having an electricity generation potential of E_{si} and associated per-unit cost of c_{si}. There are N_d internal electricity demands (residential, commercial, etc.) in the system, and for every demand, there is an electricity requirement of E_{dj} with a maximum acceptable per-unit cost of c_{dj}. There is a resource (typically diesel, a non-renewable energy source), which is assumed not to have any limitation for electricity generation, and a per-unit cost of c_{rs}. Typically, cost of electricity from resource is subsidized. Finally, unutilized potential of internal energy sources may be termed as waste, according to the terminologies used in Pinch Analysis. The objective is to minimize the requirement of resource in the system. A network representing this reduction problem is shown in Figure 1.

The constraints in the optimization model are expressed as follows:

$$\sum_{j=1}^{N_d} e_{ij} + e_{iw} = E_{si} \qquad \text{for every internal source } i \qquad (1)$$

$$\sum_{i=1}^{N_s} e_{ij} + e_{rsj} = E_{dj} \qquad \text{for every internal demand } j \qquad (2)$$

where e_{ij} is supply of electricity from source i to demand j, e_{rsj} is supply of electricity from resource to demand j, and e_{iw} is unutilized electricity generation potential of source i. Cost of electricity supplied to any demand must be lower than the overall acceptable cost for that demand. This can be mathematically expressed as:

$$e_{rsj} \cdot c_{rs} + \sum_{i=1}^{N_s} e_{ij} \cdot c_{si} \le E_{dj} \cdot c_{dj} \qquad \text{for every internal demand } j \qquad (3)$$

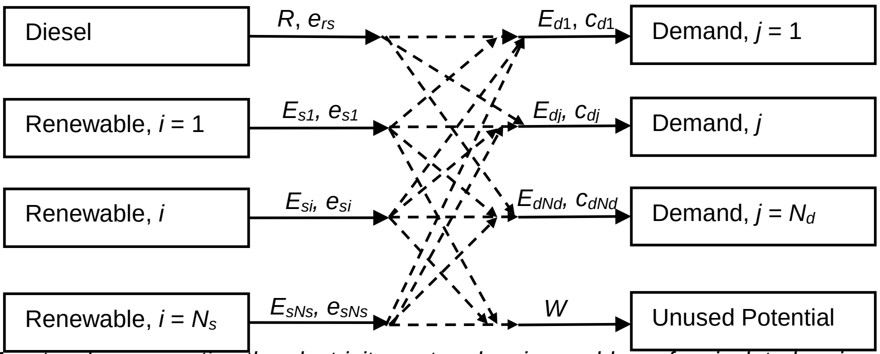

Figure 1: A network representing the electricity sector planning problem of an isolated region

As explained earlier, to reduce the dependency on the diesel import, to reduce the economic subsidy on electricity generation, and to improve the energy security of the region, electricity generated from the diesel based captive power plant must be reduced. In other words, the objective is to minimize resource requirement.

$$R = \sum_{j=1}^{N_d} e_{rsj} \tag{4}$$

The overall optimization problem is to minimize Eq(4) subject to Eq(1)-(3). This is equivalent to the generalized Pinch Analysis problem and may be solved using any established techniques.

3. Case study for Lakshadweep Islands

Lakshadweep is a group of islands in the Laccadive Sea, south western coast of India. These islands were called Laccadive, Minicoy, and Aminidivi Islands with total surface area of 32 km^2. This is an Union Territory of the Government of India. Based on 2011 census, population of Lakshadweep archipelago is 64,473.

The Lakshadweep electricity department is the authority that manages the power generation in the region. At present, electrical power generated in Lakshadweep is obtained from diesel generating (DG) sets powered by high-speed diesel. Diesel for power generation and transport needs are imported from mainland India (Beypore port, Kerala). The entire energy infrastructure of Lakshadweep is heavily dependent on the supply of the diesel. The actual cost of generation of electricity through DG sets is about 19 Rs./kWh (GOI, 2014a). However, the electricity is heavily subsidized by the Government of India and the consumers pay very less amount for electricity. The subsidy provided by the government in current energy mix is calculated to be 624.52 10^6 Rs/y. An energy sector planning approach that maximizes self sufficiency in power generation needs to be urgently addressed. Moreover, Lakshadweep is an archipelago of small, low-lying islands that are under threat from the rise in sea level due to global warming. The details of electrical energy demands in various sectors are given in Table 1 (GOI, 2014a). Residential sector being the largest consumer of electricity, consume 72 % of total annual electricity consumptions. Commercial sector consumes 24 % of the total electricity consumption and the remaining electricity caters to industrial, public services like street lighting, and some temporary connections. Rate of acceptable cost for various sectors are also given in Table 1 (GOI, 2014a).

The potentials of different renewable energy sources (NIC, 2004) and expected per-unit cost of generation of renewable electricity (GOI, 2014b) are given in Table 2. It should be noted that solar photovoltaic, wind, and biomass based power generations are only three possible renewable sources for power generation. It may be noted that per-unit cost of electricity, generated from these renewable resources are much lower than that of diesel based electricity generation.

The problem of optimum mix between non-renewable and renewable energy sources is solved by using minimum waste targeting algorithm (Bandyopadhyay, 2006) of Pinch Analysis. It may be noted that the problem is a linear programming (LP) problem and may be solved using many different techniques. For a LP problem, with special mathematical structures, Pinch Analysis is computationally more efficient and provides physical insight to the problem. The subsidized per-unit cost of electricity from DG set (c_{rs}) is assumed to be 4 Rs./kWh. The minimum resource requirement (i.e., electricity from DG set) and the minimum unutilized renewable energy source (i.e., waste) are calculated to be 32.52 GWh/y and 14.52

GWh/y, respectively. This leads to saving of 136.72 × 10^6 Rs./y in subsidy. Moreover, the electricity is available to the consumer at cheaper rates (4 Rs./kWh).

Table 1: Details of electrical energy demands and corresponding acceptable cost

Demand	Electricity Demand, E_{dj} (GWh/y)	Maximum acceptable per-unit cost of electricity, c_{dj} (Rs./kWh)
D1: Residential	31.17	4
D2: Commercial	10.34	6
D3: Industrial	0.39	4.5
D4: Public Street Light	1.07	4
D5: Temporary Connections	0.07	7

Table 2: Details of renewable energy sources and cost of electricity generation

Source	Energy Generation Potential, E_{si} (GWh/y)	Per-unit cost of renewable electricity, c_{si} (Rs./kWh)
S1: Solar PV	8.402	6.99
S2: Wind	8.675	5.77
S3: Biomass	7.959	6.25

Effects of variation in subsidized per-unit cost of electricity from DG set (c_{rs}) on the total subsidy are shown in Figure 2. It may be observed that there exists an optimum value of subsidized per-unit cost of electricity from DG set. If the cost of electricity from DG set is subsidized to 1.93 Rs./kWh, total subsidy provided by the government is the minimum. Compared to the present subsidy, a saving of 317.08 × 10^6 Rs./y can be realized. If the subsidized per-unit cost of electricity from DG is less than 1.93 Rs./kWh, entire renewable potential is utilized (i.e., no waste) and the 18 GWh/y of electricity needs to be generated from the DG set. Further increase in subsidized per-unit cost of DG, results in unutilized renewable energy sources. The same amount of energy is to be supplied by DG and the overall subsidy increases. Variations of the minimum electricity generation from DG set and unutilized renewable energy sources, as function of subsidized per-unit cost of electricity from DG set (c_{rs}), are shown in Figure 3.
Effects of variation in the maximum acceptable per-unit cost of electricity for commercial (c_{d2}), industrial (c_{d3}), and temporary connections (c_{d5}) on the total subsidy, the minimum electricity generation from DG set, and unutilized renewable energy sources are shown in Figures 4 and 5. As expected, the total subsidy (without integration of renewable energy sources) decreases with increase in the maximum acceptable per-unit cost of electricity. With increased cost of electricity for commercial, industrial, and temporary connections, the optimum value of subsidized per-unit cost of electricity from DG set increases (Figure 4). It may be noted that the optimum value of c_{rs} (this also corresponding to complete utilization of renewable potential) is 2.45 Rs./kWh (Figure 5).

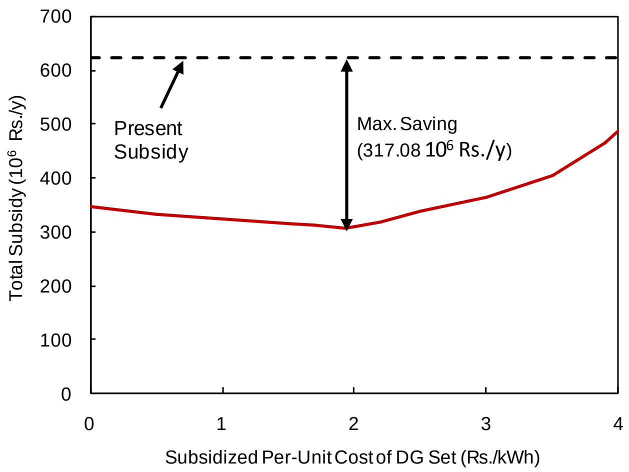

Figure 2: Effects of variation in subsidized per-unit cost of electricity from DG set on total subsidy.

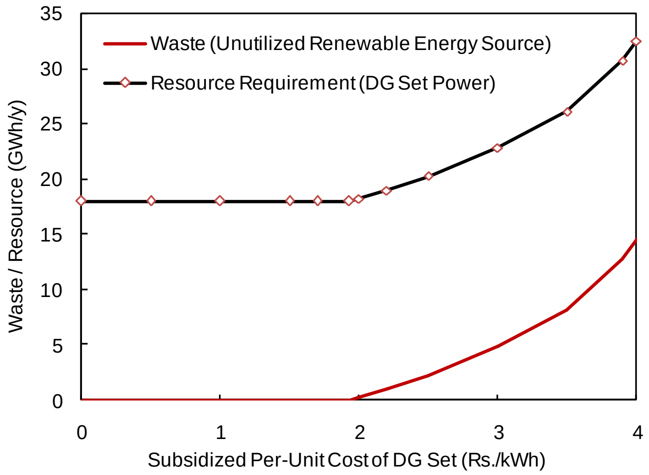

Figure 3: Effects of variation in subsidized per-unit cost of electricity from DG set on DG-based electricity generation and unutilized renewable sources.

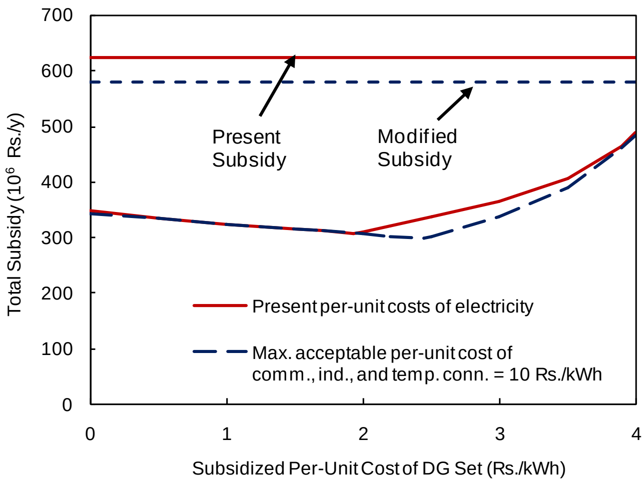

Figure 4: Effects of variation in maximum acceptable per-unit cost of energy for commercial, industrial, and temporary connections on the total subsidy.

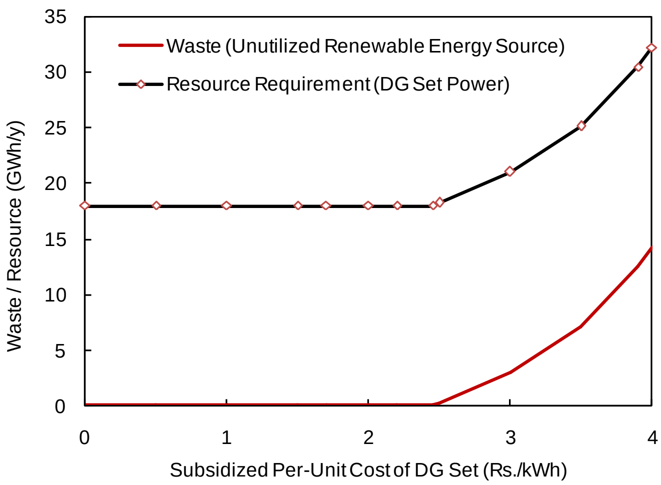

Figure 5: Effects of variation in maximum acceptable per-unit cost of energy for commercial, industrial, and temporary connections on electricity generated from DG set and unutilized renewable potential.

4. Conclusions

Reduction in energy consumption from non-renewable energy sources is very important due to ever-increasing threat of global warming. In this paper, a Pinch Analysis based approach is used to determine the optimum overall energy mix between renewable and non-renewable energy sources for an isolated region. Applicability of the proposed methodology is demonstrated through an illustrative case study of Lakshadweep Islands, India. The approach in the case study has the added benefits of reducing the dependency of Lakshadweep's economy on external sources, as well as reducing the burden of annual subsidy in electricity borne by the government. The subsidy provided by the government in the current energy mix is 624.52×10^6 Rs./y. Using renewable energy sources, the maximum saving in the subsidy of 317.08×10^6 Rs./y may be achieved. The total subsidy (without integration of renewable energy sources) decreases and the optimum value of subsidized per-unit cost of DG set increases with increase in maximum acceptable per-unit cost of energy. Future research is directed towards studying the economic and socio-political scenario of the entire archipelago and to recommend appropriate policy recommendations.

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