CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081163

Cost Optimal Sizing of Hybrid Power Systems: a Pinch Analysis Approach

Nitin Dutt Chaturvedi

Department of Chemical and Biochemical Engineering, Indian Institute of Technology Patna, Bihta, Patna -801103 (Bihar), India
nitind@iitp.ac.in

Technologies related to the advancement of renewable energy are growing very fast. Development in renewable energy technologies, reliability, and environmental restrictions generates the requirement of a hybrid power system (HPS). Proper financial management is necessary to ensure the profitability and sustainability of any project. So, while planning a HPS an essential factor that should be taken into account is cost. This factor can be included in planning a HPS via pinch analysis through the concept of prioritization. This concept is a well-established technique in Process Integration for designing cost-optimal networks for recovery and conservation of resources such as heat, mass, water, carbon, gas, properties and batch, production. However, its application in planning HPSs still needs development. This paper extends the concept of prioritization for planning HPS to develop cost-optimal HPS. The cost of power generation depends on the type of power resource. The time of availability of each source is also taken into account. The methodology presented in this paper calculates the power rating of resources required for satisfying the power demands with the objective to minimize the overall cost of electricity in HPS.

1. Introduction

In conventional combustion-based power generation, fuel combustion releases various hazardous air pollutants that have a negative impact on the environment (Vairo et al., 2014). The technologies related to renewable Hybrid Power Systems (HPSs) are widely accepted due to the advances in renewable energy technologies, reliability, and environmental restrictions (Chen et al., 2015). The technologies related to renewable HPSs are widely accepted due to the advances in renewable energy technologies, reliability and environmental restrictions (Mohammad Rozali et al., 2016). Broadly solar, wind, hydro and biomass are the renewable energy sources utilized for generating the electric power. Cost is an important factor that should be taken into account while developing an HPS. An approach is developed to minimize the cost in an off-grid HPS while satisfying the power demands (PDs). An HPS combines the use of intermittent electrical energy from various resources. This makes the HPS more appropriate for industrial applications compared to using an individual renewable energy (RE) resource supply system. Bhandari et al. (2015) reviewed several methodologies and criteria for the optimization of the hybrid RE system. This review emphasized that a hybrid RE system has higher power reliability in comparison with a single generation RE system.
Several studies on the design of HPS consider the economics have been conducted. Wan Alwi et al. (2012) first introduced the composite plot of time versus electricity known as the Power Composite Curves (PCC) to determine the minimum electricity targets and the electricity supply pinch point for an HPS. Further, Ho et al. (2012) introduced the electric system cascade analysis to determine electricity targets with consideration of the battery and inverter charging/discharging efficiencies. Mohammad Rozali et al. (2013) presented a storage cascade table for designing HPS having collective AC-DC types of current. Later, a methodology is presented by Giaouris et al. (2014) for determining optimal strategies for power management in renewable energy smart-grids. Chen et al. (2014) proposed mixed-integer linear programming (MILP) models for modelling the off-grid HPS to determine the outsourcing target and best electricity pairing for an HPS. Mohammad Rozali et al. (2015a) applied concepts of pinch analysis to optimize the overall electricity cost for an HPS via load shifting. Further, an algebraic method to determine cost-effective storage technology for an HPS which considers various storage

Paper Received: 30/04/2020; Revised: 12/06/2020; Accepted: 15/06/2020
Please cite this article as: Chaturvedi N.D., 2020, Cost Optimal Sizing of Hybrid Power Systems: A Pinch Analysis Approach, Chemical Engineering Transactions, 81, 973-978 DOI:10.3303/CET2081163

technologies is developed by Mohammad Rozali et al. (2015b). Recently, Yee Tay et al. (2020) proposed a method to integrate diesel plant with renewable energy technologies into grid-tied hybrid system using pinch analysis. It should be noted that process integration based methodologies for the sizing of HPS do not directly focus on the cost-optimal sizing of HPS. (Mohammad Rozali et al., 2016)

Proper financial management is necessary to ensure profitability and sustainability (Ongpeng et al., 2019). Cost optimal resource planning can be carried out using concepts of pinch analysis. For cost optimal allocation of water resources, a methodology is developed by Shenoy and Bandyopadhyay (2007) introduced the concept of prioritized cost which is a function of the pinch point. Later, the concept of prioritization is utilized widely by researchers. The concept of prioritization is utilized for multiple installations aggregate production planning which minimizes the energy consumption of production facilities by (Chaturvedi, 2017). Sinha and Chaturvedi (2018) developed a dual objective approach in production planning for minimizing carbon emission and energy consumption based on the concept of prioritization. The concept of prioritization based on pinch point is a well-established technique in Process Integration for designing cost-optimal networks for recovery and conservation of resources such as heat, mass, water, carbon, gas, properties and batch, production. However, its application to power systems analysis still needs development. This paper extends the concept of prioritization to develop a cost-optimal HPS that calculates the optimal mix of power rating from the individual resource aims to minimize the overall cost. It calculates the power rating requirement from different power resources (PRs) in an HPS based on PDs to minimize the cost of electricity.

2. Problem Definition

The general problem of cost-optimal electricity targeting in HPS may be given as follows.

- A set of power resources (PR_i), (i=1, 2,....n). Each resource is available for a fixed duration of time [E_{soi}, E_{ei}]. The cost of per unit power generation for each resource (C_{si}) is also given.
- A set of power demands (PD_k) (k=1, 2,....m). Each demand has its power requirement (P_{Dk}) and is required for a fixed duration of time [E_{dok}, E_{dek}].
- Total time horizon [0, T_h] of power sources and demand

The objective is to determine the power rating requirement (PRR) from each PR which leads to the minimum total cost of power supply. Note that, the battery system will store the surplus power. However, it is assumed that PR will not supply beyond its availability in time using the battery system.

3. Methodology

In this section, the methodology for cost-optimal targeting in HPSs is presented. The methodology consists of three main parts, i.e. (1) generation of power demand composite curve (PDCC) (2) Calculation of pinch point and prioritization, (3) Calculation of cost-optimal targets. Figure 1 shows the flow chart of the following algorithm.

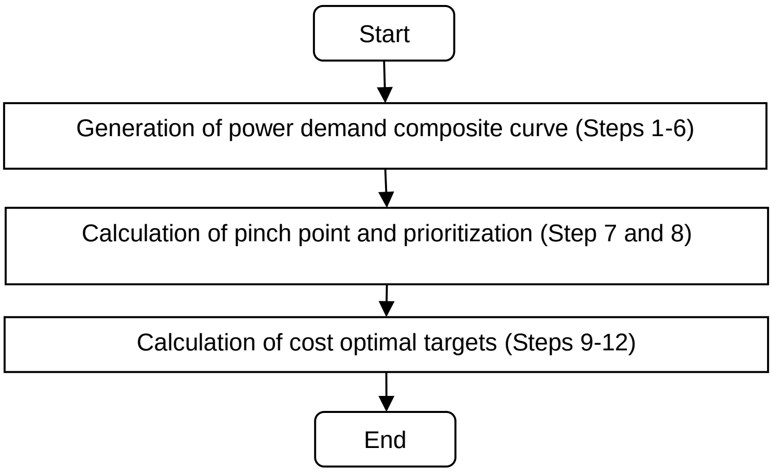

Figure 1: Flow chart showing parts involved in the proposed algorithm

Step 1: All the endpoints of time as determined are tabulated in decreasing order in the first column. Let E_k denote the value of time point for the kth row then,

$$E_1 < E_2 < \cdots < E_k < \cdots < E_n \quad (1)$$

Step 2: In the second column, the sum of power rating corresponding to any particular time point are tabulated as net power rating. Power rating associated with starting time points are taken as positive and power rating associated ending time points are taken as negative. For the k^{th} row, the net power rating is represented as P_k
Step 3: In the next column cumulative net power ratings are tabulated. Eq(2) gives cumulative net power ratings flow at a time point, E_k.

$$Cum\ P_k = \sum_{l=1}^{k} P_k \tag{2}$$

Step 4: The fourth column represents the net power requirement (R_k) for each time interval. Cumulative net power rating is multiplied by the difference of the last two time points to calculate the net power requirement. Eq(3) mathematically represents the net power requirement (R_k) for each time interval.

$$R_k = \begin{cases} 0, & for\ k = 1 \\ (E_k - E_{k-1})\left(\sum_{l=1}^{k} P_k\right), & for\ k > 1 \end{cases} \tag{3}$$

Step 5: In the fifth column, the net power requirement is cascaded for the k^{th} row ($R_{cas,k}$) it may be expressed as Eq(4).

$$R_{cas,k} = \sum_{l=1}^{k} R_k \tag{4}$$

Step 6: A curve between column 1 and column 5 can be plotted taking time points (column 1) on the y-axis and cascaded power requirement (column 5) on the x-axis.
Step 7: Draw prioritization line (PL) with maximum slope starting from time initial point (the initial point at the start is zero) such that it does not crosses PDCC and calculate pinch time as the time where power supply line touches PDCC. The concept is similar to the concept of targeting multiple resources in water allocation networks (Shenoy and Bandyopadhyay, 2007), aggregate production planning (Chaturvedi, 2017), etc. The prioritized cost (PC) of each power resource can be calculated using the following equation.

$$PC_i = \frac{C_{si}}{E_p - E_{is}} \tag{5}$$

Where E_p is the Pinch Point, E_{is} is the starting time of the ith power resource (PRi), and PC_i is prioritized cost of the ith power resource (PRi).
Step 8: Calculate the prioritized cost of each PR. Arrange the PR in increasing order of prioritized cost to form a prioritized sequence.
Step 9: Introduce the least prioritized cost PR in the time of its availability via a Sectional Power Supply Line (PSL). An SPSL for a section of PDCC [Eos, Ees] can be drawn from the initial point of availability of this PR such that it is just below the section of PDCC [Eos, Ees] for which SPSL is to be drawn.
Step 10: Choose the next PR in prioritized sequence and plot SPSL via repeating steps 7, 8 and 9 for the portion where this PR is available in the remaining portion of PDCC
Step 11: Continue the same procedure until the total PDCC receives power supply. The curve consists of all SPSL that can be named as Composite Power Supply Curve (CPSC).
Step 12: PRR from individual PR can be calculated based on CPSC. The inverse of the slope of the SPSL will give PRR from PRs for the corresponding section of PDCC.

4. Illustrative example

In this section, the proposed algorithm is applied to a PD scenario and optimum values of PRR for different PRs are calculated which minimizes the overall cost of electricity. Tables 1 and 2 tabulate the limiting data for power resources and demands for this example. In Table 1, the power requirement data of four appliances are given. The three available resources for power supply along with their time of availability are given in Table 2. Figure 2 shows the Gantt chart for PDs and PRs. First, following the steps from 1 to 6 PDCC is generated in Figure 3. Next, initial PL is drawn and the pinch point is calculated to be at 15 h (Step 7). The prioritized cost of PRs can be calculated using Eq(5). Prioritized cost for solar, wind and biomass power are calculated to be 1.5 ($/kWh)/h, 1.83 ($/kWh)/h and 1.67 ($/kWh)/h (Step 8). The prioritized cost for solar power is least; however, it is available from 9 to 17 h. A line is drawn from Point A on PDCC such that it is just below the part of PDCC. The inverse of the slope of this line is 266.67 kW.

Table 1: Limiting data for PDs in Example 1

	Start time (h)	End time (h)	Time interval (h)	Power rating (kW)	Electricity consumption (kWh)
Appliance 1	10	18	8	20	160
Appliance 2	0	24	24	60	1,440
Appliance 3	8	18	10	20	200
Appliance 4	2	15	13	170	2,210

Table 2: Limiting data for PRs in Example 1

	Time		Time interval (h)	Cost ($/kWh)
	From	To		
Solar	9	17	8	9
Wind	3	9	6	22
Biomass	0	24	24	25

The PRR of solar power should be 266.67 kW (Step 9). Next for the region of PDCC below point A there are two available PRs biomass and wind the pinch point is calculated to be at 9 h. The prioritized costs of wind and biomass are calculated to be 3.67 ($/kWh)/h and 2.78 ($/kWh)/h. Hence, SPSC in this section is drawn starting from origin following the same steps. The inverse of the slope of this line (i.e line 'OA' in Figure 4, where point 'O' is the origin) is 194.45 kW. For the PDCC, as the biomass power is already introduced. It is available in this section also the requirement is lesser than the available. No extra power is required in this section. A line from point C is plotted such that it is just below the part of PDCC. Figure 4 shows the CPSC for this example. The inverse of the slope of this line OA is 194.45 kW. The PRR of biomass should be 194.45 kW (0-24 h). Next, the inverse of the slope of the line AC is 266.67 kW. As biomass power (194.45 kW) is already introduced. Only 72.22 kW of solar power is required. Final PRRs from PRs are shown in Table 3. Final PRRs from PRs are shown in Table 3. The overall cost of electricity supply is calculated to be 121,869.8 $. The biomass is the power available for 24 h, if it is supplied to all appliances the overall cost will be 134,000 $ (calculated based on initial PL). This amounts to a 9 % cost reduction.

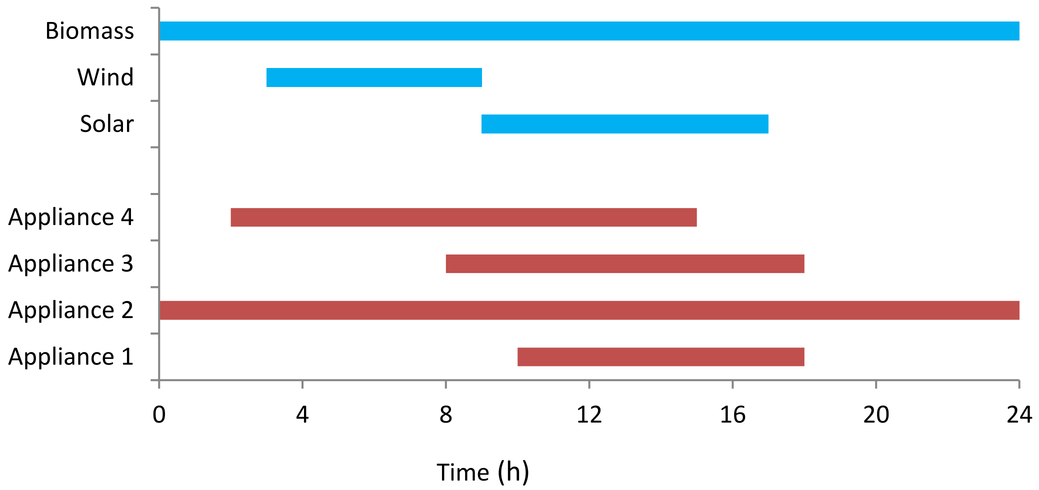

Figure 2: Gantt chart of Example of power requirement and power resources

Table 3: Cost optimal PRR for Example

	Time		Time interval (h)	PRR (kW)
	From	To		
Solar	9	17	8	72.22
Biomass	0	24	24	194.45

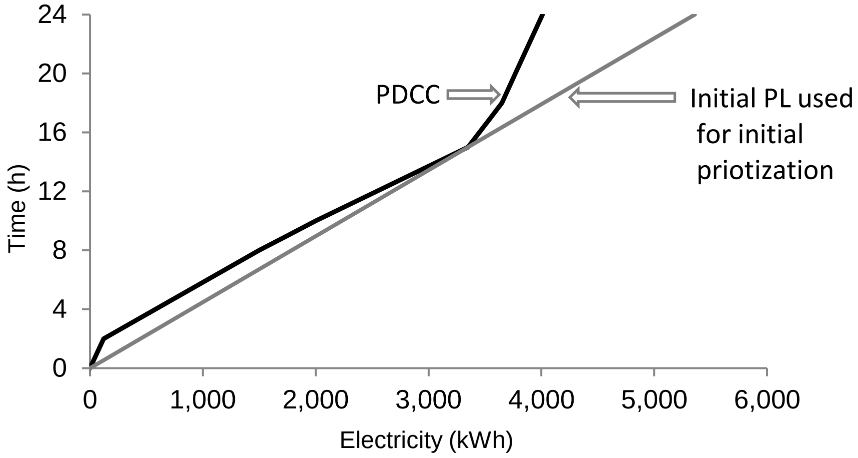

Figure 3: Generation of initial PL in Example

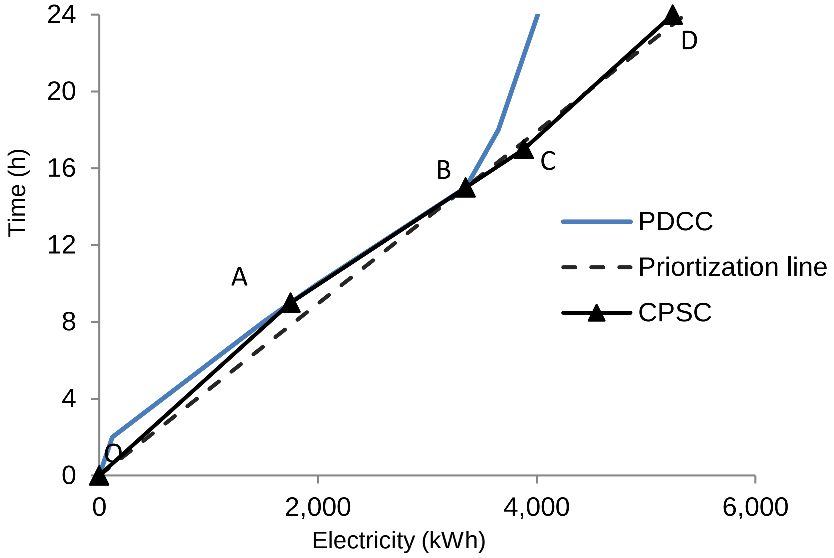

Figure 4: Generation of CPSC in Example

5. Conclusions

In the current scenario, the hybrid power generation system is far and wide acceptance due to the developments in renewable energy technologies, reliability, and environmental restrictions. Proper financial management is necessary to ensure profitability and sustainability. During calculations of the power rating from HPS generation financial planning is important. The process integration developments in HPS have not directly focused on the cost-optimal sizing of HPS. This paper presents a methodology to calculate the PRR from power resources in HPS based on demands to minimize the overall cost of electricity. The methodology is based on the concept of prioritization. The cost of power generation depends on the type of PR. The time of availability of each resource and demand is taken into account. The methodology is illustrated via an example where three PRs (solar wind and biomass) are available. The results directed towards the utilization of only two power resources solar and biomass. Utilizing wind power may lead to an increase in overall cost. A cost reduction of 9 % is estimated in comparison to a single power resource (i.e. biomass) supply. Future research is directed towards including other objectives while optimizing HPS such as carbon emission.

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