Optimal Sizing of Peak-Shaving Generators Using Load Duration Curves and Genetic Algorithms

by

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Abstract: *Rising electricity costs and the risk of supply shortages make ownership of on-site generation an attractive choice for large consumers. These generators can control costs by reducing energy consumption during peak demand times, resulting in reduced power demand and lower energy charges. An economically optimal peak-shaving generator rating will produce the greatest consumer benefit with the least capital investment. This paper develops the Annual Worth Constant Rate and Annual Worth Declining Block Rate models for determining the economically optimal size and annual operating time of peak-shaving generators. The models use load duration curves developed from interval meter data to characterize usage. The models include an exponential generator capital cost function, constant supplier demand charges, and constant generator operation and maintenance costs. Numerical examples demonstrate the models and show the impact of parameter variations on monetary benefits.*

Index: energy management, electric power, engineering economics, optimization, genetic algorithms

I. Introduction

Deregulation of the electric utility industry presented opportunities for competition that promised consumers benefits such as reduced rates and the introduction of new, more efficient technologies. These benefits remain largely unrealized in most deregulated markets today [1, 2]. Instead, the policy changes created markets with multiple suppliers, volatile energy prices, and greater rate and supply risk for consumers. This is particularly true for industrial customers who now must enter into shorter-term contracts and evaluate proposals from many competing suppliers. Higher electric rates increase operating costs significantly and affect a firm’s ability to compete globally.

Industrial customers can reduce costs due to price increases and supply uncertainty by installing a peak-shaving generator (PSG) on their premises [3, 4]. These generators reduce the consumer electric load metered by the electric supplier during times of high system demand, thus reducing electric energy charges. A PSG can also provide a backup supply to cover curtailed power when suppliers exercise an interruptible rate clause in a supply contract. Facilities that own and operate PSG's present a more constant load profile to the grid that attracts lower rates from service providers. Owners of PSG's benefit economically through reduced demand charges, reduced purchased energy costs, and higher service security.

Though PSG's can offer customers economic benefits, the purchase, installation, operation, and maintenance costs reduce these benefits. An economically optimal PSG maximizes consumer benefits and prevents unnecessary investment. This paper presents two models for finding the optimal size and annual operating time for a customer-owned PSG with constant and declining block rates. The models use a load duration curve to characterize consumer annual electric demand and energy consumption. Constructing the load curve requires load power demand data that is available from most large consumer's metering installation. These models give large electrical consumers tools for planning a PSG purchase.

II. Load Duration Curves and PSG Operation

Electric utilities use load duration curves to schedule generation to meet system demand. The load duration curve is a statistical representation of electric load that shows the number of hours a load is expected to meet or exceed a given demand over a specified time interval such as a month or year. The load duration curve is the cumulative probability distribution of demand frequency for a load's demand probability distribution [5]. The PSG optimization developed in [6] assumes a uniform load demand distribution that gives a linear load duration curve. The underlying demand probability distribution can take any form in practice. The following method makes no assumption about the underlying distribution.

Plotting an interval demand histogram gives a load frequency plot of a consumer's power demand comprised of discrete intervals. Fig. 1 shows a typical interval demand histogram.

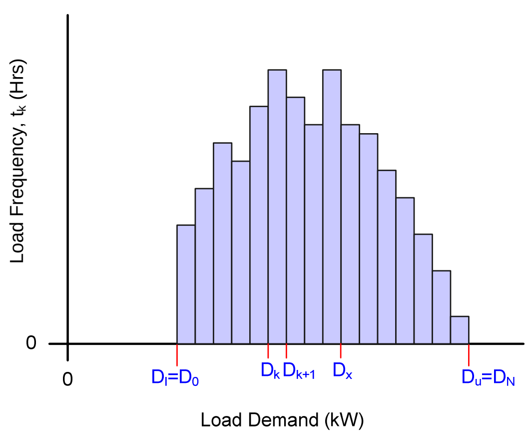

Fig. 1. Typical Load Demand Histogram.

The demand values range from a maximum power demand, D_u to a minimum value of D_l. Dividing this range into N intervals produces histogram classes. Each interval $D_k - D_{k+1}$ contains the number of hours that the load falls in the sub-interval. Plotting the number of hours verses the load demand values gives the load frequency curve. Summing the load frequency times, t_k, from D_0 to D_x gives the accumulated time values, t_D for the load duration curve associated with the load demand histogram.

Equation (1) expresses the accumulated time values as a function of the demand interval D_x.

$$t_D(D_x) = \begin{cases} T_m - \sum_{k=0}^{x} t_k & x > 0 \\ T_m & x = 0 \end{cases} \qquad x = 0,1,2,\ldots N \tag{1}$$

Where: T_m = total load operating time (Hrs)
N = number of histogram classes
t_k = load frequency in interval k-k+1 (Hrs)
D_x = demand level for interval k-k+1 (kW)

Plotting $t_D(D_x)$ verses D_x produces the load duration curve in Fig. 2.

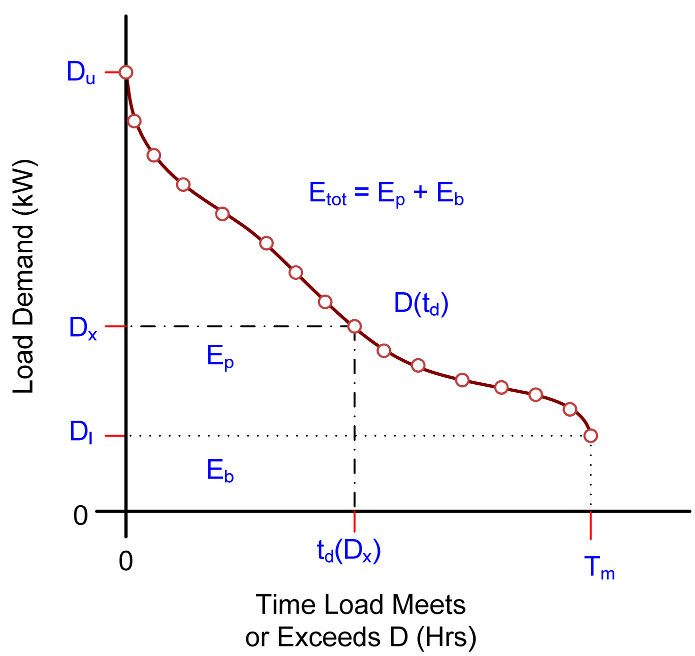

Fig. 2. Load Duration Curve Constructed from Load Frequency Plot.

Define a polynomial fitted to the load duration points as the load duration function, D(t). The area below this function represents the total energy, E_{tot} the load consumes during the period T_m. Assume this period is 8760 hours (1 year) for the remaining discussion. The area between D_u and D_l in Fig. 2 represents the peak energy, E_p, the load consumes during the year while the area below D_l represents the base energy, E_b. The sum of these values is the total annual consumer energy usage. Equation (2) defines the total annual energy consumption as the integral of the load duration function from zero to T_m.

$$E_{tot} = \int_0^{T_m} D(t)\,dt \qquad \textbf{(2)}$$

Fig. 3 shows the development of the PSG energy and demand relationships for an arbitrary load duration function.

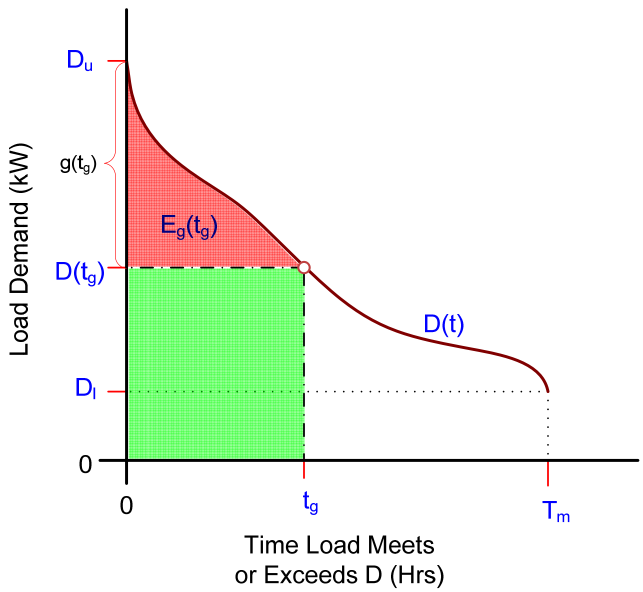

Fig. 3. PSG Energy and Demand Reduction as a Function of PSG Operating Time.

Define t_g as the PSG annual operating time and the energy it produces during this time as $E_g(t_g)$. The energy a PSG produces is the difference between the total energy consumed by the load to t_g and a base energy which is the product of $D(t_g)$ and t_g. Equation (3) combines (2) with this product to give an expression for PSG energy production as a function of its annual operating time.

$$E_g(t_g) = \int_0^{t_g} D(t)\,dt - D(t_g)t_g \qquad \textbf{(3)}$$

Referring to Fig. 3 again, when a PSG runs for the operating time t_g the consumer energy supplier sees a demand reduction that is the difference between the annual maximum demand and the value of $D(t_g)$. This assumes that the PSG operates at full capacity when in service and is available to run when peak consumer loading occurs. The difference between D_u and $D(t_g)$ is the size of PSG that generates enough peak-shaving energy to reduce the annual consumer power demand to $D(t_g)$. Equation (4) defines the capacity of PSG in terms of these variables.

$$g(t_g) = D_u - D(t_g) \tag{4}$$

Where: $g(t_g)$ = PSG capacity in kW for operating time t_g,
D_u = maximum annual interval demand (kW),
$D(t_g)$ = load duration function for PSG operating time t_g,
t_g = PSG annual operating time.

Any consumer that has demand metering can obtain the data for constructing a load duration curve. The demand intervals can range from five minutes to one hour. The previous development assumes a demand interval of one hour. Consumer data for shorter intervals are easily converted to an hourly basis. Plotting the resulting data points will suggest what type of function best applies to the curve. Polynomials fitted by the least-squares method give good approximations of load duration curves. The simplest function for practical load data may be a piece-wise linear fit based on inspection of the load duration curve plot.

III. Electric Energy and PSG Costs

Energy service providers can offer a large consumer a wide variety of electric rates in an attempt to win their load in a competitive market. One type of rate structure offered to large energy consumers is an energy plus demand charge. These charges consist of an energy rate in dollars per kWh and a power demand rate in dollars per kW. The energy usage and power demand set during the billing interval determine total consumer charges. This rate structure can have time-of-use and seasonal rates that capture the costs associated with producing and delivering electricity when system demand is greatest. These temporal effects are ignored in this development since the load duration curve obscures the seasonal and daily cycles of a consumer.

One month is a typical billing period. Power demands are reset each month unless a demand ratchet is in place. This study examines the consumer benefits of owning a PSG under an energy plus demand rate with a monthly demand reset. This work models and compares two energy rates: constant average annual energy rates and declining block energy rates. Dividing the total annual energy charge by the annual consumption gives the average annual rate, c_{eave}. The rate is constant for the study period. Energy costs decrease after a pre-defined amount of energy consumption occurs in a declining block rate (DBR). Further price reductions can occur for larger energy consumption values if the rate includes more blocks. The annual energy cost for a DBR increases at lower rates as the consumer exceeds each consumption threshold.

Equation (5) describes a three block DBR as a function of load energy consumption.

$$c_{edb}(e) = c_{e0} - \Delta c_1 \Phi(e - e_0)(e - e_0) - \Delta c_2 \Phi(e - e_1)(e - e_1) \tag{5}$$

Where: c_{e0} = Block 0 rate (\$/kWh),
Δ_{c1} = Block 1 rate decrement (\$/kWh),
Δ_{c2} = Block 2 rate decrement (\$/kWh),
e_0 = Block 0 energy threshold (kWh),
e_1 = Block 1 energy threshold (kWh),
$\Phi()$ = unit step function.

This study assumes a fixed consumer power demand charge, c_d, for the cost analysis with the units of \$/kW-month.

Any consumer considering the purchase of a PSG must assess the annual costs incurred in purchasing, operating and maintaining the equipment. Purchase and installation costs for a small-scale generator suitable for PSG service decrease as their rated capacity increases. Examining the typical installed costs of diesel-fueled PSG units suggests an exponential relationship between PSG capital costs and generator capacity [7]. Equation (6) describes the capital costs of the PSG as a function of its rated capacity.

$$CC_{psg}(P) = \alpha \cdot P^{-n} \quad \textbf{(6)}$$

Where: $CC_{psg}(P)$ = the annual capital cost of a PSG with capacity P (\$/kW-year)

A least-squares curve fit to actual cost data finds the values of parameters, α and n.

The variable costs of owning a PSG are fuel charges, operation and maintenance costs. This study assumes that the PSG runs at full capacity whenever it operates, so generator efficiency is constant. With this assumption, fuel consumption is proportional to PSG capacity. Multiplying the fuel consumption rate by the fuel cost in \$/kWh produces the PSG fuel charge. Maintenance costs are assumed to be proportional to PSG energy production and expressed in \$/kWh. The sum of these charges defines the annual operation and maintenance costs for as PSG as c_{epsg} in \$/kWh.

IV. Annual Worth Constant Rate Model of PSG Operation

One method of determining the economic benefit of owning a PSG is to determine the annual worth [8]. A consumer gains economically from owning a PSG if the annual costs of purchasing electricity from suppliers are greater than the annual costs of owning and operating a PSG with its associated cost savings from energy and power demand reductions. The annual worth is the difference between the annual cost of electricity without a PSG and the annual cost with the PSG. Computing the annual worth quantifies the consumer's benefits from investing in a PSG. This section develops the Annual Worth Constant Rate (AWCR) model equation. AWCR assumes that the electric energy rates are constant and that the consumer's load duration curve does not change over the life of the PSG.

Large electric consumers pay for both energy consumption and the power demand that they impose on the electric grid. This cost structure includes an energy rate and a power demand rate. The sum of the energy costs and the power demand costs determine the annual electricity cost for a consumer operating under this rate structure. Equation (7) defines the annual electricity cost for a consumer operating without a PSG and having a constant annual energy and demand charge.

$$AC_{cwo} = c_{eave}\, E_{tot} + 12\, c_d\, D_u \tag{7}$$

Where: AC_{cwo} = consumer annual electricity cost without a PSG and a constant annual energy and demand charge ($)
D_u = maximum annual hourly power demand (kW)
E_{tot} = total annual electric energy consumption (kWh)
c_{eave} = average supplier energy rate ($/kWh)
c_d = supplier monthly demand rate ($/kW-month)

The first term of (7) represents the annual energy cost and the second the annual demand charge.

Introducing a PSG at a consumer's site reduces the energy consumption and power demand measured by the supplier meter. This reduces both the energy and demand charges imposed on the consumer. The consumer also incurs the annual capital, fuel and maintenance costs of owning the PSG. Equations (3) and (4) show that the energy production and power reduction are both functions of the PSG operating time, t_g.

Equation (8) includes (3) and (4) and gives the annual electricity cost and operating expenses of the PSG as a function of its annual operating time.

$$AC(t_g)_{cw} = c_{eave}\,(E_{tot} - E_g(t_g)) + 12\, c_d\, D(t_g) + CC_{psg}(g(t_g))\, g(t_g) + c_{epsg}\, E_g(t_g) \tag{8}$$

Where: $AC(t_g)_{cw}$ = annual electricity cost assuming a constant average energy and demand charge with a PSG operating for t_g hours ($)
$E_g(t_g)$ = annual energy production of PSG operating for t_g hours (kWh)
$g(t_g)$ = PSG rating (kW)
$D(t_g)$ = load duration function value at t_g.
c_{epsg} = fuel and maintenance costs ($/kWh)
$CC_{psg}(g(t_g))$ = capital cost of owning PSG with rating of $g(t_g)$ ($/kW-year)

This equation has four cost components, the charge for net consumer energy, the annual demand charge, the capital cost of PSG capacity, and the production cost of PSG energy. PSG operation reduces the annual energy consumption by $E_g(t_g)$ and the peak demand to the value $D(t_g)$. The equation uses the same constant average annual rate as Equation (7) and has a capital cost function in the form of (6) that is a function of PSG capacity.

The difference between Equations (7) and (8) is the annual worth of owning a PSG [8]. Equation (9) defines the function for a constant average electric energy rate and an exponentially decreasing capital cost function. A positive value for this function indicates that a consumer benefits from owning a PSG that operates for time, t_g, and has

$$\begin{aligned} AW_c(t_g) &= AC_{cwo} - AC(t_g)_{cw} \\ AW_c(t_g) &= c_{eave}\, E_g(t_g) + 12\, c_d\, (D_u - D(t_g)) - CC_{psg}(g(t_g))\, g(t_g) - c_{epsg}\, E_g(t_g) \end{aligned} \quad \textbf{(9)}$$

a capacity given by Equation (4). The first two factors in (9) are the energy and demand benefits due to operating a PSG of size $g(t_g)$ for t_g hours annually while the last two factors are the capital and production costs of PSG operation.

The economically optimal PSG rating will have the capacity $g(t_g)$ and the annual operating time t_g that maximizes Equation (9). Since E_g, g and D are functions of t_g, maximizing $AW(t_g)_c$ with respect to t_g finds an optimal annual operating time for a PSG defined as t_{gmax}. The optimal capacity derives from Equation (4) when evaluated at t_{gmax}. Equation (10) expresses this maximization problem, which is the AWCR model.

$$\begin{aligned} &\max\ AW_c(t_g)\ \ \text{w.r.t.}\ t_g\ \ t_g \in [0\ T_m] && \text{(a)} \\ &g_{max} = D_u - D(t_{g\,max}) && \text{(b)} \end{aligned} \quad \textbf{(10)}$$

It is a one dimensional maximization problem that can be solved using a number of methods [9]. The exponential capital cost function requires use of non-linear optimization techniques to find the optimal operating time in (10a). Substituting the result of (10a) into (10b) finds the optimal capacity by subtracting the value of the load duration function evaluated at t_{gmax} from the maximum annual demand, D_u.

V. Annual Worth Declining Block Rate Model of PSG Operation

This section develops the Annual Worth Declining Block Rate (AWDBR) model for optimal PSG Sizing. Including a DBR rate in energy with demand billing makes the optimization problem more complex. Operating a PSG decreases the net electric energy that the supplier meters, causing the DBR to increase if the metered energy falls below a block threshold. The energy thresholds and the block rate values determine when the rate changes occur and how much economic impact the consumer sees. Equation (11) represents the consumer annual electricity cost without a PSG operating and includes the DBR function. The first term of (11) is the annual energy cost and the second is the annual demand charge.

$$AC_{dbwo} = c_{edb}(E_{tot}) + 12\, c_d\, D_u \quad \textbf{(11)}$$

Equation (12) represents the annual cost of operating with the PSG under the DBR. The first term is the energy cost including the PSG production. The second term is the annual demand charge with the reduction of consumer demand to $D(t_g)$ due to PSG capacity. The last two terms are the PSG capital cost and annual operating costs respectively.

$$AC_{dbw}(t_g) = c_{edb}(E_{tot} - E_g(t_g)) + 12\, c_d D(t_g) + CC_{psg}\big(g(t_g)\big)g(t_g) + c_{epsg}\; E_g(t_g) \qquad \textbf{(12)}$$

Taking the difference between (11) and (12) finds the annual worth function for a consumer billed using a DBR, a constant demand rate, and an exponentially decreasing PSG capital cost [8]. Equation (13) expresses this function.

$$AW_{db}(t_g) = c_{edb}(E_{tot}) - c_{edb}(E_{net}(t_g)) + 12\, c_d (D_u - D(t_g)) - CC_{psg}\big(g(t_g)\big)g(t_g) - c_{epsg}\; E_g(t_g) \qquad \textbf{(13)}$$

Where: $c_{edb}()$ = DBR cost function ($),
$E_{net}(t_g) = E_{tot}$-$E_g(t_g)$, net energy metered by the electricity supplier (kWh)

The first two terms in (13) represent the change in consumer electric energy charges that occur through the DBR function. Changes in the net metered energy may cause an energy charge increase if the PSG production reduces the metered value below the block energy threshold. The third term reflects the reduction in demand charges resulting from PSG operation while the last terms reflect the PSG capital, operating, and maintenance costs. As in the constant average rate case, maximizing the annual worth function with respect to t_g finds an optimal PSG operating time, t_{dbmax}. The optimal capacity of the PSG under a DBR is g_{dbmax} when operating at t_{dbmax}. Equation (14) states this maximization problem and defines the optimal PSG capacity value. This is the AWDBR model

$$\begin{aligned} &\max\ AW_{db}(t_g) \quad \text{w.r.t. } t_g \quad t_g \in [0\ T_m] && \text{(a)} \\ &g_{db\max} = D_u - D(t_{db\max}) && \text{(b)} \end{aligned} \qquad \textbf{(14)}$$

Introducing the discontinuous DBR function produces an objective function that includes discontinuities also. Genetic algorithms solve this type of optimization problem effectively and give good estimates of the optimal value [10].

Genetic algorithms solve optimization problems by simulating biological evolution numerically. The algorithm starts by randomly selecting a population of possible solutions to the optimization problem. It then evaluates the objective function using every member of the population to determine their fitness. The fittest population members produce the largest objective values in a maximization problem. The algorithm continues with the current generation of solutions "breeding" to produce another generation of possible solutions. Solutions "breed" based in part on their fitness. Breeding includes less fit solutions to increase the solution search area and increase the likelihood of finding the global optimum. Parent solutions produce fitter off-spring solutions through genetic combination and mutation processes. The fitter off-spring replaces a portion of the solution population each generation. This process continues until objective improvement decreases below a predefined threshold or a fixed number of generations have evolved [11].

Introducing a PSG can cause the consumer DBR rate to increase. Increasing PSG operating time, t_g, increases PSG energy production which decreases net metered energy.

The DBR increases in discrete steps as the net metered energy decreases causing rate increases. Block rate energy threshold values determine when the rate changes occur along with the total energy consumption. When the total consumer energy consumption is high relative to the block rate threshold values, PSG production does not impact the block rate. When total consumer energy consumption and the last block rate threshold are nearly equal, an increase in rate is possible.

Examination of the annual worth functions for PSG operation indicates that the load duration function is critical to determining the economic feasibility of consumer PSG ownership. In this formulation, both the optimal PSG capacity and its energy production depend on the load duration function, D(t). Actual load duration data produces complex curves represented best by piece-wise linear approximations or polynomial curve fits of the load duration function.

VI. Numerical Examples

In this section, numerical examples demonstrate how to compute the optimal size and operating time using the AWCR and AWDBR models given in (10) and (14). The examples demonstrate both models with a quadratic fit to load duration data. Equation (15) fits a parabola through the points, $(0, D_u)$ and (T_m, D_l) and Fig. 4 graphs the result. The examples assume one year of load operation so $T_m = 8760$ hours. The base values of D_u and D_l are 750 kW and 100 kW respectively.

$$D(t) = \left[\frac{D_u - D_l}{T_m^2}\right](t - T_m)^2 + D_l \qquad \textbf{(15)}$$

The examples use installed cost data from three sizes of diesel-fueled PSG's to determine the capital cost equation parameters. The capital cost calculations uses a 20 year life and a rate of return of 4% for computing the \$/kW-year values. Table 1 summarizes installed cost data and the capital costs for the three PSG ratings. Equation (16) presents results of the parameter calculations for this data.

$$CC_{psg}(P) = 61.9\, P^{-0.294} \;\; \$/\text{kW - year} \qquad \textbf{(16)}$$

The first study uses the AWCR model with a constant electricity demand rate of c_d=6\$/kW, an energy rate of c_{eave}= 0.04 \$/kWh, and a PSG operation and maintenance cost, c_{epsg} = 0.12 \$/kWh. Figures 5, 6 and 7 summarize the results of numerical tests

Table-1 Diesel PSG Capital Cost Data

PSG Rating (kW)	Installed Cost ($)	Per Unit Cost of Capacity ($/kW)	Capital Cost ($/kW-year)
900	100,000	111	8.176
400	60,000	150	11.037
125	25,000	200	14.716

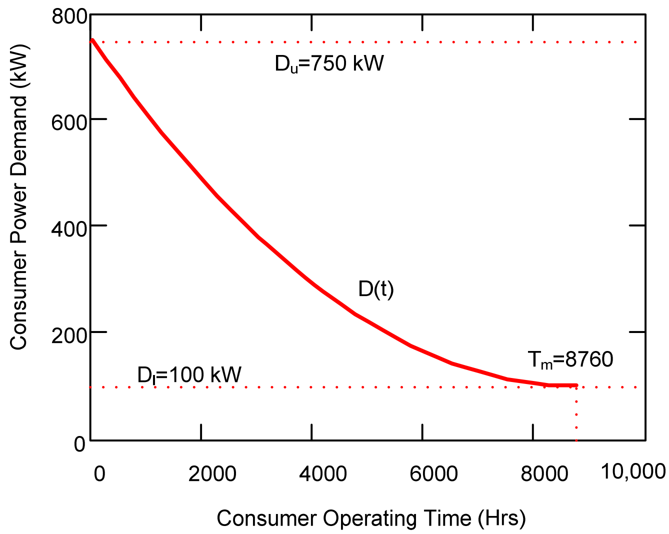

Fig. 4. Quadratic Curve Fit to Load Duration Data.

using the AWCR model where PSG operation and maintenance cost and load duration curve parameters vary.

Fig. 5 shows the impact of increasing PSG fuel and maintenance costs on the realized savings of PSG ownership. The percent annual savings increase as the operation and maintenance (O&M) costs approach the supplier's average annual energy rate. If the PSG's O&M costs equal the supplier's energy rate, the maximum annual worth occurs when the PSG runs 100% of the year and has a capacity of $g_{max}=D_u-D_l$. PSG capacity, operating times and savings decrease as the ratio of supplier rates to PSG O&M costs increase.

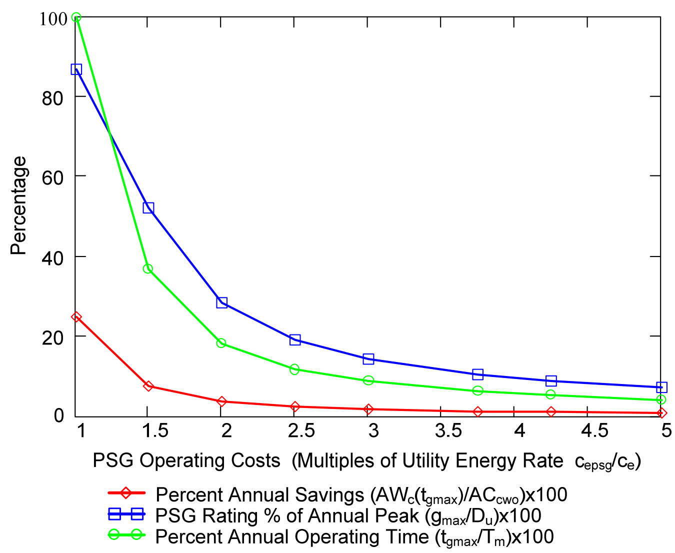

Fig. 5. Impact of Increasing PSG Operation and Maintenance Costs on Capacity, Operating Time and Annual Savings.

Figures 6 and 7 show the impact of load duration curve parameter changes. In Fig. 6, the peak demand value, D_u, varies from 400 to 1200 kW while the base demand value is fixed at 100 kW. This increases both the annual demand peak and the peak energy defined in Fig. 2. Both the capacity and the annual operating time increase over this range of variation with a PSG capacity rating of 27% of peak and operating time of 16% of the year for the peak-to-base ratio of 12. The base ratio for the annual worth percentage is seven. As the demand ratio increases the normalized benefits increase non-linearly to a maximum of 450% of the base.

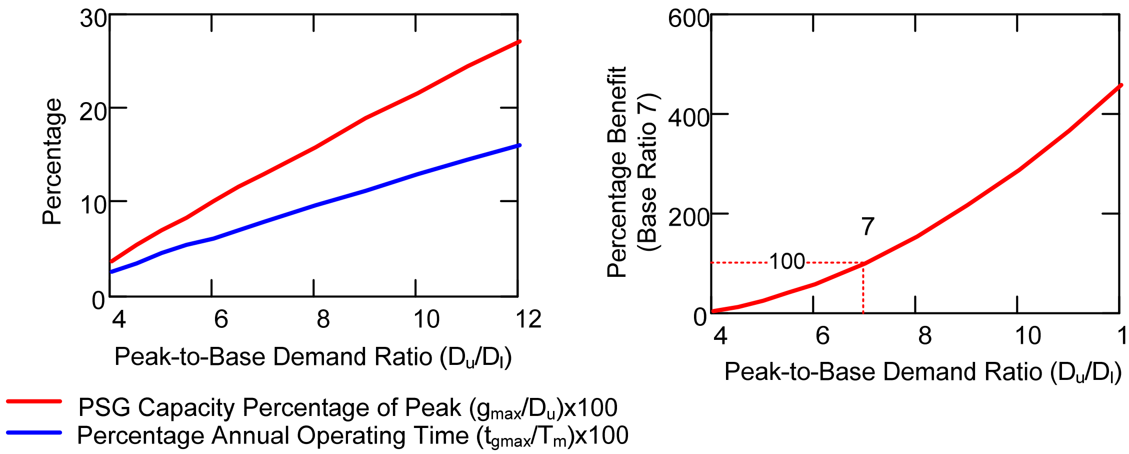

Fig. 6. Impact of Increasing Values of Demand Peak on PSG Capacity, Operating Time and Annual Benefits.

In Fig. 7 the base demand parameter, D_l, varies from 100 kW to 450 kW while the peak demand remains fixed at 750 kW. Varying this parameter increases the consumer's base

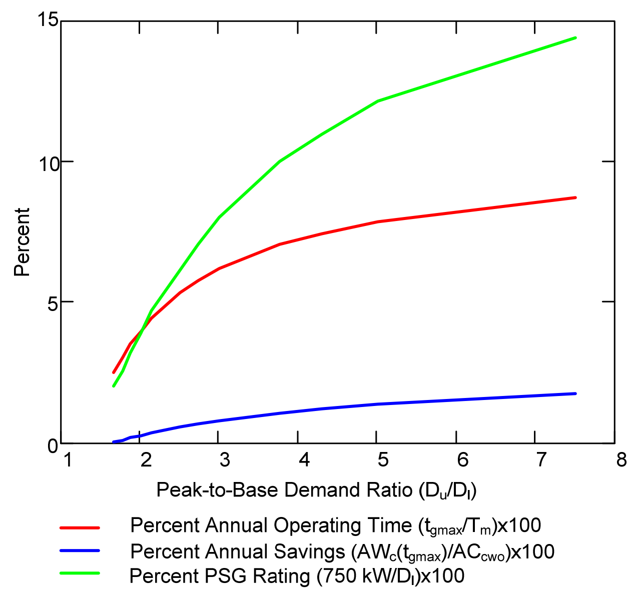

Fig. 7. Impact of Increasing Values of Base Demand on PSG Capacity, Operating Time and Annual Savings.

energy without changing the annual peak demand. Consumers with a low peak-to-base ratio have low percentage savings and smaller optimal PSG capacities. Annual PSG operating time also decreases as the peak-to-base ratio decreases. Higher base demand values reduce the peak energy that a PSG could produce which reduces the PSG energy cost benefits. Higher base demand values also reduce the benefits that derive from load demand reduction

A numerical example of the AWDBR model illustrates the interactions of the rate parameters with the PSG costs. This example uses a three-tier DBR. Since the DBR produces a discontinuous objective function, a genetic algorithm finds the optimal solutions for the test cases [12]. The examples assume a quadratic load duration function. In the first example, the PSG O&M cost, the supplier demand rate, the DBR decrements, and the block energy thresholds are constant. The Block 0 rate is varied.

Table 2 lists the impact of varying the rate from 0.12 $/kWh to 0.08 $/kWh on the annual worth, the PSG optimal capacity and operating time.

Table-2 DBR Test Case Summaries

c_{epsg} = 0.12 $/kWh c_d = 6 $/kW Δc_1=0.035 $/kWh Δc_2 =0.025 $/kWh e_0= 2.5x10^6 kWh e_1=2.7x10^6 kWh				
c_0 ($/kWh)	Annual Worth ($)	Annual Operating Time (Hrs)	PSG Capacity (kW)	Weighted Average Energy Cost ($/kWh)
0.08	2,199	602	86	0.069
0.09	2,484	672	96	0.078
0.10	2,844	761	108	0.087
0.11	10,658	6526	607	0.095
0.12	29,329	8760	650	0.104

The peak and base demand values are held constant at the values of D_u=750 kW and D_l=100 kW respectively. As in the AWCR model, as the cost difference between the supplier and PSG energy rates decrease, the annual worth of owning the PSG increases. The PSG capacity and operating time reach a maximum when the Block 0 rate equals PSG O&M cost. The last column lists the weighted average energy cost for each DBR. This is found by summing the energy cost for each rate and dividing this sum by the total energy.

The block thresholds have an impact on the optimal PSG capacity. Fig. 8ab shows plots of annual worth functions with two sets of PSG parameters. In Fig. 8b the Block 1-2 threshold increased from 2.7 to 2.8 million kWh. Annual load energy consumption does not exceed this value. As a result, this rate transition does not take place, the highest two rates determine the supplier energy costs, and the optimal PSG capacity and operating time. The annual worth function in Fig. 8a shows both rate transitions and the impact on annual worth. The annual worth function reaches the lowest rate with a Block 1-2 threshold set at 2.7 million kWh. This reduces the optimal capacity of the PSG from 157 kW to 108 kW and the annual worth to the consumer from $4325 to $2844.

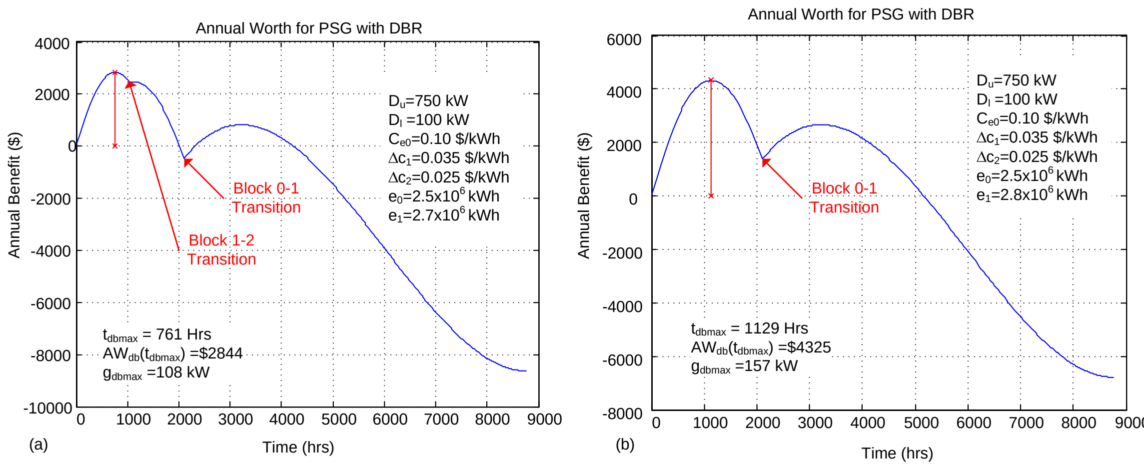

Fig. 8. Annual Worth Plots for Two Declining Block Rate Energy Thresholds.

VII. Conclusion

Increasing electricity rates and supply uncertainty make owning on-site generation an attractive method of reducing electric energy costs and assuring service continuity. Determining the economically optimal size for the generator requires consideration of the costs and the benefits of ownership. This work introduced the Annual Worth Constant Rate (AWCR) and Annual Worth Declining Block Rate (AWDBR) models that use consumer load duration curves to relate power demand and generator operating time. The models represent the annual worth of owning and operating a PSG under a constant average annual energy and a declining block energy rate. Maximizing the annual worth models with respect to generator run time finds the optimal PSG annual operating time. The difference between the annual peak power demand and the demand value of the load duration function at optimal operating time gives the optimal rating for a PSG. Numerical examples of the AWCR model show that the peak/base demand ratio and the energy cost differences between supplier and consumer PSG operation have a significant impact on the economic viability of owning a PSG. The AWDBR model introduces discontinuities to the annual worth function. Genetic algorithms find optimal solutions effectively when objective functions include discontinuities. Numerical tests using a genetic algorithm demonstrate the AWDBR model for a three tier declining block rate. Results indicate rate parameters that produce lower weighted average energy costs reduce optimal economic size and operating time of a PSG. The rate block energy threshold values reduce the optimal economic size if load energy consumption exceeds all block tiers, resulting in the lowest energy cost.

References

[1] Steven N. Isser, "Electricity Deregulation: Kilowatts for Nothing and Your BTUs for Free," Review of Policy Research, Vol. 20, No. 2, pp. 219-238, June 2003.

[2] N. K. Trehan, R. Saran, "Electric Utility Deregulation: Failure or Success," IEEE Nuclear Science Symposium Conference Record, Vol. 7, pp. 4614-4617, October 16-22, 2004.
[3] W. G. Scott, "Microturbine Generators for Distribution Systems," IEEE Industry Applications Magazine, Vol. 4, No. 3, pp. 57-62, May/June 1998.
[4] P. A. Daly, J. Morrison, "Understanding the Potential Benefits of Distributed Generation on Power Delivery Systems," Rural Electric Power Conference, April 29-May 1, Little Rock, AK , pp. A2/1-A2/13, 2001.
[5] Allen J. Wood, Bruce F. Wollenberg, Power Generation Operation and Control, John Wiley & Sons, New York, NY, 1984.
[6] Jorge B. Wong, "Statistical Modeling of Electric Demand and Peak-Shaving Generator Economic Optimization," Energy Engineering, Vol. 101, No.3, pp. 7-17, 2004.
[7] Installation, Operation, and Maintenance Costs for Distributed Generation Technologies, EPRI, Palo Alto, CA: 2003. 1007675, Available online: www.energy.ca.gov/distgen_oii/documents/dgwg/R+D-3.pdf
[8] Leland T. Blank, Anthony J. Tarquin, Engineering Economy 4th Ed., McGraw-Hill, 1998.
[9] Ronald E. Miller, Optimization: Foundations and Application, Wiley, NY, 2000.
[10] Robert E. Dorsey, Walter J. Mayer, "Genetic Algorithms for Estimation Problems with Multiple Optima, Nondifferentiability, and Other Irregular Features," Journal of Business and Economic Statistics, Vol. 13, No.1, pp. 53-66, January, 1995.
[11] D.A Coley, An Introduction to Genetic Algorithms for Scientists and Engineers, World Scientific Publishing, 1999.
[12] Michael Gordy, "A Matlab Routine for Function Maximization Using a Genetic Algorithm," Available online: ftp://all.repec.org/RePEc/cod/html/Matlab/gordy.m.