CHAPTER 15

MICROPOWER SYSTEM MODELING WITH HOMER

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15.1 INTRODUCTION

The HOMER Micropower Optimization Model is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micropower systems and to facilitate the comparison of power generation technologies across a wide range of applications. HOMER models a power system's physical behavior and its life-cycle cost, which is the total cost of installing and operating the system over its life span. HOMER allows the modeler to compare many different design options based on their technical and economic merits. It also assists in understanding and quantifying the effects of uncertainty or changes in the inputs.

A *micropower system* is a system that generates electricity, and possibly heat, to serve a nearby load. Such a system may employ any combination of electrical generation and storage technologies and may be grid-connected or autonomous, meaning separate from any transmission grid. Some examples of micropower systems are a solar–battery system serving a remote load, a wind–diesel system serving an isolated village, and a grid-connected natural gas microturbine providing electricity and heat to a factory. Power plants that supply electricity to a high-voltage transmission system do not qualify as micropower systems because they are not

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dedicated to a particular load. HOMER can model grid-connected and off-grid micropower systems serving electric and thermal loads, and comprising any combination of photovoltaic (PV) modules, wind turbines, small hydro, biomass power, reciprocating engine generators, microturbines, fuel cells, batteries, and hydrogen storage.

The analysis and design of micropower systems can be challenging, due to the large number of design options and the uncertainty in key parameters, such as load size and future fuel price. Renewable power sources add further complexity because their power output may be intermittent, seasonal, and nondispatchable, and the availability of renewable resources may be uncertain. HOMER was designed to overcome these challenges.

HOMER performs three principal tasks: simulation, optimization, and sensitivity analysis. In the simulation process, HOMER models the performance of a particular micropower system configuration each hour of the year to determine its technical feasibility and life-cycle cost. In the optimization process, HOMER simulates many different system configurations in search of the one that satisfies the technical constraints at the lowest life-cycle cost. In the sensitivity analysis process, HOMER performs multiple optimizations under a range of input assumptions to gauge the effects of uncertainty or changes in the model inputs. Optimization determines the optimal value of the variables over which the system designer has control such as the mix of components that make up the system and the size or quantity of each. Sensitivity analysis helps assess the effects of uncertainty or changes in the variables over which the designer has no control, such as the average wind speed or the future fuel price.

Figure 15.1 illustrates the relationship between simulation, optimization, and sensitivity analysis. The optimization oval encloses the simulation oval to represent the fact that a single optimization consists of multiple simulations. Similarly, the sensitivity analysis oval encompasses the optimization oval because a single sensitivity analysis consists of multiple optimizations.

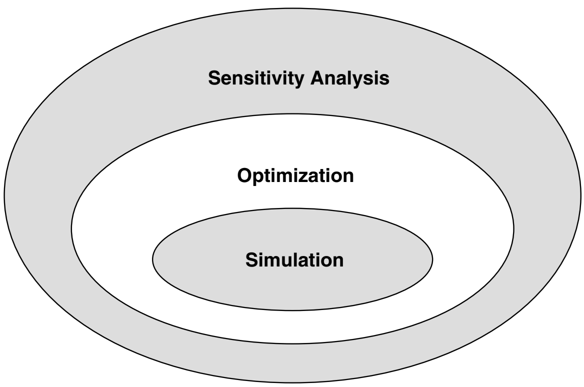

Figure 15.1 Conceptual relationship between simulation, optimization, and sensitivity analysis.

To limit input complexity, and to permit fast enough computation to make optimization and sensitivity analysis practical, HOMER's simulation logic is less detailed than that of several other time-series simulation models for micropower systems, such as Hybrid2 [1], PV-DesignPro [2], and PV*SOL [3]. On the other hand, HOMER is more detailed than statistical models such as RETScreen [4], which do not perform time-series simulations. Of all these models, HOMER is the most flexible in terms of the diversity of systems it can simulate.

In this chapter we summarize the capabilities of HOMER and discuss the benefits it can provide to the micropower system modeler. In Sections 15.2 through 15.4 we describe the structure, purpose, and capabilities of HOMER and introduce the model. In Sections 15.5 and 15.6 we discuss in greater detail the technical and economic aspects of the simulation process. A glossary defines many of the terms used in the chapter.

15.2 SIMULATION

HOMER's fundamental capability is simulating the long-term operation of a micropower system. Its higher-level capabilities, optimization and sensitivity analysis, rely on this simulation capability. The simulation process determines how a particular *system configuration*, a combination of system components of specific sizes, and an operating strategy that defines how those components work together, would behave in a given setting over a long period of time.

HOMER can simulate a wide variety of micropower system configurations, comprising any combination of a PV array, one or more wind turbines, a run-of-river hydro-turbine, and up to three generators, a battery bank, an ac–dc converter, an electrolyzer, and a hydrogen storage tank. The system can be grid-connected or autonomous and can serve ac and dc electric loads and a thermal load. Figure 15.2 shows schematic diagrams of some examples of the types of micropower systems that HOMER can simulate.

Systems that contain a battery bank and one or more generators require a dispatch strategy, which is a set of rules governing how the system charges the battery bank. HOMER can model two different dispatch strategies: load-following and cycle-charging. Under the load-following strategy, renewable power sources charge the battery but the generators do not. Under the cycle-charging strategy, whenever the generators operate, they produce more power than required to serve the load with surplus electricity going to charge the battery bank.

The simulation process serves two purposes. First, it determines whether the system is feasible. HOMER considers the system to be feasible if it can adequately serve the electric and thermal loads and satisfy any other constraints imposed by the user. Second, it estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime. The life-cycle cost is a convenient metric for comparing the economics of various system configurations. Such comparisons are the basis of HOMER's optimization process, described in Section 15.3.

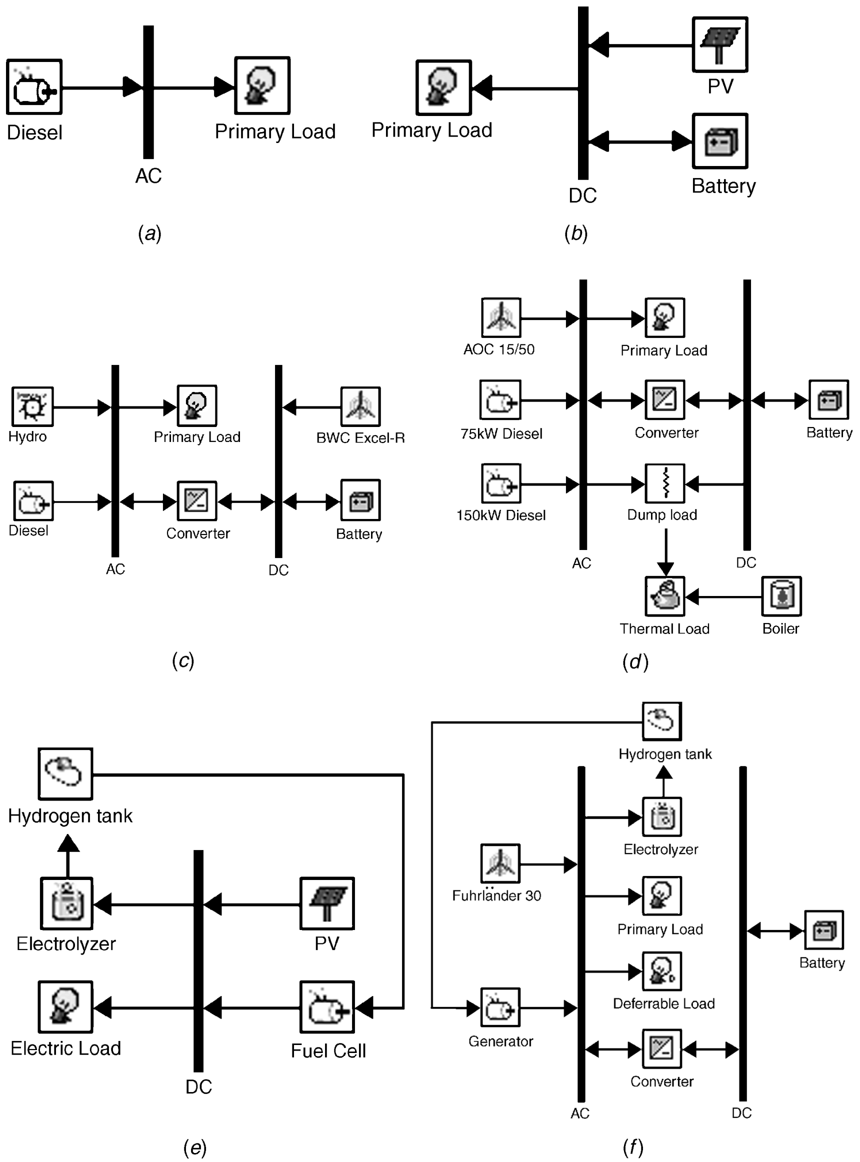

Figure 15.2 Schematic diagrams of some micropower system types that HOMER models: (*a*) a diesel system serving an ac electric load; (*b*) a PV–battery system serving a dc electric load; (*c*) a hybrid hydro–wind–diesel system with battery backup and an ac–dc converter; (*d*) a wind–diesel system serving electric and thermal loads with two generators, a battery bank, a boiler, and a dump load that helps supply the thermal load by passing excess wind turbine power through a resistive heater; (*e*) a PV–hydrogen system in which an electrolyzer converts excess PV power into hydrogen, which a hydrogen tank stores for use in a fuel cell during times of insufficient PV power; (*f*) a wind-powered system using both batteries and hydrogen for backup, where the hydrogen fuels an internal combustion engine generator; (*g*) a grid-connected PV system; (*h*) a grid-connected combined heat and power (CHP) system in which a microturbine produces both electricity and heat; (*i*) a grid-connected CHP system in which a fuel cell provides electricity and heat.

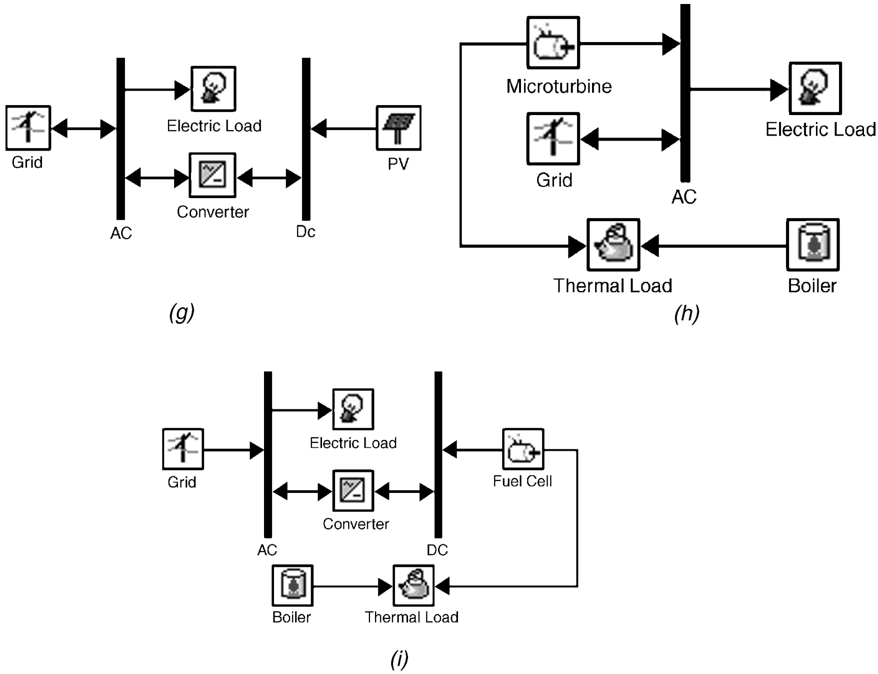

Figure 15.2 (*Continued*)

HOMER models a particular system configuration by performing an hourly time series simulation of its operation over one year. HOMER steps through the year one hour at a time, calculating the available renewable power, comparing it to the electric load, and deciding what to do with surplus renewable power in times of excess, or how best to generate (or purchase from the grid) additional power in times of deficit. When it has completed one year's worth of calculations, HOMER determines whether the system satisfies the constraints imposed by the user on such quantities as the fraction of the total electrical demand served, the proportion of power generated by renewable sources, or the emissions of certain pollutants. HOMER also computes the quantities required to calculate the system's life-cycle cost, such as the annual fuel consumption, annual generator operating hours, expected battery life, or the quantity of power purchased annually from the grid.

The quantity HOMER uses to represent the life-cycle cost of the system is the *total net present cost* (NPC). This single value includes all costs and revenues that occur within the project lifetime, with future cash flows discounted to the present. The total net present cost includes the initial capital cost of the system components, the cost of any component replacements that occur within the project lifetime, the cost of maintenance and fuel, and the cost of purchasing power from the grid. Any revenue from the sale of power to the grid reduces the total NPC. In Section 15.6 we describe in greater detail how HOMER calculates the total NPC.

For many types of micropower systems, particularly those involving intermittent renewable power sources, a one-hour time step is necessary to model the behavior of the system with acceptable accuracy. In a wind–diesel–battery system, for example, it is not enough to know the monthly average (or even daily average) wind power output, since the timing and the variability of that power output are as important as its average quantity. To predict accurately the diesel fuel consumption, diesel operating hours, the flow of energy through the battery, and the amount of surplus electrical production, it is necessary to know how closely the wind power output correlates to the electric load, and whether the wind power tends to come in long gusts followed by long lulls, or tends to fluctuate more rapidly. HOMER's one-hour time step is sufficiently small to capture the most important statistical aspects of the load and the intermittent renewable resources, but not so small as to slow computation to the extent that optimization and sensitivity analysis become impractical. Note that HOMER does not model electrical transients or other dynamic effects, which would require much smaller time steps.

Figure 15.3 shows a portion of the hourly simulation results that HOMER produced when modeling a PV–battery system similar to the one shown in Figure 15.2*b*. In such a system, the battery bank absorbs energy when the PV power output exceeds the load, and discharges energy when the load exceeds the PV power output. The graph shows how the amount of energy stored in the battery bank drops during three consecutive days of poor sunshine, October 24–26. The depletion of the battery meant that system could not supply the entire load on October 26 and 27. HOMER records such energy shortfalls and at the end of the simulation determines whether the system supplied enough of the total load to be considered feasible according to user-specified constraints. HOMER also uses the simulation results to calculate the battery throughput (the amount of energy that cycled through the battery over the year), which it uses to calculate the lifetime of the battery. The lifetime of the battery affects the total net present cost of the system.

HOMER simulates how the system operates over one year and assumes that the key simulation results for that year (such as fuel consumption, battery throughput, and surplus power production) are representative of every other year in the project

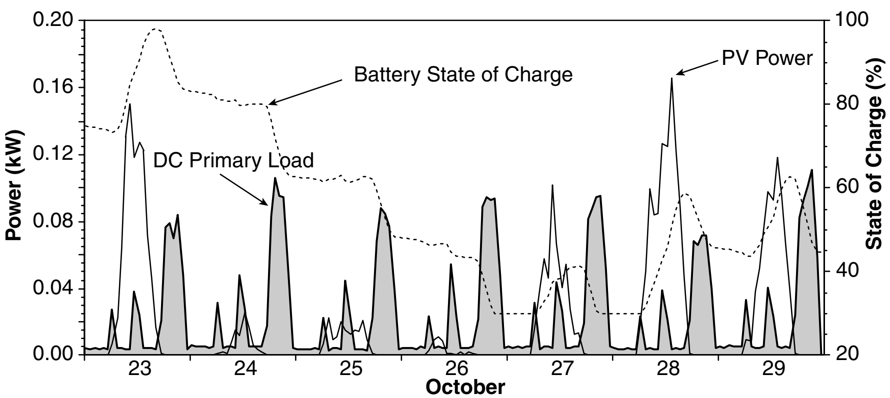

Figure 15.3 Sample hourly simulation results.

lifetime. It does not consider changes over time, such as load growth or the deterioration of battery performance with aging. The modeler can, however, analyze many of these effects using sensitivity analysis, described in Section 15.4. In Sections 15.5 and 15.6 we discuss in greater detail the technical and economic aspects of HOMER's simulation process.

15.3 OPTIMIZATION

Whereas the simulation process models a particular system configuration, the optimization process determines the best possible system configuration. In HOMER, the best possible, or *optimal*, system configuration is the one that satisfies the user-specified constraints at the lowest total net present cost. Finding the optimal system configuration may involve deciding on the mix of components that the system should contain, the size or quantity of each component, and the dispatch strategy the system should use. In the optimization process, HOMER simulates many different system configurations, discards the infeasible ones (those that do not satisfy the user-specified constraints), ranks the feasible ones according to total net present cost, and presents the feasible one with the lowest total net present cost as the optimal system configuration.

The goal of the optimization process is to determine the optimal value of each decision variable that interests the modeler. A decision variable is a variable over which the system designer has control and for which HOMER can consider multiple possible values in its optimization process. Possible decision variables in HOMER include:

- The size of the PV array
- The number of wind turbines
- The presence of the hydro system (HOMER can consider only one size of hydro system; the decision is therefore whether or not the power system should include the hydro system)
- The size of each generator
- The number of batteries
- The size of the ac–dc converter
- The size of the electrolyzer
- The size of the hydrogen storage tank
- The dispatch strategy (the set of rules governing how the system operates)

Optimization can help the modeler find the optimal system configuration out of many possibilities. Consider, for example, the task of retrofitting an existing diesel power system with wind turbines and batteries. In analyzing the options for redesigning the system, the modeler may want to consider the arrangement of components shown in Figure 15.4, but would not know in advance what number of wind turbines, what number of batteries, and what size of converter minimize

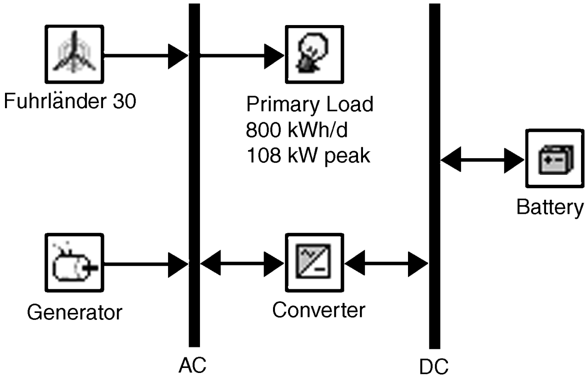

Figure 15.4 Wind–diesel system.

the life-cycle cost. These three variables would therefore be decision variables in this analysis. The dispatch strategy could also be a decision variable, but for simplicity this discussion will exclude the dispatch strategy. In Section 15.5.4 we discuss dispatch strategy in greater detail.

HOMER allows the modeler to enter multiple values for each decision variable. Using a table like the one shown in Figure 15.5, the user enters any number of values for each decision variable. The spacing between values does not have to be regular. In this example, the modeler chose to simulate five quantities of wind turbines, ranging from zero to four; the one existing generator size; seven quantities of batteries, ranging from zero to 128; and four converter sizes, ranging from zero to 120 kW. This table shows the *search space*, which is the set of all possible system configurations over which HOMER can search for the optimal system configuration. This search space includes 140 distinct system configurations because the possible values of the decision variables comprise 140 different combinations: five quantities of wind turbines multiplied by seven quantities of batteries, multiplied by four sizes of converter.

In the optimization process, HOMER simulates every system configuration in the search space and displays the feasible ones in a table, sorted by total net present

	FL30 (Quantity)	Gen (kW)	Batteries (Quantity)	Converter (kW)
1	0	135.00	0	0.00
2	1		16	30.00
3	2		32	60.00
4	3		48	120.00
5	4		64	
6			96	
7			128	
8				

Figure 15.5 Search space comprising 140 system configurations ($5 \times 1 \times 7 \times 4 = 140$).

cost. Figure 15.5 shows the results of the sample wind–diesel retrofit analysis. Each row in the table represents a feasible system configuration. The first four columns contain icons indicating the presence of the different components, the next four columns indicate the number or size of each component, and the next five columns contain a few of the key simulation results: namely, the total capital cost of the system, the total net present cost, the levelized cost of energy (cost per kilowatthour), the annual fuel consumption, and the number of hours the generator operates per year. The modeler can access the complete simulation results, including hourly data, for any particular system configuration; this table is a summary of the simulation results for many different configurations.

The first row in Figure 15.6 is the optimal system configuration, meaning the one with the lowest net present cost. In this case, the optimal configuration contains one wind turbine, the 135-kW generator, 64 batteries, and a 30-kW converter. The second-ranked system is the same as the first except that it contains two wind turbines instead of one. The third-ranked system is the same as the first except that it contains fewer batteries. The eighth- and tenth-ranked systems contain no wind turbines.

HOMER can also show a subset of these overall optimization results by displaying only the least-cost configuration within each system category or type. In the overall list shown in Figure 15.6, the top-ranked system is the least-cost configuration within the wind–diesel–battery system category. Similarly, the eighth-ranked system is the least-cost configuration within the diesel–battery system category.

FL30	Gen (kW)	Batt.	Conv. (kW)	Initial Capital	Total NPC	COE ($/kWh)	Diesel (L)	Gen (hrs)
1	135	64	30	$ 216,500	$ 849,905	0.273	75,107	4,528
2	135	64	30	$ 346,500	$ 854,660	0.274	54,434	3,350
1	135	48	30	$ 200,500	$ 855,733	0.275	78,061	4,910
2	135	48	30	$ 330,500	$ 856,335	0.275	57,654	3,685
2	135	32	30	$ 314,500	$ 873,322	0.280	62,394	4,139
2	135	96	60	$ 401,000	$ 878,370	0.282	48,139	2,603
2	135	64	60	$ 369,000	$ 880,421	0.282	52,999	3,195
	135	64	30	$ 86,500	$ 885,175	0.284	101,290	5,528
1	135	96	30	$ 248,500	$ 887,379	0.285	74,193	4,346
	135	48	30	$ 70,500	$ 888,528	0.285	104,009	6,067
1	135	32	30	$ 184,500	$ 889,688	0.285	85,310	5,615
2	135	96	30	$ 378,500	$ 890,504	0.286	52,442	3,136
2	135	48	60	$ 353,000	$ 891,896	0.286	57,316	3,615
2	135	32	60	$ 337,000	$ 905,959	0.291	62,312	4,080
2	135	128	60	$ 433,000	$ 907,508	0.291	45,596	2,226
1	135	64	60	$ 239,000	$ 911,667	0.292	77,753	4,613
	135	96	30	$ 118,500	$ 912,410	0.293	101,003	5,330

Figure 15.6 Overall optimization results table showing system configurations sorted by total net present cost.

FL30	Gen (kW)	Batt.	Conv. (kW)	Initial Capital	Total NPC	COE ($/kWh)	Diesel (L)	Gen (hrs)
1	135	64	30	$ 216,500	$ 849,905	0.273	75,107	4,528
	135	64	30	$ 86,500	$ 885,175	0.284	101,290	5,528
	135			$ 0	$ 996,273	0.320	132,357	8,760
1	135			$ 130,000	$ 1,130,637	0.363	127,679	8,740

Figure 15.7 Categorized optimization results table.

The categorized optimization results list, shown in Figure 15.7, makes it easier to see which is the least-cost configuration for each category by eliminating the need to scroll through the longer list of systems displayed in the overall list.

The results in Figure 15.7 show that under the assumptions of this analysis, adding wind turbines and a battery bank would indeed reduce the life-cycle cost of the system. The initial investment of $216,500 for the optimal system leads to a savings in net present cost of $146,000 compared to the existing diesel system, shown in the third row. (Note that the diesel-only system has a capital cost of zero because the existing diesel generator requires no capital investment.) The optimization results tables allow this kind of comparison because they display more than just the optimal system configuration. The overall optimization results table in particular tends to show many system configurations whose total net present cost is only slightly higher than that of the optimal configuration. The modeler may decide that one of these suboptimal configurations is preferable in some way to the configuration that HOMER presents as optimal. For example, the simulation results may show that a system configuration with a slightly higher total net present cost than the optimal configuration does a better job of avoiding deep and extended discharges of the battery bank, which can dramatically shorten battery life in real systems. This is a technical detail that is beyond the scope of the model, but one that the modeler can take into consideration in making a final design decision.

15.4 SENSITIVITY ANALYSIS

In Section 15.3 we described the optimization process, in which HOMER finds the system configuration that is optimal under a particular set of input assumptions. In this section we describe the sensitivity analysis process, in which HOMER performs multiple optimizations, each using a different set of input assumptions. A sensitivity analysis reveals how sensitive the outputs are to changes in the inputs.

In a sensitivity analysis, the HOMER user enters a range of values for a single input variable. A variable for which the user has entered multiple values is called a *sensitivity variable*. Almost every numerical input variable in HOMER that is not a decision variable can be a sensitivity variable. Examples include the grid power price, the fuel price, the interest rate, or the lifetime of the PV array. As described in Section 15.4.2, the magnitude of an hourly data set, such as load and renewable resource data, can also be a sensitivity variable.

The HOMER user can perform a sensitivity analysis with any number of sensitivity variables. Each combination of sensitivity variable values defines a distinct sensitivity case. For example, if the user specifies six values for the grid power price and four values for the interest rate, that defines 24 distinct sensitivity cases. HOMER performs a separate optimization process for each sensitivity case and presents the results in various tabular and graphic formats.

One of the primary uses of sensitivity analysis is in dealing with uncertainty. If a system designer is unsure of the value of a particular variable, he or she can enter several values covering the likely range and see how the results vary across that range. But sensitivity analysis has applications beyond coping with uncertainty. A system designer can use sensitivity analysis to evaluate trade-offs and answer such questions as: How much additional capital investment is required to achieve 50% or 100% renewable energy production? An energy planner can determine which technologies, or combinations of technologies, are optimal under different conditions. A market analyst can determine at what price, or under what conditions, a product (e.g., a fuel cell or a wind turbine) competes with the alternatives. A policy analyst can determine what level of incentive is needed to stimulate the market for a particular technology, or what level of emissions penalty would tilt the economics toward cleaner technologies.

15.4.1 Dealing with Uncertainty

A challenge that often confronts the micropower system designer is uncertainty in key variables. Sensitivity analysis can help the designer understand the effects of uncertainty and make good design decisions despite uncertainty. For example, consider the wind–diesel system analysis in Section 15.3. In performing this analysis, the modeler assumed that the price of diesel fuel would be $0.60 per liter over the 25-year project lifetime. There is obviously substantial uncertainty in this value, but many other inputs may be uncertain as well, such as the lifetime of the wind turbine, the maintenance cost of the diesel engine, the long-term average wind speed at the site, and even the average electric load. Sensitivity analysis can help the modeler to determine the effect that variations in these inputs have on the behavior, feasibility, and economics of a particular system configuration; the robustness of a particular system configuration (in other words, whether it is nearly optimal in all scenarios, or far from optimal in certain scenarios); and how the optimal system configuration changes across the range of uncertainty.

The spider graph in Figure 15.8 shows the results of a sensitivity analysis on three variables. In this analysis, the modeler fixed the system configuration to the wind–diesel system that appears in the first row of the optimization table in Figure 15.6, but entered multiple values for three input variables: the diesel fuel price, the wind turbine lifetime, and the generator O&M (operating and maintenance) cost. For each variable, the modeler entered values ranging from 30% below to 30% above a best estimate. Figure 15.8 shows how sensitive the total net present cost is to each of these three variables. The relative steepness of the three curves shows that the total NPC is more sensitive to the fuel price than to the other two

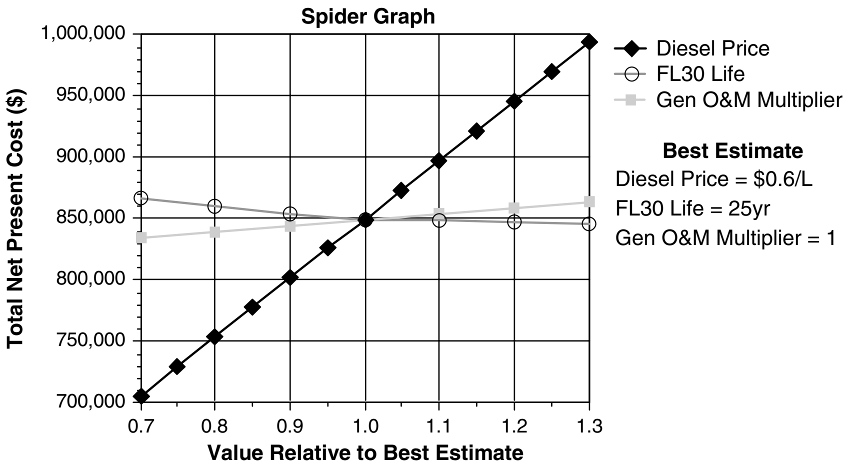

Figure 15.8 Spider graph showing the effect of changes in three sensitivity variables.

variables. Such information can help a system designer to establish the bounds of a confidence interval or to prioritize efforts to reduce uncertainty.

A sensitivity analysis can also incorporate optimization. Figure 15.9 shows the results of a second sensitivity analysis on the wind–diesel system from Section 15.3. The modeler performed this analysis to see whether the fuel price, which Figure 15.8 identified as the most important of the uncertain variables, affects the optimal system configuration. This time the modeler used the search space shown in Figure 15.5 and entered a range of fuel prices above and below the best-estimate

Diesel ($/L)	FL30	Gen (kW)	Batt.	Conv. (kW)	Total NPC
0.420		135	48	30	$ 688,679
0.450		135	48	30	$ 721,987
0.480	1	135	64	30	$ 753,695
0.510	1	135	64	30	$ 777,748
0.540	1	135	64	30	$ 801,800
0.570	1	135	64	30	$ 825,852
0.600	1	135	64	30	$ 849,905
0.630	2	135	64	30	$ 872,093
0.660	2	135	64	30	$ 889,525
0.690	2	135	64	30	$ 906,957
0.720	2	135	64	30	$ 924,389
0.750	2	135	64	30	$ 941,821
0.780	2	135	64	30	$ 959,253

Figure 15.9 Tabular sensitivity results showing optimal system configuration changing with fuel price.

	FL30	Gen (kW)	Batt.	Conv. (kW)	Total NPC
		135	48	30	$ 688,679
		135	64	30	$ 690,550
	1	135	64	30	$ 705,590
	1	135	48	30	$ 705,704
		135	32	30	$ 708,090
		135	96	30	$ 718,337

Figure 15.10 Optimization results for the $0.42 per liter fuel price sensitivity case.

value of $0.60 per liter. The tabular results in Figure 15.9 show that as the fuel price increases, the optimal system configuration changes from a diesel–battery system to a wind–diesel–battery system comprising one wind turbine, and as the fuel price increases further, to a wind–diesel–battery system comprising two wind turbines.

The arrow in Figure 15.9 highlights the best estimate scenario with a fuel price of $0.60 per liter. The optimal system configuration for this scenario (one wind turbine, a 135-kW generator, 64 batteries, and a 30-kW converter) is optimal for five of the 13 sensitivity cases. An investigation of the overall optimization results tables for the other sensitivity cases shows that this system configuration is nearly optimal for those sensitivity cases as well. For example, Figure 15.10 shows the optimization results table for the lowest fuel price scenario ($0.42 per liter). The system configuration that was optimal in the $0.60 per liter scenario ranks third in this scenario, with a total NPC of $705,590, which is only 2.4% higher than the total NPC of the optimal configuration. For the most expensive fuel scenario, it ranks fifth, with a total NPC only 3.6% higher than the optimal configuration. It is therefore a fairly robust solution in that it performs well across the given range of fuel prices. By contrast, the diesel–battery system that is optimal in the lowest fuel price scenario ranks thirty-sixth in the highest fuel price scenario, with a total NPC 13.5% higher than the optimal configuration. The analysis shows that the diesel–battery system would have a higher risk than the wind–diesel–battery system because it is far from optimal under some fuel price scenarios.

With this kind of information, a modeler can make informed decisions despite uncertainty in important variables. As in the example above, a sensitivity analysis can reveal how different system configurations perform over a wide range of possible scenarios, helping the designer assess the risks associated with each.

15.4.2 Sensitivity Analyses on Hourly Data Sets

One of HOMER's most powerful features is its ability to do sensitivity analyses on hourly data sets such as the primary electric load or the solar, wind, hydro, or biomass resource. HOMER's use of scaling variables enables such sensitivity analyses. Each hourly data set comprises 8760 values that have a certain average value. But each hourly data set also has a corresponding scaling variable that the modeler can use to scale the entire data set up or down. For example, a user may specify hourly primary load data with an annual average of 120 kWh/day, then specify 100, 150, and 200 kWh/day for the primary load scaling variable. In the course

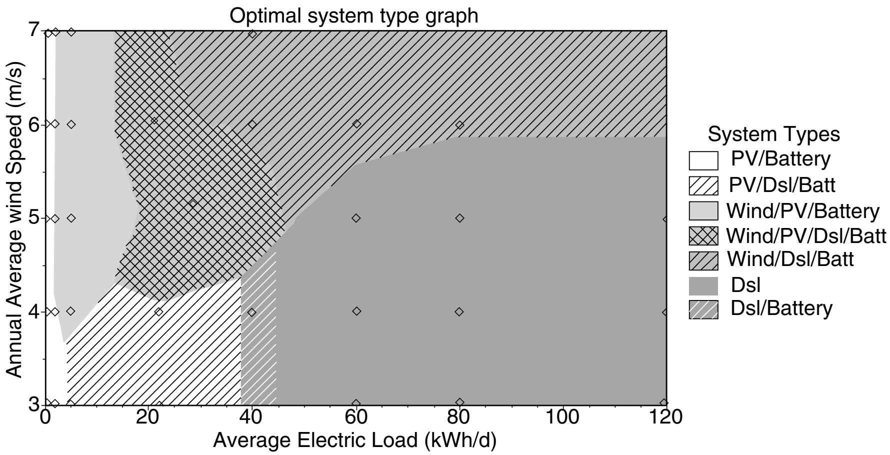

Figure 15.11 Optimal system graph.

of the sensitivity analysis, HOMER will scale the load data so that it averages first 100 kWh/day, then 150 kWh/day, and finally, 200 kWh/day. This scaling process changes the magnitude of the load data set without affecting the daily load shape, the seasonal pattern, or any other statistical properties. HOMER scales renewable resource data in the same manner.

Figure 15.11 shows the results of a sensitivity analysis over a range of load sizes and annual average wind speeds. The modeler specified eight values for the average size of the electric load and five values for the annual average wind speed. The axes of the graph correspond to these two sensitivity variables. At each of the 40 sensitivity cases, HOMER performed an optimization over a search space comprising more than 5000 system configurations. The diamonds in the graph indicate these sensitivity cases, and the color of each diamond indicates the optimal system type for that sensitivity case. At an average load of 22 kWh/day and an average wind speed of 4 m/s, for example, the optimal system type was PV–diesel–battery. At an average load of 40 kWh/day and the same wind speed, the optimal system type was diesel–battery. HOMER uses two-dimensional linear interpolation to determine the optimal system type at all points between the diamonds.

The graph in Figure 15.11 shows that for the assumptions used in this analysis, PV–battery systems are optimal for very small systems, regardless of the wind speed. At low wind speeds, as the load size increases the optimal system type changes to PV–diesel–battery, diesel–battery, then pure diesel. At high wind speeds, as the load size increases, the optimal system type changes to wind–PV–battery, wind–PV–diesel–battery, and finally, wind–diesel–battery. To an energy planner intending to provide electricity to many unelectrified communities in a developing country, such an analysis could help decide what type of micropower system to use for different communities based on the load size and average wind speed of each community.

15.5 PHYSICAL MODELING

In Section 15.2 we discussed the role of simulation and briefly described the process HOMER uses to simulate micropower systems. In this section we provide greater detail on how HOMER models the physical operation of a system. In HOMER, a micropower system must comprise at least one source of electrical or thermal energy (such as a wind turbine, a diesel generator, a boiler, or the grid), and at least one destination for that energy (an electrical or thermal load, or the ability to sell electricity to the grid). It may also comprise conversion devices such as an ac–dc converter or an electrolyzer, and energy storage devices such as a battery bank or a hydrogen storage tank.

In the following subsections we describe how HOMER models the loads that the system must serve, the components of the system and their associated resources, and how that collection of components operates together to serve the loads.

15.5.1 Loads

In HOMER, the term *load* refers to a demand for electric or thermal energy. Serving loads is the reason for the existence of micropower systems, so the modeling of a micropower system begins with the modeling of the load or loads that the system must serve. HOMER models three types of loads. Primary load is electric demand that must be served according to a particular schedule. Deferrable load is electric demand that can be served at any time within a certain time span. Thermal load is demand for heat.

Primary Load Primary load is electrical demand that the power system must meet at a specific time. Electrical demand associated with lights, radio, TV, household appliances, computers, and industrial processes is typically modeled as primary load. When a consumer switches on a light, the power system must supply electricity to that light immediately—the load cannot be deferred until later. If electrical demand exceeds supply, there is a shortfall that HOMER records as *unmet load.*

The HOMER user specifies an amount of primary load in kilowatts for each hour of the year, either by importing a file containing hourly data or by allowing HOMER to synthesize hourly data from average daily load profiles. When synthesizing load data, HOMER creates hourly load values based on user-specified daily load profiles. The modeler can specify a single 24-hour profile that applies throughout the year, or can specify different profiles for different months and different profiles for weekdays and weekends. HOMER adds a user-specified amount of randomness to synthesized load data so that every day's load pattern is unique. HOMER can model two separate primary loads, each of which can be ac or dc.

Among the three types of loads modeled in HOMER, primary load receives special treatment in that it requires a user-specified amount of operating reserve. Operating reserve is surplus electrical generating capacity that is operating and can respond instantly to a sudden increase in the electric load or a sudden decrease in the renewable power output. Although it has the same meaning as the more common term *spinning reserve*, we call it *operating reserve* because batteries, fuel cells, and the grid can provide it, but they do not spin. When simulating the operation of the system, HOMER attempts to ensure that the system's operating capacity is always sufficient to supply the primary load and the required operating reserve. Section 15.5.4 covers operating reserve in greater detail.

Deferrable Load Deferrable load is electrical demand that can be met anytime within a defined time interval. Water pumps, ice makers, and battery-charging stations are examples of deferrable loads because the storage inherent to each of those loads allows some flexibility as to when the system can serve them. The ability to defer serving a load is often advantageous for systems comprising intermittent renewable power sources, because it reduces the need for precise control of the timing of power production. If the renewable power supply ever exceeds the primary load, the surplus can serve the deferrable load rather than going to waste.

Figure 15.12 shows a schematic representation of how HOMER models the deferrable load. The power system puts energy into a "tank" of finite capacity, and energy drains out of that tank to serve the deferrable load. For each month, the user specifies the average deferrable load, which is the rate at which energy drains out of the tank. The user also specifies the storage capacity in kilowatthours (the size of the tank), and the maximum and minimum rate at which the power system can put energy into the tank. Note that the energy tank model is simply an analogy; the actual deferrable load may or may not make use of a storage tank.

When simulating a system serving a deferrable load, HOMER tracks the level in the deferrable load tank. It will put any excess renewable power into the tank, but as long as the tank level remains above zero, HOMER will not use a dispatchable power source (a generator, the battery bank, or the grid) to put energy into the tank. If the level in the tank drops to zero, HOMER temporarily treats the deferrable load as a primary load, meaning that it will immediately use any available power source to put energy into the tank and avoid having the deferrable load go unmet.

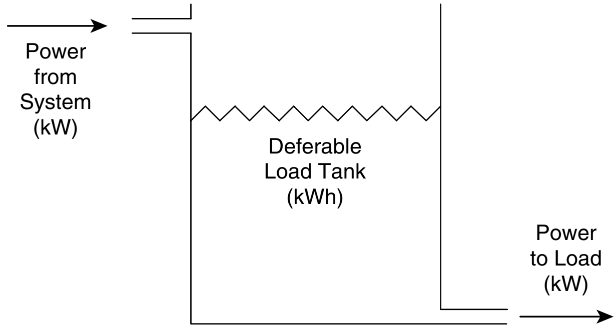

Figure 15.12 Deferrable load tank analogy.

Thermal Load HOMER models thermal load in the same way that it models primary electric load, except that the concept of operating reserve does not apply to the thermal load. The user specifies the amount of thermal load for each hour of the year, either by importing a file containing hourly data or by allowing HOMER to synthesize hourly data from 24-hour load profiles. The system supplies the thermal load with either the boiler, waste heat recovered from a generator, or resistive heating using excess electricity.

15.5.2 Resources

The term *resource* applies to anything coming from outside the system that is used by the system to generate electric or thermal power. That includes the four renewable resources (solar, wind, hydro, and biomass) as well as any fuel used by the components of the system. Renewable resources vary enormously by location. The solar resource depends strongly on latitude and climate, the wind resource on large-scale atmospheric circulation patterns and geographic influences, the hydro resource on local rainfall patterns and topography, and the biomass resource on local biological productivity. Moreover, at any one location a renewable resource may exhibit strong seasonal and hour-to-hour variability. The nature of the available renewable resources affects the behavior and economics of renewable power systems, since the resource determines the quantity and the timing of renewable power production. The careful modeling of the renewable resources is therefore an essential element of system modeling. In this section we describe how HOMER models the four renewable resources and the fuel.

Solar Resource To model a system containing a PV array, the HOMER user must provide solar resource data for the location of interest. Solar resource data indicate the amount of global solar radiation (beam radiation coming directly from the sun, plus diffuse radiation coming from all parts of the sky) that strikes Earth's surface in a typical year. The data can be in one of three forms: hourly average global solar radiation on the horizontal surface (kW/m^2), monthly average global solar radiation on the horizontal surface (kWh/m$^2\cdot$day), or monthly average clearness index. The clearness index is the ratio of the solar radiation striking Earth's surface to the solar radiation striking the top of the atmosphere. A number between zero and 1, the clearness index is a measure of the clearness of the atmosphere.

If the user chooses to provide monthly solar resource data, HOMER generates synthetic hourly global solar radiation data using an algorithm developed by Graham and Hollands [7]. The inputs to this algorithm are the monthly average solar radiation values and the latitude. The output is an 8760-hour data set with statistical characteristics similar to those of real measured data sets. One of those statistical properties is autocorrelation, which is the tendency for one day to be similar to the preceding day, and for one hour to be similar to the preceding hour.

Wind Resource To model a system comprising one or more wind turbines, the HOMER user must provide wind resource data indicating the wind speeds the turbines would experience in a typical year. The user can provide measured hourly wind speed data if available. Otherwise, HOMER can generate synthetic hourly data from 12 monthly average wind speeds and four additional statistical parameters: the Weibull shape factor, the autocorrelation factor, the diurnal pattern strength, and the hour of peak wind speed. The Weibull shape factor is a measure of the distribution of wind speeds over the year. The autocorrelation factor is a measure of how strongly the wind speed in one hour tends to depend on the wind speed in the preceding hour. The diurnal pattern strength and the hour of peak wind speed indicate the magnitude and the phase, respectively, of the average daily pattern in the wind speed. HOMER provides default values for each of these parameters.

The user indicates the anemometer height, meaning the height above ground at which the wind speed data were measured or for which they were estimated. If the wind turbine hub height is different from the anemometer height, HOMER calculates the wind speed at the turbine hub height using either the logarithmic law, which assumes that the wind speed is proportional to the logarithm of the height above ground, or the power law, which assumes that the wind speed varies exponentially with height. To use the logarithmic law, the user enters the surface roughness length, which is a parameter characterizing the roughness of the surrounding terrain. To use the power law, the user enters the power law exponent.

The user also indicates the elevation of the site above sea level, which HOMER uses to calculate the air density according to the U.S. Standard Atmosphere, described in Section 2.3 of White [6]. HOMER makes use of the air density when calculating the output of the wind turbine, as described in Section 15.5.3.

Hydro Resource To model a system comprising a run-of-river hydro turbine, the HOMER user must provide stream flow data indicating the amount of water available to the turbine in a typical year. The user can provide measured hourly stream flow data if available. Otherwise, HOMER can use monthly averages under the assumption that the flow rate remains constant within each month. The user also specifies the residual flow, which is the minimum stream flow that must bypass the hydro turbine for ecological purposes. HOMER subtracts the residual flow from the stream flow data to determine the stream flow available to the turbine.

Biomass Resource The biomass resource takes various forms (e.g., wood waste, agricultural residue, animal waste, energy crops) and may be used to produce heat or electricity. HOMER models biomass power systems that convert biomass into electricity. Two aspects of the biomass resource make it unique among the four renewable resources that HOMER models. First, the availability of the resource depends in part on human effort for harvesting, transportation, and storage. It is consequently not intermittent, although it may be seasonal. It is also often not free. Second, the biomass feedstock may be converted to a gaseous or liquid fuel, to be consumed in an otherwise conventional generator. The modeling of the biomass resource is therefore similar in many ways to the modeling of any other fuel.

The HOMER user can model the biomass resource in two ways. The simplest way is to define a fuel with properties corresponding to the biomass feedstock and then specify the fuel consumption of the generator to show electricity produced versus biomass feedstock consumed. This approach implicitly, rather than explicitly, models the process of converting the feedstock into a fuel suitable for the generator, if such a process occurs. The second alternative is to use HOMER's biomass resource inputs, which allow the modeler to specify the availability of the feedstock throughout the year, and to model explicitly the feedstock conversion process. In the remainder of this section we focus on this second alternative. In the next section we address the fuel inputs.

As with the other renewable resource data sets, the HOMER user can indicate the availability of biomass feedstock by importing an hourly data file or using monthly averages. If the user specifies monthly averages, HOMER assumes that the availability remains constant within each month.

The user must specify four additional parameters to define the biomass resource: price, carbon content, gasification ratio, and the energy content of the biomass fuel. For greenhouse gas analyses, the carbon content value should reflect the net amount of carbon released to the atmosphere by the harvesting, processing, and consumption of the biomass feedstock, considering the fact that the carbon in the feedstock was originally in the atmosphere. The gasification ratio, despite its name, applies equally well to liquid and gaseous fuels. It is the fuel conversion ratio, indicating the ratio of the mass of generator-ready fuel emerging from the fuel conversion process to the mass of biomass feedstock entering the fuel conversion process. HOMER uses the energy content of the biomass fuel to calculate the thermodynamic efficiency of the generator that consumes the fuel.

Fuel HOMER provides a library of several predefined fuels, and users can add to the library if necessary. The physical properties of a fuel include its density, lower heating value, carbon content, and sulfur content. The user can also choose the most appropriate measurement units, either L, m^3, or kg. The two remaining properties of the fuel are the price and the annual consumption limit, if any.

15.5.3 Components

In HOMER, a *component* is any part of a micropower system that generates, delivers, converts, or stores energy. HOMER models 10 types of components. Three generate electricity from intermittent renewable sources: photovoltaic modules, wind turbines, and hydro turbines. PV modules convert solar radiation into dc electricity. Wind turbines convert wind energy into ac or dc electricity. Hydro turbines convert the energy of flowing water into ac or dc electricity. HOMER can only model run-of-river hydro installations, meaning those that do not comprise a storage reservoir.

Another three types of components, generators, the grid, and boilers, are dispatchable energy sources, meaning that the system can control them as needed. Generators consume fuel to produce ac or dc electricity. A generator may also produce thermal power via waste heat recovery. The grid delivers ac electricity to a grid-connected system and may also accept surplus electricity from the system. Boilers consume fuel to produce thermal power.

Two types of components, converters and electrolyzers, convert electrical energy into another form. Converters convert electricity from ac to dc or from dc to ac. Electrolyzers convert surplus ac or dc electricity into hydrogen via the electrolysis of water. The system can store the hydrogen and use it as fuel for one or more generators. Finally, two types of components store energy: batteries and hydrogen storage tanks. Batteries store dc electricity. Hydrogen tanks store hydrogen from the electrolyzer to fuel one or more generators.

In this section we explain how HOMER models each of these components and discuss the physical and economic properties that the user can use to describe each.

PV Array HOMER models the PV array as a device that produces dc electricity in direct proportion to the global solar radiation incident upon it, independent of its temperature and the voltage to which it is exposed. HOMER calculates the power output of the PV array using the equation

$$P_{\text{PV}} = f_{\text{PV}} Y_{\text{PV}} \frac{I_T}{I_S} \tag{15.1}$$

Where, f_{PV} is the PV derating factor, Y_{PV} the rated capacity of the PV array (kW), I_{T} the global solar radiation (beam plus diffuse) incident on the surface of the PV array (kW/m^2), and I_{S} is 1 kW/m^2, which is the standard amount of radiation used to rate the capacity of the PV array. In the following paragraphs we describe these variables in more detail.

The rated capacity (sometimes called the peak capacity) of a PV array is the amount of power it would produce under standard test conditions of 1 kW/m^2 irradiance and a panel temperature of 25°C. In HOMER, the size of a PV array is always specified in terms of rated capacity. The rated capacity accounts for both the area and the efficiency of the PV module, so neither of those parameters appears explicitly in HOMER. A 40-W module made of amorphous silicon (which has a relatively low efficiency) will be larger than a 40-W module made of polycrystalline silicon (which has a relatively high efficiency), but that size difference is of no consequence to HOMER.

Each hour of the year, HOMER calculates the global solar radiation incident on the PV array using the HDKR model, explained in Section 2.16 of Duffie and Beckmann [5]. This model takes into account the current value of the solar resource (the global solar radiation incident on a horizontal surface), the orientation of the PV array, the location on Earth's surface, the time of year, and the time of day. The orientation of the array may be fixed or may vary according to one of several tracking schemes.

The derating factor is a scaling factor meant to account for effects of dust on the panel, wire losses, elevated temperature, or anything else that would cause the output of the PV array to deviate from that expected under ideal conditions. HOMER does not account for the fact that the power output of a PV array decreases with increasing panel temperature, but the HOMER user can reduce the derating factor to (crudely) correct for this effect when modeling systems for hot climates.

In reality, the output of a PV array does depend strongly and nonlinearly on the voltage to which it is exposed. The maximum power point (the voltage at which the power output is maximized) depends on the solar radiation and the temperature. If the PV array is connected directly to a dc load or a battery bank, it will often be exposed to a voltage different from the maximum power point, and performance will suffer. A maximum power point tracker (MPPT) is a solid-state device placed between the PV array and the rest of the dc components of the system that decouples the array voltage from that of the rest of the system, and ensures that the array voltage is always equal to the maximum power point. By ignoring the effect of the voltage to which the PV array is exposed, HOMER effectively assumes that a maximum power point tracker is present in the system.

To describe the cost of the PV array, the user specifies its initial capital cost in dollars, replacement cost in dollars, and operating and maintenance (O&M) cost in dollars per year. The replacement cost is the cost of replacing the PV array at the end of its useful lifetime, which the user specifies in years. By default, the replacement cost is equal to the capital cost, but the two can differ for several reasons. For example, a donor organization may cover some or all of the initial capital cost but none of the replacement cost.

Wind Turbine HOMER models a wind turbine as a device that converts the kinetic energy of the wind into ac or dc electricity according to a particular power curve, which is a graph of power output versus wind speed at hub height. Figure 15.13 is an example power curve. HOMER assumes that the power curve

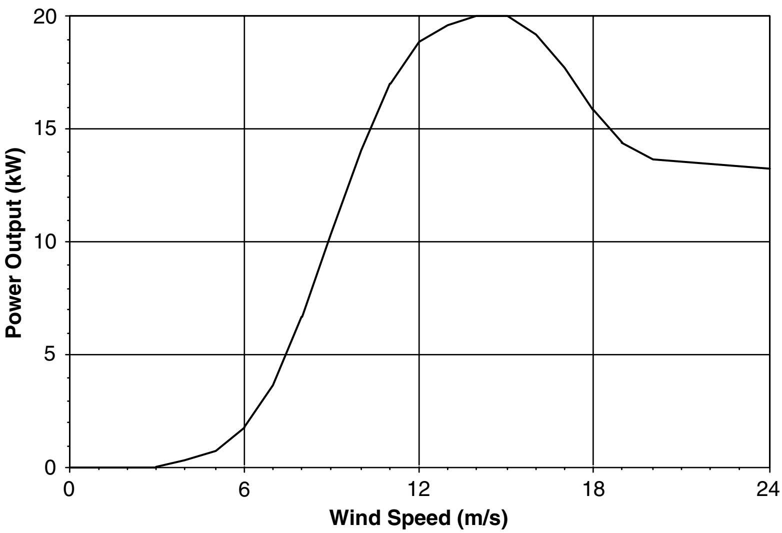

Figure 15.13 Sample wind turbine power curve.

applies at a standard air density of $1.225\,\text{kg/m}^3$, which corresponds to standard temperature and pressure conditions.

Each hour, HOMER calculates the power output of the wind turbine in a four-step process. First, it determines the average wind speed for the hour at the anemometer height by referring to the wind resource data. Second, it calculates the corresponding wind speed at the turbine's hub height using either the logarithmic law or the power law. Third, it refers to the turbine's power curve to calculate its power output at that wind speed assuming standard air density. Fourth, it multiplies that power output value by the air density ratio, which is the ratio of the actual air density to the standard air density. As mentioned in Section 15.5.2, HOMER calculates the air density ratio at the site elevation using the U.S. Standard Atmosphere [6]. HOMER assumes that the air density ratio is constant throughout the year.

In addition to the turbine's power curve and hub height, the user specifies the expected lifetime of the turbine in years, its initial capital cost in dollars, its replacement cost in dollars, and its annual O&M cost in dollars per year.

Hydro Turbine HOMER models the hydro turbine as a device that converts the power of falling water into ac or dc electricity at a constant efficiency, with no ability to store water or modulate the power output. The power in falling water is proportional to the product of the stream flow and the head, which is the vertical distance through which the water falls. Information on the stream flow available to the hydro turbine each hour comes from the hydro resource data. The user also enters the available head and the head loss that occurs in the intake pipe due to friction. HOMER calculates the net head, or effective head, using the equation

$$h_{\text{net}} = h(1 - f_h) \tag{15.2}$$

where h is the available head and f_h is the pipe head loss.

The user also enters the turbine's design flow rate and its acceptable range of flow rates. HOMER calculates the flow through the turbine by

$$\dot{Q}_{\text{turbine}} = \begin{cases} \min\left(\dot{Q}_{\text{stream}} - \dot{Q}_{\text{residual}}, w_{\max}\dot{Q}_{\text{nom}}\right) & \dot{Q}_{\text{stream}} - \dot{Q}_{\text{residual}} \geq w_{\min}\dot{Q}_{\text{nom}} \\ 0 & \dot{Q}_{\text{stream}} - \dot{Q}_{\text{residual}} < w_{\min}\dot{Q}_{\text{nom}} \end{cases} \tag{15.3}$$

where $\dot{Q}_{\text{stream}}$ is the stream flow, $\dot{Q}_{\text{residual}}$ the residual flow, $\dot{Q}_{\text{nom}}$ the turbine design flow rate, and $w_{\min}$ and $w_{\max}$ are the turbine's minimum and maximum flow ratios. The turbine does not operate if the stream flow is below the minimum, and the flow rate through the turbine cannot exceed the maximum.

Each hour of the simulation, HOMER calculates the power output of the hydroturbine as

$$P_{\text{hyd}} = \eta_{\text{hyd}}\rho_{\text{water}}g h_{\text{net}}\dot{Q}_{\text{turbine}} \tag{15.4}$$

where η_{hyd} is the turbine efficiency, ρ_{water} the density of water, g the gravitational acceleration, h_{net} the net head, and $\dot{Q}_{turbine}$ the flow rate through the turbine. The user specifies the expected lifetime of the hydro-turbine in years, as well as its initial capital cost in dollars, replacement cost in dollars, and annual O&M cost in dollars per year.

Generators A generator consumes fuel to produce electricity, and possibly heat as a by-product. HOMER's generator module is flexible enough to model a wide variety of generators, including internal combustion engine generators, microturbines, fuel cells, Stirling engines, thermophotovoltaic generators, and thermoelectric generators. HOMER can model a power system comprising as many as three generators, each of which can be ac or dc, and each of which can consume a different fuel.

The principal physical properties of the generator are its maximum and minimum electrical power output, its expected lifetime in operating hours, the type of fuel it consumes, and its fuel curve, which relates the quantity of fuel consumed to the electrical power produced. In HOMER, a generator can consume any of the fuels listed in the fuel library (to which users can add their own fuels) or one of two special fuels: electrolyzed hydrogen from the hydrogen storage tank, or biomass derived from the biomass resource. It is also possible to cofire a generator with a mixture of biomass and another fuel.

HOMER assumes the fuel curve is a straight line with a y-intercept and uses the following equation for the generator's fuel consumption:

$$F = F_0 Y_{gen} + F_1 P_{gen} \tag{15.5}$$

where F_0 is the fuel curve intercept coefficient, F_1 is the fuel curve slope, Y_{gen} the rated capacity of the generator (kW), and P_{gen} the electrical output of the generator (kW). The units of F depend on the measurement units of the fuel. If the fuel is denominated in liters, the units of F are L/h. If the fuel is denominated in m^3 or kg, the units of F are m^3/h or kg/h, respectively. In the same way, the units of F_0 and F_1 depend on the measurement units of the fuel. For fuels denominated in liters, the units of F_0 and F_1 are L/h·kW.

For a generator that provides heat as well as electricity, the user also specifies the heat recovery ratio. HOMER assumes that the generator converts all the fuel energy into either electricity or waste heat. The heat recovery ratio is the fraction of that waste heat that can be captured to serve the thermal load. In addition to these properties, the modeler can specify the generator emissions coefficients, which specify the generator's emissions of six different pollutants in grams of pollutant emitted per quantity of fuel consumed.

The user can schedule the operation of the generator to force it on or off at certain times. During times that the generator is neither forced on or off, HOMER decides whether it should operate based on the needs of the system and the relative costs of the other power sources. During times that the generator is forced on, HOMER decides at what power output level it operates, which may be anywhere between its minimum and maximum power output.

The user specifies the generator's initial capital cost in dollars, replacement cost in dollars, and annual O&M cost in dollars per operating hour. The generator O&M cost should account for oil changes and other maintenance costs, but not fuel cost because HOMER calculates fuel cost separately. As it does for all dispatchable power sources, HOMER calculates the generator's fixed and marginal cost of energy and uses that information when simulating the operation of the system. The fixed cost of energy is the cost per hour of simply running the generator, without producing any electricity. The marginal cost of energy is the additional cost per kilowatthour of producing electricity from that generator.

HOMER uses the following equation to calculate the generator's fixed cost of energy:

$$c_{\text{gen,fixed}} = c_{\text{om,gen}} + \frac{C_{\text{rep,gen}}}{R_{\text{gen}}} + F_0 Y_{\text{gen}} c_{\text{fuel,eff}} \tag{15.6}$$

where $c_{\text{om,gen}}$ is the O&M cost in dollars per hour, $C_{\text{rep,gen}}$ the replacement cost in dollars, R_{gen} the generator lifetime in hours, F_0 the fuel curve intercept coefficient in quantity of fuel per hour per kilowatt, Y_{gen} the capacity of the generator (kW), and $c_{\text{fuel,eff}}$ the effective price of fuel in dollars per quantity of fuel. The effective price of fuel includes the cost penalties, if any, associated with the emissions of pollutants from the generator.

HOMER calculates the marginal cost of energy of the generator using the following equation:

$$c_{\text{gen,mar}} = F_1 c_{\text{fuel,eff}} \tag{15.7}$$

where F_1 is the fuel curve slope in quantity of fuel per hour per kilowatthour and $c_{\text{fuel,eff}}$ is the effective price of fuel (including the cost of any penalties on emissions) in dollars per quantity of fuel.

Battery Bank The battery bank is a collection of one or more individual batteries. HOMER models a single battery as a device capable of storing a certain amount of dc electricity at a fixed round-trip energy efficiency, with limits as to how quickly it can be charged or discharged, how deeply it can be discharged without causing damage, and how much energy can cycle through it before it needs replacement. HOMER assumes that the properties of the batteries remain constant throughout its lifetime and are not affected by external factors such as temperature.

In HOMER, the key physical properties of the battery are its nominal voltage, capacity curve, lifetime curve, minimum state of charge, and round-trip efficiency. The capacity curve shows the discharge capacity of the battery in ampere-hours versus the discharge current in amperes. Manufacturers determine each point on this curve by measuring the ampere-hours that can be discharged at a constant current out of a fully charged battery. Capacity typically decreases with increasing discharge current. The lifetime curve shows the number of discharge–charge cycles the battery can withstand versus the cycle depth. The number of cycles to failure typically decreases with increasing cycle depth. The minimum state of charge is the

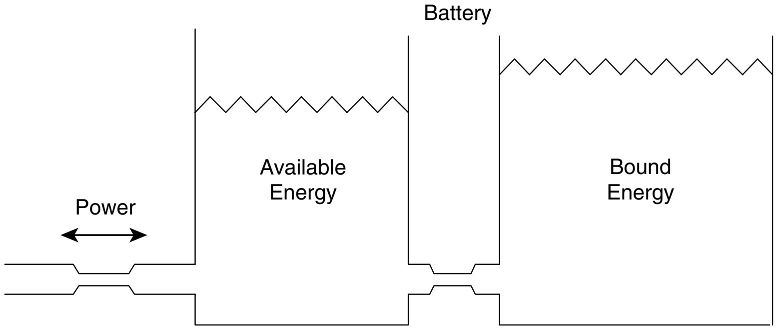

Figure 15.14 Kinetic battery model concept.

state of charge below which the battery must not be discharged to avoid permanent damage. In the system simulation, HOMER does not allow the battery to be discharged any deeper than this limit. The round-trip efficiency indicates the percentage of the energy going into the battery that can be drawn back out.

To calculate the battery's maximum allowable rate of charge or discharge, HOMER uses the kinetic battery model [8], which treats the battery as a two-tank system as illustrated in Figure 15.14. According to the kinetic battery model, part of the battery's energy storage capacity is immediately available for charging or discharging, but the rest is chemically bound. The rate of conversion between available energy and bound energy depends on the difference in "height" between the two tanks. Three parameters describe the battery. The maximum capacity of the battery is the combined size of the available and bound tanks. The capacity ratio is the ratio of the size of the available tank to the combined size of the two tanks. The rate constant is analogous to the size of the pipe between the tanks.

The kinetic battery model explains the shape of the typical battery capacity curve, such as the example shown in Figure 15.15. At high discharge rates, the available tank empties quickly, and very little of the bound energy can be converted to available energy before the available tank is empty, at which time the battery can no longer withstand the high discharge rate and appears fully discharged. At slower discharge rates, more bound energy can be converted to available energy before the available tank empties, so the apparent capacity increases. HOMER performs a curve fit on the battery's discharge curve to calculate the three parameters of the kinetic battery model. The line in Figure 15.15 corresponds to this curve fit.

Modeling the battery as a two-tank system rather than a single-tank system has two effects. First, it means the battery cannot be fully charged or discharged all at once; a complete charge requires an infinite amount of time at a charge current that asymptotically approaches zero. Second, it means that the battery's ability to charge and discharge depends not only on its current state of charge, but also on its recent charge and discharge history. A battery rapidly charged to 80% state of charge will be capable of a higher discharge rate than the same battery rapidly discharged to 80%, since it will have a higher level in its available tank. HOMER tracks the levels in the two tanks each hour, and models both these effects.

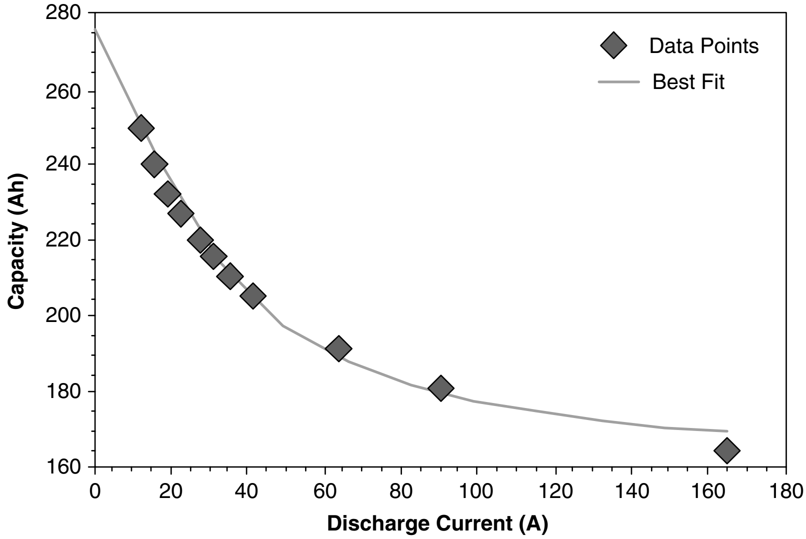

Figure 15.15 Capacity curve for deep-cycle battery model US-250 from U.S. Battery Manufacturing Company (www.usbattery.com).

Figure 15.16 shows a lifetime curve typical of a deep-cycle lead–acid battery. The number of cycles to failure (shown in the graph as the lighter-colored points) drops sharply with increasing depth of discharge. For each point on this curve, one can calculate the lifetime throughput (the amount of energy that cycled through the battery before failure) by finding the product of the number of cycles, the depth of discharge, the nominal voltage of the battery, and the aforementioned maximum capacity of the battery. The lifetime throughput curve, shown in Figure 15.16 as black dots, typically shows a much weaker dependence on the cycle depth. HOMER makes the simplifying assumption that the lifetime throughput is independent of the depth of discharge. The value that HOMER suggests for this lifetime throughput is the average of the points from the lifetime curve above the minimum state of charge, but the user can modify this value to be more or less conservative.

The assumption that lifetime throughput is independent of cycle depth means that HOMER can estimate the life of the battery bank simply by monitoring the amount of energy cycling through it, without having to consider the depth of the various charge–discharge cycles. HOMER calculates the life of the battery bank in years as

$$R_{\text{batt}} = \min\left(\frac{N_{\text{batt}} Q_{\text{lifetime}}}{Q_{\text{thrpt}}}, R_{\text{batt},f}\right) \tag{15.8}$$

where N_{batt} is the number of batteries in the battery bank, Q_{lifetime} the lifetime throughput of a single battery, Q_{thrpt} the annual throughput (the total amount of

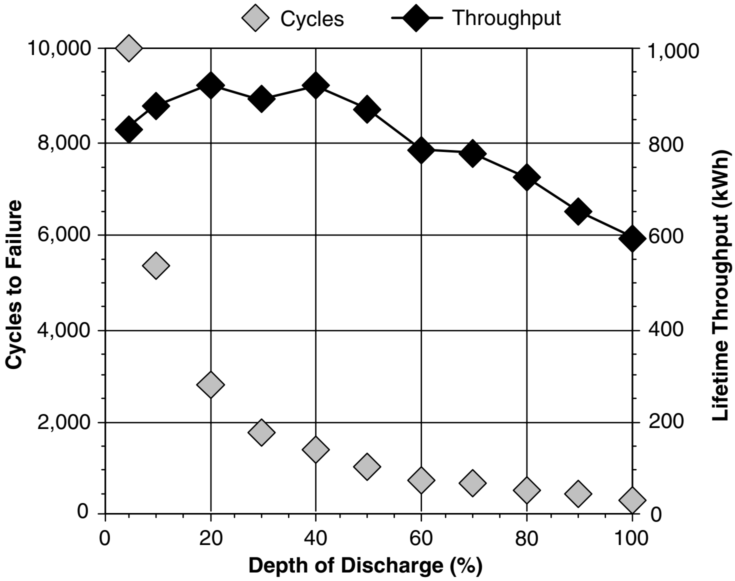

Figure 15.16 Lifetime curve for deep-cycle battery model US-250 from U.S. Battery Manufacturing Company (www.usbattery.com).

energy that cycles through the battery bank in one year), and $R_{\text{batt},f}$ the float life of the battery (the maximum life regardless of throughput).

The user specifies the battery bank's capital and replacement costs in dollars, and the O&M cost in dollars per year. Since the battery bank is a dispatchable power source, HOMER calculates its fixed and marginal cost of energy for comparison with other dispatchable sources. Unlike the generator, there is no cost associated with "operating" the battery bank so that it is ready to produce energy; hence its fixed cost of energy is zero. For its marginal cost of energy, HOMER uses the sum of the battery wear cost (the cost per kilowatthour of cycling energy through the battery bank) and the battery energy cost (the average cost of the energy stored in the battery bank). HOMER calculates the battery wear cost as

$$c_{\text{bw}} = \frac{C_{\text{rep,batt}}}{N_{\text{batt}} Q_{\text{lifetime}} \sqrt{\eta_{\text{rt}}}} \tag{15.9}$$

where $C_{\text{rep,batt}}$ is the replacement cost of the battery bank (dollars), N_{batt} is the number of batteries in the battery bank, Q_{lifetime} is the lifetime throughput of a single battery (kWh), and η_{rt} is the round-trip efficiency.

HOMER calculates the battery energy cost each hour of the simulation by dividing the total year-to-date cost of charging the battery bank by the total year-to-date amount of energy put into the battery bank. Under the load-following dispatch strategy, the battery bank is only ever charged by surplus electricity, so the cost associated with charging the battery bank is always zero. Under the cycle-charging strategy, however, a generator will produce extra electricity (and hence consume additional fuel) for the express purpose of charging the battery bank, so the cost associated with charging the battery bank is not zero. In Section 15.5.4 we discuss dispatch strategies in greater detail.

Grid HOMER models the grid as a component from which the micropower system can purchase ac electricity and to which the system can sell ac electricity. The cost of purchasing power from the grid can comprise an energy charge based on the amount of energy purchased in a billing period and a demand charge based on the peak demand within the billing period. HOMER uses the term *grid power price* for the price (in dollars per kilowatthour) that the electric utility charges for energy purchased from the grid, and the *demand rate* for the price (in dollars per kilowatt per month) the utility charges for the peak grid demand. A third term, the *sellback rate*, refers to the price (in dollars per kilowatthour) that the utility pays for power sold to the grid.

The HOMER user can define and schedule up to 16 different rates, each of which can have different values of grid power price, demand rate, and sellback rate. The schedule of the rates can vary according to month, time of day, and weekday/weekend. For example, HOMER could model a situation where an expensive rate applies during weekday afternoons in July and August, an intermediate rate applies during weekday afternoons in June and September and weekend afternoons from June to September, and an inexpensive rate applies at all other times.

HOMER can also model *net metering*, a billing arrangement whereby the utility charges the customer based on the net grid purchases (purchases minus sales) over the billing period. Under net metering, if purchases exceed sales over the billing period, the consumer pays the utility an amount equal to the net grid purchases times the grid power cost. If sales exceed purchases over the billing period, the utility pays the consumer an amount equal to the net grid sales (sales minus purchases) times the sellback rate, which is typically less than the grid power price, and often zero. The billing period may be one month or one year. In the unusual situation where net metering applies to multiple rates, HOMER tracks the net grid purchases separately for each rate.

Two variables describe the grid's capacity to deliver and accept power. The maximum power sale is the maximum rate at which the power system can sell power to the grid. The user should set this value to zero if the utility does not allow sellback. The maximum grid demand is the maximum amount of power that can be drawn from the grid. It is a decision variable because of the effect of demand charges. HOMER does not explicitly consider the demand rate in its hour-by-hour decisions as to how to control the power system; it simply calculates the demand charge at the end of each simulation. As a result, when modeling a grid-connected generator, HOMER will not turn on the generator simply to save demand charges. But it will turn on a generator whenever the load exceeds the maximum grid demand. The maximum grid demand therefore acts as a control parameter that affects the operation and economics of the system. Because it is a decision variable, the user can enter multiple values and HOMER can find the optimal one.

The user also enters the grid emissions coefficients, which HOMER uses to calculate the emissions of six pollutants associated with buying power from the grid, as well as the avoided emissions resulting from the sale of power to the grid. Each emissions coefficient has units of grams of pollutant emitted per kilowatthour consumed.

Because it is a dispatchable power source, HOMER calculates the grid's fixed and marginal cost of energy. The fixed cost is zero, and the marginal cost is equal to the current grid power price plus any cost resulting from emissions penalties. Since the grid power price can change from hour to hour as the applicable rate changes, the grid's marginal cost of energy can also change from hour to hour. This can have important effects on HOMER's simulation of the system's behavior. For example, HOMER may choose to run a generator only during times of high grid power price, when the cost of grid power exceeds the cost of generator power.

Boiler HOMER models the boiler as an idealized component able to provide an unlimited amount of thermal energy on demand. When dispatching generators to serve the electric load, HOMER considers the value of any waste heat that can be recovered from a generator to serve the thermal load, but it will not dispatch a generator simply to serve the thermal load. It assumes that the system can always rely on the boiler to serve any thermal load that the generators do not. To avoid situations that violate this assumption, HOMER ensures that a boiler exists in any system serving a thermal load, it does not allow any consumption limit on the boiler fuel, and it does not allow the boiler to consume biomass or stored hydrogen (since either of those fuels could be unavailable at times).

The idealized nature of HOMER's boiler model means that the user must specify only a few physical properties of the boiler. The user selects the type of fuel the boiler consumes and enters the efficiency with which it converts that fuel into heat. The only other properties of the boiler are its emissions coefficients, which are in units of grams of pollutant emitted per quantity of fuel consumed.

As it does for all dispatchable energy sources, HOMER calculates the fixed and marginal cost of energy from the boiler. The fixed cost is zero. HOMER calculates the marginal cost using the equation

$$c_{\text{boiler,mar}} = \frac{3.6 c_{\text{fuel,eff}}}{\eta_{\text{boiler}} \text{LHV}_{\text{fuel}}} \tag{15.10}$$

where $c_{\text{fuel,eff}}$ is the effective price of the fuel (including the cost of any penalties on emissions) in dollars per kilogram, η_{boiler} is the boiler efficiency, and LHV_{fuel} is the lower heating value of the fuel in MJ/kg.

Converter A converter is a device that converts electric power from dc to ac in a process called *inversion*, and/or from ac to dc in a process called *rectification*. HOMER can model the two common types of converters: solid-state and rotary. The converter size, which is a decision variable, refers to the inverter capacity, meaning the maximum amount of ac power that the device can produce by inverting dc power. The user specifies the rectifier capacity, which is the maximum amount of dc power that the device can produce by rectifying ac power, as a percentage of the inverter capacity. The rectifier capacity is therefore not a separate decision variable. HOMER assumes that the inverter and rectifier capacities are not surge capacities that the device can withstand for only short periods of time, but rather, continuous capacities that the device can withstand for as long as necessary.

The HOMER user indicates whether the inverter can operate in parallel with another ac power source such as a generator or the grid. Doing so requires the inverter to synchronize to the ac frequency, an ability that some inverters do not have. The final physical properties of the converter are its inversion and rectification efficiencies, which HOMER assumes to be constant. The economic properties of the converter are its capital and replacement cost in dollars, its annual O&M cost in dollars per year, and its expected lifetime in years.

Electrolyzer An electrolyzer consumes electricity to generate hydrogen via the electrolysis of water. In HOMER, the user specifies the size of the electrolyzer, which is a decision variable, in terms of its maximum electrical input. The user also indicates whether the electrolyzer consumes ac or dc power, and the efficiency with which it converts that power to hydrogen. HOMER defines the electrolyzer efficiency as the energy content (based on higher heating value) of the hydrogen produced divided by the amount of electricity consumed. The final physical property of the electrolyzer is its minimum load ratio, which is the minimum power input at which it can operate, expressed as a percentage of its maximum power input. The economic properties of the electrolyzer are its capital and replacement cost in dollars, its annual O&M cost in dollars per year, and its expected lifetime in years.

Hydrogen Tank In HOMER, the hydrogen tank stores hydrogen produced by the electrolyzer for later use in a hydrogen-fueled generator. The user specifies the size of the hydrogen tank, which is a decision variable, in terms of the mass of hydrogen it can contain. HOMER assumes that the process of adding hydrogen to the tank requires no electricity, and that the tank experiences no leakage.

The user can specify the initial amount of hydrogen in the tank either as a percentage of the tank size or as an absolute amount in kilograms. It is also possible to require that the year-end tank level must equal or exceed the initial tank level. If the user chooses to apply this constraint, HOMER will consider infeasible any system configuration whose hydrogen tank contains less hydrogen at the end of the simulation than it did at the beginning of the simulation. This ensures that the system is self-sufficient in terms of hydrogen. The economic properties of the hydrogen tank are its capital and replacement cost in dollars, its annual O&M cost in dollars per year, and its expected lifetime in years.

15.5.4 System Dispatch

In addition to modeling the behavior of each individual component, HOMER must simulate how those components work together as a system. That requires hour-by-hour decisions as to which generators should operate and at what power level, whether to charge or discharge the batteries, and whether to buy from or sell to the grid. In this section we describe briefly the logic HOMER uses to make such decisions. A discussion of operating reserve comes first because the concept of operating reserve significantly affects HOMER's dispatch decisions.

Operating Reserve Operating reserve provides a safety margin that helps ensure reliable electricity supply despite variability in the electric load and the renewable power supply. Virtually every real micropower system must always provide some amount of operating reserve, because otherwise the electric load would sometimes fluctuate above the operating capacity of the system, and an outage would result.

At any given moment, the amount of operating reserve that a power system provides is equal to the operating capacity minus the electrical load. Consider, for example, a simple diesel system in which an 80-kW diesel generator supplies an electric load. In that system, if the load is 55 kW, the diesel will produce 55 kW of electricity and provide 25 kW of operating reserve. In other words, the system could supply the load even if the load suddenly increased by 25 kW. In HOMER, the modeler specifies the required amount of operating reserve, and HOMER simulates the system so as to provide at least that much operating reserve.

Each hour, HOMER calculates the required amount of operating reserve as a fraction of the primary load that hour, plus a fraction of the annual peak primary load, plus a fraction of the PV power output that hour, plus a fraction of the wind power output that hour. The modeler specifies these fractions by considering how much the load or the renewable power output is likely to fluctuate in a short period, and how conservatively he or she plans to operate the system. The more variable the load and renewable power output, and the more conservatively the system must operate, the higher the fractions the modeler should specify. HOMER does not attempt to ascertain the amount of operating reserve required to achieve different levels of reliability; it simply uses the modeler's specifications to calculate the amount of operating reserve the system is obligated to provide each hour.

Once it calculates the required amount of operating reserve, HOMER attempts to operate the system so as to provide at least that much operating reserve. Doing so may require operating the system differently (at a higher cost) than would be necessary without consideration of operating reserve. Consider, for example, a wind–diesel system for which the user defines the required operating reserve as 10% of the hourly load plus 50% of the wind power output. HOMER will attempt to operate that system so that at any time, it can supply the load with the operating generators even if the load suddenly increased by 10% and the wind power output suddenly decreased by 50%. In an hour where the load is 140 kW and the wind power output is 80 kW, the required operating reserve would be 14 kW + 40 kW = 54 kW. The diesel generators must therefore provide 60 kW of electricity plus 54 kW of operating reserve, meaning that the capacity of the operating generators must be at least 114 kW. Without consideration of operating reserve, HOMER would assume that a 60-kW diesel would be sufficient.

HOMER assumes that both dispatchable and nondispatchable power sources provide operating capacity. A dispatchable power source provides operating capacity in an amount equal to the maximum amount of power it could produce at a moment's notice. For a generator, that is equal to its rated capacity if it is operating, or zero if it is not operating. For the grid, that is equal to the maximum grid demand. For the battery, that is equal to its current maximum discharge power, which depends on state of charge and recent charge–discharge history, as described in Section 15.5.3. In contrast to the dispatchable power sources, the operating capacity of a nondispatchable power source (a PV array, wind turbine, or hydro turbine) is equal to the amount of power the source is currently producing, as opposed to the maximum amount of power it could produce.

For most grid-connected systems, the concept of operating reserve has virtually no effect on the operation of the system because the grid capacity is typically more than enough to cover the required operating reserve. Unlike a generator, which must be turned on and incurring fixed costs to provide operating capacity, the grid is always "operating" so that its capacity (which is usually very large compared to the load) is always available to the system. Similarly, operating reserve typically has little or no effect on autonomous systems with large battery banks, since the battery capacity is also always available to the system, at no fixed cost. Nevertheless, HOMER still calculates and tracks operating reserve for such systems.

If a system is ever unable to supply the required amount of load plus operating reserve, HOMER records the shortfall as *capacity shortage*. HOMER calculates the total amount of such shortages over the year and divides the total annual capacity shortage by the total annual electric load to find the capacity shortage fraction. The modeler specifies the maximum allowable capacity shortage fraction. HOMER discards as infeasible any system whose capacity shortage fraction exceeds this constraint.

Control of Dispatchable System Components Each hour of the year, HOMER determines whether the (nondispatchable) renewable power sources by themselves are capable of supplying the electric load, the required operating reserve, and the thermal load. If not, it determines how best to dispatch the dispatchable system components (the generators, battery bank, grid, and boiler) to serve the loads and operating reserve. This determination of how to dispatch the system components each hour is the most complex part of HOMER's simulation logic. The nondispatchable renewable power sources, although they necessitate complex system modeling, are themselves simple to model because they require no control logic—they simply produce power in direct response to the renewable resource available. The dispatchable sources are more difficult to model because they must be controlled to match supply and demand properly, and to compensate for the intermittency of the renewable power sources.

The fundamental principle that HOMER follows when dispatching the system is the minimization of cost. HOMER represents the economics of each dispatchable energy source by two values: a fixed cost in dollars per hour, and a marginal cost of energy in dollars per kilowatthour. These values represent all costs associated with

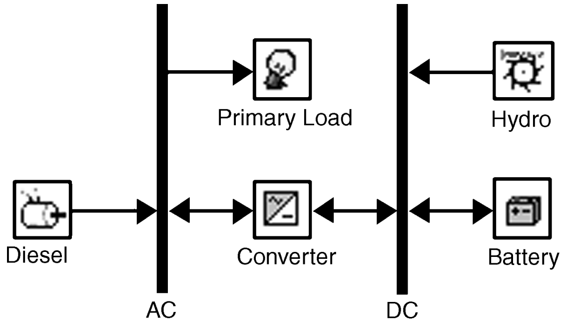

Figure 15.17 Hydro–diesel–battery system.

producing energy with that power source that hour. The sections above on the generator, battery bank, grid, and boiler detail how HOMER calculates the fixed and marginal costs for each of these components. Using these cost values, HOMER searches for the combination of dispatchable sources that can serve the electrical load, thermal load, and the required operating reserve at the lowest cost. Satisfying the loads and operating reserve is paramount, meaning that HOMER will accept any cost to avoid capacity shortage. But among the combinations of dispatchable sources that can serve the loads equally well, HOMER chooses the one that does so at the lowest cost.

For example, consider the hydro–diesel–battery system shown in Figure 15.17. This system comprises two dispatchable power sources, the battery bank and the diesel generator. Whenever the net load is negative (meaning the power output of the hydro turbine is sufficient to serve the load), the excess power charges the battery bank. But whenever the net load is positive, the system must either operate the diesel or discharge the battery, or both, to serve the load. In choosing among these three alternatives, HOMER considers the ability of each source to supply the ac net load and the required operating reserve, and the cost of doing so. If the diesel generator is scheduled off or has run out of fuel, it has no ability to supply power to the ac load. Otherwise, it can supply any amount of ac power up to its rated capacity. The battery's ability to supply power and operating reserve to the ac load is constrained by its current discharge capacity (which depends on its state of charge and recent charge–discharge history, as described in Section 15.5.3) and the capacity and efficiency of the ac–dc converter. If both the battery bank and the diesel generator are capable of supplying the net load and the operating reserve, HOMER decides which to use based on their fixed and marginal costs of energy.

Figure 15.18 shows one possible cost scenario, where the diesel capacity is 80 kW and the battery can supply up to 40 kW of power to the ac bus, after conversion losses. This scenario is typical in that the battery's marginal cost of energy exceeds that of the diesel. But because of the diesel's fixed cost, the battery can supply small amounts of ac power more cheaply than the diesel. In this case the crossover point is around 20 kW. Therefore, if the net load is less than 20 kW, HOMER will serve the load by discharging the battery. If the net load is greater

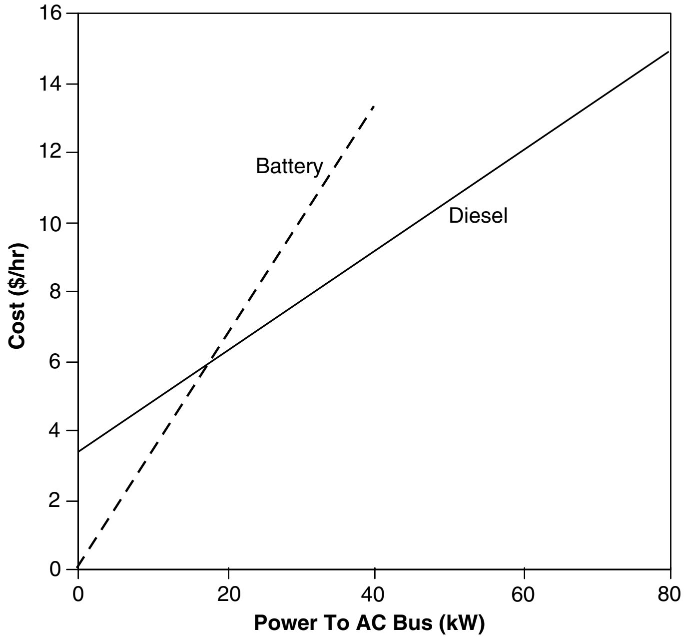

Figure 15.18 Cost of energy comparison.

than 20 kW, HOMER will serve the load with the generator instead of the battery, even if the battery is capable of supplying the load.

HOMER uses the same cost-based dispatch logic regardless of the system configuration. When simulating a system comprising multiple generators, HOMER will choose the combination of generators that can most cheaply supply the load and the required operating reserve. When simulating a grid-connected microturbine supplying both heat and electricity, HOMER will operate the microturbine whenever doing so would save money compared to the alternative, which is to buy electricity from the grid and produce heat with a boiler.

HOMER's simulation is idealized in the sense that it assumes the system controller will operate the system so as to minimize total life-cycle cost, when in fact a real system controller may not. But HOMER's "economically optimal" scenario serves as a useful baseline with which to compare different system configurations.

Dispatch Strategy The economic dispatch logic described in the preceding section governs the production of energy to serve loads and hence applies to all systems that HOMER models. But for systems comprising both a battery bank and a generator, an additional aspect of system operation arises, which is whether (and how) the generator should charge the battery bank. One cannot base this battery-charging logic on simple economic principles, because there is no deterministic way to calculate the value of charging the battery bank. The value of charging the battery in one hour depends on what happens in future hours. In a wind–diesel–battery system, for example, charging the battery bank with diesel power in one hour would be of some value if doing so allowed the system to avoid operating the diesel in some subsequent hour. But it would be of no value whatsoever if the system experienced more than enough excess wind power in subsequent hours to charge the battery bank fully. In that case, any diesel power put into the battery bank would be wasted because the wind power would have fully charged the battery bank anyway.

Rather than using complicated probabilistic logic to determine the optimal battery-charging strategy, HOMER provides two simple strategies and lets the user model them both to see which is better in any particular situation. These dispatch strategies are called *load-following* and *cycle-charging*. Under the load-following strategy, a generator produces only enough power to serve the load, and does not charge the battery bank. Under the cycle-charging strategy, whenever a generator operates, it runs at its maximum rated capacity (or as close as possible without incurring excess electricity) and charges the battery bank with the excess. Barley and Winn [9] found that over a wide range of conditions, the better of these two simple strategies is virtually as cost-effective as the ideal predictive strategy. Because HOMER treats the dispatch strategy as a decision variable, the modeler can easily simulate both strategies to determine which is optimal in a given situation.

The dispatch strategy does not affect the decisions described in the preceding section as to which dispatchable power sources operate each hour. Only after these decisions are made does the dispatch strategy come into play. If the load-following strategy applies, whichever generators HOMER selects to operate in a given hour will produce only enough power to serve the load. If the cycle-charging strategy applies, those same generators will run at their rated output, or as close as possible without causing excess energy.

An optional control parameter called the set-point state of charge can apply to the cycle-charging strategy. If the modeler chooses to apply this parameter, once the generator starts charging the battery bank, it must continue to do so until the battery bank reaches the set-point state of charge. Otherwise, HOMER may choose to discharge the battery as soon as it can supply the load. The set-point state of charge helps avoid situations where the battery experiences shallow charge–discharge cycles near its minimum state of charge. In real systems, such situations are harmful to battery life.

Load Priority HOMER makes a separate set of decisions regarding how to allocate the electricity produced by the system. The presence of both an ac and a dc bus complicates these decisions somewhat. HOMER assumes that electricity produced on one bus will go first to serve primary load on the same bus, then primary load on the opposite bus, then deferrable load on the same bus, then deferrable load on the opposite bus, then to charge the battery bank, then to grid sales, then to serve the electrolyzer, and then to the dump load, which optionally serves the thermal load.

15.6 ECONOMIC MODELING

Economics play an integral role both in HOMER's simulation process, wherein it operates the system so as to minimize total net present cost, and in its optimization process, wherein it searches for the system configuration with the lowest total net present cost. This section describes why life-cycle cost is the appropriate metric with which to compare the economics of different system configurations, why HOMER uses the total net present cost as the economic figure of merit, and how HOMER calculates total net present cost.

Renewable and nonrenewable energy sources typically have dramatically different cost characteristics. Renewable sources tend to have high initial capital costs and low operating costs, whereas conventional nonrenewable sources tend to have low capital and high operating costs. In its optimization process, HOMER must often compare the economics of a wide range of system configurations comprising varying amounts of renewable and nonrenewable energy sources. To be equitable, such comparisons must account for both capital and operating costs. Life-cycle cost analysis does so by including all costs that occur within the life span of the system.

HOMER uses the total net present cost (NPC) to represent the life-cycle cost of a system. The total NPC condenses all the costs and revenues that occur within the project lifetime into one lump sum in today's dollars, with future cash flows discounted back to the present using the discount rate. The modeler specifies the discount rate and the project lifetime. The NPC includes the costs of initial construction, component replacements, maintenance, fuel, plus the cost of buying power from the grid and miscellaneous costs such as penalties resulting from pollutant emissions. Revenues include income from selling power to the grid, plus any salvage value that occurs at the end of the project lifetime. With the NPC, costs are positive and revenues are negative. This is the opposite of the net present value. As a result, the net present cost is different from net present value only in sign.

HOMER assumes that all prices escalate at the same rate over the project lifetime. With that assumption, inflation can be factored out of the analysis simply by using the real (inflation-adjusted) interest rate rather than the nominal interest rate when discounting future cash flows to the present. The HOMER user therefore enters the real interest rate, which is roughly equal to the nominal interest rate minus the inflation rate. All costs in HOMER are real costs, meaning that they are defined in terms of constant dollars.

For each component of the system, the modeler specifies the initial capital cost, which occurs in year zero, the replacement cost, which occurs each time the component needs replacement at the end of its lifetime, and the O&M cost, which occurs each year of the project lifetime. The user specifies the lifetime of most components in years, but HOMER calculates the lifetime of the battery and generators as described in Section 15.5.3. A component's replacement cost may differ from its initial capital cost for several reasons. For example, a modeler might assume that a wind turbine nacelle will need replacement after 15 years, but the tower and foundation will last for the life of the project. In that case, the replacement cost would be considerably less than the initial capital cost. Donor agencies or buy-down programs might cover some or all of the initial capital cost of a PV array but none of the replacement cost. In that case, the replacement cost may be greater than the initial capital cost. When analyzing a retrofit of an existing diesel system, the initial capital cost of the diesel engine would be zero, but the replacement cost would not.

To calculate the salvage value of each component at the end of the project lifetime, HOMER uses the equation

$$S = C_{\text{rep}} \frac{R_{\text{rem}}}{R_{\text{comp}}} \tag{15.11}$$

where S is the salvage value, C_{rep} the replacement cost of the component, R_{rem} the remaining life of the component, and R_{comp} the lifetime of the component. For example, if the project lifetime is 20 years and the PV array lifetime is also 20 years, the salvage value of the PV array at the end of the project lifetime will be zero because it has no remaining life. On the other hand, if the PV array lifetime is 30 years, at the end of the 20-year project lifetime its salvage value will be one-third of its replacement cost.

For each component, HOMER combines the capital, replacement, maintenance, and fuel costs, along with the salvage value and any other costs or revenues, to find the component's annualized cost. This is the hypothetical annual cost that if it occurred each year of the project lifetime would yield a net present cost equivalent to that of all the individual costs and revenues associated with that component over the project lifetime. HOMER sums the annualized costs of each component, along with any miscellaneous costs, such as penalties for pollutant emissions, to find the total annualized cost of the system. This value is an important one because HOMER uses it to calculate the two principal economic figures of merit for the system: the total net present cost and the levelized cost of energy.

HOMER uses the following equation to calculate the total net present cost:

$$C_{\text{NPC}} = \frac{C_{\text{ann,tot}}}{\text{CRF}(i, R_{\text{proj}})} \tag{15.12}$$

where $C_{\text{ann,tot}}$ is the total annualized cost, i the annual real interest rate (the discount rate), R_{proj} the project lifetime, and $\text{CRF}(\cdot)$ is the capital recovery factor, given by the equation

$$\text{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{15.13}$$

where i is the annual real interest rate and N is the number of years.

HOMER uses the following equation to calculate the levelized cost of energy:

$$\text{COE} = \frac{C_{\text{ann,tot}}}{E_{\text{prim}} + E_{\text{def}} + E_{\text{grid,sales}}} \tag{15.14}$$

where $C_{\text{ann,tot}}$ is the total annualized cost, E_{prim} and E_{def} are the total amounts of primary and deferrable load, respectively, that the system serves per year, and

$E_{grid,sales}$ is the amount of energy sold to the grid per year. The denominator in equation (15.14) is an expression of the total amount of useful energy that the system produces per year. The levelized cost of energy is therefore the average cost per kilowatthour of useful electrical energy produced by the system.

Although the levelized cost of energy is often a convenient metric with which to compare the costs of different systems, HOMER uses the total NPC instead as its primary economic figure of merit. In its optimization process, for example, HOMER ranks the system configurations according to NPC rather than levelized cost of energy. This is because the definition of the levelized cost of energy is disputable in a way that the definition of the total NPC is not. In developing the formula that HOMER uses for the levelized cost of energy, we decided to divide by the amount of electrical load that the system actually serves rather than the total electrical demand, which may be different if the user allows some unmet load. We also decided to neglect thermal energy but to include grid sales as useful energy production. Each of these decisions is somewhat arbitrary, making the definition of the levelized cost of energy also somewhat arbitrary. Because the total NPC suffers from no such definitional ambiguity, it is preferable as the primary economic figure of merit.

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GLOSSARY

Annualized cost: the hypothetical annual cost value that if it occurred each year of the project lifetime would yield a net present cost equivalent to the actual net present cost. HOMER calculates the annualized cost of each system component and of the entire system.

Autonomous: not connected to a larger power transmission grid. Autonomous power systems are often called *off-grid systems*. An autonomous system must be controlled carefully to match electrical supply and demand.

Battery energy cost: the average cost per kilowatthour of the energy stored in the battery bank.

Battery wear cost: the cost per kilowatthour of cycling energy through the battery bank. HOMER can calculate this value because it assumes that a certain amount of energy can cycle through the battery bank before it needs replacement. Every kilowatthour of energy that cycles through the battery bank reduces its life span by a known amount.

Beam radiation: solar radiation that travels from the sun to Earth's surface without any scattering by the atmosphere. Beam radiation is also called *direct radiation*.

Capacity shortage: a shortfall that occurs between the required amount of operating capacity (load plus required operating reserve) and the actual operating capacity the system can provide.

Clearness index: the fraction of the solar radiation striking the top of the atmosphere that makes it though the atmosphere to strike the surface of the Earth.

Constraint: a condition that system configurations must satisfy. HOMER discards systems that do not satisfy the applicable constraints. For example, the HOMER user may impose a constraint that all system configurations must serve at least 99% of the electrical demand over the year.

Decision variable: a variable over which the system designer has control, and for which HOMER can consider multiple values in its optimization process. Examples include the number of batteries in the system or the size of the ac–dc converter.

Demand rate: the fee the electric utility applies each month to the peak hourly grid demand. If the demand rate is $5/kW per month and the peak hourly demand in January is 75 kW, the demand charge for January will be $375.

Diffuse radiation: solar radiation that has been scattered by the atmosphere.

Dispatch strategy: a set of rules that controls how a system charges the battery bank.

Extraterrestrial radiation: the solar radiation striking the top of EARTH's atmosphere. One can calculate the quantity of extraterrestrial radiation precisely for any location on earth at any time.

Feasibility: the state of being feasible or infeasible. A feasible system configuration is one that satisfies the constraints imposed by the user. An infeasible system is one that violates one or more constraints.

Grid power price: the price the utility charges for power purchased from the grid. In HOMER, this price can vary according to month, day of the week, and time of day.

Levelized cost of energy: the average cost per kilowatthour of electricity produced by the system.

Life-cycle cost: the total cost of installing and operating a component or system over a specified time span, typically many years.

Micropower system: a system that produces electrical and possibly thermal power to serve a nearby load.

Net load: the load minus the renewable power available to serve the load.

Net metering: a billing scheme by which the utility charges a micropower system operator for the net grid purchases (purchases minus sales) over the billing period.

Operating capacity: the total amount of electrical generation capacity that is operating (and ready to produce electricity) at any one time. A generator that is not operating provides no operating capacity. A 200-kW generator that is operating provides 200 kW of operating capacity.

Operating reserve: surplus electrical generation capacity (above that required to meet the current electric load) that is operating and able to respond instantly to a sudden increase in the electric load or a sudden decrease in the renewable power output.

Replacement cost: the cost of replacing a component at the end of its useful lifetime. The replacement cost may differ from the initial capital cost for several reasons: only part of the component may need replacement, a donor organization may cover the initial capital cost but not the replacement cost, fixed costs may be shared among many components initially but not at the time of replacement, and so on.

Residual flow: the minimum stream flow that must bypass the hydro turbine for ecological purposes.

Search space: the set of all system configurations over which HOMER searches for the optimum during the optimization process.

Sellback rate: the price the utility pays for power sold to the grid. In HOMER, this value can vary according to month, day of the week, and time of day.

Sensitivity variable: an input variable for which the modeler enters multiple values rather than just one.

System configuration: a combination of particular numbers and sizes of components, plus an operating strategy that defines how those components work together.

Unmet load: electrical load that the power system is unable to serve. Unmet load occurs when the electrical demand exceeds the supply.