CHAPTER FOUR

DIESEL GENERATOR PERFORMANCE AND DISPATCH MODELS

N'allez pas la-bas. Ces monstres utilisent la vapeur. C'est une invention du diable. \Don't go there. Those monsters use steam. It's an invention of the devil."

|Alphonse Daudet: \Lettres de mon Moulin"

The central component of a hybrid power system is the diesel engine generator, which typically operates at a fixed rotational speed, powering an electrical generator. Both synchronous and induction generators are used. In multiple generator installations, diesels are dispatched in order to follow load. In hybrid installations with multiple diesels, a typical load-following strategy is to reduce the apparent load by the output from the renewables.

4.1 Diesel Generator Performance Model

From an energy perspective, diesel generator performance modeling involves the calculation of fuel use under various operating conditions. Typically, the calculations rely on loading and fuel use rates for the combined diesel and generator, including inefficiencies in both. In the discussion of diesel systems, it is important to distinguish between apparent demand and load. Apparent demand is defined as the power requested by the system from the system of diesel generators; load is the actual output of the system of diesels, which is not necessarily the same, since there could be an excessive shortfall. A power system may demand 1000 kW from a generation system on a peak day, but the generator may only be loaded to 950 kW if that is its maximum output. Also, in multiple systems with renewable generation, the apparent demand is a portion of the total demand allocated to an individual unit.

4.1.1 *Fuel Consumption*

Most information sources on diesel engines report performance data as a function of rpm, since typical applications are for variable speed operation such as transportation (Cummins, 1993). For example, Figure 4.1 shows the power output of a diesel engine as a function of rpm and fuel use rate. For static applications, these data can be converted to constant-speed data at typical diesel generator operating speeds (dashed lines). Figure 4.2 shows the fuel use rate data of Figure 4.1 plotted for 1200, 1800, and 2400 rpm operating speeds. Multiplying the kW output times the g/kWh at the kW transforms the *specific fuel consumption* (sfc) *curve* data in Figure 4.2 into *linear* mass flow rate of fuel as a function of apparent demand. Figure 4.3 shows the resulting linear mass flow rates of fuel.

According to Hunter and Elliot (1994), the fuel use at idle is approximately 25 percent of the fuel use at maximum output. In addition, at lightly-loaded output below 40 percent, *coking* can take place in the exhaust manifold of the diesel. Coke is a viscous semi-liquid polymerized substance formed from diesel fuel which has not been completely combusted, and can be a significant fire hazard if allowed to build up. To avoid coking, standard practice is to limit diesel loading to between 25 percent and 40 percent of the rated maximum.

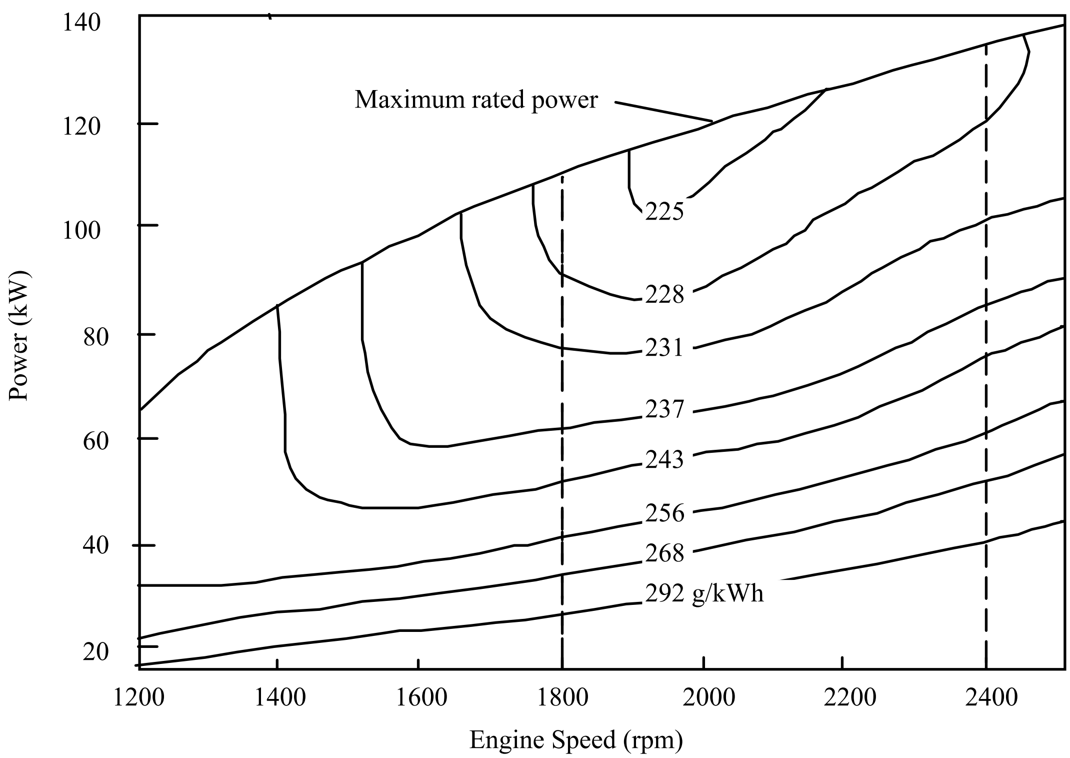

Figure 4.1 Diesel power output and full use per rpm (adapted from Heywood, 1989).

Given that fuel use is a linear function of power (as shown in Figure 4.3), and that the diesel generator has a minimum and maximum allowable loading, the coordinates of the two end points of the fuel line are all the information needed to simulate the performance of the engine using a parametric model. The fuel data implicitly include the generator losses. The model does not allow operation below the minimum rating, nor above the maximum rating. Thus, a portion of the output below minimum loading is dumped, and apparent demand above the maximum is unmet. Thus, the power output and fuel-use of a diesel can be presented as in figure 4.4. Input performance data of interest are therefore:

- Minimum load specified by manufacturer, 25 - 40% of rated (typically in kW)
- Fuel-use rate at minimum load (typically in liters/hour or kg/hour)
- Maximum load specified by manufacturer
- Fuel-use rate at maximum load

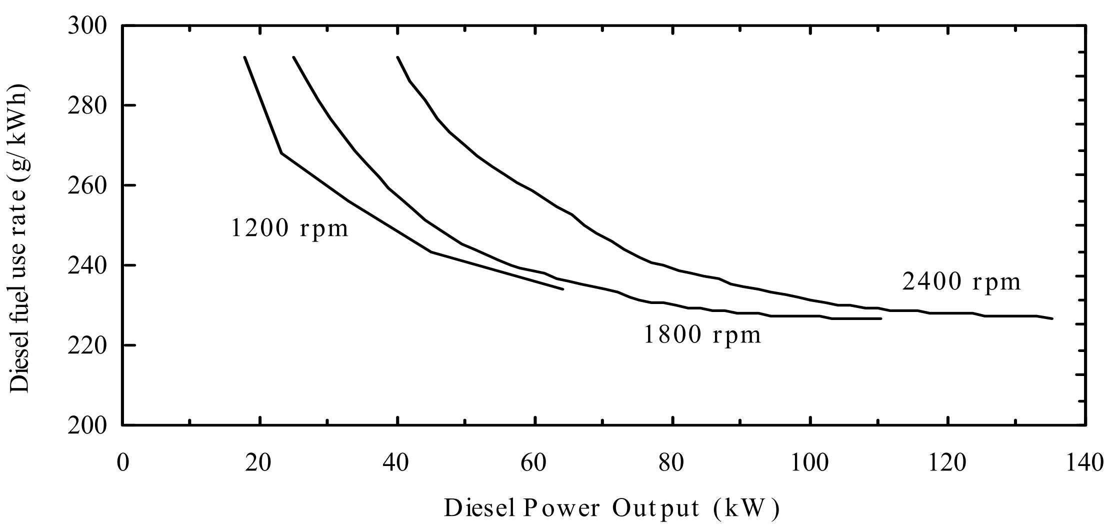

Figure 4.2 Fuel use rate data of Figure 4.1 for 1200, 1800 and 2400 rpm.

4.1.2 *Efficiency and Waste Heat Modeling*

Since the heating value (lower heating value, LHV, given the need to avoid condensation in exhaust piping) is known, and the fuel-use is also known, then the efficiency and waste heat energy production can be inferred. The specific fuel consumption of a fuel is the inverse of its heating value, so that for diesel fuel with an LHV of 11.63 kWh/kg, its *sfc* is 0.086 kg/kWh.

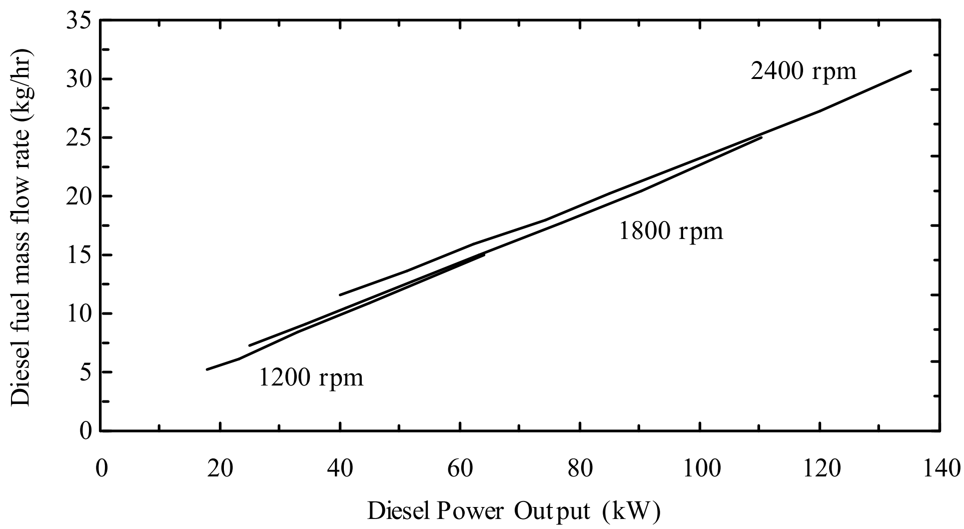

Figure 4.3 Mass flow rate of fuel as a function of demand, for 1200, 1800, and 2400 rpm operating speeds.

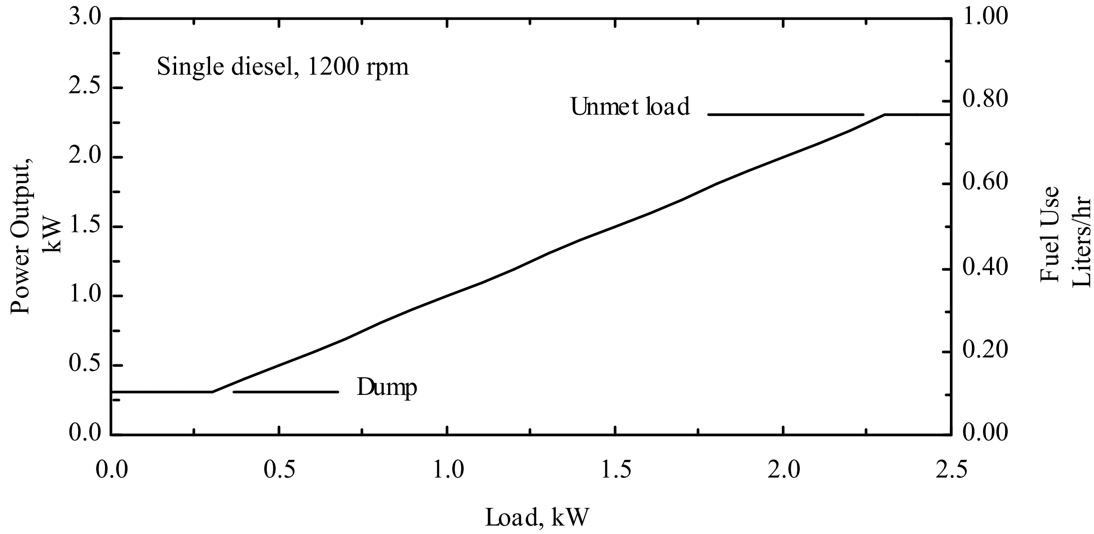

Figure 4.4. Typical diesel output as a function of load.

The waste heat is calculated by using the thermal efficiency and the output power. Waste heat values are valuable information because in many hybrid power systems, especially in cold climates, the waste heat is put to use in a cogeneration application. Given the *sfc* of the diesel at a particular output, the thermal efficiency can be calculated as

$$\eta_{thermal} = \frac{sfc_{fuel}}{sfc_{engine}} \tag{4.1}$$

The expression for determining the waste heat is

$$Q_{waste} = P_{diesel}\left(\frac{1}{\eta_{thermal}} - 1\right) \tag{4.2}$$

4.1.3 *TRNSYS Type 90: Diesel Engine*

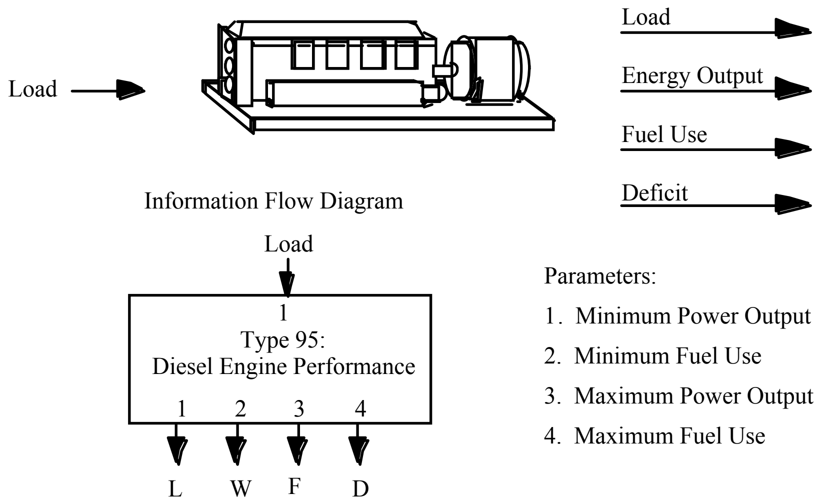

Figure 4.5 TRNSYS Type 90: Diesel Generator

The TRNSYS Type 90 diesel generator component estimates the amount of fuel, waste heat, and power output of the generator as a function of load. The information flow diagram for the diesel generator is depicted in Figure 4.5. The parameters required by Type 90 are:

- Minimum power output, kW, and specific fuel use at minimum power, kg/kWh

- Maximum power output, kW, and specific fuel use at maximum power, kg/kWh.

Below the minimum apparent demand, output values are set to the minimum. Above maximum apparent demand, output values are set the maximum. In this way, the system simulation can calculate dumped energy and unmet load. The TRNSYS diesel component calculates waste heat produced by the engine generator based on the heating value of diesel fuel, rate of fuel use, and net output of the generator.

Table 4.1 lists the parameters and input data used by Type 90. Data from various diesel generators are furnished in Appendix F. Type 90 outputs values of energy delivered, energy wasted, and fuel used per timestep.

4.2 Diesel Dispatch Modeling and Strategies

Diesel generators must be controlled in order to meet a desired output. Setting the control value of a single diesel generator to equal apparent demand causes it to follow the load, as presented in Figure 4.4. When there is more than one diesel, a controller is required to dispatch a portion of the total to each diesel. The apportioning of the load to each unit is determined by employing a control strategy. The most common strategy employed, stated simply, is:

Select the least-cost combination of units able to meet apparent demand.

The determination of least cost is based on the specific fuel consumption of each diesel to be controlled by the dispatcher. In general, large diesels can operate at lower speeds and higher efficiencies than small diesels. The *sfc* of a diesel at a particular output is therefore a measure of its efficiency.

Table 4.1 TRNSYS Type 90 input variables and parameters with typical values for an example diesel.

Parameter	Source	Value	Units
MinPower	data file	0.90	kW
MinSFC	data file	0.35	kg/kWh
MaxPower	data file	2.30	kW
MaxSFC	data file	0.39	kg/kWh
Diesel Demand kW	input data	2.10	kW, example
timestep	input data	1.00	hour
SFC at Demand kW	interpolated	.384	kg/kWh
SFC Fuel (1/LHV)	reference 1	.086	kg/kWh
Energy, timestep	Diesel Demand kW x timestep	2.10	kWh
Fuel mass	SFC at Demand kW x Energy, timestep	0.81	kg
Fuel volume per kg	reference 2	1.16	li/kg
Fuel volume	Fuel mass x Fuel volume per kg	0.94	liters
Thermal Efficiency	SFC Fuel / SFC at Demand kW	0.22	percent
Waste heat, kWh .	timestep x (Diesel Demand kW / Thermal Efficiency - Diesel Demand kW)	7.32	kWh

The dispatcher requires information concerning the operating characteristics of the diesels to be dispatched in order to perform this function. Dispatching is accomplished by sending a demand value to each diesel. In the simplest case of two 161 kWe diesels, with one more efficient than the other (diesel 1), this strategy results in plots such as shown in Figure 4.6. From zero load to minimum of diesel 1, output is constant at the minimum of diesel 1 in order to meet load. Waste energy is dumped. When demand is between the minimum output of diesel 1, 64 kWe, and the sum of the maximum of diesel 1 minus the minimum of diesel 2, diesel 1 follows load. When the output of the diesel 1 reaches its maximum minus the minimum of the more expensive diesel, 161 kWe, it reduces its output so the total will follow load. At loads greater than the maximum of both diesels, 322 kWe, there is unmet load. The behavior of two diesels can be extended to larger systems.

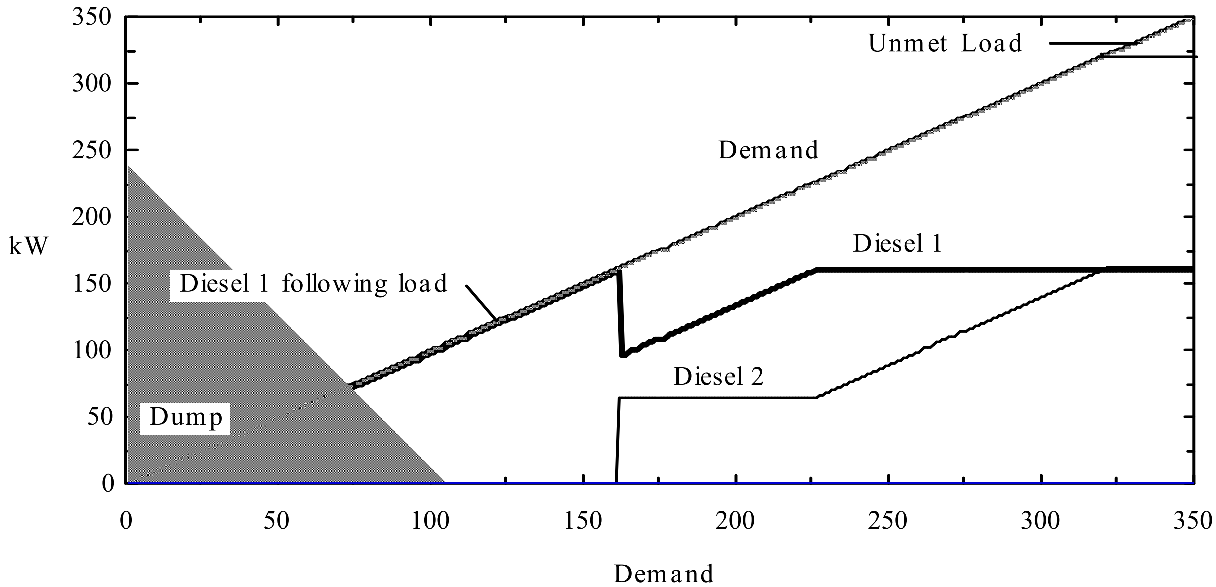

Figure 4.6. Dispatch strategy for two diesel generators.

Figure 4.7 shows the output of a system of five diesels dispatched using the same least-cost strategy employed for the two diesels. By comparing Figures 4.4, 4.6 and 4.7 it is apparent that the performance of diesel systems is generally divided into several regions (distinguished by the shading in Figure 4.6). These regions are described as:

Below the minimum rating of the *cheapest diesel*. In this region, the dispatcher searches through the operating characteristics of each diesel to find the cheapest single diesel or combination of small diesels to meet load.

Operating range of the cheapest diesel. Cheapest diesel follows the load between its minimum and maximum loads.

Operating range of the cheapest diesel, minus the minimum output of the *next cheapest diesel*. In this region, output of the cheapest diesel is reduced in order to allow for the minimum output of the *next cheapest* to be included.

Operating range of the next cheapest diesel, plus maximum of cheapest diesel. In this region, the output is equal to the cheapest diesel plus the load following in the range of the next cheapest unit.

This pattern is repeated for the remaining diesels. Any wind or solar generation serves to reduce the apparent load to the diesels. When there is stored energy available, the diesels operate whenever the state of charge falls below a user-defined setpoint.

4.2.1 *Factors Influencing Diesel Dispatching*

The most significant factors influencing dispatching are the size range and total output of the system of diesels. Diesels with identical characteristics are adequately able to sequentially meet apparent demand from their minimum rating to maximum apparent demand, but dump energy when apparent demand is below the minimum of a single engine. A set of diesels covering a wide range of sizes is better able to meet low apparent demand, but costs more to operate at higher power output due to the fact that the smaller, less fuel-saving, diesels are acting as peaking units. If the load being served varies only from 40% to 100% of peak demand, inclusion of more than one diesel in the generation portfolio may not be required.

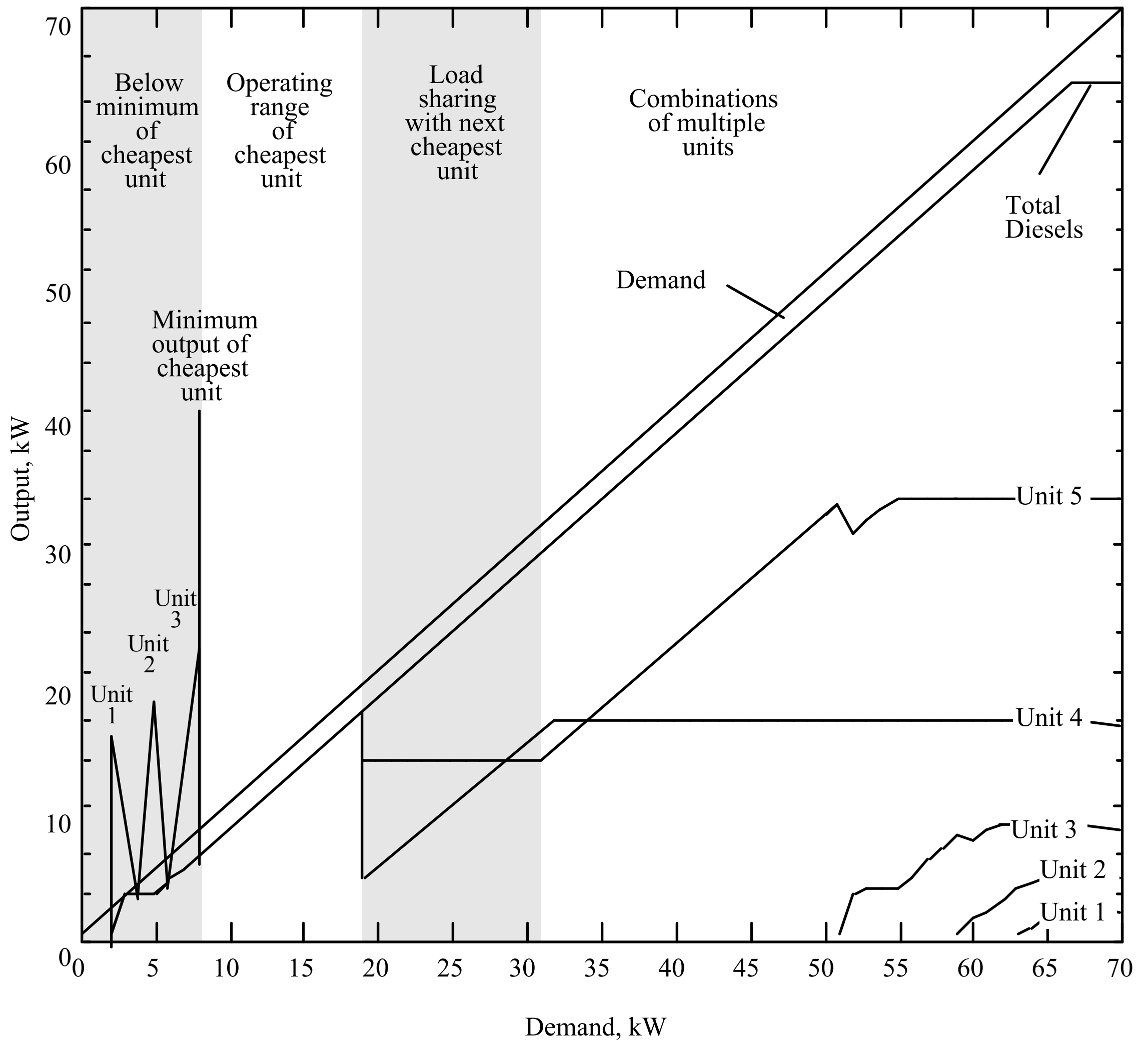

Figure 4.7. Dispatch strategy for two diesel generators.

A general rule for sizing the diesels in the system can be inferred, knowing the load duration curve of the electrical system to be served. The sizing criteria are:

- The output of all of the diesels must be able to meet peak demand.
- The size of each diesel is ideally 40 percent of the rating of the next largest diesel.

The number (and therefore size) of the diesels for a system can be inferred by the low-demand conditions experienced by the system. For example, if apparent demand varies between 50% and 100% of peak, then a single diesel may be the most cost effective, since it is the largest (cheapest) unit that can serve the load over its entire range of variation.

4.2.2 *Least Cost Dispatch Strategies*

Dispatch strategies are divided into two sets. The first are those performed when there is no energy storage in the system. The second are those performed when there is storage available. The no-storage strategies are more limited. Given the performance of a single diesel generator as in Figure 4.4, or a system of diesel generators, the dispatch strategy is to follow apparent demand. Dump energy may be produced when loads fall below the minimum, and loads above the maximum will not be met.

When there are multiple diesels in a no-storage system, one or more of the diesels may be required to be operating constantly, perhaps for frequency and/or power factor control on the system. Power factor is a measure of the proportion of the AC system which is carrying in-phase AC current.

When there is no storage, the list of options is varied. Some strategies include:

- Install battery storage sized to meet maximum apparent demand for the short period during startup of the diesel. Thus, the diesel could be shut off without risk of loss-of-load when renewables can meet total demand. When using one-hour time steps, modeling of this strategy is similar to the modeling of the no-storage condition, since over the course of the hour an entire charge-discharge-charge cycle may have taken place.

- Charge a moderate-size battery when the state of charge (SOC) is below a floor level. Discharge the battery when its SOC is high, and apparent loads are low, to offset the need for diesel operation for longer periods. This option has good potential cost benefit as well as providing improved system reliability.

- Employ the batteries to alter the daily demand on the system. For example, use the storage to firm-up supply from the renewables by averaging their output over time. Another strategy in the same context is to shift energy to meet peak loads from day to night.

The components developed in this work can be applied to research in these areas. However, for purposes of developing the component models and initial simulations, the only option used with storage is the SOC-based charging criteria.

Barley (1996) has categorized a considerable number of operating strategies, both with and without storage. More sophisticated strategies involve the use of forecasting software to provide additional flexibility and intelligence to the control of the storage and diesels.

4.2.3 *TRNSYS Type 92: Diesel Controller*

Type 92 dispatches diesel generators according to a least-cost strategy. The component can handle up to five different diesel generators. The diesels can be similar or different. Type 92 programs itself by reading in the fuel use parameters for each of the diesels to be dispatched in order to determine the fuel use rate for each unit. The dispatcher then ranks each generator by fuel-use rate and performs the dispatching per timestep according to the least-cost methodology illustrated in Figure 4.7.

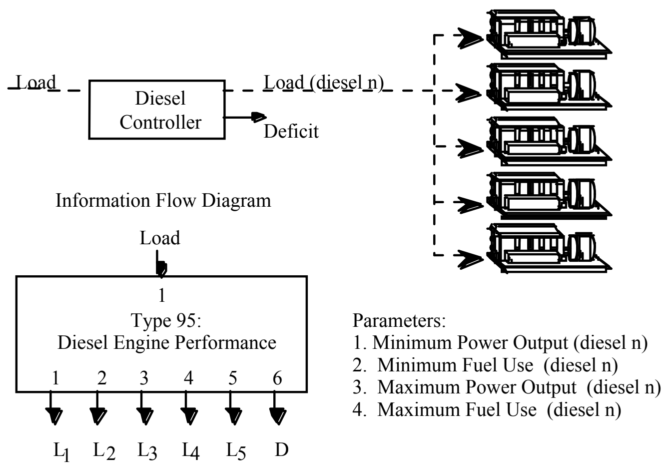

Figure 4.8 TRNSYS Type 92: Diesel Dispatcher

The output of Type 92 is a demand for each of the diesels. Fuel use, waste heat and output energy per time step are calculated by the Type 90 diesel component, not by Type 92.

The Type 92 Diesel dispatcher also internally sums up the renewable energy production in the time step and subtracts the total from the load prior to determining the apparent demand for each diesel. In this sense, the dispatcher also serves the role of the AC bus. Type 92 also performs energy accounting to calculate dump energy and unmet load. Type 92 uses makes use of the term \deficit" as its description of unmet load using the results of this energy accounting. A listing of Type 92 Diesel Dispatcher is provided in Appendix A.