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**Impact of Dispersed Solar and Wind
Systems on Electric Distribution
Planning and Operation**

R. W. Boardman

R. Patton

D. H. Curtice

Systems Control, Inc.

**OPERATED BY
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IMPACT OF DISPERSED SOLAR AND WIND SYSTEMS ON
ELECTRIC DISTRIBUTION PLANNING AND OPERATION

R. W. Boardman R. Patton D. H. Curtice
Systems Control, Incorporated

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✓ Systems Control, Incorporated 950 1051
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24

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TABLE OF CONTENTS

IMPACT OF DISPERSED SOLAR & WIND SYSTEMS (DSW)
ON ELECTRIC DISTRIBUTION PLANNING & OPERATIONS

	<u>Page</u>
ABSTRACT	
ACKNOWLEDGEMENT	
1.0 INTRODUCTION	1-1
1.1 DSW IN ELECTRIC DISTRIBUTION SYSTEMS	1-1
1.2 ISSUES AND PROBLEMS	1-4
1.3 STUDY OBJECTIVES	1-6
1.4 ASSESSMENT PROCEDURE	1-6
1.5 SYNOPSIS	1-13
2.0 THE IMPACT OF DSW ON ELECTRIC DISTRIBUTION SYSTEM PLANNING AND OPERATION	2-1
2.1 IMPACT OF DSW ON DISTRIBUTION PLANNING	2-1
2.1.1 Distribution Planning With and Without DSW Devices	2-1
2.1.2 Simulation of DSW Options	2-5
2.2 ASSESSMENT COMPONENTS	2-8
2.2.1 Distribution Capacity Component	2-10
2.2.2 Reliability Benefit of DSW	2-10
2.2.3 Dispersal Cost Component	2-13
2.2.4 Production Cost Component	2-14
2.2.5 Replacement Capacity Component	2-17
2.3 EFFECTS OF DISPERSED PHOTOVOLTAIC AND WIND ENERGY CONVERSION ELECTRIC SYSTEMS ON DISTRIBUTION OPERATIONS	2-19
2.3.1 Identification of Problems and Requirements	2-19
2.3.2 Protection Equipment Coordination	2-20
2.3.3 Safety Problems of Dispersed Generators	2-26
2.3.4 Effects of Dispersed Generators on Voltage	2-33

TABLE OF CONTENTS (Continued)

	<u>Page</u>
3.0 MODELING OF PHOTOVOLTAIC AND WIND ENERGY CONVERSION SYSTEMS	3-1
3.1 WIND ENERGY CONVERSION SYSTEMS (WECS)	3-1
3.1.1 WECS Characteristics	3-1
3.1.2 WECS Performance Models	3-3
3.1.3 Data Requirements	3-5
3.1.4 Model Limitations	3-6
3.2 PHOTOVOLTAIC (PV) SYSTEMS	3-7
3.2.1 PV System Characteristics	3-7
3.2.2 PV System Performance Model	3-10
3.2.3 Data Requirements	3-11
3.2.4 Model Limitations	3-11
3.3 STATISTICS SUMMARY MODEL	3-11
3.3.1 Functions of Statistics Model	3-11
3.3.2 Inputs/Outputs of the Model	3-13
4.0 DSW CASE STUDIES	4-1
4.1 UTILITY DESCRIPTIONS	4-1
4.1.1 Southern California Edison (SCE) - A Summer-Peaking Utility	4-1
4.1.2 Consumers Power Company (CP) - A Winter-Peaking Utility	4-11
4.2 METEOROLOGICAL DATA	4-20
4.2.1 Meteorological Data Requirement	4-20
4.2.2 Data Acquisition	4-21
4.2.3 Data Analysis	4-22
4.2.4 Assurance of Quality Data	4-24
4.3 DSW EQUIPMENT SPECIFICATIONS	4-28
4.3.1 Photovoltaic System Design Parameters for Various Applications	4-28
4.3.2 WECS Design Parameters for Various Applications	4-38
4.3.3 Storage System Design Parameters for Various Applications	4-40

TABLE OF CONTENTS (Continued)

	<u>Page</u>
4.4 DSW PERFORMANCE STATISTICS	4-43
4.5 DSW CASE DESCRIPTIONS	4-55
4.5.1 Development of DSW Strategies	4-55
4.5.2 Development of DSW Options	4-59
5.0 CASE STUDY RESULTS	5-1
5.1 DSW CASE STUDY RESULTS WITH VARIOUS BACKUP STORAGE CAPACITIES	5-1
5.2 DISTRIBUTION SYSTEM PLACEMENT CASE STUDY RESULTS . .	5-11
5.3 DSW TECHNOLOGY CASE STUDY RESULTS	5-26
5.4 DSW DEVICE PENETRATION CASE STUDY RESULTS	5-32
6.0 CONCLUSIONS	6-1
6.1 CASE STUDY CONCLUSIONS	6-1
6.2 OPERATIONAL ISSUES	6-3

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IMPACT OF DISPERSED SOLAR AND WIND SYSTEMS ON
ELECTRIC DISTRIBUTION PLANNING AND OPERATION

R. W. Boardman R. Patton D. H. Curtice
Systems Control, Incorporated

ABSTRACT

Small-scale dispersed solar photovoltaic and wind generation (DSW) will affect the generation, transmission, and distribution systems of an electric utility. This study examines the technical and economic impacts of dispersing DSW devices within the distribution system. The assessment method, developed in a previous Systems Control International study entitled "Impacts of Dispersing Storage and Generation in Electric Distribution Systems," is extended to include dispersed intermittent generation. Effects of DSW devices on capital investments, reliability, operating and maintenance costs, protection requirements, and communication and control requirements are examined. A DSW operation model is developed to help determine the dependable capacity of fluctuating solar photovoltaic and wind generation as part of the distribution planning process. Specific case studies using distribution system data and renewable resource data for Southern California Edison Company and Consumers Power Company are analyzed to gain insights into the effects of interconnecting DSW devices.

While results were case-specific and applicable only to distribution systems studied, some important general conclusions can be made. The DSW devices were found to offer some distribution investment savings, depending on their availability during peak loads. For a summer-peaking utility, for example, dispersing photovoltaic systems is more likely to defer distribution capital investments than dispersing wind systems. Dispersing storage devices to increase DSW's dependable capacity for distribution systems needs is not economically attractive. Spatial diversity among dispersed wind generators may improve their dependable capacity at the bulk generation level, but for the relatively small service area of a distribution system, this improvement is insignificant. Substation placement of DSW and storage devices is found to be more cost effective than feeder or customer placement.

The effects of DSW on distribution system operation are also examined. Results show that small customer-owned DSW devices are not likely to disrupt present time-current distribution protection coordination, though one exception may be when sections of distribution systems containing DSW devices are isolated. Present maintenance work procedures, if properly enforced, are adequate to ensure workmen's safety. Physically disconnecting DSW devices during maintenance will prolong repair times. Regulating voltages within appropriate limits will become more complex with intermittent generation along the distribution feeders.

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1. INTRODUCTION

1.1 DISPERSED SOLAR AND WIND SYSTEMS IN ELECTRIC DISTRIBUTION SYSTEMS

With increased attention directed toward national energy needs and priorities over the past few years, the technologies of solar and wind generation have emerged as potentially important and commercially viable sources of power. The basic technologies are hardly new, although recent developments in hardware design and manufacture have revolutionized the industries [1-2].

The concept of integrating these technologies into conventional electric utility distribution systems, however, is relatively new. Earlier studies of solar and wind energy were generally confined to applications such as irrigation water pumping, remote communications, and water heating. More recently the integration of solar and wind devices into existing electric utility distribution systems has been a topic of increasing interest [3-7]. Subjects such as power conditioning, phase synchronization, security, and reliability, to mention a few, are now receiving increased attention from business, government, and utility investigators.

Some authors question the suitability of integrating these technologies into electric utility systems, arguing that their costs can be justified only in forms of the cost of the off-peak utility fuels they displace [3]. Furthermore the fluctuating nature of wind and solar power raises serious questions regarding generation availability when needed.

Other authors [2,4] concede operational limitations, but maintain that these may be greatly reduced by choosing appropriately sized electrical storage devices. In addition there may be other benefits conferred upon the utility system by an appropriate choice of site for the solar or wind generator. Locating these devices in the utility distribution system rather than in a central generation location may create an entirely novel situation because the devices may then be used to alleviate load distribution problems. Regardless of bulk system benefits, solar and wind generation in distribution system locations may allow capital deferments of distribution equipment.

An earlier study by Systems Control, Inc., for the U.S. Department of Energy, Division of Electric Energy Systems, has developed a consistent, unified methodology for evaluating effects of dispersing storage and generation (DSG) devices within electric distribution systems [8]. The present study expands upon the previous study and considers the effects of placing solar and wind generation devices within the distribution system. The effects of device outages due to failure and climatic conditions, generation cost differences, and economies of scale are treated explicitly.

The methodology extends previous studies such as the EPRI Wind and Photovoltaic Requirement Assessment Studies which evaluated the impact of Dispersed Solar and Wind (DSW) generation technologies on the bulk supply system by comparing the bulk supply system with and without the new technologies. In these studies, the devices are assumed to be planned and operated to satisfy bulk supply system needs. However, within the distribution system, DSW devices may be operated in a manner different from supply system economic dispatch principles.

This study focuses on the incremental cost and benefits by comparing the overall power system with DSW devices to the bulk supply system with the new technologies. This is illustrated in Figure 1-1.

* SCOPE OF THIS STUDY

FIGURE 1-1 DSW ASSESSMENT METHODOLOGY

The methodology includes detailed simulations of distribution systems expansion planning with and without DSW devices. The result from applying this methodology can then be integrated with previous study results to obtain a comprehensive assessment of DSW devices on the entire electric power system.

1.2 ISSUES AND PROBLEMS

The earlier study [8] describes numerous issues associated with introducing dispersed storage and generation (DSG) devices into the distribution system. They include:

Distribution Investment. Dispersed storage and generation (DSG) devices may affect investment in the distribution system.

Reliability. Service reliability will likely be affected by DSG devices.

Use Conflicts. Conflicts between the use of DSG devices for distribution and bulk supply requirements may occur.

Delivery Losses. Device placement within the distribution system will affect the line energy losses.

Capital and Operating Costs. Economies of scale may have significant cost effects. A system of DSG devices will incur additional costs due to communications, control, and maintenance costs.

Technical Problems. Integration of DSG devices within a utility network will require additional equipment for protection, synchronization, etc.

Utility Procedures. New utility planning and operational procedures will be needed.

Environmental and Institutional Issues. Local environmental problems may make siting difficult.

Financial and Rate Issues. New rate structures may be required.

The same issues which pertain to DSG devices also pertain to dispersed solar and wind (DSW) generation devices with or without storage considered in this study. However, additional technical, operational, and economic considerations exist for DSW devices. They include:

Technical Issues. What is an appropriate level of penetration in the distribution system for DSW devices? How should spatial diversity be considered? Should DSW devices be installed with or without a battery storage backup? Should the capability to control their operation exist at both local and central locations? What is the difference in system impact between solar and wind devices operated by the utility versus the customer?

Operational Issues. No less important are the issues associated with the routine operation of the DSW devices. Their introduction into the distribution system will change conventional procedures and planning criteria. It may also complicate or enhance other realms of the overall utility operation. For example, the presence of DSW generation may affect the distribution load estimation and capacity reserve requirements due to inherently greater non-availability probabilities.

The foregoing also alludes to a characteristic of solar and wind devices which may significantly affect utility operation - namely, the question of resource variation. How should the varying nature of DSW generation be factored into reliability and outage calculations? Under what circumstances should average output be judged an acceptable planning criteria? What availability factor can be assigned to DSW generation?

In other areas of utility operation, DSW devices may significantly change the status quo. Line synchronization, voltage control, and fault isolation are problems to which increased attention will need to be directed. The maintenance of DSW and associated hardware will impose new constraints and costs upon the utility. In addition the communications requirement will certainly affect utility operating procedures.

Economic Issues

The key economic issue addressed in this study is the benefit to utility distribution planners of DSW devices in their distribution systems compared to the cost of centralized solar and wind technologies. Other economic issues concern the use of storage to increase the benefit of DSW generation, optimizing the amount of DSW generation and choosing the most effective placement for the devices.

1.3 STUDY OBJECTIVES

The objective of this study was to extend the methodology of the previous study [8] to address the topics mentioned above. The DSG methodology is an integral part of the DOE Load Management Program and is described in [8]. This study follows the same guidelines - to develop an assessment methodology and to demonstrate the methodology using case studies to gain some insights into the effect of interconnecting DSW devices with the utility distribution system.

1.4 ASSESSMENT PROCEDURE

This study is based on the analysis of a series of case studies in which hypothetical DSW devices were placed in utility distribution networks. Based on extensive wind and solar data, a computer program, called the DSW Operations Model, was developed to simulate the short-term operation of both photovoltaic (PV) systems and wind energy conversion systems (WECS). This program was structured so that its output could be used as input to the assessment model developed in the DSG study. This computer program was used in a scenario analysis to provide the final DSW evaluation.

Portions of the distribution systems from two utilities were chosen for scenario analysis. The first utility, Southern California

Edison, is summer peaking and has a thermally-limited distribution system in an urban area. This utility was studied with hypothetical photovoltaic and wind energy conversion systems installed in its distribution systems. These systems were located on both the supply-side and the customer-side of the customer's meter for the solar PV cases, but only on the supply side for the WECS cases. Customer-side generation studies were performed with and without dedicated storage (i.e. storage devices intended to serve local load¹). Supply-side generation studies were performed to evaluate DSW performance with and without the benefit of system storage (i.e. storage intended to serve aggregate system load).

The second utility, Consumers Power Company, is winter peaking and has a voltage-limited distribution system in a rural area. This system was studied with hypothetical WECS installed in its distribution system. The same general categories of case studies considered for the first utility system were also considered for this utility system.

Five basic evaluation components were used to determine the impact of DSW devices upon the distribution systems studied. The five evaluation components measure distribution capacity, reliability benefit, dispersion cost, production cost, and replacement cost. These components determine the incremental benefit and cost of DSG and DSW devices to the utility distribution systems and generation system. The components are briefly described below and are described in detail in Chapter 2 of this report.

¹ The definition of dedicated storage used here differs from the conventional definition since the storage device may be charged by either the utility grid or solar device. The conventional definition of dedicated storage allows the storage device to be charged only by the solar device.

Distribution Capacity Component. This component is the difference in conventional distribution system costs between the policies where DSW devices are used and where they are not used. Distribution capacity benefits occur when conventional distribution investments are deferred, cancelled, or required by DSW devices.

Reliability Components. The reliability component is the value of additional expected service continuity provided by DSW during distribution system outages. The approach is to compute the reduction in expected unserved energy possible with DSW devices with and without storage, and then assign a value to this reduction reflecting the nature of load served by the device. The dispersed devices must be designed to supply only preselected loads before repair crews can restore partial or total service. This component includes the effect of the energy limitation of storage devices on the reliability benefit.

Dispersal Cost Component. The component is the cost difference for DSW equipment between dispersed use and centralized use. The Dispersal Cost Component includes the power capacity, the energy storage capacity, and the communications and control equipment costs. This component captures the effect of diseconomies of scale, capacity effect of loss savings, and load diversity.

Production Cost Component. The use of DSW devices for distribution objectives causes the total system production costs to be different than when DSW devices are operated for bulk system objectives only. The Production Cost Component, which includes operating and maintenance costs, is the difference between the production costs of the two types of uses. The Production Cost Component is calculated separately for two kinds of days: (1) days when DSW is operated for distribution needs; this occurs on the days when both distribution and bulk-supply peaks occur, and on the days when only the distribution loads peak; and (2) days when DSW is operated for bulk-supply needs; this occurs on the days

when only the bulk-supply system peaks and on the remaining days of the year.

Replacement Capacity Component. A replacement capacity cost is levied against a dispersed storage device on the days of the year when both the distribution and bulk supply systems experience peaks but the dispersed device is operated for distribution needs only. The Replacement Capacity Component occurs because DSW devices under local control may not provide the full equivalent power capacity for the duration needed by the bulk supply system. An average marginal capacity cost is levied to reflect the need for additional backup capacities.

Sixteen case studies have been run for this project. They are listed in Table 1.1 and include eleven cases for the first utility and five cases for the second utility. These cases were grouped for comparison to assess DSW impacts. Table 1.2 lists these comparison studies.

Table 1.1 DSW CASES

SOUTHERN CALIFORNIA EDISON/PV/SUPPLY-SIDE CASES

1. Substation Placement Without Storage
2. Substation Placement With System Storage
- 3.* Feeder Placement With System Storage
4. Feeder Placement Without Storage
5. Central Placement Without Storage
6. Central Placement With System Storage

SOUTHERN CALIFORNIA EDISON/PV/CUSTOMER-SIDE CASE

7. Customer Placement Without Storage
8. Customer Placement With Dedicated Storage

SOUTHERN CALIFORNIA EDISON/WIND/SUPPLY-SIDE CASES

9. Substation Placement With System Storage
10. Feeder Placement With System Storage
11. Central Placement With System Storage

CONSUMERS POWER COMPANY/WIND/SUPPLY-SIDE CASES

12. Substation Placements With System Storage, Without Spatial Diversity
- 13* Substation Placements With System Storage, With Spatial Diversity
14. Feeder Placement With System Storage, Without Diversity
15. Central Placement With System Storage

CONSUMERS POWER COMPANY/WIND/CUSTOMER-SIDE CASES

16. Customer Placement With Dedicated Storage With Diversity

* Three year penetration cases.

TABLE 1.2 DSW CASE COMPARISONS

PLACEMENT COMPARISONS:

Cases [1, 4, 5, 7]	Comparison of central vs substation vs. feeder vs. customer placement of PV systems without storage in the SCE system.
Cases [2, 3, 6, 8]	Comparison of central vs. substation vs. feeder vs. customer placement of PV systems with storage in the SCE system.
Cases [9, 10, 11]	Comparison of central vs. substation vs. feeder vs. customer placement of wind generators with storage in the SCE system.
Cases [12, 14, 15, 16]	Comparison of central vs. substation vs. feeder vs. customer placement of wind generators with storage in the CPC system.

DISTRIBUTION SYSTEM COMPARISONS:

Cases [9, 12]	Comparison of SCE and CPC for wind substation placement cases.
Cases [10, 14]	Comparison of SCE and CPC for wind feeder cases.
Cases [11, 15]	Comparison of SCE vs. CPC for wind central placement cases.

STORAGE COMPARISONS:

Cases [3, 4]	Comparison of storage vs. no storage for SCE feeder PV placements.
Cases [7, 8]	Comparison of storage vs. no storage for SCE customer PV placements.
Cases [1, 2]	Comparison of storage vs. no storage for SCE substation PV cases.

TABLE 1.2 (Continued)

TECHNOLOGY COMPARISONS:*

Cases [2, 9, DSG]	Comparison of wind vs. PV vs. Fuel Cell/Diesel generation for SCE substation cases.
Cases [3, 10, DSG]	Comparison of wind vs. PV vs. Fuel Cell/Diesel generation for SCE feeder cases.
Cases [6, 11, DSG]	Comparison of wind vs. PV vs. Fuel Cell/Diesel generation for SCE central cases.

PENETRATION COMPARISONS:

Case [3]	Comparison of 1, 2, and 3 year DSW scenarios for feeder PV cases with storage.
Case [10]	Comparison of 1, 2, and 3 year DSW scenarios for SCE feeder wind cases with storage.
Case [13]	Comparison of 1, 2, and 3 year DSW scenarios for CPC substation wind cases with storage and with diversity.

* Comparisons with previous DSG cases for Fuel Cells and Diesel generators are indicated by "DSG"

1.5 SYNOPSIS

This report is structured into three principal parts:

PART I BACKGROUND

- Chapter 1 - Introduction
- Chapter 2 - Impact of DSW on Electric Distribution
System Planning and Operation

PART II DISPERSED SOLAR AND WIND GENERATION

- Chapter 3 - Modeling of Solar Photovoltaic &
Wind Energy Conversion Systems
- Chapter 4 - DSW Case Studies

PART III RESULTS AND CONCLUSIONS

- Chapter 5 - Case Study Results
- Chapter 6 - Conclusions

Parts I and II present the methodology and relate this study to the earlier DSG study. They also present the data used in the case studies. Part III presents the numerical results of the case studies, analyzes the results, and presents study conclusions.

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2. THE IMPACT OF DSW ON ELECTRIC DISTRIBUTION SYSTEM PLANNING AND OPERATION

This chapter describes the method developed for evaluating the impact of dispersed solar and wind systems with or without storage on utility distribution system planning and operation. The groundwork for this analysis is based on a previous study: "Impact of Dispersing Storage and Generation in Distribution Systems." [8] The following Section 2.1 describes the method used to evaluate the impact of DSW on distribution planning. Section 2.2 defines the assessment components used to quantify the impact of DSW on distribution planning. Section 2.3 discusses the impact of DSW on distribution operation.

2.1 IMPACT OF DSW ON DISTRIBUTION PLANNING

This section describes the steps used to evaluate the impact of DSW devices on distribution planning. In many respects these steps are identical to the steps developed in the previous DSG project. Indeed this study relies heavily on the planning work previously performed, but expands upon it in order to evaluate DSW devices explicitly.

2.1.1 Distribution Planning With and Without DSW Devices

The earlier study used conventional distribution planning methods (without DSG or DSW devices) to establish a distribution system base case. The "ACORN II" (Automatic Computation of Radial Networks) Model [9] was used to establish the distribution load forecast and to identify specific reinforcement options to satisfy the new load reliably and at minimum cost. The "ACORN II" model accepts as input the growth of loads in the network and determines the network configuration subject to the following criteria: the acceptable voltage drop limit in the network, the thermal behavior of the components and the possibilities

for connections with neighboring zones of the network. A complete description of the conventional distribution planning procedure is described in Reference 8, Chapter 4 and is illustrated in Figure 2-1.

The distribution system base case was the same for both DSG and DSW studies. In brief this case identified the required feeder and substation capacities to accommodate the load growth of the distribution system. Different conventional options such as reinforcement of existing facilities or construction of new lines were considered and the least-cost conventional distribution expansion plan was chosen.

For the distribution system of Southern California Edison the best conventional plan required additions to transformer and underground line capacity. For the distribution system of Consumers Power Company, the best conventional plan required a new line to relieve voltage problems at the end of a feeder.

The major point of departure between the DSG and DSW studies occurs during the second step of the methodology. The earlier report described distribution planning options utilizing DSG devices which could help eliminate violations of distribution planning criteria. Different DSG options were presented, differing with respect to device location, size, and operating mode. The primary difference between the previous DSG study and the present DSW study approach is due to the unscheduled and intermittent nature of DSW devices.

For firm generation sources such as the fuel cells or batteries, one kW of firm capacity is credited to the utility for each kW of capacity addition to these devices. Intermittent generation sources such as photovoltaic systems and WECS systems cannot replace existing generation on a one-for-one basis due to their dependence on meteorological

FIGURE 2-1 CONVENTIONAL DISTRIBUTION PLANNING

variables. Based on a statistical analysis of meteorological data for each site, the availability factor of these intermittent technologies was found to vary from 5% to 32%.

The present DSW study therefore differs from the earlier DSG study in this respect: To achieve a given level of load reduction, significantly more DSW generation capacity was required than was DSG capacity. As a consequence, there were periods of peak load when much of the DSW energy could not be used and periods where no relief from DSW was available at critical times. The presence of backup batteries minimized these load violations by storing excess energy for use at critical times. However tradeoffs exist between storage capacities versus distribution system benefits.

In many other respects, however, the procedure to evaluate planning with DSW devices is similar to the previous DSG study. First, the specific criteria violations relieved by the base case expansion plan without DSW are identified. Then, each of the violations is analyzed to determine whether DSW can provide similar relief. For example, the overloading of substation transformers during an outage of a neighboring substation might be relieved under conventional single contingency planning by an additional transformer. Such an outage also might be relieved by the placement of DSW devices at the substation. Strategies are defined for relieving selected violations for a designated period. To implement these strategies, options are developed with DSW devices of various sizes placed at selected locations.

Potential locations for DSW devices range from the high-voltage bus of the distribution substation to the customer site. No environmental constraints were considered in the study, although suitable factors could be included by the planner for specific applications.

2.1.2 Simulation of DSW Options

The previous DSG report described two computer simulation models which were used in the next step of the methodology. The Load Model synthesized average daily load curves for different customer types. These curves are combined according to the customer mixture in a particular neighborhood. Next the model aggregated the resulting loads throughout the distribution system. The primary output of the Load Model was the aggregate load curve for every node throughout the distribution system (as shown in Figure 2-2). A detailed description of the Load Model is given in Chapter 4 of reference [8].

The second computer simulation model used in both the DSG and the DSW studies was the Operations Model. Using the aggregate load curves from the Load Model as input, the Operations Model simulated the operation of the dispersed devices, revised the local and aggregate load curves, and provided components used to evaluate the cost and benefit of these devices. A detailed description of this model also is found in Chapter 4 of reference [8].

The DSW simulation procedure consisted of using the Load Model to calculate distribution system loads exclusive of DSW devices at all nodes. The Load Model was then rerun representing DSW generation at specific nodes as negative loads. Modeling of the DSW output is discussed in Section 3. Appropriate availability factor adjustments to the DSW generation were made on the basis of the hourly power output statistics obtained from the DSW performance models.

Finally the resulting distribution system aggregate loads (including DSW) were input into the Operations Model so that storage usage could be simulated and the assessment components calculated. Storage operations were simulated, and the assessment components were calculated as in the DSG study. Figure 2-3 illustrates this procedure.

FIGURE 2-2 LOAD MODEL

FIGURE 2-3 USE OF MODELS IN DSW SIMULATION

2.2 ASSESSMENT COMPONENTS

This section describes the five assessment components that are considered in this study to determine the dispersion credit of the DSW devices. These assessment components include both the distribution system impacts and the incremental bulk supply system impacts of DSW devices sited in the distribution system. The five assessment components are briefly summarized below and discussed in detail in the following sections.

- Distribution Capacity Component - This component is the difference in distribution system reinforcement costs between the cases where DSW devices are used and where they are not used.
- Reliability Component - This component is the value of additional expected service continuity provided by DSW during distribution system outages.
- Dispersal Cost Component - This component is the capital cost difference for DSW equipment between dispersed use and centralized use.
- Production Cost Component - This component is the difference in production costs when DSW equipment is operated for distribution needs instead of bulk supply.
- Replacement Capacity Component - This component is a cost levied against dispersed storage devices on days when both the distribution needs and bulk supply systems experience peaks but the dispersed device is operated for distribution needs only.

Figure 2-4 shows the information flow from the planning models to the assessment components. In each assessment component calculation, there are two types of data: one for the dispersed technology case, the other for the centralized technology case. Differences between the two sets of data determine the assessment component. A positive component value indicates a benefit. A negative value is a cost. The sum of the five assessment components is the net benefit or net cost.

The net benefit (or cost) is the difference in the incremental cost and incremental benefit realized as dispersible devices are placed in the radial distribution system rather than in the bulk supply system. This net benefit is also called the dispersion credit.

FIGURE 2-4 ASSESSMENTS MODELS AND PLANNING STEPS

The value of each assessment component is computed as the present worth of annual revenue requirements. All costs and benefits are discounted to the reference year. That is, if the present value discount rate is r , and the benefit flow of the j^{th} component is $B_{1j}, B_{2j}, \dots, B_{nj}$ for n years, the present value of all benefits at the initial year is:

$$PV(B) = \sum_{k=1}^n \left[(1+r)^{-k} \sum_{j=1}^5 B_{kj} \right]$$

2.2.1 Distribution Capacity Component

The distribution capacity component is the difference in distribution reinforcement costs between the cases where DSW is used and where it is not used. Distribution capacity benefits occur when distribution investments are deferred or cancelled. The capital cost of DSW technologies is included in the dispersal cost component, not in the distribution capacity component.

2.2.2 Reliability Benefit of DSW

Since the photovoltaic or wind energy conversion systems are dispersed in the distribution system, they have a potential for satisfying a portion of the demand at a substation or on a feeder when the substation or feeder has been disconnected from central generation for any reason. However, there are several constraints which reduce this potential:

- (1) The capacity available will only be sufficient to meet a portion of the load.
- (2) The load to be supplied must be automatically isolated from the rest of the system.
- (3) The output of the DSW system must be able to follow the load.

The implications of these requirements are:

- (1) Specific loads must be preselected to be supplied by the DSW system in the event of the failure of or isolation from the central supply.
- (2) The hardware necessary to isolate the selected loads must be installed. This includes sensors, switches, and protective devices. Note that protection against the possibility of local problems must be included.
- (3) The selected loads must not exceed the capacity of the DSW system.
- (4) Since DSW devices have variable and essentially uncontrollable output, the load following requirement can only be satisfied only if the DSW system includes a storage component or a load management system.

Under the conditions described above, the DSW generator, with an associated storage device, will reduce the expected unserved energy (EUE) in its neighborhood.

The procedure used to estimate the reliability benefit of DSW is outlined in Figure 2-5. The first step is to estimate how much energy will be in storage as a function of time of day. To estimate this quantity, the power and energy capacity of the storage devices must be specified as well as the energy storage control strategy. This analysis assumes that the storage is charged during the off-peak period, held for a period while the load is increasing, discharged during the period of peak loading, and remains empty for a period until recharging commences, to complete the cycle.

The next step is to select the load that will receive the emergency support. Note that if these are critical loads, additional backup generation will be necessary in order to meet the load for outages occurring during the period when the storage does not have sufficient energy to supply the load for the duration of the outage. In an actual implementation; the magnitude and profile of the specific loads would

FIGURE 2-5 RELIABILITY COMPONENT

have to be known. For this analysis it was assumed that: (1) the load profile was the same as that of the total load at the same point; and (2) the peak load equaled the power capacity of the battery.

Next, the load is adjusted to account for the output from the DSW device. The details of this calculation are described in Section 2.1.2 of this report.

The reduction in EUE may then be calculated. In order to evaluate the reduction of unserved energy, four random variables have to be considered: the time the outage occurs, the duration of the outage, the amount of energy in storage, and the level of load during outage. The latter three random variables are usually correlated with the time the outage occurs. The model treats the level of load and the energy in storage as deterministic functions of the time of day. The dependence of restoration time on the time of occurrence is ignored.

From the past outage record, a probability density function $f_i(t)$ can be developed for the outage duration, t , during which the designated loads are supplied by the storage i . The data are usually expressed as frequency and duration of outage occurrence for an area.

We assume that outages are equally likely to occur at any hour of any day. Then the time of occurrence, the random variable t , has a uniform probability distribution. The reduction in EUE is then calculated by integrating over the random variables. The value of the reduction in EUE is estimated by multiplying by an average value of unserved energy.

2.2.3 Dispersal Cost Component

The dispersal cost component is the capital cost difference for DSW equipment between dispersed use and centralized use. It is the incremental cost of dispersing the various technologies rather than

locating them centrally. If applicable the dispersal cost accounts for diseconomies of scale in DSW equipment and the cost for communications and control equipment. The dispersal cost is calculated differently for dispersed photovoltaic and wind energy conversion systems and for dispersed storage.

2.2.4 Production Cost Component

The use of DSW for distribution benefits causes the total generation production cost to differ from that of the equivalent central device with bulk supply objectives. The production component measures the difference between the costs of the two types of operations.

The production cost benefit is calculated separately for two kinds of days in a year.

- Days when DSW devices are operated for distribution benefits. This is the sum of K_1 conflicting-capacity days and K_2 local-capacity days.
- Days when DSW devices are operated with bulk supply objectives. This is the sum of K_3 central-capacity days and K_4 normal days.

The production cost component includes the cost of fuel consumed as well as operating and maintenance costs. Not included are reductions in losses due to leveled load, which was estimated to be insignificant for storage when compared to the magnitude of the production cost component.

The unit operating and maintenance cost of a dispersed device is expected to be higher than that of centralized devices. It requires more effort to monitor, locate, and travel to the device. Therefore, the unit operating and maintenance cost (\$/kWh) depends on the size of the power capacity of DSW devices.

The production component on K_1 and K_2 type of days B_4^1 is calculated by:

$$B_4^1 = \sum_{k=1}^{K_1+K_2} B_{k4}^1$$

For a single day this relationship can be expressed as follows:

$$B_4^1 = H[L(t), U_1(\cdot)] - \sum_i H[f_i(t), u_i(\cdot)] - H[L(t) - \sum_i f_i(t) \beta_i, U_0(\cdot)]$$

where:

- $L(t)$ = Load as seen by the bulk supply system
- $U_i(\cdot)$ = A vector of incremental cost curves of central generators and the equivalent central device as functions of power output.
- $f_i(t)$ = The output of a single DSW device.
- $F(t)$ = The net load during the operating mode of the equivalent central device.
- $H[L(t), U_1(\cdot)]$ = Production cost of using generators with incremental cost U_1 to meet the load $L(t)$.

Thus B_4^1 is the bulk power production cost with equivalent central capacity under central control minus the combined production cost of the dispersed devices and the bulk power production cost to supply the load modified by the dispersed devices. Operating and maintenance costs are included in U_0 , U_1 , and u_i . β_i is the allowance factor to account for the energy losses in the transmission and distribution systems up to the location of the device i . The term $u_i(\cdot)$ includes only operating and maintenance costs, since fuel costs are zero for DSW devices. For storage devices the first term in the equation is replaced by $H[L(t) - F(t), U_1(\cdot)]$.

The total annual production component on days when DSW devices are operated with bulk supply objectives is given by:

$$B_4^2 = \sum_{k=1}^{K_3 K_4} B_{k4}^2$$

where B_{k4}^2 is the production component on a single day.

This quantity is calculated for the DSW devices under central control with bulk supply objectives. The DSW devices are operated individually at an incremental production cost of u_1/β_1 , which accounts for losses. Operated in this manner, the DSW unit is treated as a conventional generator in the dispatching of units.

For dispersed generation, for a given day, B_4^2 can be estimated as follows:

$$B_4^2 = H[L(t), U_1(\cdot)] - H[L(t), U_2(\cdot)]$$

where U_2 is the vector of incremental cost curves of the bulk power generators and those of the dispersed devices u_1/β_1 .

For storage, $L(t)$ is replaced by $L(t) - F(t)$ in both terms, and the incremental cost of the storage devices includes only operating and maintenance costs,

The total annual production component is given by:

$$B_4 = B_4^1 + B_4^2$$

These components for each year are used in the present worth analysis.

2.2.5 Replacement Capacity Component

A replacement capacity cost is levied against dispersed storage devices connected with a DSW device on conflicting capacity days if they are operated with only distribution objectives. This cost is the capacity penalty against dispersed storage for not providing the full capacity for the time needed by the bulk power system. Figure 2-6 illustrates the replacement capacity cost phenomenon, showing the differences between the operating curves of the central and combined dispersed devices as seen by the bulk supply system between peak periods t_1 to t_2 .

Mathematically, using the previous notations and letting q (\$/kWh) be the average unit central capacity cost between the peak period from t_1 to t_2 , the replacement capacity cost is calculated as:

$$B_5 = K_1 \int_{t_1}^{t_2} \left[\sum_i f_i(t) \beta_i - F(t) \right] q \, dt$$

This expression places a cost on the difference between the operating curve of the equivalent device located centrally and the sum of the operations of the individual dispersed devices.

The unit capacity cost, q , represents the cost of acquiring generating capacity during the system peak period. It can be the cost of capacity transactions between utilities, or it may be the capacity cost of peaking units prorated by the annual hours of use. For the latter case, if C is the total capital cost of a peaking unit, a the annualization factor, and b the number of hours the unit is used in a year, then $q = Ca/b$.

ORNL-DWG 80-6202 ETD

FIGURE 2-6 GENERATION OUTPUTS FORM EQUIVALENT CENTRAL AND COMBINED DISPERSED DEVICES

2.3 EFFECTS OF DISPERSED PHOTOVOLTAIC AND WIND ENERGY CONVERSION ELECTRIC SYSTEMS ON DISTRIBUTION OPERATIONS

This section presents the analysis of the operational effects of connecting dispersed photovoltaic (PV) and wind energy conversion systems (WECS) in an existing distribution system. It defines problems associated with these power sources, describes the effects produced by their operation, and identifies possible solutions. Specifically, the concerns are focused on problems created by adding dispersed sources in a distribution system.

2.3.1 Identification of Problems and Requirements

Three broad problem areas are addressed concerning dispersed photovoltaic and wind energy conversion systems.

- 1) Effects these dispersed sources have on the utility's protection equipment
- 2) Safety hazards posed by the presence of dispersed sources to the utility's line crews
- 3) Effects dispersed sources have on a distribution feeder's voltage profile

It is assumed that dispersed generation sources will meet National Electrical Manufacturers Association (NEMA), American National Standards Institute (ANSI), etc., standards applicable to large generators.

The principal problems associated with DSW generation sources are:

- protection equipment coordination
- safety of utility line crews
- voltage fluctuations

These problems are analyzed assuming various penetrations of dispersed generation sources connected to an existing distribution system.

2.3.2 Protection Equipment Coordination

Background

Coordination of overcurrent devices along a distribution circuit means that these devices, properly arranged, will clear faults from lines and equipment according to a prearranged sequence of operation. Line fuses, circuit reclosers, relayed circuit breakers, and line sectionalizers are the overcurrent devices used most commonly in distribution systems. When properly applied and coordinated these devices can eliminate outages caused by temporary faults and reduce the extent of the outage from persistent faults to the smallest section possible, thus affecting the fewest customers.

On overhead distribution circuits a large portion of the faults (70 to 80 percent) are temporary, i.e., tree limbs momentarily contacting the line, lightning sparkover of insulators, etc.

Overcurrent devices are designed not to open the temporarily faulted section, providing that the temporary fault is self clearing. Some faults can be temporary if the circuit voltage can be removed quickly, and restored after the faults' electrical arc path has been extinguished. Reclosers and reclosing circuit breakers provide the function of de-energizing a fault's electric arc by removing the circuit's voltage and then re-establishing the voltage after the fault has been cleared.

If a fault disappears during the period when the recloser opens the circuit, reclosing and re-establishing the voltage will be successful. If the fault persists, a preprogrammed number of reclosing operations may be attempted, depending on the design of the recloser. The recloser will lock open, de-energizing the circuit after all reclosing operations have been exhausted, or the fault will be isolated by operation of a fuse or sectionalizer.

Permanent faults (or persistent faults) are those that require repair or replacement of equipment before the voltage can be restored in the faulted section. Overcurrent protection schemes are designed to disconnect the faulted section from the system automatically so that a minimum number of customers are affected. Isolation of permanent faults is usually accomplished by the operation of line fuses, although it can also be achieved by operation of the reclosers or sectionalizers.

Problems Introduced by the Presence of Dispersed Sources

Distribution circuits are designed to serve connected loads. The coordination of overcurrent protection equipment for abnormal conditions relies on the fact that fault current flows in one direction: from the utility's generators toward the loads. The presence of dispersed sources suggests that normal condition current flow will be disrupted, and coordination schemes, developed for load conditions only, may be influenced.

Protection equipment coordination problems may result due to the fault current contributed by dispersed sources. During a fault on the utility's line the additional fault current produced by dispersed sources may cause overcurrent protection equipment to open which would not open without the presence of dispersed sources. Such a situation would be unacceptable to the utility because customers connected to the line section containing the dispersed sources would be subjected to increased outages.

The electrical characteristics of photovoltaic and wind energy conversion systems determine the magnitude of the fault current produced by these sources. The possible electrical configurations are:

- 1) inverters; line and forced-commutated where the dc source, whether photovoltaic arrays or synchronous generator rectified to dc, is converted to constant frequency ac
- 2) synchronous generator; constant rotor speed controlled by blade pitch angle
- 3) induction generator; variable rotor speed within slip constraints of the generator

For any fault on the utility's line the fault current contribution from inverters is limited. Line-commutated inverters faulted on the ac line will fail to commute within less than a cycle. If the dc source is a photovoltaic array the dc fault current produced is limited to 1.5 p.u. and can be expected to produce an insignificant fault current contribution to utility faults [10]. Other dc sources, such as an alternator rectified to dc, will produce high dc fault current. But the momentary fault contribution from a line-commutated inverter is limited in duration to less than one cycle.

During a single cycle the dc fault current will rise on the ac side of the inverter. Because of the distribution transformer this dc current will not reach the primary. A spiked ac fault current may appear on the primary with a duration of less than a cycle. The magnitude of this spike depends on the dc source, which in this case is an alternator-rectifier configuration; its maximum fault current will probably be less than 4 or 5 per unit [10].

Forced-commutated inverters will also fail to commute when faulted on the ac side, providing that they cannot commute dc fault current above their rated value. That is, if the dc source is capable of producing fault current of greater magnitude than the inverters ability to commute, the inverter will fail to commute.

If the dc source is a photovoltaic array, which has a limited fault current capability due to its large internal impedance typically in the range of 1.5 p.u., a forced-commutated inverter may continue to contribute fault current to a utility fault until interrupted by its own protection equipment. Such an interrupting device could detect a rapid rate of rise of the dc current and isolate the dc source within a couple of cycles. Even if such a device failed to operate, the maximum fault current contribution would be limited to 1.5 p.u., assuming the force-commutated inverter continues to commute.

Wind-turbine generators using a synchronous generator rectified to dc will produce high dc fault current. During a fault on the ac side the inverter will either fail to commute excessively high fault current or its own protection equipment will isolate the dc source. In either case its fault current contribution will be interrupted, and a continuous contribution is not possible.

Wind-turbine generators using an induction generator can be treated as a motor of equivalent rating because their fault current characteristics are identical; an 8 kilowatt induction generator has the same fault current characteristics as a 10 horsepower induction motor. The blocked rotor reactance is used to calculate the fault current contribution to a utility line fault.

Small induction generator wind-turbine generators can be analyzed assuming the blocked rotor reactance of induction motors operating at less than 600 volts. These machines will typically be owned by utility customers and located in distribution systems. A typical reactance for such small wind-turbine generators is .25 per unit. The duration of fault current contribution is limited by the design of the induction generator and is confined to a couple of cycles. Any fault current produced after the first couple of cycles is insignificant and can be ignored [11].

Synchronous generator wind-turbine generators are capable of large fault current. Subtransient and transient reactance for large wind-turbine generators has been calculated in the range of .33 per unit for large wind-turbine generators. Small wind-turbine generators have subtransient reactance in the range of .25 per unit [12].

Because a synchronous generator can continue to contribute for a utility fault, its overcurrent protection equipment must be designed to interrupt fault current during the subtransient or transient time

interval (within the first few cycles). If not interrupted by its own protection equipment a synchronous generator without a voltage regulator supporting the generator's field (permanent magnet synchronous generators) will produce steady-state fault current approximately equal to load current (synchronous reactance of 1.0 per unit). Such a situation is probably unlikely because the generator's overcurrent protection equipment will probably detect the fault during the first few cycles and disconnect the generator.

Based on the above discussion, the induction and synchronous generator wind-turbine generators are the only dispersed power sources that pose a potential coordination problem. Their momentary fault current contribution magnitude is high and may cause line fuses or other overcurrent devices to open erroneously during a utility line fault.

Because only the momentary (the first couple of cycles) fault current contribution from the induction and synchronous generators is of interest it is possible to determine the fault current contribution necessary to cause line fuses to open on distribution circuits.

Fuse links used in line fuses on distribution circuits are specified according to their voltage, maximum fault current available at the application point (interrupting capacity), and the load current (continuous current). The continuous circuit rating of a fuse signifies the normal load current requirements of the protected equipment. These requirements take into account overload currents, transient currents, etc. of the protected equipment, when properly applied, and thus place limits on the additional load that can be placed in the protection zone of the line fuse. For example, a 12T fuse link has a continuous current rating of 18 amperes and installed on a 7.2 kV (line-to-neutral) distribution feeder, it would provide protection for about 390 kW of load. A 12T fuse link will open for momentary fault current of 400 A (minimum clearing time 2 cycles at 400 A symmetrical fault current).

The amount of induction generator capacity required to produce sufficient momentary fault current to open a 12T fuse line is calculated using the blocked rotor reactance value given above. The amount of capacity required to open a 12T fuse, correctly applied to protect around 390 kW of load is 2160 kVA an amount that obviously exceeds the load protected by the 12T fuse.

This result suggests that an induction generator dispersed source, large enough to cause a line fuse to open during a utility fault, must be considerably larger than the load protected by the fuse. A larger generator would require a new conductor with the appropriate fuse needed for protection. Under these circumstances the new fuse would be sized recognizing the fault current contribution of the generator.

Application and coordination of overcurrent protection equipment changes among the utilities. The application rules used in the preceding discussion are ideal, but they suggest that dispersed sources located in distribution systems to serve a given load will probably not disrupt protection equipment coordination developed from load conditions. In the above example the induction generator was used to calculate the fault current contributed by a dispersed source. Using a synchronous generator would have shown a greater amount of capacity was required over that calculated for the induction generator, because of the larger subtransient reactance for synchronous generators.

Effects of Reverse Current Flow

During some time periods, the total load on a distribution circuit may dip below the power output of the dispersed sources. This may happen more often with wind-turbine generators than with photovoltaic systems. Provided that the total penetration of dispersed sources is greater than the lowest load on the circuit, the dispersed sources may reverse the current flow on the circuit. The effect of reverse current

flow on protection equipment coordination has been examined and is discussed below.

In general, fault studies used to size and coordinate overcurrent protection systems neglect the effects of load currents, except to ensure that the selected overcurrent device has a continuous current capacity capable of handling normal load current variations. Coordination focuses on short-circuit currents to size and locate protection devices.

Dispersed generators located on the load side of the distribution system's substation are small compared with the utility's central generation and as discussed previously their equivalent reactance is large compared with the utility's short-circuit impedance.

During a fault on the utility's line this large reactance limits the contribution from dispersed sources. Their contribution in a reverse direction to the utility's short-circuit current is insignificant compared with the utility's short-circuit current.

Although net load current may be reversed at a particular time, the net short-circuit current will flow in one direction only, from the utility's generators toward the fault.

2.3.3 Safety Problems of Dispersed Generators

Initial investigation of safety problems revealed that utilities are concerned about one problem associated with customer-owned dispersed generation: feedback from a customer's generator into de-energized conductor and equipment. For example, while working on equipment in a purposely de-energized section of a distribution network, uncontrolled generators, such as those owned by customers, could create a voltage in the work area exposing workers to hazardous electrical shock.

Several utilities were contacted to obtain their views on safety and other issues associated with customer-owned generation. In addition, two utilities' standard work procedures and concerns for customer-owned generation were obtained after meetings with their protection engineers.

In the following sections current work procedures are presented and analyzed to determine their adequacy for dispersed generators. Two utilities' work procedures are discussed and compared with the general guidelines established by federal agencies. Then dispersed generators are analyzed to determine if new safety hazards are posed by these sources and what requirements are placed on these generators to comply with utility line-crew work procedures.

Work Procedures with Dispersed Generators

Federal and state agencies and public utility commissions are primarily responsible for specifying work procedure guidelines. These guidelines are passed down from federal agencies to state agencies under a general federal mandate that employers provide a safe work environment for their employees. The federal agency responsible for these guidelines is the Occupational Safety and Health Administration (OSHA). OSHA's guidelines are suggested work procedures that are then adopted and/or amended by appropriate state agencies, such as CAL-OSHA in the State of California.

Each state's agency, like CAL-OSHA, has a different method for drawing up safety procedures used by utility line-crews. For example, CAL-OSHA consists of three divisions: a rules and standards board, an administrative agency, and judicial review board. A seven-member board made up of union, industrial, government, and nonallied representatives reviews changes to rules and standards proposed by the Rules and Standards Board. This seven-member board convenes monthly public meeting for the

purpose of considering changes or additions to safety procedures. Organizations such as unions, utilities, the Public Utility Commission, and others can attend these meetings and monitor the board's decisions. Suggested rule changes are placed in the hands of a committee, appointed by the seven-member board, coordinated with a rules and standards group within CAL-OSHA. Final adoption of any rule is the responsibility of the seven-member board.

The safety procedures that apply to utilities are adaptations of or amendments to Federal OSHA guidelines entitled "Safety and Health Regulations for Construction - Power Transmission and Distribution." All but five states--Washington, California, Hawaii, Alaska, and Oregon--have adopted the Federal guidelines as stated by OSHA. These five states have generally gone beyond OSHA guidelines and have adopted stricter requirements.

These guidelines state, "When de-energizing lines and equipment operated in excess of 600 volts, and the means of disconnecting from electric energy is not visibly open or visibly locked out," the following provisions shall be complied with:

- The particular section of line or equipment to be de-energized shall be clearly identified and it shall be isolated from all sources of voltage.
- Notification and assurance from the designated employee shall be obtained that:
 - 1) all switches and disconnectors through which electric energy may be supplied to the particular section of line or equipment to be worked have been de-energized;
 - 2) all switches and disconnectors are plainly tagged indicating that men are at work; and that
 - 3) where design of such switches and disconnectors permits, they have been rendered inoperable.

- After all designated switches and disconnectors have been opened, rendered inoperable, and tagged, visual inspection or tests shall be conducted to insure that equipment or lines have been de-energized.
- Protective grounds shall be applied on the disconnected lines or equipment to be worked on.
- When more than one independent crew requires the same line on equipment to be de-energized, a prominent tag for each independent crew shall be placed on the line or equipment by the designated employee in charge.

When a crew working on a line or equipment can clearly see that the means of disconnecting from electric energy are visibly open or visibly locked out, the following provision shall be followed:

- Guards and barriers shall be erected as necessary to adjacent energized lines.

Southern California Edison (SCE)

At the time of this report, Southern California Edison did not have specific work procedures for customer-owned generation. Their standard work procedures are outlined here as they pertain to customer-owned generators.

For distribution networks, Southern California Edison requires that all conductors and equipment normally operated at a voltage in excess of 600 volts shall not be worked on until de-energized and the normally energized parts have been tested with an approved device for the indication of voltage. All conductors must be short-circuited and grounded between the point where the work is being performed and all possible sources of supply. Grounding devices shall first be connected to a ground before being brought in contact with a conductor of the circuit to be grounded. To ensure that conductors and equipment remain de-energized while workers are exposed to potentially hazardous electrical shock, tags are placed on switches and disconnect equipment. These tags signal that work is being performed and cannot be removed until proper authority is given.

Consumers Power Company (CP)

Standard work procedures for Consumers Power Company are almost the same as those for Southern California Edison. This is a result of Federal Occupational Safety and Health Administration (OSHA) guidelines which have been adopted, in one form or another, by all states.

Consumers Power Company's standard work procedures require that all conductors and equipment normally operated above 600 volts must be considered energized until working clearance has been obtained. After the conductor or equipment has been de-energized, all phases must be tested by approved test equipment to ensure they are de-energized. All switches, jumpers, or equipment must be tagged to indicate that work is being performed and to define a working area. After conductors or equipment have been de-energized and tested, approved grounding equipment must be installed to ensure no possible sources of power can create a voltage between ground and the work area.

Consumers Power Company has work procedures for customer-owned generators. They follow the same procedure outlined above except that they specify that workers must disconnect and tag the customer's generator before testing for voltage.

Exposure to secondary voltage, 600 volts or less, requires working clearance on conductors and equipment; both utilities require that all sources of power be disconnected and confirmed by visual inspection and a test for voltage.

Discussions with both utilities indicated that they require some parallel generators to have an isolation switch located at the generator that is always accessible to utility line-crews. Although the utilities do not claim that this requirement is a direct result of

safety procedures, it is obvious that it stems from these procedures--specifically, the requirement that all possible sources of electrical energy be disconnected.

The requirement that customers with generators have an isolation switch may not always be necessary or desirable. It is not necessary for disconnecting many customers because the utility can use the fuse cut-out located on the primary side of the distribution transformer. Figure 2-7 shows the location of this fuse cut-out. If opened, as required by the safety procedures to disconnect all possible sources of electric energy, then the customer's load and generator are disconnected from the feeder.

Figure 2-7 Simple one-line diagram of the secondary system for serving residential or light commercial areas

This fuse cut-out disconnect procedure is desirable for the customer with a generator that can operate without the utility's line voltage (stand-alone) because it allows his generator to continue to supply his loads, even though the feeder has been de-energized for repairs. Workers are protected because an open circuit exists between the feeder and the generator.

If the work area is between the distribution transformer and the customers junction box (secondary voltage), this disconnect procedure does not protect the workers; disconnection from the feeder does not stop the stand-alone generator from creating a voltage in the line or equipment. In this case the utility would still need an isolation switch at the generator to comply with the safety procedures.

Customers with generators that are dependent upon the utility's line voltage for operation may not embrace this fuse disconnection procedure with the same enthusiasm as owners of stand-alone generators. If only the generator is disconnected, complying with safety procedures, then when service is reestablished, the customer's loads would also be included. Later his generator would be reconnected, possibly losing some energy produced but receiving the same reliability of service provided to all customers.

In either case the safety procedures require that all possible sources of electric energy be disconnected, locked out, and tagged. Thus, the only requirement is that utility line crews know which customers have their own generators.

Safety procedures are sufficient to protect utility workers even with customer-owned generators. But more time will be required to do work on distribution conductors and equipment as customer-owned generators increase in number. Extra time will be required to switch on and off each generator.

Requiring a disconnect switch at each customer's generator is a straightforward interpretation of the safety procedures. But it may be excessive because locking out the fuse cut-out on the high side of the transformer is safer because the customer cannot tamper with the disconnect. In addition, for those customers with generators that can operate without the utility, switching off the generator deprives the owner of potential benefits of owning his own generation.

2.3.4 Effects of Dispersed Generators on Voltage

As dispersed power sources are located in the utility's distribution, the utility may experience voltage control problems. Depending on the type of generators used, reactive power demands may be increased which may also affect line losses and voltage.

This study has examined distribution feeder voltage profiles assuming various penetration of dispersed sources. The steady-state analysis of two types of power sources have been examined using a load flow program:

- 1) voltage-source generators; forced-commutated inverter, and synchronous generator
- 2) voltage-dependent generators; line-commutated and induction generator

The questions addressed include: effects dispersed generators have on voltage profiles and voltage regulation equipment, and effects of voltage-dependent generators on line losses.

Feeder Analyzed

The feeder used for these studies is shown in Figure 2-8. This feeder is part of Consumers Power Company within Leednau County. Characteristics of this substation are shown in Table 2.1.

ORNL-DWG 80-6204 ETD

Figure 2-8 Sutton's Bay Feeder
Showing Nodes and Feeder Section
Distances

TABLE 2.1

SUTTONS BAY DISTRIBUTION SYSTEM

Primary Feeder Voltage - - - - - 12.47/7.2 kV
 Subtransmission Voltage
 to substation - - - - - 46 kV (line-to-line)

Customer Mix (%)

Residential Type				Commercial/Industrial
1	2	3	4	
				17%
4%	50%	19%	10%	

Peak Load - - - - - 2179 kW and 198 kVAR
 (feeder and utility both winter peaking)

Various penetrations of dispersed generators were assumed to be connected on the feeder distributed along the line starting from the farthest load point at the end of the feeder. Each penetration was determined based on a percentage of peak load, i.e., 5, 20, and 50 percent of peak load represents the power output of the dispersed generators. Each penetration case was compared with the base case without dispersed generators. All cases assume steady-state behavior of loads and generators.

Discussion of Results

When dispersed sources are producing power their output changes the feeder's voltage profile. Voltage source generators such as forced-commutated inverter systems and synchronous generators produce their own reactive power and tend to increase the voltage at the point of connection by reducing the load. Voltage-dependent sources such as line-commutated inverter systems and induction generators draw reactive power to produce real power output. They also tend to increase the voltage, but to a lesser extent than voltage-source generators. Tables 2.2 and 2.3 show the results of the load flow cases for various penetrations of dispersed generators.

In general, as the penetration of dispersed sources increases along a feeder both the minimum and maximum voltage points on the feeder increase. This happens irrespective of the generator type, i.e., voltage sources or voltage dependent. For low penetrations, 5 and 20 percent, the increased voltage profile does not exceed the utility's maximum voltage criteria. However, higher penetrations cause the maximum voltage criteria to be exceeded.

In all cases examined the dispersed generators narrowed the range between the feeder's minimum and maximum voltage points. This is caused by the high resistance characteristics of the distribution feeder;

TABLE 2.2

DISPERSED SOURCES: INDUCTION GENERATOR, LINE-COMMUTATED INVERTER

# BUS	BASE-CASE SECONDARY VOLTAGE MAGNITUDE	5% PENETRATION SECONDARY VOLTAGE MAGNITUDE	20% PENETRATION SECONDARY VOLTAGE MAGNITUDE	50% PENETRATION SECONDARY VOLTAGE MAGNITUDE
SUB	1.000	1.000	1.000	1.000
381	1.000	1.000	1.000	1.000
382	.996	.996	.996	.996
383	.984	.984	.986	.983
384	.972	.973	.976	.972
385	.968	.970	.972	.968
386	.968	.969	.972	.967
388	.965	.966	.969	.964
389	.960	.962	.965	.960
390	.958	.960	.963	.958
392	.956	.958	.962	.957
393	.954	.956	.960	.956
394	.951	.953	.958	.954
395	.950	.953	.958	.954
398	.949	.952	.958	.953
499	.947	.950	.956	.951
484	.943	.946	.952	.946
436	.935	.937	.943	.935
437	.929	.932	.938	.929
438	.927	.929	.935	.926
439	.924	.926	.932	.922
447	.922	.925	.931	.921
448	.919	.922	.928	.917
495	.919	.922	.928	.917
449	.918	.921	.927	.917
400	.950	.954	.960	.958
401	.951	.954	.962	.963
402	.952	.955	.964	.966
493	.952	.956	.965	.968
403	.956	.961	.974	.986
498	.959	.966	.982	1.001
404	.958	.966	.984	1.007
405	.956	.966	.990	1.023
406	.954	.967	.999	1.046
407	.954	.969	1.006	1.063
408	.952	.970	1.014	1.082
409	.951	.971	1.023	1.106
410	.950	.974	1.036	1.135
425	.955	.970	1.006	1.062
426	.955	.970	1.005	1.061
428	.954	.967	.998	1.045
429	.958	.966	.984	1.006
488	.959	.966	.982	1.001
430	.945	.949	.957	.960
431	.939	.943	.951	.953
432		.939	.947	.950
434		.954	.960	.958
497		.954	.960	.958

TABLE 2.3
DISPERSED SOURCES: SYNCHRONOUS GENERATOR OR
FORCED-COMMUTATED INVERTER-OPERATING
1 p.u. POWER FACTOR

# BUS	BASE-CASE SECONDARY VOLTAGE MAGNITUDE	5% PENETRATION SECONDARY VOLTAGE MAGNITUDE	20% PENETRATION SECONDARY VOLTAGE MAGNITUDE	50% PENETRATION SECONDARY VOLTAGE MAGNITUDE
SUB	1.000	1.000	1.000	1.000
381	1.000	1.000	1.000	1.000
382	.996	.996	.997	.997
383	.984	.985	.986	.988
384	.972	.974	.977	.980
385	.968	.970	.974	.977
386	.968	.970	.973	.976
388	.965	.967	.970	.974
389	.960	.962	.967	.970
390	.958	.961	.965	.969
392	.956	.959	.964	.969
393	.954	.957	.963	.968
394	.951	.955	.961	.968
395	.950	.954	.961	.968
398	.949	.953	.961	.968
499	.947	.951	.959	.966
484	.943	.947	.955	.962
436	.935	.939	.947	.954
437	.929	.934	.942	.949
438	.927	.931	.939	.946
439	.924	.928	.936	.944
447	.922	.927	.935	.942
448	.919	.923	.931	.939
495	.919	.923	.931	.939
449	.918	.923	.931	.939
400	.950	.955	.964	.973
401	.951	.956	.967	.979
402	.952	.958	.969	.983
493	.952	.958	.971	.985
403	.956	.964	.982	1.003
498	.959	.969	.991	1.019
404	.958	.969	.993	1.025
405	.956	.970	1.002	1.047
406	.954	.972	1.015	1.077
407	.954	.975	1.025	1.099
408	.952	.977	1.035	1.125
409	.951	.979	1.049	1.156
410	.950	.984	1.066	1.195
425	.955	.976	1.023	1.094
426	.955	.975	1.023	1.093
428	.954	.972	1.014	1.076
429	.958	.969	.993	1.025
488	.959	.969	.991	1.019
430	.945	.951	.963	.976
431	.939	.941	.957	.969
432		.941	.953	.966
434		.956	.964	.973
497		.956	.964	.973

as load is reduced by the output of the dispersed generators the real current is reduced which significantly increases the voltage. The effect is seen clearly when comparing the synchronous generator and the induction generator cases. Even though the induction generator increases the reactive current there is very little difference between the voltage profiles for the two cases.

Voltage regulation equipment used by utilities is deployed to maintain a reasonable voltage swing. Regulation equipment is located and adjusted to account for load variations that occur. Dispersed generators affect the voltage by increasing the voltage profile, but they influence the voltage only when they are operating. At low penetrations, 5 and 20 percent the voltage swing is not significantly affected. The minimum voltage during load variations occurs during the peak load condition without the dispersed generators operating. With the dispersed generators producing power the minimum voltage is increased, but not significantly. The maximum voltage will probably occur during the lightest load condition with the dispersed generators producing power. With low penetrations, 5 and 20 percent, the maximum voltage will probably not exceed the utility's maximum voltage criteria.

High penetrations of dispersed generators increase the maximum voltage over the utility's maximum voltage criteria for peak load conditions and can be expected to further increase the voltage during light load conditions. Feeder voltage swing under these conditions will be extreme and will likely exceed the voltage regulating equipments' ability to regulate the voltage.

Regulating voltage with dispersed generators will be more difficult as the penetration of dispersed generators increase on a given feeder. The particular feeder examined in this study used a combination of fixed and switch capacitors and line voltage boosters. Boosters are designed to raise the voltage by a fixed amount over a zero setting.

Dispersed generators, in low penetrations, will probably not significantly affect the operation of boosters already in place and adjusted for load conditions. Depending on the reliability and control of the dispersed generator's power output the utility might be able to remove a booster.

Regulating voltage on a feeder will be more difficult with dispersed wind-turbine generators than with photovoltaic systems. Wind-turbine generators produce power when the wind speed is high enough to spin the rotor. Although their output is not completely random, wind and seasonal patterns are not sufficiently reliable to adjust voltage regulation equipment and account for the various combinations of power output and load.

Photovoltaic systems produce power within a given time interval, although this time interval moves with the seasons. Unlike wind-turbine generators, photovoltaic systems will not produce power in the middle of the night. Their power output is more reliable and tends to follow load build-up, especially during the morning load increase.

Capacitor compensation requirements for dispersed generators depend on the generator type and penetration. Voltage-source generators i.e., synchronous generator and forced-commutated inverter systems, produce their own reactive power and will not significantly change line losses, as the penetration increases they reduce line losses because less current is drawn due to the reduced load. Voltage-dependent generators, i.e., line-commutated inverter and induction generators require reactive power to produce real power output, and depending on their penetration and operating power factor they will increase the line losses.

For the cases examined there was insignificant increases in the line losses with the voltage-dependent sources operating over a power factor range of 40 to 80 percent. With a 50 percent penetration of these sources the line losses were increased less than 15 percent.

Although the line losses were not increased significantly with a large penetration of voltage-dependent sources distributed along the feeder, the substations power factor was significantly lower with the dispersed sources than without. Typically utilities would use the lower power factor as an indication of increased line losses. The results of this study suggest that additional capacitor compensation is not required to reduce losses because the line losses are not increased significantly, even with a large penetration.

2-42

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3. MODELING OF PHOTOVOLTAIC AND WIND ENERGY CONVERSION SYSTEMS

3.1 WIND ENERGY CONVERSION SYSTEMS (WECS)

3.1.1 WECS Characteristics

The amount of power available in a freely flowing wind stream of cross-sectional Area A is equal to this area times the speed of the wind stream V, times the kinetic energy of a volume of the wind stream. That is,

Power = (volumetric flow rate) x (kinetic energy per unit volume)

$$P_w = (AV) \frac{\rho V^2}{2}$$

where ρ = air density.

Not all the kinetic energy can be extracted from the moving air stream by a wind energy conversion system. For example, Figure 3-1 compares the theoretical maximum power available in a moving air stream with the actual power output of the pitch-controlled NASA 100 kW Plumbrook unit [14].

Figure 3-1 also illustrates four parameters which are often used in describing the performance of pitch-controlled wind energy conversion systems. These parameters are defined below:

V_i - Cut-in wind speed (lowest wind speed at which power is generated)

V_r - Rated wind speed (wind speed of which rated power is generated)

V_0 - Cut-out wind speed (wind speed of which the WECS must be shut down)

P_r - Rated power (power generated at rated wind speed)

Section 3.1.2 describes various models which can be used to estimate the power output of a WECS as a function of wind speed using the parameters defined above.

FIGURE 3-1 THEORETICAL POWER AVAILABLE IN A WIND STREAM AND ACTUAL POWER OUTPUT FOR THE NASA 100 kW PLUMBROOK WECS

3.1.2 WECS Performance Models

The power output of pitch-controlled WECS can be modeled in terms of cut-in speed V_i , rated speed V_r , and cut-out speed V_0 . These three parameters are used to determine a model which gives a simple calculation of the power output at any given wind speed. For example, for wind speeds less than V_i , no power is generated by the machine; for wind speeds greater than V_r , and less than V_0 , the output of the WECS is limited to the rated power. For wind speeds between V_i and V_r , many modeling techniques can be used to estimate the power output. A straight line or linear interpolation between V_i and V_r can be used, as was done in early wind power applications studies [15]. Another technique is a quadratic approximation to determine the output between V_i and V_r . This approach allows greater accuracy than the straight line approximation, since actual tests show that the machine power output is not linear to the wind speed.

Analytically, the quadratic power output function $P(V)$ is given by:

$$P(V) = \begin{cases} 0 & V \leq V_i \\ A + BV + CV^2 & V_i < V \leq V_r \\ P_r & V_r < V \leq V_0 \\ 0 & V > V_0 \end{cases}$$

where V is the hub height wind speed, P_r the rated power, and A , B , and C are coefficients determined by:

$$A + BV_i + CV_i^2 = 0$$

$$A + BV_r + CV_r^2 = P_r$$

$$A + BV_c + CV_c^2 = P_r \frac{V_c}{V_r}^3$$

where $V_c = \frac{V_i + V_r}{2}$. The first two equations can be obtained from boundary conditions. The last equation is an approximation based on the fact that the power output is proportional to the cube of the wind speed. These three simultaneous linear equations can be solved for constants A, B, and C which define the quadratic model.

A cubic model for the power output as a function of wind speed can also be used.

$$P(V) = \begin{cases} 0 & V \leq V_i \\ A + BV + CV^2 + DV^3 & V_i < V \leq V_r \\ P_r & V_r < V \leq V_0 \\ 0 & V > V_0 \end{cases}$$

where

V_i = cut-in wind speed

V_0 = cut-out wind speed

V_r = rated wind speed

P_r = rated power

The constants, A, B, C, and D, used in the cubic approximation over the interval $V_i < V < V_r$ are determined from the following boundary conditions:

$$P(V_i) = 0$$

$$P(V_r) = P_r$$

$$P(V') = P_r \left(\frac{V'}{V_r} \right)^3$$

$$P(V'') = P_r \left(\frac{V''}{V_r} \right)^3$$

where

$$V' = 1/3 (2V_i + V_r)$$

$$V'' = 1/3 (V_i + 2V_r)$$

Preliminary results obtained using the cubic approximation show a slightly improved accuracy over the quadratic approximation at low wind speeds which are just above cut-in. The cubic model was selected for use in this project.

3.1.3 Data Requirements

The input data required by the cubic wind model described in the previous section are wind speed measurements taken at the hub height of the WECS at regular intervals of time. The wind speed data obtained from Battelle Northwest Laboratories for the Ludington, Michigan and Riverside, California sites to be studied in this project were taken at hourly intervals over a one-year period from May, 1977 to April, 1978. The measurements were taken of two anemometer heights: 18.7 m and 45.7 m at Ludington; and 9.1 m and 45.7 m at Riverside. Wind speeds were adjusted to the hub height of the WECS using the

empirical power law relationship generally obeyed by vertical wind speed profiles [16]. This relationship can be expressed as:

$$V/V_1 = \left(Z/Z_1 \right)^P$$

where V_1 is the wind speed at anemometer height Z_1 and P is an exponent dependent on ground roughness and other meteorological factors. A median value of P commonly used is 0.167. The value of P used in the project was determined by comparing the actual wind speed at the two anemometer heights throughout the year.

The output of the wind model is the hourly electrical power output of the WECS.

3.1.4 Model Limitations

The following limitations of the wind model must be recognized:

- The model does not accurately model fixed pitch WECS which do not have a cut-out windspeed.
- Dynamic inertial behavior of the WECS is not modeled (e.g., start-up time requirements).
- Transient response is not modeled (e.g., reaction to gusting).
- Variations in power output due to wind speed measurement within the hour are not modeled.
- The cut-out wind speed is assumed to be the same for increasing and decreasing winds; actually they are usually different.

However, since the model is intended for evaluating the planning impacts, consideration of the hourly dynamics are adequate. Detailed modeling of the transient dynamics is not deemed cost effective for this research.

3.2 PHOTOVOLTAIC (PV) SYSTEMS

3.2.1 PV System Characteristics

In this section the characteristics of photovoltaic cells, concentrators, and power conditioning equipment are briefly described.

Photovoltaic cells are semiconductor devices which generate a flow of electricity in an external circuit when exposed to a source of photons with energy in excess of the intrinsic semiconductor material band gap. Many different cell materials and cell fabrication techniques are employed, resulting in a wide range of performance and cost. The theoretical efficiency for several materials is shown in Figure 3-2 as a function of band gap (band gap in electron volts is equivalent to the energy required to raise a valence electron into the conduction state) for several temperature levels. This theoretical conversion efficiency for single cells is a complex interaction of fundamental material properties, the fabrication process and the spectral content of the irradiant energy. As illustrated, the net result of this interaction is a theoretical maximum efficiency between 25 and 30% for an optimum band gap material of 1.5 eV exposed to the spectral distribution of sunlight at the earth's surface. Obtainable efficiencies vary with material and cell construction, and range from a few percent to more than half the theoretical value.

Single crystal silicon is the most highly developed and commercially available material for photovoltaic conversion at this time. It has the advantages of high conversion efficiency, approximately 12% with experimental cell efficiencies in excess of 16%, long life expectancy, and the raw material is abundant. Its basic disadvantage is high fabrication cost. Significant effort is being expended to reduce costs by the development of automated fabrication techniques. Cost reduction to \$2000/peak kW by 1982 and \$500/peak kW by 1986 in 1975 dollars are major goals of the DOE Photovoltaic Conversion Program for non-concentrating photovoltaic arrays [17].

ORNL-DWG 80-6206 ETD

FIGURE 3-2 MAXIMUM THEORETICAL EFFICIENCY OF PHOTOVOLTAIC SYSTEMS
AS A FUNCTION OF BAND GAP ENERGY

Source: Joseph A. Merrigan, Sunlight to Electricity,
MIT Press, Cambridge, Massachusetts, 1975.

Cadmium sulfide/copper sulfide cells have received considerable research attention because of relatively inexpensive techniques for preparing the cells and because of high absorptance of sunlight in copper sulfide, which allows the use of thin material films. The main disadvantages of the cadmium sulfide/copper sulfide cell are its low conversion efficiency of about 6 percent and limited life expectancy. The best experimentally-demonstrated efficiency for thin film cells is about 8 percent. The limited life appears to be caused by chemical reactions with contaminants, including moisture, phase changes in the copper sulfide, and the migration of copper ions.

Gallium arsenide, GaAs, has also received a good deal of experimental attention since it has a number of theoretical advantages. GaAs has extremely high conversion efficiency; its band gap is near the theoretically optimum value for semiconductor material responding to the solar spectral energy distribution. GaAs cells can be fabricated in thin films. They have low equivalent electrical resistance in the junction region, and the ability to operate efficiently at elevated temperature. This combination of advantages results in GaAs having higher performance than single crystal silicon, and making GaAs attractive for high concentration applications.

Other semiconductor materials under research and development for photovoltaic applications include cadmium-telluride CdTe, polycrystalline silicon, and compound cells using frequency splitters to utilize more of the incident spectral energy.

PV systems can contain either flat-plate, non-concentrating designs or various forms of concentrating collectors. In those systems without concentration, the largest cost item is the PV cell material. The use of optical concentration reduces cell cost at the expense of increased collector cost. Concentration ratios of over 1000 are theoretically possible. However, at high concentration levels, the efficiency of the cells is reduced, cooling equipment is required, and more complex tracking systems are necessary, thus resulting in increased costs.

3.2.2 PV System Performance Model

Sandia Laboratories has developed a state-of-the-art, fully comprehensive photovoltaic-system performance model called "SOLCEL-II" [18,19]. Similar, though less comprehensive models have also been developed by General Electric Company [20] and Systems Control, Inc. After several trial computer runs using all of these models, Sandia's SOLCEL-II model was selected for use in the project for the following reasons:

- The tracking and collector subroutines have options to model all tracking and concentrating modes of operation. Both the GE and the SCI models have limited capabilities in this area.
- The SOLCEL-II model includes optimization subroutines for optimizing storage capacity, array size, tilt angle, and other system parameters. No optimization is possible in the GE and SCI models.
- The photovoltaic conversion subroutine used in SOLCEL-II uses semiconductor current-voltage curves to model the electrical output of the cells. The GE and SCI models use a simpler approach based on a reference cell efficiency at 28°C and a temperature coefficient which lowers cell efficiencies for temperatures above 28°C.

(For more complete information on Sandia's SOLCEL-II model, refer to reference [18], or contact Mr. Ed Hoover of Sandia Laboratories at (505) 264-7315).

3.2.3 Data Requirements

Hourly meteorological data including both total horizontal and direct normal insolation, ambient temperature, and wind speed measurements are required by the SOLCEL-II model. The hourly electrical demand of the user must also be specified. The principal outputs of the model are shown in Table 3.1 which is a sample of the actual computer printout for a one-day simulation of a photovoltaic system sited at Albuquerque, New Mexico.

3.2.4 Model Limitations

The following limitations of the photovoltaic-performance model must be recognized:

- (i) Transient response of the system is not modeled, (e.g., response to a cloud passing over).
- (ii) System output within each hour is not modeled, but is assumed constant.
- (iii) Inter-array shading effects are not modeled accurately within the SOLCEL-II model. However, these effects were studied and are discussed in Section 4.2.
- (iv) The results of the SOLCEL-II model have not been compared with experimental results to verify the accuracy of the model.

3.3 STATISTICS SUMMARY MODEL

3.3.1 Functions of Statistics Model

The Statistics Summary Model processes the hourly power outputs from the solar PV and WECS models and then computes the hourly histograms of means and variances of these hourly outputs for each month. Using these means and variances, the model constructs month-averaged and year-averaged hourly output curves. These curves give mean outputs as well as mean outputs plus or minus one standard deviation.

TABLE 3.1 EXAMPLE OF SOLCEL-II OUTPUT

PHOTOVOLTAIC SYSTEM MODEL PERFORMANCE MONITORING												
DAY NUMBER: 1			LOAD DATA									
SOLAR DATA			DAY: 346									
DAY: 349			DATE: 7-12-14									
DATE: 621214			COMMENTS:									
COMMENTS:												
TIME	WIND SPEED	AMOUNT	CELL TEMP	TOTAL INCLATION	COLLECTOR POWER	CHARGE BATTERIES	BATTERY POWER	BAT SOC	COOLING POWER	TRACKING POWER	LOAD DEMAND	UTILITY POWER
0.00	0.0	272.0	272.00.		0.	-8593.	8599.	.170.	0.		8190.	0.
1.00	1.5	272.0	272.00.		0.	-7630.	7630.	.120.	0.		7320.	0.
2.00	3.0	272.0	272.00.		0.	-9355.	9355.	.070.	0.		8420.	0.
3.00	3.0	272.0	272.00.		0.	-.10+3E+050.		.070.	0.		9620.	3609.
4.00	0.0	272.0	272.00.		0.	-77+3.	0.	.070.	0.		7130.	7431.
5.00	2.0	271.0	271.00.		0.	-9232.	0.	.070.	0.		8720.	8735.
6.00	0.0	270.0	270.00.		0.	-8+46.	0.	.070.	0.		8+00.	8414.
7.00	3.0	263.0	260.00.		0.	-8965.	0.	.070.	0.		8500.	8514.
8.00	3.0	270.0	304.8	292.3	12.56	-7752.	0.	.07	.5918E-05	35.31	7360.	7435.
9.00	0.0	273.0	371.0	.1550E+00	.1334E+05	4503.	0.	.09	415.6	85.31	7940.	0.
10.00	1.5	277.0	355.9	.1963E+06	.1569E+05	6734.	0.	.12	815.6	85.31	7510.	0.
11.00	1.5	275.0	354.9	.2257E+05	.2353E+05	.1170E+050.		.18	1215.	85.31	7030.	0.
12.00	1.5	281.0	364.5	.22650E+05	.2062E+05	.1177E+050.		.24	1200.	85.31	7090.	0.
13.00	1.0	283.0	366.3	.2234E+05	.2022E+05	.1302E+050.		.30	1180.	85.31	5650.	0.
14.00	1.0	284.0	363.0	.2292E+05	.2095E+05	.1293E+050.		.36	1204.	85.31	6290.	0.
15.00	1.5	285.0	365.7	.1967E+06	.1566E+05	5117.	0.	.38	808.2	85.31	8130.	0.
16.00	1.5	285.0	372.5	.1562E+06	.1341E+05	3522.	0.	.40	424.6	85.31	8730.	0.
17.00	1.0	282.0	364.0	350.7	15.08	-6074.	6674.	.37	.1164E-04	85.31	6130.	0.
18.00	0.0	291.0	241.00.		0.	-9140.	9146.	.320.	0.		8650.	0.
19.00	0.0	277.0	277.00.		0.	-8022.	8122.	.230.	0.		8180.	0.
20.00	1.0	274.0	274.00.		0.	-.1072E+05	.1092E+05	.220.	0.		9990.	0.
21.00	3.6	276.0	276.00.		0.	-9492.	9492.	.170.	0.		8910.	0.
22.00	0.0	276.0	276.00.		0.	-9293.	9293.	.130.	0.		8770.	0.
23.00	2.0	275.0	275.00.		0.	-8740.	8740.	.080.	0.		8310.	0.

The model then provides hourly variation and percent variations of month-averaged mean. They are summarized as follows:

- Month- and year-averaged hourly power-generation profile
- Hourly excursions ($\pm 1\sigma$) from the mean and the variance of power output for different months and the year
- Hourly variation and its percentage of month-averaged mean.

These statistics will be used to estimate the long-term variation of solar and wind resources and to develop the DSW strategies.

3.3.2 Inputs/Outputs of the Model

Basically, the inputs are the hourly power outputs from the solar PV model (SOLCEL II) and from the WECS model. The power outputs could be of a year's or even longer duration.

The outputs of the Statistics Summary Model have been alluded to in Section 3.3.1. They consist of the daily mean generation profiles and the associated excursions from the mean. Examples of such outputs are shown in Appendix B.

3-14

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4. DSW CASE STUDIES

The DSW assessment models described in Chapters 2 and 3 were used to study the impact of DSW devices on portions of the distribution system of two U.S. utilities. The utilities studied are the same as those studied in the previous DSG study. Southern California Edison is a summer-peaking utility with a thermally-limited distribution system in an urban area. Consumers Power Company is a winter-peaking utility with a voltage-limited system in a rural area. Section 4.1 gives a brief description of the utilities involved in this study. A detailed description is given in the previous DSG study. Section 4.2 describes the meteorological data used in the study, Section 4.3 describes the DSW equipment specifications, Section 4.4 summarizes the performance statistics of the DSW devices, and Section 4.5 describes the DSW case studies.

4.1 UTILITY DESCRIPTIONS

4.1.1 Southern California Edison (SCE) - A Summer-Peaking Utility

Southern California Edison is a large utility in the southwestern part of the United States, providing service to a population of 7.7 million people residing in an area over 50,000 square miles in size. The utility owns and operates generation, transmission, and distribution facilities. Energy consumption in 1975 was 26% residential, 32% commercial, and 36% industrial; 16.4% of the residential customers have central air conditioning.

In 1975 the system peak demand of 10,193 MW occurred during September. Southern California Edison is a summer-peaking utility whose peak load grew at an average annual rate of 4.6% from 1975 to 1979, as shown in Figure 4-1. The seasonal variation of the monthly peak load in 1975 is illustrated in Figure 4-2. Figure 4-3 shows the peak day load curve for Southern California Edison. Based on this figure, the peak

FIGURE 4-1 YEARLY SYSTEM PEAK DEMAND

FIGURE 4-2 MONTHLY PEAK DEMAND

FIGURE 4-3 PEAK DAY DEMAND CURVE - SOUTHERN CALIFORNIA EDISON

day load factor is 75.8%. This is substantially higher than the 60.3% annual load factor experienced by the utility over the year. Figure 4-3 also shows that the system peak daily load occurs during the hot afternoon hours between 1 pm and 5 pm.

Southern California Edison had a total generating capability of 12,468 MW in 1975 and 1976. Table 4.1 shows the generation mix. Oil-fired generation provided 59% of the energy. An additional 17% came from coal-fired units, 17% from gas-fired units, and 6% from nuclear units.

Average prices for fuel consumed in 1975 is tabulated in Table 4.2. The cost of light distillate is lower than that of residual fuel, due to prior distillate contracts.

The above generation system data, together with individual plant heat rates, average rates, and maintenance requirements, are used in computing the Production Cost Component described in Section 2.2.4.

The incremental generating capacity cost, which represents the cost of acquiring generating capacity during system peak period, is taken to be \$100/kW with an associated annual carrying charge of 14.0%. These data, together with the system peak period load data, are used to compute the Replacement Capacity Cost Component described in Section 2.2.5.

The loss allowance factor for the transmission and subtransmission systems, defined in Section 4.4, averages 3.4% of the energy generated. The distribution system accounted for 3.6%, of which the distribution planning models show approximately 2% is lost in the primary system and 1.6% in the secondary distribution system.

The DSW and DSG case studies considered the conventional distribution planning of a 13 square mile area serviced by a large sub-

TABLE 4.1 SCE GENERATION MIX TABLE

SIZE (MW)	NUMBER OF UNITS	CAPACITY (MW)	PERCENT OF TOTAL CAPACITY
FOSSIL			
0-99	12 (0, 12)**	718 (0, 718)	6 (0, 6)
100-199	8 (0, 8)	1314 (0, 1314)	11 (0, 11)
200-299	6 (0, 6)	1300 (0, 1300)	10 (0, 10)
300-399	8 (2, 6)	2718 (768, 1950)	22 (6, 16)
400-499	6 (2, 4)	2805 (885, 1920)	22 (7, 15)
500+	2 (0, 2)	1500 (0, 1500)	12 (0, 12)
SUBTOTAL	42 (4, 38)	10355 (1653, 8702)	83 (13, 70)
NUCLEAR	1	344	3
HYDRO	36	1173	9
GAS TURBINE	11	555	5
TOTAL	90	12427	100

*FOR 1975. A 572 MW COMBINED CYCLE PLANT WAS INSTALLED IN 1977, DURING THE PERIOD COVERED IN THE STUDY.

**NUMBERS IN PARENTHESES (A, B) SHOW SPLIT BETWEEN COAL-FIRED (A) AND OIL-FIRED (B) UNITS. UTILITY 1 IS PREDOMINATELY OIL-FIRED.

TABLE 4.2 AVERAGE FUEL COSTS

FUEL TYPE	COST (¢/MBTU)	
	SCE	CP
COAL	29	96
RESIDUE	267	223
LIGHT DISTILLATES	197	209
NATURAL GAS	85	126
NUCLEAR	17	37

substation with a load of 58 MW in 1975 and a load density of 4.5 MW/square miles. The substation serves 15,000 customers with an 80% residential load in an urban area. This distribution area was selected because of the availability of 24-hour load data for the primary feeders and the substation.

Two substation transformers step down the supply voltage from 66 kV to 12 kV, as illustrated by the one-line diagram in Figure 4-4. Subtransmission transformers in the same substation convert the 220 kV supply to 66 kV. The primary circuits were constructed as a network with loops but have been operated radially with normally-open ties to adjacent primary circuits. Load growth averaged seven percent a year from 1975 to 1976 and was expected to diminish to five percent after 1977. The substation peak load occurs in the summer as does the total system peak. Conventional distribution system planning was primarily concerned with thermal overloading of transformers and getaways, the first circuit sections leaving the substation. The getaways have been gradually converted from overhead conductors (653 ASCR) to underground cables (1000 KCMIL-CLP) since 1972 because of local ordinances, cutting their thermal capacity in half.

The distribution planners used single-contingency criteria to identify the reinforcements for substation transformers and getaway circuits; thermal loading limits must not be exceeded during normal and outage conditions for the largest transformer or on any getaway circuit. Typical normal and emergency thermal limits are illustrated in Table 4.3. The emergency thermal limit of an underground cable is usually higher than that of normal operation. Voltage is allowed to vary between 11.4 kV and 12.0 kV. During emergencies the minimum voltage allowed is 11.7 kV.

The SCI distribution planning model ACORN (Automatic Computation of Radial Networks) [9] was used to verify that voltage and current

4-9

FIGURE 4-4 ONE-LINE DIAGRAM OF SUBSTATION - SOUTHERN CALIFORNIA EDISON

TABLE 4.3 TYPICAL DISTRIBUTION EQUIPMENT THERMAL LIMITS

DISTRIBUTION EQUIPMENT	NORMAL CRITERIA	EMERGENCY CRITERIA
SUBSTATION TRANSFORMER (MVA)	14	20
PRIMARY CIRCUITS (AMPERES)		
336 ACSR	530	590
653 ACSR	820	920
1000 MCM CLP	450	450
500 PILC COPPER	278	278

limits were relieved by the proposed reinforcement plans. The three-phase primary distribution circuits were represented with 115 nodes and 165 branches, with more detailed representation of loads in the six residential feeders. Figure 4-5 shows the distribution system represented. The commercial and industrial feeders are not connected with the residential feeders except at the substation switchgear, and no reinforcements of these non-residential feeders were anticipated for the coming years. With the assistance of the area planning and operating distribution engineers, peak loads and the customer mix at the nodes representing 50 to 150 customers were estimated. The resulting substation load constructed from the diversified customer loads approximated the actual substation load.

The results from the ACORN model showed that the reinforcement plans did satisfy the planning criteria and that they were the least cost alternative.

4.1.2 Consumers Power Company (CP) - A Winter-Peaking Utility

Consumers Power Company provides electric service to 3.3 million people residing in the eastern part of the United States in an area over 28,000 square miles in size. The utility owns and operates generation, transmission, and distribution facilities. Of the total energy sales to ultimate customers in 1975, 32% were residential, 23% commercial, and 45% industrial. In 1975, 3.6% of the residential customers had electric space heating. Total system peak demand in 1975 was 4,204 MW occurring during December. The peak load grew at an average annual rate of 4.5% from 1975 to 1979. (See Figure 4-1.) Figure 4-2 shows the seasonal variation of the monthly peak load in 1975. The annual load factor is 66.5%. Peaks occurred from 8 am to 10:30 am and 5 pm to 8 pm.

Consumers Power Company had a total generating capability of 5,742 MW in 1975 and 1976. Of the total energy generated in 1975, 67% was generated from coal-fired units, 15% from oil-fired units, and 13% from nuclear units. Table 4.4 shows the generation mix for 1975.

FIGURE 4-5 PRIMARY DISTRIBUTION SYSTEM - SOUTHERN CALIFORNIA EDISON

TABLE 4.4 GENERATION MIX - CONSUMERS POWER COMPANY*

SIZE (MW)	NO. OF UNITS	CAPACITY (MW)	% OF TOTAL CAPACITY
FOSSIL			
0- 99	20 (3, 17)**	815 (198, 617)	15 (4, 11)
100-199	7 (7, 0)	949 (949, 0)	17 (17, 0)
200-299	3 (3, 0)	795 (795, 0)	14 (14, 0)
300-399	1 (1, 0)	385 (385, 0)	7 (7, 0)
400-499	0 (0, 0)	0 (0, 0)	0 (0, 0)
500-	1 (0, 1)	605 (0, 605)	11 (0, 11)
SUBTOTAL	32(14, 18)	3549(2327,1222)	64 (42, 22)
NUCLEAR	2	887	16
GAS TURBINE	13	320	.6
HYDRO	13	131	2
PUMPED STORAGE	6	636	12
TOTAL	66	5523	100

*FOR 1975. A 663 MW OF OIL-FIRED GENERATION WAS ADDED IN 1977 DURING THE TIME INTERVAL STUDIED.

**NUMBERS IN PARENTHESES (A, B) SHOW SPLIT BETWEEN COAL-FIRED (A) AND OIL-FIRED (B) UNITS. SOUTHERN CALIFORNIA EDISON IS PREDOMINATELY COAL-FIRED.

Average prices of fuel consumed in 1975 range from 96¢/MBTU for coal, 23¢/MBTU for residue fuel oil, to 37¢/MBTU for nuclear fuel (see Table 4.2). Due to prior contractual arrangement, the average price of light distillate is less than that of residue fuel. The above supply system data are used in computing the Production Cost and Capacity Cost Components described in Sections 2.2.4 and 2.2.5.

The losses for the rural Consumers Power region were higher than for the urban Southern California Edison region. The losses were 6.7% for the transmission and subtransmission systems. The distribution system losses amounted to another 3.9%.

The distribution system selected for both DSG and DSW case studies is serviced by four substations with a total load of 14 MW in 1975. Rural in nature, this distribution system covers an area of 350 square miles. The system serves 3,500 customers with mostly (71%) residential loads and other loads for recreation (including a large ski resort), schools, and small manufacturers. This distribution area was chosen because of its history of expansion since 1975. Furthermore the 13 kV primary distribution system is the same voltage level as that of Southern California Edison.

The four distribution substations are connected by a 46 kV radial subtransmission system as shown in Figure 4-6. The three-phase primary circuits within each substation area are radial with no switching capability to transfer load to other feeders in case of equipment outage. Portions of the primary system are 4 kV while some are single-phased. The subtransmission lines are mostly aluminum (No. 2 ACSR) and copper (No. 2) overhead with the primary distribution lines up of smaller copper lines.

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FIGURE 4-6 ONE-LINE DIAGRAM OF SUBTRANSMISSION
SYSTEM - CONSUMERS POWER COMPANY

The load characteristics of each substation in 1975 are shown in Table 4.5. After 1975 the peak load at the substations grew at an average annual rate of 7% - 9% except for substation 3 which had a smaller average growth rate of 4.2%. All substation loads are winter-peaking, except substation 3. The loads in substation 3 peaked in summer, reflecting the summer resort character of the area. Table 4.5 also shows the mix of customers in the area serviced by each substation based on estimates by the area distribution engineers. Load shapes of the total system load of each substation are illustrated in Figure 4-7.

The main thrust of conventional distribution planning is to maintain voltages within proper ranges for the subtransmission and primary system in view of the low load density and long radial circuits. For the 46 kV nominal voltage transmission system, the planning criteria requires that voltages be kept within 92% to 105% of nominal voltage. For the primary system, the nominal voltage is 12.5 kV, and minimum and maximum voltages are 97% and 105%. Other criteria considered in planning include short circuit duty and thermal loading capacity for this area, but these criteria usually were secondary reasons for reinforcement. Subtransmission lines were loaded only up to 40% of maximum capacity, and distribution lines rarely reached 30% of maximum capacity. Violation of the voltage criteria during the normal operation was the overriding concern of the area distribution planners.

Distribution system expansion since 1975 included a two-year project to replace a 33-mile (No. 4 ACSR) section of a primary feeder from substation 1 by higher capacity, lower impedance (336 ACSR) lines. The intent was to improve the voltage regulation of the primary feeders, and the total cost was \$50,000. For the radial subtransmission system a new line (336 ACSR) was constructed in 1976 to relieve voltage criteria violations at substation 2 and substation 4 (see Figure 4-6). The second project cost was \$714,000.

TABLE 4.5 PEAK-LOAD COMPOSITION - CONSUMERS POWER COMPANY

SUBSTATION NUMBER	PEAK DEMAND (KW)	AVG. ANNUAL GROWTH RATE (%)	CUSTOMER TYPE (%)				
			RESIDENTIAL TYPE				COMMERCIAL AND INDUSTRIAL
			1	2	3	4	
1	3939	8.9	9	27	6	5	53
2	3628	8.7	6	45	6	18	25
3	2858	4.2	4	50	19	10	17
4	3132	7.7	8	46	15	10	21

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FIGURE 4-7 BULK SUPPLY AND DISTRIBUTION LOAD
SHAPES - CONSIMERS POWER COMPANY

Two Systems Control, Inc. distribution planning models, ACORN [9] and a model developed by R. Podmore [21], were used to verify the improvements made by the proposed expansion plans given the load conditions. The primary system modeled by ACORN has 185 branches. The results verified that the planning criteria are met, and that the project undertaken was the least expensive. The results also indicated no further violations of the voltage criteria on the primary system before 1981. The subtransmission system was represented as a radial network with nine branches by the second model, which has a more detailed load flow subprogram. The relief provided by the proposed subtransmission expansion plan was verified.

4.2 METEOROLOGICAL DATA

This section describes the wind speed and solar radiation resource data collected for the project.

4.2.1 Meteorological Data Requirement

For the summer-peaking, urban, distribution network of Southern California Edison, both photovoltaic (PV) and wind energy conversion systems (WECS) were studied. For the winter-peaking, rural network of Consumers Power Company, only the WECS were analyzed. The following meteorological data were needed to model these dispersed solar and wind technologies:

- a) A minimum of one year of hourly measurements of the following meteorological variables for a site within the service area of Southern California Edison.
 - Total insolation incident on a horizontal surface
 - Direct insolation incident on a horizontal surface
 - Dry bulb temperature
 - Wind speed

Additional data for several nearby sites would also be required to analyze the spatial diversity of the solar and wind resources.

- b) A minimum of one year of hourly wind speed measurements for a promising wind energy conversion system site within the service area of Consumers Power Company. Additional wind speed data for several nearby sites would also be required to analyze the spatial diversity of the wind resource.
- c) Long-term statistics on the insolation and wind speed measurements for both utility territories to determine the long-term variation of solar and wind resources.

4.2.2 Data Acquisition

The following solar and wind data were obtained to meet the resource data requirements of the project:

- a) Ten years (1/1/65 - 12/31/74) of hourly wind measurements for Walnut, California were obtained from the South Coast Air Quality Management District (SCAQMD). The data for 1974 would be used. Data for Pomona and Azusa, both approximately twelve miles from Walnut, were obtained in addition to the Walnut data to conduct wind correlation studies at a later date if desired. The hourly wind speed measurements were average integrated values.
- b) One year (5/1977 - 4/19/78) of hourly wind speed measurements for Riverside, California and Ludington, Michigan have been obtained from Battelle Northwest Labs. Riverside and Ludington are two of seventeen candidate sites with excellent wind energy potential where DOE plans to field-test the WECS. Battelle Northwest Labs has been collecting data for these sites over the last several years. The Ludington site data was selected for use in the project after a search for other hourly wind speed data closer to the Leelanau County failed. Previous studies [22] have shown that the Ludington data were typical of the coastal area of Michigan between Muskegon and Bit Rock Point. The Riverside wind data was selected for use in the project after a preliminary assessment of the wind power potential of a MOD-OA 200kW WECS using the Walnut data indicated an annual capacity factor of less than 5%. The annual capacity factor of a MOD-OA 200 kW WECS using the Riverside data is slightly over 30%. The Battelle wind data from Riverside and Ludington consist of fifteen-minute average wind measurements for each hour taken at heights of 18.7 and 45.2 meters.

- c) Two years (1976 and 1977) of total solar radiation and ambient air temperature measurements for Walnut and twelve other California locations have been obtained from the West Associates Solar Resource Evaluation Project (WASREP). Data for the additional twelve sites, listed in Table 4.6 were obtained at no additional charge for future solar correlation studies if desired. The WASREP data included information on total insolation in watts/square meter, and temperature in °F for fifteen-minute intervals throughout the year.
- d) A statistical analysis of wind speed measurements taken at Riverside and Ludington over a twenty-year period have been obtained from Battelle Northwest Laboratory. The statistics included mean wind speeds for each month, averaged over the twenty-year period.
- e) No long-term statistics on the solar radiation for Walnut, California were available. However, a statistical analysis of the insolation data over a twenty-three year period for Santa Maria, California has been obtained [23]. Santa Maria is approximately 150 miles from Walnut. The statistics included the mean, median, and standard deviation of the daily total solar radiation for each month of the year, averaged over the twenty-three year period.

All these data bases were stored on magnetic tapes. They are readily accessible through the software of the UNIVAC 1108 system.

4.2.3 Data Analysis

Some of the acquired data were processed to make them compatible with the input data requirements of the models. It was also necessary to ensure that the selected data base was representative of the long-term statistics.

Data analysis was conducted to ensure compatibility of the WASREP solar insolation data for Walnut with the photovoltaic system performance models. Although direct insolation measurements were included in addition to total insolation measurements for many of the WASREP stations, this data base was missing for the Walnut station. Since both direct and total insolation measurements were required to accurately model the performance of photovoltaic systems, the Liu-Jordan method was used to split the total insolation into direct and diffuse components.

TABLE 4.6 WEST ASSOCIATES SOLAR RESOURCES MONITORING STATIONS

Walnut, California	Barstow, California
Total Insolation	Total Insolation
Dry Bulb Temp.	Direct Insolation
	Dry Bulb Temp.
Huntington Beach, California	Eldorado, California
Total Insolation	Total Insolation
Dry Bulb Temp.	Dry Bulb Temp.
Lancaster, California	Victorville, California
Total Insolation	Total Insolation
Direct Insolation	Direct Insolation
Dry Bulb Temp.	Dry Bulb Temp.
Mandalay, California	Yucca Valley, California
Dry Bulb Temp.	Total Insolation
Total Insolation	Direct Insolation
	Dry Bulb Temp.
El Segundo, California	Ridgecrest, California
Total Insolation	Total Insolation
Dry Bulb Temp.	Direct Insolation
	Dry Bulb Temp.
Pardee, California	Blythe, California
Total Insolation	Total Insolation
Dry Bulb Temp.	Direct Insolation
	Dry Bulb Temp.
Laguna Bell, California	
Dry Bulb Temp.	
Total Insolation	

Source: West Associates Solar Resource Evaluation Project, "Solar Energy Measurements at Selected Sites Throughout Southern California During 1976 by Southern California Edison," June 1977.

Assuring the representativeness of the selected data called for a comparison of the long-term statistics with the selected data. For the wind speed data of Ludington, the twenty-year statistics were compared with the monthly wind speeds for 1977/1978. Table 4.7 summarized the two sets of data, showing a close agreement between the selected year's data and the long-term statistics.

Table 4.8 compared the twenty-year monthly mean wind speeds with the selected wind data (5/1977 - 4/1978) for the Riverside site. Again, reasonably close agreement existed between the two sets of data.

Although it was relatively easy to assess the representativeness of the selected wind data, the insolation data for Walnut presented a problem since no long-term statistics for Walnut were available. However long-term statistics for a nearby location, Santa Maria, California, were found and are shown in Table 4.9.

From the table, one can see that the standard deviation of the daily total solar radiation is small compared with the mean daily total radiation for each month of the year. As a result, one can infer that the data from one year would be similar to those from another year. This observation suggests that the two-year (1976 and 1977) insolation data selected for Walnut is representative of the long-term characteristic of the solar radiation resource.

4.2.4 Assurance of Quality Data

The acquired data were checked to segregate the erroneous and missing data. Consistency tests were performed after putting the data on magnetic tapes. Any bad data points were detected and either discarded or corrected. Few bad data points existed in the data base and only a few data voids were present.

TABLE 4.7
COMPARISON OF THE MAY 1977 - APRIL 1978 MONTHLY MEAN WIND SPEEDS
WITH THE 20 YEAR AVERAGE MONTHLY WIND SPEEDS
FOR RIVERSIDE, CALIFORNIA

	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR
MAY 1977-APRIL 1978 MEAN WIND SPEEDS (M/S)	4.1	3.3	4.3	3.8	3.9	4.7	4.9	5.1	5.3	---	5.2	4.8
20 YEAR AVERAGE MONTHLY MEAN WIND SPEEDS (M/S)	4.5	4.0	3.8	3.7	3.8	4.3	4.6	4.7	5.2	5.0	5.0	5.1

SOURCE: BATTELLE NORTHWEST LABORATORIES

TABLE 4.8
COMPARISON OF THE MAY 1977 - APRIL 1978 MONTHLY MEAN WIND SPEEDS
WITH THE 20 YEAR AVERAGE MONTHLY WIND SPEEDS
FOR RIVERSIDE, CALIFORNIA

	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC	JAN	FEB	MAR	APR
MAY 1977-APRIL 1978 MEAN WIND SPEEDS (M/S)	2.4	N/A	N/A	N/A	1.5	1.2	1.2	1.2	1.5	2.0	2.0	N/A
20 YEAR AVERAGE MONTHLY MEAN WIND SPEEDS (M/S)	2.6	2.6	2.6	2.6	2.1	2.1	2.1	2.1	2.1	2.1	2.6	N/A

SOURCE: BATTELLE NORTHWEST LABORATORIES

TABLE 4.9
DAILY LONG-TERM SOLAR RADIATION STATISTICS
FOR SANTA MARIA, CALIFORNIA
(DAILY TOTAL RADIATION KJ/M²)

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
MEAN	9,815	13,021	17,842	21,801	24,294	26,654	26,588	23,980	19,533	15,492	11,047	9,160
MEDIAN	10,801	14,442	19,184	24,169	26,680	28,335	27,843	24,652	20,612	16,065	11,855	10,288
AVG. STD. DEV.	2,798	3,997	4,402	5,613	5,617	4,321	2,869	3,037	3,743	3,982	2,754	2,234

SOURCE: Irving Hall, Richard Prairie, Herbert Anderson, Eldon Boes, "Generation of Typical Meteorological Years for Twenty-Six SOLMET Stations," SAND 78-1601, August 1978.

A one-month gap was found in the 1977 Southern California Edison (SCE) solar-radiation data for Walnut, California. This gap was filled using data for the corresponding period from the 1976 data tape.

Two gaps were found in the Battelle wind data for Riverside: a three-day gap and a one-day gap. These gaps were filled by repeating the data for previous days. The three-day gap was filled by repeating the three preceding days of data; the one-day gap was filled by repeating the previous day of data.

4.3 DSW EQUIPMENT SPECIFICATIONS

This section describes the photovoltaic (PV) system and Wind Energy Conversion System (WECS) specifications selected for study in the project. System designs were selected for three applications: residential, small commercial, and industrial. Section 4.3.1 describes the photovoltaic system designs selected for each of these applications. Section 4.3.2 describes the wind energy conversion systems selected for each application. Section 4.3.3 summarizes the battery specification and costs reported in the earlier DSG study.

4.3.1 Photovoltaic System Design Parameters For Various Applications

For purposes of this study, flat-plate array photovoltaic design concepts were selected for the residential, small commercial and industrial applications. The decision to use flat-plate array system designs for these applications instead of tracking flat-plate array or concentrator systems was based on present economics and the development status of the various technologies. The value of the additional energy that can be collected using either single axis or two-axis tracking of a flat-plate array system would not be justified because of the required additional system complexity and cost. For the smaller residential

application, the selecting of a flat-plate system is augmented by space requirements. Concentrator systems require more land or roof area than flat-plate systems for comparable power levels.

Residential Application

The system parameters generated for a residential application are based on the assumption that current state-of-the-art silicon cells will be utilized. The selected photovoltaic module configuration utilizes a glass superstrate laminate. The encapsulation most commonly used on these modules is a PVB covered by a mylar or tedlar film.

The sizing of the system was based on average daily insolation for each month, and either constant or variable loads for those months. The monthly weather and load data utilized for sizing the residential photovoltaic system are presented in Tables 4.10 and 4.11. The base load for a residential application was determined based on load data for Southern California Edison. The load profile determined would be typical for a residence in the Riverside, California area, which is close to the assumed location selected for this study. The system design specifications for the residential system are shown in Table 4.12.

Small Commercial Application

The insolation data used for sizing the small commercial system is presented in Table 4.10. Load data for the small commercial system, given in average daily energy consumption for each month is presented in Table 4.11. The photovoltaic array, rated at 64.8 kW for 1 kW/m^2 insolation conditions and 28°C cell temperature, could support a continuous 11.90 kW load. The array tilt angle selected will provide maximum energy generation, while compromising somewhat on the energy production profile as compared to the load demand profile over the year. The system design specifications for the small commercial systems are also presented in Table 4.12.

TABLE 4.10

MONTHLY INSOLATION DATA AS MEASURED ON A HORIZONTAL
SURFACE AND ON 31°, 35° INCLINED PLANES, RESPECTIVELY

	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC
Horizontal	257	344	459	518	576	617	649	589	504	368	293	246
Tilted 31°	393	463	536	527	536	549	586	573	552	463	429	393
Tilted 35°	404	471	538	521	524	535	572	564	551	469	440	405

Values given are in Langley per day.

TABLE 4.11

MONTHLY LOAD DATA

	JAN	FEB	MAR	APR	MAY	JUN	JULY	AUG	SEP	OCT	NOV	DEC
Residential System	30.70	27.79	28.31	32.14	27.19	34.45	42.19	45.13	38.22	30.86	30.11	33.41
Small Commercial System	351.60	280.20	271.20	280.20	312.00	399.00	436.80	403.20	280.80	234.00	240.00	327.60

Values given are in KWH/Day average daily energy consumption for each day.

Load Data Reference: Final Report, Photovoltaic Systems
Concept Study, Spectrolab, Inc.
April 1977. Vol. II of V, Section 4.4.

TABLE 4.12

SOLAR PHOTOVOLTAIC SYSTEM DESIGN SPECIFICATIONS

	RESIDENTIAL APPLICATION	COMMERCIAL APPLICATION	INDUSTRIAL APPLICATION
Rated Power (KW)	8.64	64.80	1995.84
System Type	Flat Plate	Flat Plate	Flat Plate
Tilt Angle	35° South Tilt	31° South Tilt	31° South Tilt
Cooling	Passive Air-Cooled	Passive Air-Cooled	Passive Air-Cooled
Nominal Voltage (Volts)	120	120	480
Peak Voltage (Volts)	135	135	540
Peak Current (Amps)	64	480	3696
Subarray Size			
Slant Height (ft)	32	12	12
Length (ft)	40	40	40
Number of Subarrays	1	20	616
Field Size			
North/South (ft)	NA ^[1]	210	800
East/West (ft)	NA	220	1150
Field Packing Factor	NA	0.196	0.250
Inverter Rating (KW) [2]	15.0	96.0	2950.0
Unit Capital Cost (\$/kW)			
Most Likely Range (\$/kW) [3]	600-1400	600-1400	600-1400
Electrical Interface			
Equipment (\$/kW)			
Most Likely Range (\$/kW)	300-500	250-450	100-200
O&M Costs			
Variable (Mills/kWh) [4]			
Fixed (\$/kW-year)	-	2.3	2.3
Unit Life (years)	15-25	15-25	15-25

[1] Not applicable

[2] Both line and self-commutating inverters will be studied

[3] Solar PV capacity is given at standard operating conditions of 28°C, 1 kW/m² incident insolation, for a silicon cell efficiency of 12% and an inverter efficiency of 87%.

[4] Based on EPRI ER-685, "Requirements Assessments of PV Power Plants in Electric Utility Systems", June, 1978.

The photovoltaic modules are the same basic modules used in the residential system and will be placed on array structures, each having a slant height of 12', an array tilt angle of 31° from horizontal, and an array length of 40 feet. Twelve modules measuring 1 foot x 4 feet would be assembled into a panel, and ten of these panels are installed on the 40 foot long array structure. An array is depicted in Figure 4-8.

Potential energy collection and shading by adjacent arrays are directly related to the distance between array rows and must be considered when determining the array field layout. Total energy collected in kWh/m^2 and the required distance between array rows in feet are plotted against the number of hours without shading in December in Figure 4-9. The information presented in Figure 4-9 is for 12 foot slant height arrays having a 31° array tilt angle installed at a 34° north latitude. Up to nine hours per day without shading in December, the required distance between array rows shows a very gradual increase. To obtain non-shading for more than nine hours per day in December, the array field would have to be enlarged dramatically while achieving only minimal increase in energy collection. Considering the above, an array field layout utilizing 40' row spacing has been selected. Twenty arrays, each rated at 3.24 kW, will be required to provide the 64.8 kW peak output mentioned earlier.

The tradeoff between array spacing and array shading is of particular interest for roof-mounted installations, where an ideal field layout making optimal use of the given space is of prime interest. A reduction in distance between arrays from 40 feet to 25 feet will result in only a 3.33% lower annual energy collection per m^2 . While this reduction does not seem very dramatic, the actual energy received on the 31° inclined plane during the month of December will be 14.20% lower as compared to 40 feet spaced array field. This reduction in energy collection would not be desirable for a stand-alone system, since the required

FIGURE 4-8 SUBARRAY CONFIGURATION SHOWING MAJOR COMPONENTS

ORNL-DWG 80-6215 ETD

LATITUDE = $34^{\circ}11'$
 ARRAY TILT ANGLE = 31°
 GREAT SLANT HEIGHT = 12 feet

DISTANCE BETWEEN
ROWS (FEET)

TOTAL RADIATION COLLECTED

$\left[\frac{\text{KWH}}{\text{m}^2} \right]$ PER YEAR

LEGEND:

- Distance Between Rows
- △ Total Incident Radiation per Year

FIGURE 4-9 POTENTIAL ENERGY COLLECTED AND DISTANCE BETWEEN ROWS
AS A FUNCTION OF NON-SHADED OPERATION IN DECEMBER

storage for such a system would be greatly increased. For a grid-augmented installation however, the energy collection profile resulting from a 25 foot spaced array field could be tolerated, since sufficient capacity should normally be available during the winter months.

Industrial Application

The economics, technical feasibility, and availability of both flat-plate and photovoltaic concentrator systems have been investigated and considered for this large industrial application. While concentrator systems are expected to be used for systems of this size in the future, proven concentrator hardware is not commercially available at this time. Thus a flat-plate system has been specified for the industrial application. The hardware to be utilized would again be of the glass laminate type, having the same basic configuration as the equipment proposed for the other two installations. The field layout considerations would be very similar as presented for the small commercial installation.

For an installation feeding directly into a utility power grid, the array tilt angle or the corresponding settings for a system utilizing variable tilting angles should be selected for optimal energy production. Based on the insolation data utilized, maximum energy production would be obtained for a 31° array tilt angle. The average daily insolation received on the array plane inclined 31° would be 500 Langleys, with minimum energy collection potential of 393 Langleys during December and a maximum of 586 Langleys during the month of July. The energy collection profile for a 31° array tilt angle is depicted in Figure 4-10, not accounting for shading that would occur in multiple run array fields during the winter. An average daily energy collection of 528.4 Langleys over the year would result if the array tilt angle would be adjusted monthly. The energy collection profile and the required array tilt angles for each month throughout the year are depicted in Figure 4-11. As compared to a fixed 31° array tilt angle, an increase of 5% in energy collected would result. The benefits of this 5% energy

FIGURE 4-10 ENERGY COLLECTION PROFILE FOR A 31° INCLINED ARRAY, FIXED TILT ANGLE

FIGURE 4-11 ENERGY COLLECTION PROFILE AND TILT ANGLE SETTINGS FOR A VARIABLE TILT ANGLE INSTALLATION

collection increase, however, must be weighed against the increased array structure cost for a variable tilt angle installation, as well as the additional manpower and maintenance requirements. Based on the rather small energy production increase for a variable tilt angle installation and the resulting uncertainties as mentioned above, a fixed 31° tilt angle installation is recommended for this large commercial installation.

A conceptual array field layout for this 2 MW flat-plate system would require 616 subarrays rated at 135 V, 24 A each. A nominal systems voltage of 480 V was assumed, resulting in a peak systems rating of 540 V at 3696 A for rated environmental conditions of 1 kW/m^2 insolation and 28°C ambient air temperature. Four subarrays would be connected in series and connected via disconnect switches, fuse and blocking diode to the unregulated DC bus. The array rows would be spaced 30 feet apart, resulting in 7.5 hours of non-shaded operation during the month of December. The effects of array shading, however, can be minimized by careful selection of the series parallel connections. All pertinent system parameters for this 2 MW industrial photovoltaic installation are also tabulated in Table 4.12.

4.3.2 WECS Design Parameters for Various Applications

This section briefly describes the WECS chosen for the residential, small commercial, and industrial applications. The WECS chosen have all been demonstrated and are commercially available from the manufacturer. A more complete description of their designs may be obtained from the manufacturer.

Residential Application

The Grumman wind-turbine generator was chosen for this application. The Grumman WECS has a power output of 15 kW at a wind speed of 11.6 m/s and a cut-in wind speed of 3.6 m/s. Although the fixed pitch

Grumman wind generator can generate powers over 15 kW at wind speeds over 11.6 m/s, the maximum output of the generator was held to 15 kW in the simulation of its performance.

Small Commercial Application

The Merkhams wind-turbine generator was chosen for the small commercial application. The Merkhams WECS has maximum power output of 45 kW at a wind speed of 12.1 m/s and a cut-in wind speed of 2.3 m/s. The maximum output of the Merkhams wind generator was held at 45 kW in the simulation of its performance.

Industrial Application

The NASA/Lewis MOD-1 wind-turbine generator was chosen for the industrial application. The MOD-1 WECS has a maximum power output of 2000 kW at a wind speed of 12.5 m/s, a cut-in wind speed of 5.4 m/s and a cut-out wind speed of 26.8 m/s.

Table 4.13 summarizes the principal design specifications for the WECS chosen for each application.

4.3.3 Storage System Design Parameters for Various Applications

Dispersible storage systems of 10 MW and less are considered in the case studies. Storage devices usually have relatively insignificant economies of scale above 10 MW. However, between 1 kW and 10 MW significant economies of scale exist. The maximum practical sizes of storage devices are about 10 MW at substations, 1 MW at primary feeders, and 10 kW at the end-use entry levels.

Storage devices have both power and storage capacity cost components. The range of capital costs of the various components of 10 MW lead-acid and advanced batteries are listed in Table 4.14. The unit

TABLE 4.13

WIND GENERATOR DESIGN SPECIFICATIONS¹

	RURAL RESIDENTIAL APPLICATION	COMMERCIAL APPLICATION	INDUSTRIAL APPLICATION
Manufacturer	Grumman	Merkham	NASA/Lewis MOD-2
Rated Power (KW)	15.0	45.0	2500.0
Rated Wind Speed (m/s)	11.6	12.1	12.5
Hub Height (m)	18.2	18.2	61.0
Cut-In Wind Speed (m/s)	3.6	2.3	5.4
Cut-Out Wind Speed (m/s)	15.7	17.9	26.8
Generator Type	Induction	Alternator/ Line-Commutated Inverter	Synchronous
Number of Phases	3	3	3
Nominal Voltage (Volts)	265/460	265/460	4160/2402
Unit Capital Cost (\$/kW)	1200	600	800
			(100th unit, 9% learning curve)
Most likely range	1100-1350	500-800	700-1000
Electrical Interface			
Equipment Cost (\$/kW)	included	350	included
Most likely range (\$/kW)	included	300-500	included
O&M Costs ²			
Variable (Mills/kWh)	--	5-10	5
Fixed (\$/kW-year)			
Unit Availability ³			
Forced outage Rate (%)			
Planned Outage Rate (%)			
Equivalent Annual Availability (%)	90	90	90
Unit Life (years)	20-30	20-30	20-30

¹ All costs are projected rough estimates only in 1979 \$.

² W.H. Robbins and R.L. Thomas, "Large Horizontal Axis Wind Turbine Development", NASA Lewis Research Center.

³ Unit availability is defined as: Total Hours of Synchronous Operation
total hours with wind speed between cut-in and cut-out.

TABLE 4.14 BATTERY CAPITAL COSTS

COMPONENT	(10 MW, 4 HOUR DEVICE)	
	LEAD-ACID BATTERY	ADVANCED BATTERY
ENERGY-RELATED (\$/KW FOR 4-HOUR)		
MODULE	148 (140-260)**	104 (120-200)
BALANCE OF PLANT	112 (100-180)	48 (32-80)
COST	260 (240-440)	152 (112-240)
POWER-RELATED (\$/KW)		
MODULE	---	---
CONVERTER	60 (60-80)	60 (60-80)
COST	60 (60-80)	60 (60-80)
TOTAL (\$/KW)	320 (300-520)	212 (172-320)

* Nominal (10 MW device) values to be used to derive unit costs for specific configurations.

**Parentheses denote range of values.

costs of the battery module and the balance of plant, \$/kWh, are the costs of installing sufficient storage capacity to generate for one hour at the rated power capacity. The table also shows nominal values within the range of values. The overall cost of lead-acid batteries is 50% greater than that of advanced batteries. Note that over 80% of the capital costs are energy capacity related.

Table 4.14 and Figures 4-12 and 4-13 contain information useful for calculating the costs of three battery components -- the module itself, the inverter, and the balance of plant -- for a range of energy and storage capacities.

The economies of scale for a 4-hour lead-acid battery, as a function of rated power capacity, are illustrated in Figure 4-12. The ordinate is a scaling factor used in subsequent calculations.

Adjustments in the costs of the battery module and the balance of plant are required for storage batteries with different energy capacities. Figure 4-13 gives the multipliers used to adjust the nominal 4-hour lead-acid batteries to find the capital costs for different storage capacities. For example, to compute the unit capital cost of 1 MW, 8-hour lead-acid battery, the unit converter/inverter cost is found by first multiplying \$60/kW (from Table 4.14) by 1.83 (from Figure 4-12), to get \$110/kW. The unit balance of plant cost is computed by multiplying $8 \times \$28$ (from Table 4.14) by 1.79 (from Figure 4-14) and 0.84 (from Figure 4-13), to get \$337/kW. The unit battery module cost is \$249/kW. The total capital cost of a 1 MW, 8-hour lead-acid battery is \$695/kW. The same calculations are repeated for lead-acid batteries of different sizes to derive the capital cost curves in Figure 4-14 and Figure 4-15.

4.4 DSW PERFORMANCE STATISTICS

The statistics processor described in Chapter 2, Section 2.3 is used to provide proper information for analyzing the characteristics

ORNL-DWG 80-6218 ETD

FIGURE 4-12 ECONOMIES OF SCALE BATTERY COMPONENTS

*BASED ON A NOMINAL 4-HOUR STORAGE CAPACITY. FOR EXAMPLE, THE UNIT COST OF AN 8-HOUR BATTERY IS .34 OF THAT OF THE 4-HOUR BATTERY.

FIGURE 4-13 ECONOMY OF SCALE: STORAGE *
CAPACITY ADJUSTMENT FACTOR

FIGURE 4-14 CAPITAL COSTS - LEAD-ACID BATTERY

FIGURE 4-15 CAPITAL COSTS: ADVANCED BATTERY

of solar and wind energy resources. The power output distributions of the photovoltaic and wind energy conversion systems plotted over the hours of day provide important information in this study.

As shown in Figures 4-16 through 4-21, the solar energy is available most of the daytime while the wind energy can be used 24 hours a day. However more uncertainties exist in the WECS power output than in the solar PV power output. This coincidence of the solar and wind energy with the peak load of utility system and their large deviations imply that maximum solar and wind energy can be achieved in conjunction with a system of energy storage.

Figures 4-16 and 4-17 show the normalized annual average and peak month average photovoltaic system power output available at Santa Maria, California.

Figures 4-18 and 4-19 show the annual average and peak month average power output of the NASA/Lewis Mod-1 2000 kW wind generator sited at Riverside, California.

Figures 4-20 and 4-21 show the annual average and peak month average power output of the NASA/Lewis Mod 1 2000 kW wind generator sited at Ludington, Michigan.

FIGURE 4-16 Year-Averaged Power Output of 10 KW Solar PV System

(Based on 1978 SCE Insolation Data for Walnut, California)

FIGURE 4-1/ Month-Averaged Power Output of 10 KW
Solar PV System

(Based on September, 1978 SCE Insolation Data for Walnut, California)

FIGURE 4-18 Year-Averaged Power Output of 2000 KW
NASA/Lewis Mod-1 Wind Generator

(Based on May, 1977 - April, 1978 Battelle Wind Data for Riverside, (California))

FIGURE 4-19 Month-Averaged Power Output of 2000 KW
NASA/Lewis Mod-1 Wind Generator

(Based on September, 1977 Battelle Wind Data for Riverside, California)

FIGURE 4-20 Year-Averaged Power Output of 2000 KW
NASA/Lewis Mod-1 Wind Generator

(Based on May, 1977 - April, 1978 Battelle Wind Data for Ludington, Michigan)

FIGURE 4-21 Month-Averaged Power Output of 2000 KW
NASA/Lewis Mod-1 Wind Generator

(Based on December, 1977 Battelle Wind Data for Ludington, Michigan)

4.5 DSW CASE DESCRIPTIONS

The previous section described the two utilities and DSW equipment selected for study and discussed conventional distribution planning without DSW devices. This section discusses distribution planning when DSW devices are available as a planning option to defer or eliminate the need for conventional distribution system investments. The placement strategies using DSW devices must satisfy the same criteria as the conventional plan without DSW.

The distribution system violations analyzed in the previous DSG report case studies again were selected for the DSW report. No attempt was made to choose special situations which would make DSW devices abnormally attractive or unattractive.

Subsection 4.5.1 describes the DSW case studies in broad, general terms. Different "strategies" are described to alleviate distribution system violations for each utility. Within a particular strategy many different "options" may exist to alleviate the distribution system violations. For example, a strategy may call for a load reduction on a transformer during the peak period, but there are various means -- wind generators, solar photovoltaic arrays, batteries, etc. -- which afford the distribution system planner many different options of achieving this objective. Subsection 4.5.2 describes the various options which were considered in the DSW study.

4.5.1 Development of DSW Strategies

For Southern California Edison (SCE) three types of placement strategies were developed. They are:

- Substation strategies to relieve normal thermal overloading of substation transformers, and

- Feeder strategies to relieve thermal overloading of both substation transformers and underground getaways in single contingencies for up to three years.
- Customer strategies to relieve substation transformer and underground getaways by the placement of DSW devices on the customer-side of the service meter.

Options implementing these strategies were simulated and evaluated with DSW devices of various sizes and locations, considered both with and without storage installations. The relief requirements of the substation transformer define the total DSW capacities required. Table 4.15 shows the relief requirements.

Placement strategies to relieve distribution criteria violations for Consumers Power Company using DSW and storage devices fall into three categories:

- Substation strategies to relieve the normal voltage regulation problem of the subtransmission system by placing DSW devices on the high voltage side of the substations,
- Feeder strategies to relieve the normal voltage regulation problem of substation 1 by placing DSW devices along the primary distribution system, and
- Customer strategies to relieve the normal voltage regulation problem of substation 1 by placing DSW devices at the customer level of the primary distribution system.

As in the case studies for Southern California Edison, various options to implement these strategies were simulated and evaluated with DSW devices of various sizes and locations, operating with and without storage. The options included substation placement of DSW devices at substations 2 and 4. DSW devices located at substations 1 and 3 required larger capacities and were not studied. Feeder placement options included placement of DSW devices at a single location near a large recreational load and siting DSW devices in different locations close to the end of the primary feeders. Customer placement options were also developed to provide feeder relief. Table 4.16 shows the substation and feeder relief capacities required.

TABLE 4.15 DSW CASE DESCRIPTION - SOUTHERN CALIFORNIA EDISON

CASES	ONE YEAR		TWO YEARS		THREE YEARS	
	CAPACITY (KW)	DURATION* (HR)	CAPACITY (KW)	DURATION (HR)	CAPACITY (KW)	DURATION (HR)
SUBSTATION STRATEGY						
SUBSTATION	4583	5.94	8518	7.12	12747	8.06
EQUIVALENT CENTRAL CAPACITY	4744	5.74	8818	6.88	13196	7.79
FEEDER STRATEGY						
SUBSTATION	334	8.50	861	9.00	2817	12.03
FEEDER 1	742	8.50	1271	9.18	1643	12.00
FEEDER 2	727	8.50	1250	9.07	1626	12.00
FEEDER 3	768	8.50	1650	9.10	2123	12.00
FEEDER 4	1005	8.50	1738	9.11	2259	12.00
FEEDER 5	1007	8.50	1748	9.14	2279	12.00
EQUIVALENT CENTRAL CAPACITY	4744	8.21	8818	8.80	13196	11.60

*FIGURES DENOTE THE EQUIVALENT HOURS OF GENERATION AT THE INSTALLED CAPACITY.

TABLE 4.16 DSW CASE DESCRIPTION - CONSUMERS POWER COMPANY

CASES	ONE YEAR		TWO YEARS		THREE YEARS	
	CAPACITY (KW)	DURATION* (HR)	CAPACITY (KW)	DURATION (HR)	CAPACITY (KW)	DURATION (HR)
SUBSTATION STRATEGY						
SUBSTATION 2	1579	7.54	3076	3.62	3650	8.74
SUBSTATION 4	1234	6.68	1724	7.41	2032	7.61
EQUIVALENT CENTRAL CAPACITY	3015	6.68	5154	7.64	6090	7.77
FEEDER STRATEGY						
FEEDER 1	276	5.35	651	7.85	1295	8.82
EQUIVALENT CENTRAL CAPACITY	304	4.86	717	6.59	1426	7.31

*FIGURES DENOTE THE EQUIVALENT HOURS OF GENERATION AT THE INSTALLED CAPACITY.

4.5.2 Development of DSW Options

Given a set of strategies, the next step in the DSG/DSW methodology is to develop a set of options, or means, to meet these objectives. We refer to the complete set of options considered in this project as "case studies." These options were chosen for study based upon several important issues regarding the integration of DSW technologies into a distribution system. The case studies fall into four broad categories:

- Comparison studies using varying proportions of DSW and storage capacities to provide the total relief capacity required. System¹ storage was considered in supply-side cases; dedicated storage was considered in customer-side cases.
- Comparison studies of DSW device placement in different portions of the distribution network. Both supply-side and customer-side placements were considered.
- Comparison studies of DSW technologies relative to each other and relative to central generation
- Comparison studies of DSW devices in varying amounts of penetration and dispersion in the utility network. Spatial diversity of wind generators was also considered for the rural Consumers Power Company system.

The next chapter describes the case studies in each of these four categories. Below is a discussion of topics germane to each set of studies.

¹ The definition of 'system' storage used in this study means that the storage device serves the aggregate load at the level of installation of the device in the distribution system. Dedicated storage serves only the local load. Both types of storage may be charged by either DSW devices or the utility.

DSW/Storage Case Studies

DSW devices are not generally considered to be firm energy supplies. In this respect, photovoltaic and wind energy conversion systems suffer in comparison to firm generation sources due to their uncertain availability for meeting loads. Meteorological conditions change continuously and prevent the power outputs of these devices from being precisely scheduled. One possible solution to this availability problem consists of coupling DSW devices with storage systems such as lead-acid or advanced technology batteries. When meteorological and load conditions permit, excess DSW energy may be stored up to the battery capacity. This energy may then be used as needed when meteorological conditions are unfavorable for DSW generation.

Interest in this set of case studies centers on the tradeoff between DSW generation capacity and storage capacity. What parameters improve as more storage is added relative to DSW capacity? What factors worsen? There would appear to be an optimum storage capacity for a given DSW capacity in a certain location, but the battery may bring benefits and costs which are totally independent of DSW implementation. As described in the DSG report, batteries may be used for load-management objectives which are distinct from those associated with DSW strategies. Therefore the "optimum" DSW/storage proportion will likely change when other costs and benefits intrinsic to batteries are examined.

Six sets of case studies highlight the considerations involved in determining the level of backup storage for DSW systems. They include:

1. PV studies for a Southern California Edison feeder
2. Wind studies for a Southern California Edison feeder
3. PV studies for a Southern California Edison substation
4. Wind studies for a Southern California Edison substation
5. Wind studies for a Consumers Power Company feeder
6. Wind studies for Consumers Power Company subtransmission

For each of the six sets of case studies, three different DSW/storage combinations were simulated:

1. 1 kW of storage capacity for every 2 kW of DSW capacity
2. 1 kW of storage capacity for every 1 kW of DSW capacity
3. 2 kW of storage capacity for every 1 kW of DSW capacity

Several solar photovoltaic case studies for Southern California Edison with no storage were also considered; the load relief for these cases was provided entirely by the photovoltaic systems. As previously discussed, dispersed solar and wind technologies cannot be depended upon to provide firm generation capacity similar to conventional fueled technologies. Fluctuating meteorological variables mean that the possibility of the power output of DSW devices dropping drastically at any point in time always exists. Based on statistical analysis of these meteorological variables, however, the probabilities of occurrence of such adverse conditions can be calculated and confidence levels can be assigned for maintaining arbitrary minimum levels of DSW output during periods of interest during each day. At sufficiently high confidence levels, DSW devices can be credited with a firm generation capacity credit. In this study a 75% confidence level threshold was used to determine an appropriate DSW availability credit during peak load periods. Based on this procedure, firm capacity factor credits during peak load periods for dispersed wind energy systems ranged from 5% to 15%. Similarly, a 50% firm capacity credit was allowed dispersed photovoltaic systems during the Southern California Edison afternoon peak load periods.

The result of this procedure means that the installed capacity of DSW devices must exceed the firm capacity of DSW devices required within a relief strategy. This statistical procedure permits us to study the trade-off between DSW and storage devices since firm capacity credits can be assigned for both types of devices.

In all case studies the total firm kW availability of 75% confidence of the DSW and storage devices was equal to the firm kW

capacity of the DSG devices considered in the previous DSG study. Thus once the installed DSW capacity was established and the storage capacity added, the total firm DSW/storage capacity was the amount required to alleviate the particular distribution system constraints and operating problems addressed in the DSG study.

Based on the DSW performance statistics presented in Section 4.4, Table 4-17, summarizes the average annual availability factors and peak availability factors of the solar photovoltaic and wind energy conversion systems studied for both utilities. The average annual availability factor was used to estimate the expected energy generated over the year by the DSW devices. The peak availability factor was used to estimate the availability credit of the DSW devices during the peak load period. The DSW peak availability factors shown for Southern California Edison are based on DSW performance statistics for the 3 pm peak loads occurring during the month of September. The DSW peak availability factors for Consumers Power Company are based on statistics for the peak load periods occurring during the month of December.

Distribution System Placement Case Studies

Important issues were raised in the DSG study pertaining to the placement of devices at various locations in the distribution network. In certain circumstances, placement high in the network near the substation was desirable. Under other conditions, device placement lower in the system along feeders or near the customer had certain advantages.

One set of case studies investigates the issues associated with DSW placement at various locations in the utility system. Four placement locations are considered: substation, feeder, customer, and central generation for both utilities. The relief capacities required for these locations are presented in Tables 4.15 and 4.16.

TABLE 4-17
 AVERAGE ANNUAL AND PEAK LOAD AVAILABILITY FACTORS
 FOR DSW TECHNOLOGIES

	<u>Southern California Edison</u>	<u>Consumers Power Company</u>
Solar Photovoltaic Systems		
Average Annual Availability Factor ¹	20%	N/A
Peak Load Availability Factor ² (75% Confidence)	50%	N/A
Wind Energy Conversion Systems		
Average Annual Availability Factors ¹	32%	17%
Peak Load Availability Factor ² (75% Confidence)	8.3%	5.0%

¹ Based on a statistical analysis of the hourly power outputs of the DSW technology over a one-year period.

² Based on a statistical analysis of the hourly power outputs of the DSW technology during the peak load periods of each utility over the peak load month involved.

Only wind generation is considered in this set of case studies because only wind generation was common to both utilities. No PV studies were undertaken for Consumers Power Company because the technology was considered inappropriate for a northern, winter-peaking utility.

DSW Technology Case Studies

This set of case studies compares the impact of dispersed wind, solar, and firm generation sources on the distribution systems of both utilities studied. One group compares solar photovoltaic generation to wind generation for Southern California Edison. In addition comparisons are drawn between this group of case studies and previous DSG case studies for Southern California Edison which used DSG fuel cell and diesel generation.

A second group in this set of DSW technology case studies compares wind generation cases for Consumers Power Company which use different assumptions regarding the spatial diversity of the wind resource for that region.

DSW Device Penetration Case Studies

The final category of case studies described in this report deals with the effect of varying the penetration of DSW devices in the respective utility distribution systems. The penetration effect was important in the DSG study, and highly dependent upon the particular distribution system. DSG devices in low but increasing penetrations were seen in some examples to offer increasing benefits. Beyond a certain level, however, which varied with the utility, the trend reversed, and in higher penetrations the benefit became negative (i.e., became a cost). Both utility distribution systems experienced a load growth from 1975 to 1977. Were DSG or DSW devices to supply relief from violations over this time, their capacities and hence their penetrations would have to grow. This set of case studies assumes that this in fact happens.

Three comparisons are described in this section:

1. Feeder PV Cases (1/2 DSW, 1/2 storage) for 1975-77, Southern California Edison
2. Feeder Wind Cases (1/2 DSW, 1/2 storage) for 1975-77, Southern California Edison
3. Substation Wind Cases (1/3 DSW, 2/3 storage) for 1975-77, Consumers Power Company

4-64

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5. CASE STUDY RESULTS

5.1 DSW CASE STUDY RESULTS WITH VARIOUS BACKUP STORAGE CAPACITIES

Figures 5-1 and 5-2 summarize the results for the DSW case studies with various backup storage capacities. Figure 5-1 is for Southern California Edison, and Figure 5-2 gives the results for Consumers Power Company. The ordinate axes are the total benefit/cost (+ is benefit, - is cost) in 1975 dollars for various amounts of storage. The abscissa gives the fraction of the total distribution system relief capacity which was satisfied by DSW devices. For example, the lowest curve on Figure 5-1 shows the total benefits or costs resulting from solar photovoltaic/battery placements along feeders of the Southern California Edison system. The lowest point on this curve indicates that a total cost of \$110,000 was incurred by the photovoltaic/battery system in which 33% of the required relief capacity was supplied by the photovoltaic device and 67% by the battery system. The six curves shown in Figures 5-1 and 5-2 correspond to the six sets of DSW/storage case studies described in Section 4.5.2.

Two observations are immediately apparent. First the general trend of the curves is upward. That is, there is an increasing benefit as less storage is used. Second, the benefits for the feeder cases rise much more rapidly than do those for the substation cases. The Southern California Edison substation benefits rise by \$38,000 for PV systems and \$46,000 for WECS as the DSW fraction increases from 1/3 to 2/3. Over the same range, the Southern California Edison feeder benefits increase by \$60,000 for the PV systems and by \$124,000 for WECS.

The sharply increasing benefits for feeder installation of DSW devices compared to substation installation of such devices is largely due to the high capital costs for dispersed batteries. The use of a larger number of smaller batteries required for the feeder cases results in significant economies of scale capital cost penalties.

FIGURE 5-1 COMPARISON OF STORAGE CASES FOR
SOUTHERN CALIFORNIA EDISON

FIGURE 5-2 COMPARISON OF STORAGE CASES FOR
CONSUMERS POWER COMPANY

Figure 5-3 shows the change in the capital and maintenance cost components, DC and MC, for the feeder and substation cases. As the PV fraction is decreased from $2/3$ to $1/3$ of the firm capacity relief requirements, the DC component decreases (becomes less beneficial) by approximately \$36,000 for the feeder case. At the same time the DC component actually increases (becomes more beneficial) for the substation case. Since there is only one large battery at the substation, increasing its size has a beneficial impact on the distribution system. The equivalent central battery would be only marginally larger. Both are of the 10 MW size and therefore subject to the same unit module costs.

The situation differs for the feeder cases because more batteries are required in the distribution system, thereby penalizing the system with respect to central system location. In addition the smaller size of feeder batteries results in higher unit costs due to economies of scale.

Maintenance costs for the feeder cases are higher than for the substation cases. The MC component is nearly zero for the substation cases, indicating very little difference between maintaining the battery at a central or substation location. The more numerous, smaller feeder batteries show increasing maintenance costs due to their numbers and to higher unit costs.

Other cost components shown include the generation credits, GC and GC', which reflect the lower electrical losses due to dispersed placement and the reliability credit RB, which reflects higher end-user reliability. The dispersion component, DR, is the T&D investment savings.

Figures 5-1 and 5-2 show curves with uniformly positive slopes. As previously mentioned, there is an increasing benefit as less storage is used. All case studies show this trend, although, as discussed above, the feeder cases show more dramatic increases in cost than the substation cases do.

FIGURE 5-3 COMPARISON OF ASSESSMENT COMPONENTS FOR SOUTHERN CALIFORNIA EDISON FEEDER PV CASE

Figure 5-4 provides some insight into why the overall trend is positive. Shown are all the assessment components for one set of case studies; Southern California Edison substation solar photovoltaic cases. The magnitudes vary with the individual case studies, but the trends are generally consistent. Figure 5-4 shows that the greatest penalty is due to replacement capacity and generation capacity losses, components RC and GC'. The decreased generation costs are due to the gain of solar photovoltaic power output as photovoltaic capacity replaces batteries and central generation.

The replacement capacity component RC is the cost levied against dispersed devices on conflicting capacity days if they are operated with only distribution objectives. As described in section 3.2 of this report, the replacement capacity component is the penalty assessed against DSW/battery systems for not providing the full capacity for the time needed by the bulk power system. The trend displayed in Figure 5-4 is contrary to intuition. It would appear at first glance that increasing the battery capacity would actually result in an improved replacement capacity value since presumably more flexibility in battery operation would be possible. The reason why this is not true is that in these case studies, storage capacity offsets DSW generation. Consequently, the firm power supplied by the bulk system to the distribution system increases with additional storage. The bulk system therefore has higher requirements which are not fully offset by the additional storage. Figures 5-5 and 5-6 show generation outputs over the peak period from equivalent central and dispersed devices for DSW fractions of 1/2 and 1/3 respectively. The shaded areas are proportional to the power which was not supplied by the DSW/battery system but was nevertheless required for bulk power objectives. This power shortfall increases as storage is increased from 1/2 to 2/3.

The general assessment of increasing storage capacity at the expense of DSW generation capacity therefore is not encouraging.

LEGEND: DB = Dispersion Component
 GC = Storage Generation Component
 GC' = DSW Generation Component
 RC = Storage Replacement Capacity Component
 RB = Reliability Component
 DC = Storage Capital Component
 DC' = DSW Capital Component
 MC = Storage Maintenance Component
 MC' = DSW Maintenance Component

FIGURE 5-4 COMPARISON OF ASSESSMENT COMPONENTS FOR
 SOUTHERN CALIFORNIA EDISON SUBSTATION PV CASE

FIGURE 5-5 COMPARISON OF CENTRALIZED VERSUS
DECENTRALIZED STORAGE SCHEDULING -
1/2 STORAGE CAPACITY CASE

FIGURE 5-6 COMPARISON OF CENTRALIZED VERSUS
DECENTRALIZED STORAGE SCHEDULING -
2/3 STORAGE CAPACITY

Reliability, the primary reason for considering storage, does increase (see the RB component in Figure 5-4), but this benefit is more than offset by the generation and replacement capacity costs. Both are caused by the loss of dispersed generation as more DSW devices are displaced by storage devices. Causality between this displacement and increased generation costs is direct. The relation between the displacement and the replacement capacity component is due to the fact that additional distribution needs must be supplied. This increasing load conflicts with bulk power objectives even though the increased battery capacity intuitively would carry a positive replacement capacity benefit. The adverse effects of the additional load are simply too great for the additional storage capacity to offset.

5.2 DISTRIBUTION SYSTEM PLACEMENT CASE STUDY RESULTS

DSW and DSG devices may be located at the distribution substation. Loads must be modified at the highest level in the network, but natural load diversity can be used to its maximum advantage.

An alternative to placing DSG or DSW devices at the distribution system substation is to locate these devices lower in the distribution system at the feeder level. Feeder loads themselves can then be modified at lower, local levels rather than the aggregate loads at the higher substation level. Thus the utility can achieve a finer articulation in operation; operating for varying local objectives rather than for large scale objectives. As the previous DSG report indicated, this capability may have certain attractions. The utility planners may place only the amount of relief which is required at the specific feeder requiring the load relief. If relief is required only on one or two feeders, this approach would be sensible when contrasted to locating a much larger DSW or DSG device at the substation to serve the same condition. Since feeder storage devices would be smaller than substation storage devices, they would also be more portable. Thus the utility could benefit from both the smaller capacity as well as the movable nature of the feeder devices.

In addition, placement of DSW devices lower in the distribution system means that the line losses will be reduced. The resulting generation credit may be sizeable. This was the case in the DSG study for Consumers Power Company distribution system. Largely rural in nature, its distribution losses were approximately 11%. Feeder placement of DSG devices reduced this amount to 6%.

On the other hand, if large, general relief is needed throughout the distribution system, feeder placement of DSW/DSG devices may be more expensive than substation placement. Economies of scale as well as

maintenance costs can favor the installation of a simple larger installation at the substation level in preference to several smaller installations at feeder placement. Furthermore, higher placement of these devices may gain a substantial diversity credit. Aggregate system loads likely will show higher diversities, and consequently may require smaller total capacity relief. In addition geographical considerations may preclude the installation of DSG/DSW devices at lower levels. The urban distribution system of Southern California Edison is more suited to substation placement, whereas the rural distribution system of Consumers Power Company could likely accommodate either substation or feeder devices.

Three simulations using 1976 data were run for Southern California Edison substation cases. These cases had varying proportions of wind to meet the required capacity - one-third, one-half, and two-thirds - the remainder being supplied by storage. Figures 5-7 and 5-8 give the results for this set of simulations.

The net dispersion credit is shown by a solid line in Figure 5-7. Since the generation credit is the dominant assessment component, its value is denoted separately in the figure by a dotted line.

Figure 5-8 shows the substation peak loads corresponding to these wind fractions. Since the device is located at the substation, component demands in the distribution system are unchanged, but the aggregate substation load is reduced.

The trends displayed in Figures 5-7 and 5-8 are due to more and more wind generation displacing bulk generation faster than capital costs increase and are intuitive. It is interesting to note, however, that the other assessment components do not behave uniformly. Figure 5-9 shows the behavior of significant (non-zero) components in the Southern California Edison simulations. In this display, the capital cost component DC changes by \$15,000 as more wind (less battery) capacity is added.

FIGURE 5-7 DISPERSION CREDIT - SOUTHERN CALIFORNIA EDISON SUBSTATION WIND GENERATION CASES

¹ This case shows a net benefit which is lower than the generation credit.

FIGURE 5-8 SUBSTATION PEAK LOAD = SOUTHERN CALIFORNIA
EDISON SUBSTATION WIND GENERATION CASES

LEGEND: DB = Dispersion Component
 GC = Storage Generation Component
 RC = Storage Replacement Capacity Component
 RB = Reliability Component
 DC = Storage Capital Component
 MC = Storage Maintenance Component

FIGURE 5-9 COMPARISON OF ASSESSMENT COMPONENTS - SOUTHERN CALIFORNIA EDISON - SUBSTATION WIND GENERATION CASES

Consequently in sufficiently high penetrations, the battery costs start to outweigh their additional benefits. This is apparent in Figure 5-7, since the case study which uses 1/3 wind and 2/3 battery capacity shows a net benefit which is lower than the generation credit. In the other cases, the net benefit is higher due to the positive effects of other components.

The same effect is not observed for Consumers Power Company however. As shown in Figure 5-10, the benefits apart from generation credit actually increase as more storage is added. Unit maintenance costs decrease (become more beneficial) and the replacement capacity component becomes more positive (beneficial) as more storage is added.

The same general trend seen in Figure 5-7 is also seen in Figure 5-5. The net credit increases as wind generation displaces batteries and central generation. Other components are largely washed out by the increasingly large generation credit.

Figure 5-11 shows this trend for Consumers Power Company over time. The net credit increases from 1975 to 1977 due to increasing generation credit. The other assessment components, though positive, decreased over time.

The under-voltage problems of Consumers Power Company were extreme for feeder 1, although the problem was also observed at other feeders in the system. As shown in Table 4.15 the DSW feeder strategy called for the installation of capacities of 276, 651, and 1295 kW for the years 1975, 1976, and 1977 respectively. Using peak availability factors of 5%, 10%, and 15% and a range of DSW/storage fractions, a set of DSW simulations were run, and the results are presented in Figures 5-12, 5-13, and 5-14.

FIGURE 5-10 DISPERSION CREDIT - CONSUMERS POWER COMPANY
SUBTRANSMISSION WIND GENERATION CASES

FIGURE 6-11. DISPERSION CREDIT FOR YEARS 75-77
CONSUMERS POWER COMPANY - SUBTRANS-
MISSION WIND GENERATION CASE

FIGURE 5-12 DISPERSION CREDIT - CONSUMERS POWER COMPANY
FEEDER WIND GENERATION CASES

LEGEND: DB = Dispersion Component
 GC = Storage Generation Component
 GC' = DSW Generation Component
 RC = Storage Replacement Capacity Component
 RB = Reliability Component
 DC = Storage Capital Component
 DC' = DSW Capital Component
 MC = Storage Maintenance Component
 MC' = DSW Maintenance Component

FIGURE 5-13 COMPARISON OF ASSESSMENT COMPONENTS
 CONSUMERS POWER COMPANY - ILLULR
 WIND GENERATION CASES

FIGURE 5-14 DISPERSION CREDIT - SOUTHERN CALIFORNIA EDISON
FEEDER WIND GENERATION CASES

Figure 5-12 shows the total distribution credit for three cases with 0, 1/3, and 1/2 of the required feeder capacity provided by wind generation. This amount is denoted by a solid line. The largest component, the generation credit, is denoted by a dotted line. As shown in Figures 5-12 and 5-13, the generation credit largely dominates the results, but the results can be affected by other factors to a lesser degree. As the wind capacity increases and the battery capacity falls, the replacement capacity, maintenance, and DSW capital costs components also fall. As more DSW capacity is added, the cost for the equipment increases, and the component benefit DC' decreases (+ is benefit, - is cost). The replacement capacity component RC falls due to the fact that less storage exists, and the capability to operate storage for both central and local objectives diminishes.

As might be expected, the storage capital cost component DC improves with decreasing amounts of storage, but its effect is more than offset by decreases in other components.

Feeder case studies for Southern California Edison proceeded in an analogous manner to those of Consumers Power Company. Based on capacity relief requirements determined in the DSG study and an 8.3% availability factor, various combinations of DSW and storage devices satisfied this requirement. Figures 5-14 and 5-15 give the results for these studies. Figure 5-14 shows the total as well as the component generation benefit. Figure 5-15 shows the individual assessment component values.

Although the same general uniform trend benefit increasing with wind fraction seen for Consumers Power Company continues for Southern California Edison, the cross-over point between cost and benefit occurs at higher wind fractions for Southern California Edison. According to Figure 5-13 almost any amount of wind generation would have a net positive effect. For Southern California Edison, however, the crossover occurs

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- RB = Reliability Component
- DC = Storage Capital Component
- DC' = DSW Capital Component
- MC = Storage Maintenance Component
- MC' = DSW Maintenance Component

FIGURE 5-15 COMPARISON OF ASSESSMENT COMPONENTS
SOUTHERN CALIFORNIA EDISON - FEEDER
WIND GENERATION CASES

at approximately 55%. That is DSW/storage devices are beneficial to the distribution system studied for Southern California Edison where the percent of relief supplied by wind generation is in excess of 55% of the total relief required.

Compared to the substation placement case studies, however, the feeder cases suffer. This is due primarily to the larger costs associated with the more numerous battery installations required by feeder cases. The capital cost component DC alone changes from -\$8493 to -\$113,020 between the substation and feeder cases where each uses 1/3 wind and 2/3 storage for relief. The DSW generation component is larger for feeder cases (\$105,000 vs \$35,000), but this net positive benefit is more than offset by negative benefits (costs) in other components.

As described earlier, feeder placement of DSW/storage devices permits the utility to more closely control component loads lower in the system. If peak loading were being controlled one might justifiably expect results where feeder peak loads were reduced for feeder placement cases in comparison to substitution placement cases. This is in fact what Figure 5-16 shows. Feeders 1-5 show substantially lower peak loads for feeder placement. In no case does the feeder case peak load exceed 40% of its value for the substation cases. There is a slight increase at the substation mode.

FIGURE 5-16 FEEDER-STRATEGY PEAK LOAD PERCENT OF SUBSTATION - STRATEGY
PEAK LOAD FOR SOUTHERN CALIFORNIA EDISON

5.3 DSW TECHNOLOGY CASE STUDY RESULTS

As mentioned previously, the principal difference between dispersed firm generation and dispersed intermittent generation is in the installed capacity required to yield equivalent firm relief capacities. For fuel cells and diesel generators, each kilowatt of rated capacity produces nearly one kilowatt of firm relief capacity. However for intermittent solar photovoltaic and wind energy conversion systems, many kilowatts of rated capacity are required for each kilowatt of firm relief capacity. Table 5.1 compares the photovoltaic and wind generator capacities required for the feeder relief strategies studied for the 50% DSW-50% storage Southern California Edison cases.

It is apparent from Table 5.1 that the capacity requirements for wind generators are much higher than those for the photovoltaic systems. Of course this is simply due to the much higher coincidence between solar radiation and the distribution system load compared to the coincidence between wind speed and load. For the utility system studied with PV systems, the distribution system's peak load was around 3 pm during the month of September. Analysis of the photovoltaic system output during this month indicated that a 50% capacity credit could be credited to the PV system during these peak load periods with approximately 70% confidence. However, analysis of the wind generator outputs during the month of September showed that only an 8.3% capacity credit could be credited to the wind generators during the peak periods. This figure assumes no spatial diversity of the wind resources exists over the geographic region studied. This is a reasonable assumption for the small urban distribution area of Southern California Edison. For the larger rural distribution area of Consumers Power Company, spatial diversity was studied and is discussed in Section 5.3.1.

TABLE 5.1

Comparison of Photovoltaic and Wind Generation Capacities
Required for Southern California Edison Feeder Relief Cases (50% DSW/50% Storage)

Southern California Edison Feeder	1976 Relief Capacity Required (kW)	PV Capacity ¹ (kW)	Storage Capacity (kW)	WECS Capacity ² (kW)	Storage Capacity (kW)
Substation	861	861	431	5185	431
Feeder 1	1271	1271	636	7651	636
Feeder 2	1250	1256	625	7519	625
Feeder 3	1650	1650	825	9925	825
Feeder 4	1738	1738	869	10454	869
Feeder 5	1748	1748	874	10514	874

1. Based on a 50% Peak Load Availability Credit.

2. Based on an 3.3% Peak Load Availability Credit.

Although the capacity requirements of dispersed solar and wind technologies are much higher than the capacity requirements of firm generation sources such as fuel cells or diesel generators, their placement in the distribution system does result in significant generation credits over central placement. For Southern California Edison, transmission losses are approximately 3.4%. Thus the dispersed placement of photovoltaic or wind capacity results in significant energy savings due to elimination of the transmission losses for that dispersed generation. Table 5.2 summarizes the generation credit of dispersed photovoltaic and wind devices for Southern California Edison.

From Table 5.2 it is apparent that the generation credit for dispersed wind generation is much larger than the generation credit for photovoltaic generation. However, it should be pointed out that a large amount of this wind generation is at off-peak hours which might be valued at a lower rate.

5.5.1 Spatial Diversity of Wind Generation

For the large rural distribution region of Consumers Power Company there may be considerable diversity between the wind resources at various sites. The presence of this spatial diversity may have a significant impact on the benefit of dispersed wind generators. Spatial diversity of the wind resource does not change the expected total annual energy generation from an array of wind generators dispersed over a region, however it does change the effective output duration curve of the generation. The probability of both zero and maximum power output is significantly reduced while the probability of intermediate power outputs is increased. The net effect of this is to increase the capacity credit allowed the array of wind generators during peak load periods.

TABLE 5.2

Comparison of the Generation Credit of Dispersed Photovoltaic and Wind
Technologies for a Southern California Edison Feeder Relief Case
(50% DSW/50% Storage)

PV		WECS	
Annual kWh's Generated	Generation Credit ³	Annual kWh's Generated ²	Generation Credit ³
0.15×10^8	$\$0.16 \times 10^5$	1.45×10^8	$\$1.58 \times 10^5$

1. Based on a Flat Plate PV system performance at Walnut, California.
Annual Availability Factor = 0.20
2. Based on NASA/Lewis MOD-1 wind generator performance at Riverside, California
Annual Capacity Factor = 0.32
3. Based on 3.4% losses and valued at 3.2¢/kWh.

To assess the impact of these higher peak availability factors on the benefit of dispersed wind generators, additional cases were run based on various peak capacity assumptions. Without spatial diversity, analysis of the Ludington wind generator output statistics for the peak month of December allowed only a 5% peak availability factor. Additional spatial diversity cases were run allowing higher peak availability factors of 10% and 15%. The assessment components for these cases are compared to the case based on a 5% availability credit in Figure 5-17. As shown, the total benefits for the 10% and 15% availability cases are lower than the benefit for the 5% availability case. This is primarily due to the reduced generation credit for these cases since less total wind capacity was required. If the reduced generation credit is not considered, the remaining benefit would increase slightly for the cases assuming spatial diversity.

The spatial diversity of wind resources at various sites is more important for bulk supply generation than for distribution requirements. Distribution requirements are generally too localized and specific for spatial diversity to contribute significantly.

LEGEND:

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- GC = Storage Generation Component
- GC' = DSW Generation Component
- RC = Storage Replacement Capacity Component
- RB = Reliability Component
- DC = Storage Capital Component
- DC' = DSW Capital Component
- MC = Storage Maintenance Component
- MC' = DSW Maintenance Component

FIGURE 5-17 COMPARISON OF ASSESSMENT COMPONENTS - SOUTHERN CALIFORNIA EDISON - SUBTRANSMISSION WIND GENERATOR CASES WITH SPATIAL DIVERSITY

5.4 DSW DEVICE PENETRATION CASE STUDY RESULTS

The results for these comparisons are shown in Figures 5-18, 5-19 and 5-20. The net benefit is denoted by a solid line and DSW generation credit is noted by a dashed line.

For Southern California Edison, the results are not particularly encouraging. Both PV and wind cases show negative total benefits for each year of the study. This is largely due to the capital cost components DC and DC' which decrease (become less beneficial) over time. More DSW/storage capacity is required, and the effect is severe. Figures 5-18 and 5-19 show component values over the 1975-77 study period.

For the PV cases, the trend is downward, suggesting that the 1/2 DSW, 1/2 storage system becomes less beneficial with time. Of course as we have seen, the greater the DSW proportion in the DSW/storage system, the greater are the benefits because of the DSW generation credit GC'. What Figures 5-18 and 5-21 show is that although the trend is negative, there exists some room for improvement. If the battery capacity could be reduced, then the capital cost component DC would improve. Its large negative value, especially in 1977, would become more positive and affect the total benefit figure less. At the same time, the DSW generation credit, GC', will increase. Since it is increasing with time, the long term benefit will also improve. The total improvement may not be enough to bring the total benefit to positive levels, and even if it were, it would probably be only marginally positive.

For the wind cases (Figures 5-19 and 5-22) results show that the total benefit is negative. The effect of the GC' component is apparent, but offsetting it are the capital cost components DC and DC'. Some of the trends observed for the PV cases are also seen for the wind cases. Decreasing firm storage capacity while increasing firm DSW

FIGURE 5-18 DISPERSION CREDIT, SOUTHERN CALIFORNIA EDISON - FEEDER PV CASES WITH STORAGE

FIGURE 5-19 DISPERSION CREDIT, SOUTHERN CALIFORNIA EDISON -
FEEDER WIND CASES WITH STORAGE

FIGURE 5-20 DISPERSION CREDIT; CONSUMERS POWER COMPANY -
SUBSTATION WIND CASES WITH STORAGE AND
WITH DIVERSITY

LEGEND: DB = Dispersion Component
 GC = Storage Generation Component
 GC' = DSW Generation Component
 RC = Storage Replacement Capacity Component
 DC = Storage Capital Component
 DC' = DSW Capital Component
 MC = Storage Maintenance Component
 MC' = DSW Maintenance Component

FIGURE 5-21 YEARLY COMPARISON OF ASSESSMENT COMPONENTS
 SOUTHERN CALIFORNIA EDISON - FEEDER PV
 CASES WITH STORAGE

LEGEND: DB = Dispersion Component
 GC = Storage Generation Component
 GC' = DSW Generation Component
 RC = Storage Replacement Capacity Component
 DC = Storage Capital Component
 DC' = DSW Capital Component
 MC = Storage Maintenance Component
 MC' = DSW Maintenance Component

FIGURE 5-22 YEARLY COMPARISON OF ASSESSMENT COMPONENTS
 SOUTHERN CALIFORNIA EDISON - FEEDER WIND
 CASES WITH STORAGE

capacity will have two beneficial effects. First, the DC components will improve. Secondly GC' components also will improve. Both of these effects are linked because central generation is being replaced by dispersed DSW generation.

The wind cases focus our attention on one limiting aspect of DSW device penetration briefly discussed earlier. In particular, DSW penetration may be severely limited due to the fact that large amounts of energy can be generated and wasted during off-peak periods since the actual installed DSW capacity greatly exceeds the firm DSW capacity. There will be times over the course of a year when the power generated by a DSW device or devices greatly exceeds the distribution system demand. If as our study suggests it is unattractive to couple DSW devices with storage backup, the flexibility of the system to use this energy is severely hampered. In effect the DSW-based distribution system acts as a large generator for the central system, and the flow of power is inward rather than outward. The implications could be both disquieting and expensive. New protection schemes and equipment must be introduced, or some means of controlling DSW generation based upon the actual distribution system demand must be discovered. This problem is not so limiting for the PV cases. Since the PV system can operate only a portion of the day - usually when the distribution system load is at its greatest - excessive generation during off-peak problems proves less of a difficulty. WECS systems operate during both on and off-peak periods so the problems are more pronounced.

Figures 5-20 and 5-23 show the results for DSW scenario comparisons for substation wind cases with storage and with diversity for Consumers Power Company. These studies for Consumers Power Company are much more promising than similar studies for Southern California Edison which were described above. Several unique characteristics of Consumers Power Company make the situation possible. First, Consumers Power Company operates with a high load factor, in the vicinity of 80%,

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 GC = Storage Generation Component
 GC' = DSW Generation Component
 RC = Storage Replacement Capacity Component
 RB = Reliability Component
 DC = Storage Capital Component
 DC' = DSW Capital Component
 MC = Storage Maintenance Component
 MC' = DSW Maintenance Component

FIGURE 5-23 YEARLY COMPARISON OF ASSESSMENT COMPONENTS
 CONSUMERS POWER COMPANY - SUBSTATION WIND
 CASES W/STORAGE AND W/DIVERSITY

because a large pumped storage load occurs during the nighttime off-peak hours. With this high load factor the attractiveness of off-peak storage is greatly diminished. Consequently a higher percentage of the firm capacity relief can be provided by DSW devices directly rather than by storage devices. The positive benefits of this action have been described above.

Second the large geographical area of Consumers Power Company means that wind diversity can play a beneficial role. With greater diversity, a smaller installed DSW capacity will provide the same firm capacity relief. Consequently, fewer or smaller DSW devices are required, and the DC' cost component for these devices is correspondingly less. The net effect then is that wind generation for Consumers Power Company is much more attractive than for Southern California Edison.

There are other intangible factors which favor winds generation for Consumers Power Company as opposed to Southern California Edison. With its higher load factor, greater diversity, and smaller devices, Consumers Power Company will not experience the same off-peak excess generation problems as Southern California Edison. Furthermore the Consumers Power Company system is more suited for DSW devices because of its largely rural nature. There are fewer siting restrictions that would be faced than would be the case if DSW devices were placed in a densely settled, urban area like that of Southern California Edison.

6. CONCLUSIONS

Several important conclusions can be drawn from the study. Section 6.1 presents the conclusions reached from the case studies performed on two utility distribution systems. Section 6.2 describes operational problems associated with integrating solar photovoltaic and wind devices into distribution systems.

6.1 CASE STUDY CONCLUSIONS

Storage

Higher total benefits were observed in cases with minimum storage (advanced batteries). The high capital cost for dispersed batteries are responsible. If they are reduced, this situation may change.

For the wind conversion systems, some storage was required to guarantee available capacity during peak load periods. High penetrations of wind capacity in the distribution system can lead to excessive energy generation during off-peak periods causing reverse power flow problems.

Solar Versus Wind Generation

Performance statistics for photovoltaic systems during the summer afternoon peak load periods of Southern California Edison (SCE) allowed a much larger peak load availability credit for the PV systems than for the wind systems. Based on the statistical analysis of the hourly power output of the DSW systems studied for Southern California Edison, PV systems generated about 50% of their rated capacity compared with 8.3% for wind systems (within 75% confidence limits during hours of peak load). This comparison illustrates that photovoltaic systems are better matched to the load demands of a summer-peaking utility than wind systems are.

Level of Dispersion

Net benefits are greater when large DSW/storage devices are placed at high levels in the distribution system than when small devices are placed at the feeder level. Lower capital and maintenance costs are incurred by a small number of DSW/storage devices in comparison to many. The diseconomies of scale for battery storage plus increased maintenance and interconnection costs for numerous DSW placements result in large cost penalties for placement at the primary distribution level.

The DSW capital cost component and the replacement capacity component are the major cost penalties incurred by dispersed DSW/battery placements. As discussed above these components basically reflect the poor economies of scale for dispersed battery storage.

Distribution Losses

The DSW generation component is the largest benefit component achieved by dispersing DSW devices - larger in fact than savings in distribution investments. The generation component reflects the bulk generation savings achieved by dispersed generation sources nearer the end-user. This placement eliminates substantial electrical losses in the transmission and distribution systems which, for rural networks, can exceed 6%.

Spatial Diversity

Spatial diversity in the wind resource over a sufficiently large geographical region may have a small effect on the benefit of wind generation. Spatial diversity does not increase the total annual energy production from an array of wind generators however, it can change the effective output duration curve of the total wind generation. The occurrences of both zero and maximum power outputs are generally reduced while the occurrences of intermediate power outputs are increased. For the small areas of most distribution systems, there is little potential for significant diversity.

6.2 OPERATIONAL ISSUES

The operational issues associated with dispersed photovoltaic and wind energy conversion systems investigated in this study included:

- Protection coordination
- Personnel safety
- Voltage regulation

Conclusions regarding these issues are summarized below.

Protection Coordination

Small dispersed generators have an equivalent internal impedance greater than the system impedance during fault conditions, and their current contribution will not be great enough to cause erroneous operation of the utility's overcurrent devices.

Personnel Safety

Present work procedures are adequate for ensuring line-crew safety. These procedures require that synchronous generator and self-commutated inverter systems provide a means of disconnecting these systems from the feeder before a working clearance is established. Line-commutated inverter and induction generator systems are not directly addressed by these same procedures because they are voltage-dependent devices. Utilities surveyed in this study did not require a disconnect on these voltage dependent devices. However, as the number of dispersed generators increases utilities will probably also require a disconnect at these devices to ensure that unlikely scenarios such as self-excited generators do not expose workers to potential hazards when testing for voltage.

As the number of dispersed generators in a distribution system increase, simply disconnecting each generator to comply with required work procedures will have the undesirable effect of increasing repair times. Alternative techniques and/or hardware need to be developed to minimize these effects both on utility and customers connected to feeders. Specifically, automatic disconnects and other techniques need to be examined to determine if they can meet safety requirements.

Voltage Regulation

As the penetration of dispersed devices increases on a given feeder, the voltage profile also tends to increase both at the maximum and minimum voltage points. Synchronous and self-commutated systems raise the voltage by reducing the load. Line-commutated and induction generator systems also increase the feeder's voltage profile but also lower the substation's power factor because they increase the reactive load.

The increased reactive load does not significantly increase line losses on a feeder with line-commutated and induction generator systems. Specifically, distribution feeders are primarily resistive and the reduced load has the predominant effect, reducing total current flow, though slightly increasing the reactive load. The net effect is a lower substation power factor with little change in the total line losses.

Future Research Needs

Interconnection hardware for small dispersed generators (< 100 MW) will be costly for the customer owning a small power production device if presently available protection equipment is required by utilities. Specifically, if the attitude persists that every conceivable

abnormal condition must be protected against, then interconnect costs will be prohibitive. There is a need to study distribution operations, both normal and abnormal conditions with dispersed generators, to identify possible new conditions that result from the presence of dispersed generators. Once these conditions have been described, the job of designing reliable interconnect protection/control hardware will be focused, and realistic costs for both the owner and utility can emerge.

For larger dispersed generators (200 MW to 2 MW) interconnection requirements and costs are somewhat independent of size. Presently utilities list protection requirements for customer-owned generators that effectively disconnect the generator whenever there is an abnormal system condition. This philosophy applied to larger generators may cause undesirable conditions such as wide voltage swings, and/or frequency deviations due to the sudden change in load in the distribution system. It may be more effective to communicate and control these larger dispersed generators by dedicated control schemes from an integrated automated system that could eliminate undesirable conditions and allow the utility to operate some dispersed generators to the utility's benefit.

There is a need for developing protection coordination and control schemes that integrate dispersed generators rather than simply accommodating these devices. Such techniques would require intelligent control strategies that available protection hardware may not presently offer. It may be possible to include dispersed generators in existing load management and/or SCADA systems, offering both flexibility and a least cost solution for utilities and owners of dispersed generators.

Techniques used to communicate within distribution systems such as power-line carrier (historically used in transmission systems) will be complicated by dispersed generators. Those systems that use converters inject power line harmonics into a line which is already noisy due to harmonic distortion produced by customer loads. In addition, high harmonic currents and voltages can cause erroneous operation of protection equipment and increased O&M costs.

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