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WIND MACHINES FOR THE CALIFORNIA AQUEDUCT

Volume 1. Executive Summary

By
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MASTER

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The Aerospace Corporation
El Segundo, California

U.S. Department of Energy

Solar Energy

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WIND MACHINES FOR THE CALIFORNIA AQUEDUCT

EXECUTIVE SUMMARY

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THE AEROSPACE CORPORATION
Energy and Transportation Division
El Segundo, California

March 1977

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INTRODUCTION

The California Aqueduct is a 684-mile long water system (Figure 1) including natural waterways and a 444-mile length of canal and tunnel, that delivers water from the mountains of Northern California to arid Southern California for agricultural, industrial and residential use. As shown in Figure 2, the elevation of the Aqueduct ascends from 16 ft above sea level at the Delta Inlet, to over 3000 ft at the Edmonston Pumping Plant to cross the Tehachapi Mountains, after which the East Branch goes even higher. Some of the energy required to pump the water over these elevations is recovered through turbine generators as the water descends to the south.

The electrical energy required for pumping will grow with time, (see Figure 3) as the full capacity of the Aqueduct is utilized. The annual Aqueduct demand will exceed approximately 3% of the electrical energy consumed in the State of California until after 1990.

The objective of the study was to examine the applicability of wind energy conversion systems to meet a part of the pumping needs of the Aqueduct. It was hoped that the intermittent nature of the wind resource would not be detrimental to the Aqueduct operations because of the inherent storage capacity of the lakes and reservoirs along the canal and the capacity of the canal itself. Furthermore, the location of the major pumping load is in the mountainous regions along the Aqueduct path where the topography naturally leads to a potential wind energy resource.

The study was limited to a conceptual evaluation of one wind energy conversion system application to a major part of the Aqueduct.

REQUIREMENTS ANALYSIS

Four pumping plants from Buena Vista to Edmonston (Figure 2) require most of the energy consumed by the Aqueduct. Flow limitations of pumps, tunnels and canals will require almost continuous operation of these pumps to meet the demand after about 1985. Other loads in the system are

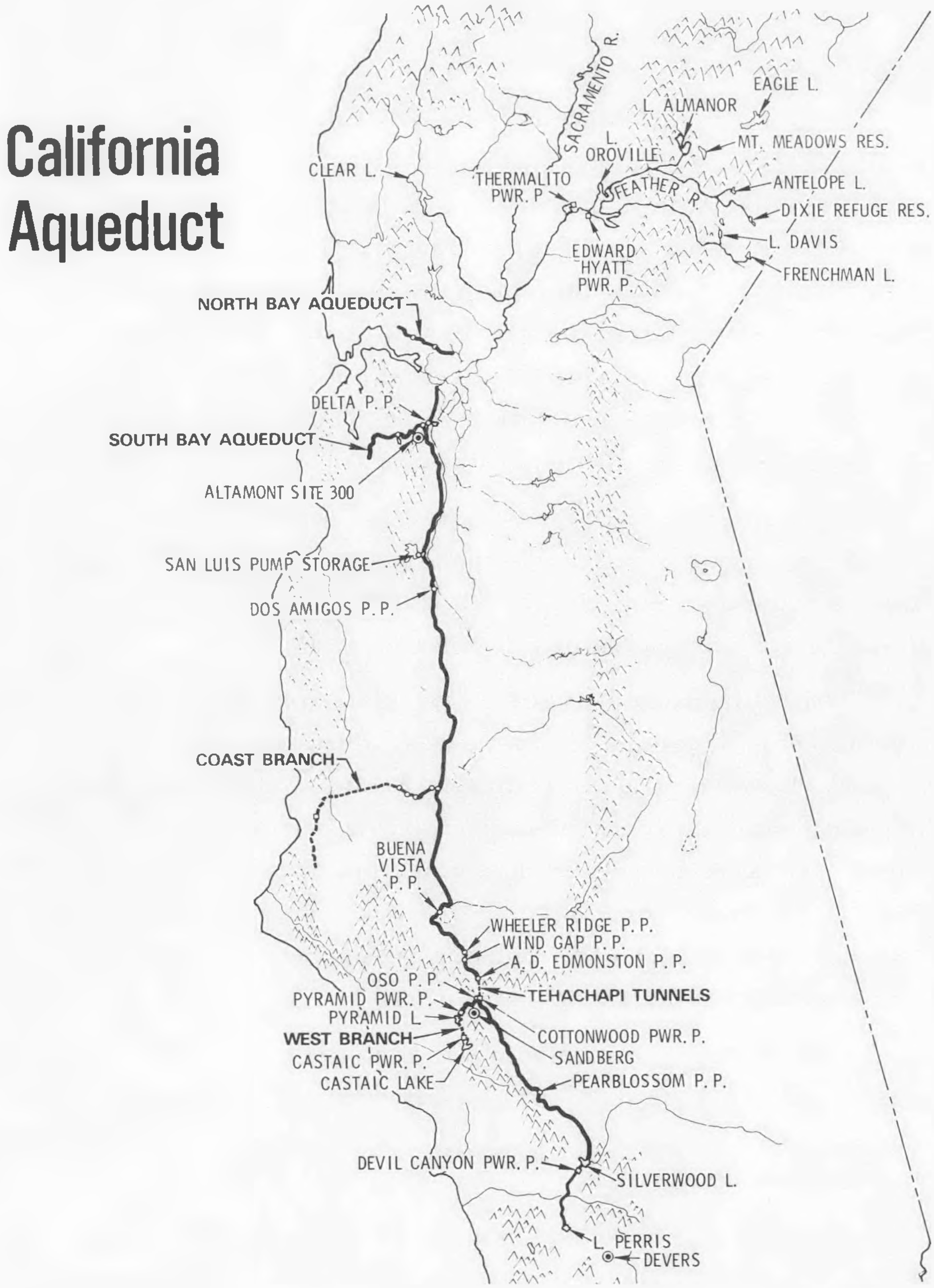


Figure 1. CALIFORNIA AQUEDUCT

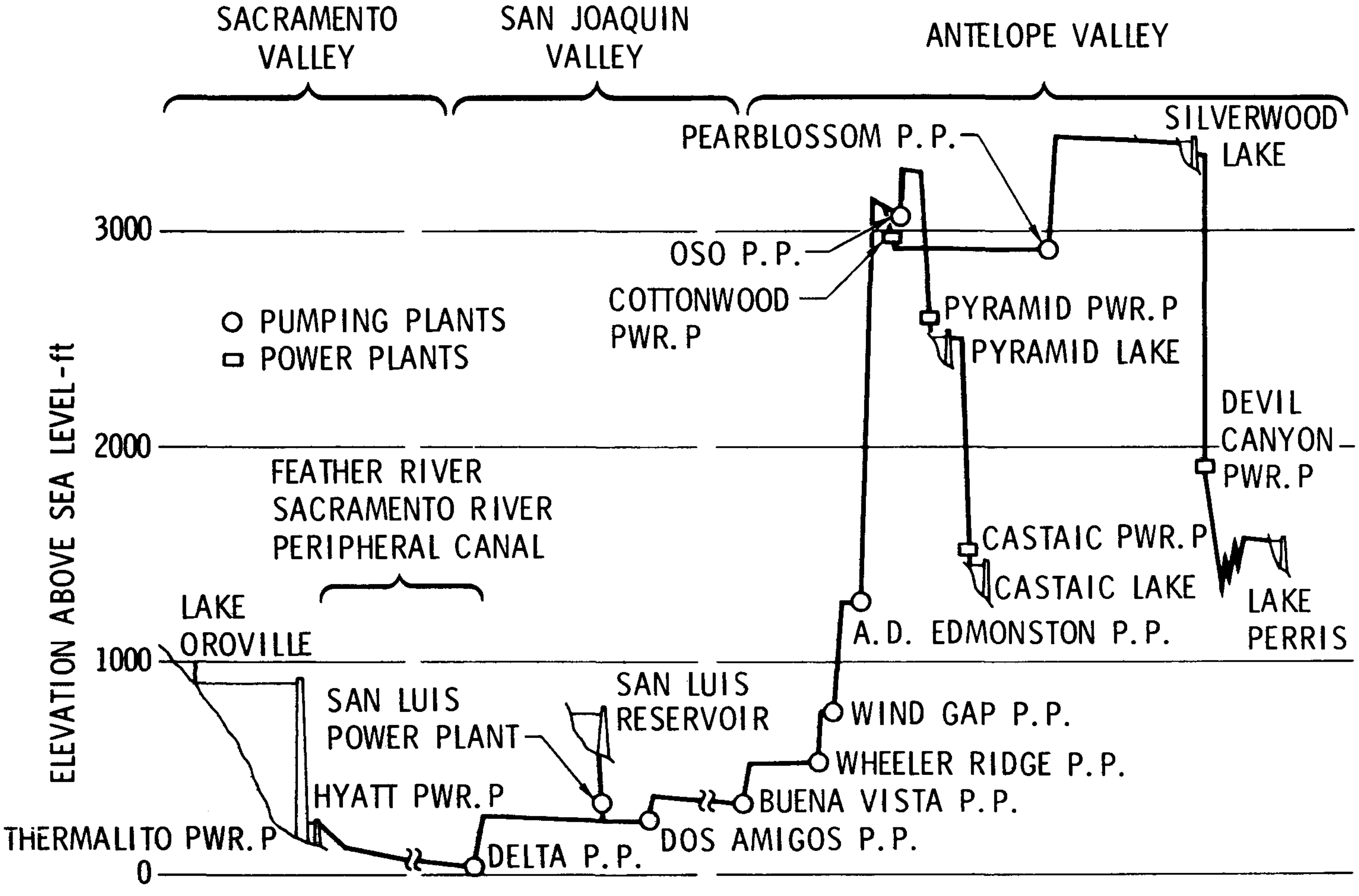
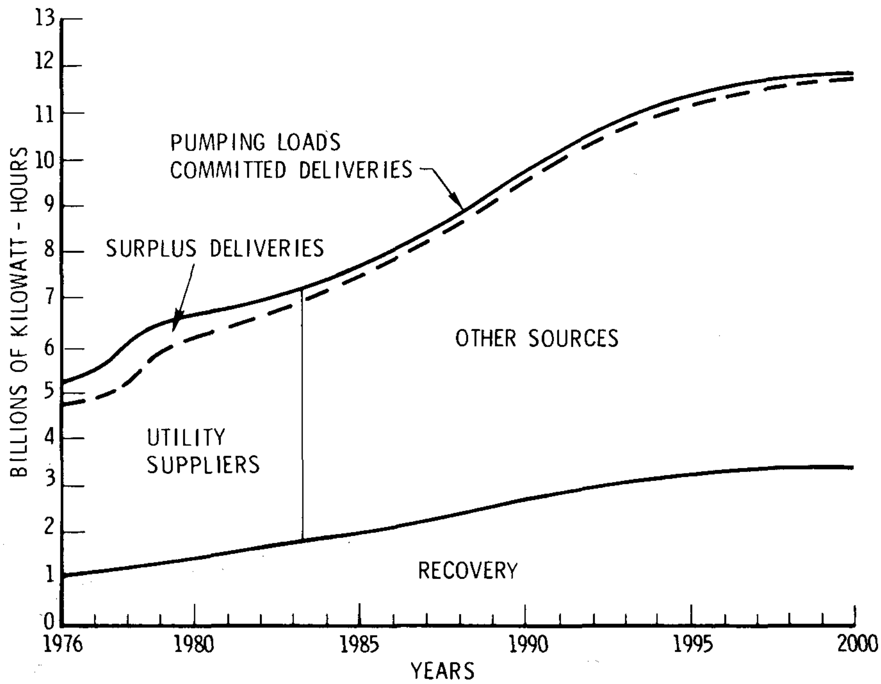


Figure 2. CALIFORNIA AQUEDUCT ELEVATION PROFILE



	California Total* Electrical Demand kWh x 10^9	Aqueduct Total Electrical Demand kWh x 10^9	Aqueduct Electrical Recovery kWh x 10^9
1973	156	2.5	0.4
1976	168	5.2	1.1
1980	203	6.7	1.4
1985	253**	7.7	1.9
1990	313**	9.8	2.7
2000	482**	11.9	3.3

*From California Public Utilities Commission, 10-year Forecasts, May 19, 1975

**Extrapolated at lowest PUC growth rate estimate.

Figure 3. STATE WATER PROJECT ESTIMATED LOADS AND RESOURCES

constrained by a complex maze of agreements and requirements necessary to maintain water levels and flows for agricultural and recreational purposes, support fishing and fish breeding, generate power, retrieve run-off water, control floods, minimize canal bank sluffing, and serve other purposes. These factors constrain pump scheduling severely.

By the time a WECS system could be operational, the Aqueduct demand will approach a constant diurnal load. By that time, flexibility of scheduling will be lost unless major changes are made in the Aqueduct structure and equipment. The load could conceivably be satisfied by some combination of a WECS system, the four utilities that now supply Aqueduct power, a possible Aqueduct-owned participation in a nuclear or coal power plant, and an energy storage component not now available in the system. Expiration of the present utility agreement, which guarantees low power rates until 1983, establishes a near term planning deadline for Aqueduct managers and planners.

WIND RESOURCE

An extensive survey was made to locate data to identify promising wind sites and characterize their wind spectra for WECS cost-performance tradeoffs. The following conclusions were reached:

(1) A large amount of wind data is available from NOAA and other sources.

(2) Most of the data are from stations located at airports and cities, which are rarely located on mountain tops or in spots with uncomfortably high winds.

(3) Some data is available from sites having attractive wind resources.

(4) This data, combined with study of the topography and weather, implies that major wind energy resources exist in a number of locations near the Aqueduct.

(5) The existence of these resources is confirmed by local reputation and other more quantitative indicators.

Large areas believed to have favorable wind resources are shown shaded in Figure 4. Wind data exists for only a few specific points in these areas.

Three sites accessible to the Aqueduct with data proving wind energy high enough for commercial exploitation were located. These are identified in Figure 1 as Altamont, Sandberg, and Devers. Only Sandberg has a long term wind record. Each of these three sites is large enough to accommodate many wind power units. The instrument point at each site is unlikely to be the highest wind energy point at that site.

SITE EVALUATION

A survey of land use restrictions, ownership, and cost turned up no serious obstructions to WECS installation near the Southern California pumping stations. All of the Tehachapi Mountain range, and many other ridge top lands in the area are privately owned and used primarily for low intensity cattle grazing. Although several locations were identified which appear to be attractive as WECS sites, a single site along Tejon Mountain near the Edmonston Pumping Plant (Figure 5) was selected for conceptual design and systems analysis.

Since the total length of the selected ridge-top WECS installation is limited, it may be advisable to locate individual wind turbine generators (WTGs) at less than the ten diameter spacing usually recommended to insure that turbulent mixing will eliminate the wake energy depletion before it

Notes:

- Numbers are representative wind speed, m/sec
- Without parentheses: median values, no height correction
- With parentheses, variant data base, e.g.: mean wind speed, or part-time data taking, or higher instrument height
- Interpreted high wind areas shaded

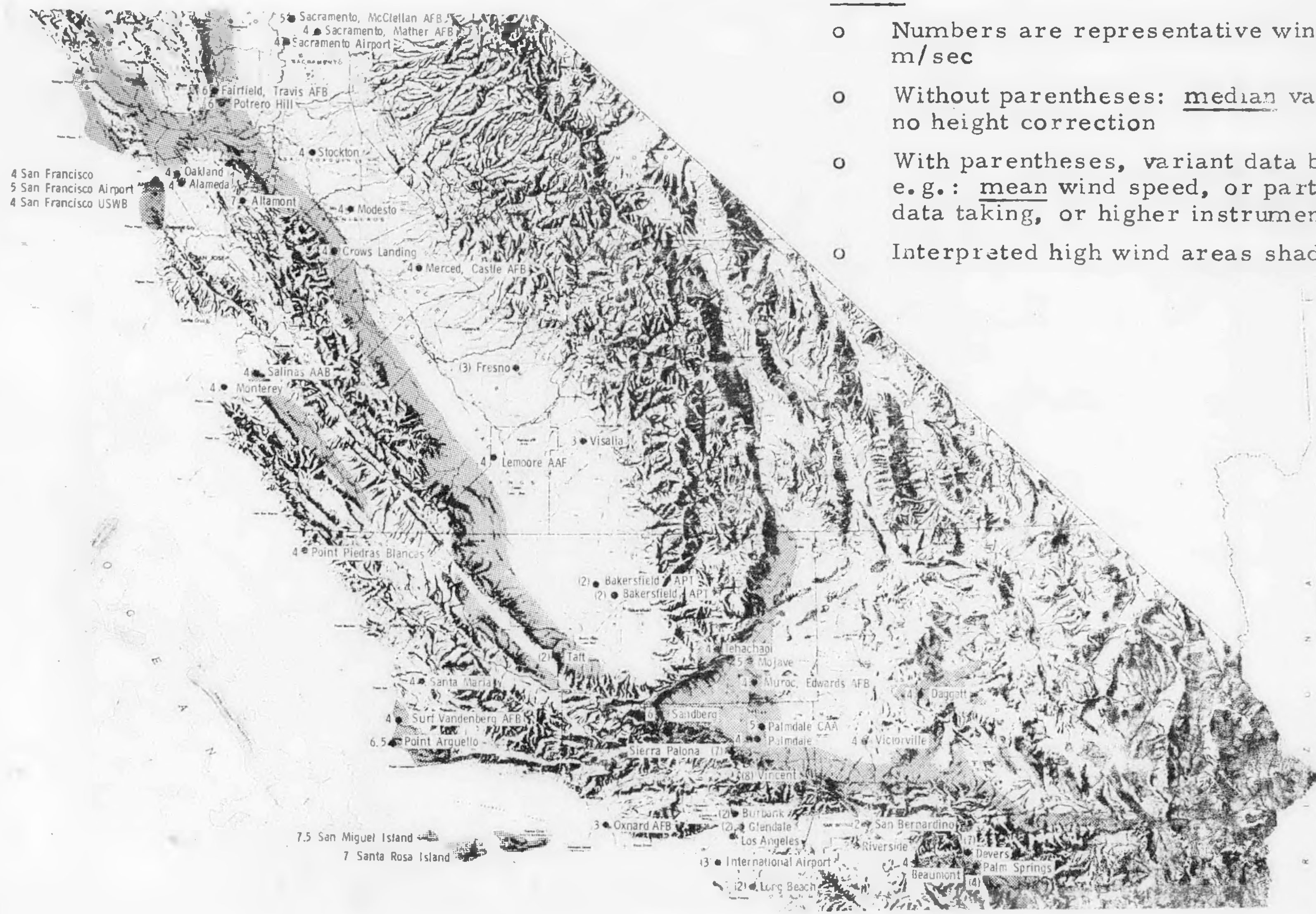
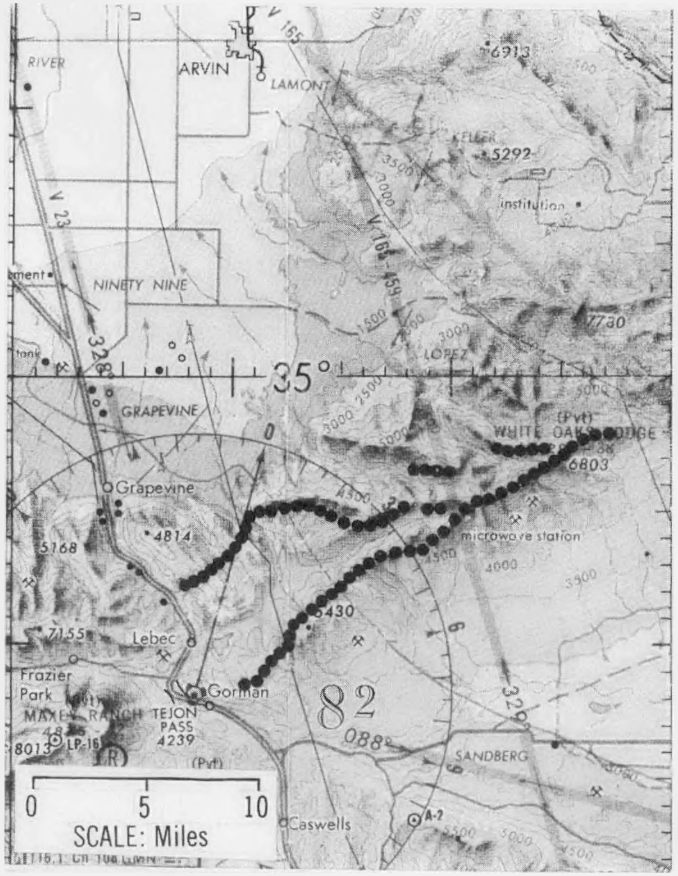


Figure 4. DISTRIBUTION OF HIGH WIND SPEED LOCATIONS



WIND MACHINE CHARACTERISTICS

- HORIZONTAL AXIS, 2 BLADE
- VARIABLE PITCH, FEATHERING
- CONSTANT SPEED, SYNCHRONOUS GEN.

SPECIFICATIONS

- 190 ft DIAMETER
- 4.16 kV
- RATED WIND: 22.5 mph
- RATED POWER: 1.5 MW

FIELD PARAMETERS

- RIDGE TOP ARRAY, NW FACING
- 200' SPACING
- UNIT RATED POWER: 40 MW/MI
- FIELD STARTS NEAR SCE POWER LINE E. OF GORMAN
- INITIAL EXPANSION N.E. AS NEEDED
- BREAK LINE AT PROPOSED CONDOR MANAGEMENT AREA
- SITES FOR RATED POWER ≈1500 MW

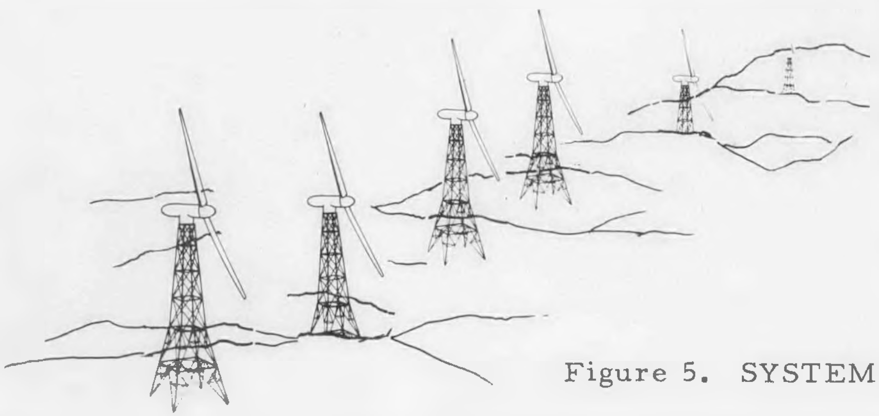


Figure 5. SYSTEM SYNTHESIS

reaches the next WTG. Figure 6 shows the flow situation at Tejon Mountain when the prevailing Northwest wind blows. On nearby Sandberg Mountain about 55% of the wind energy comes from this direction and another 11% from the opposite (SE) direction.

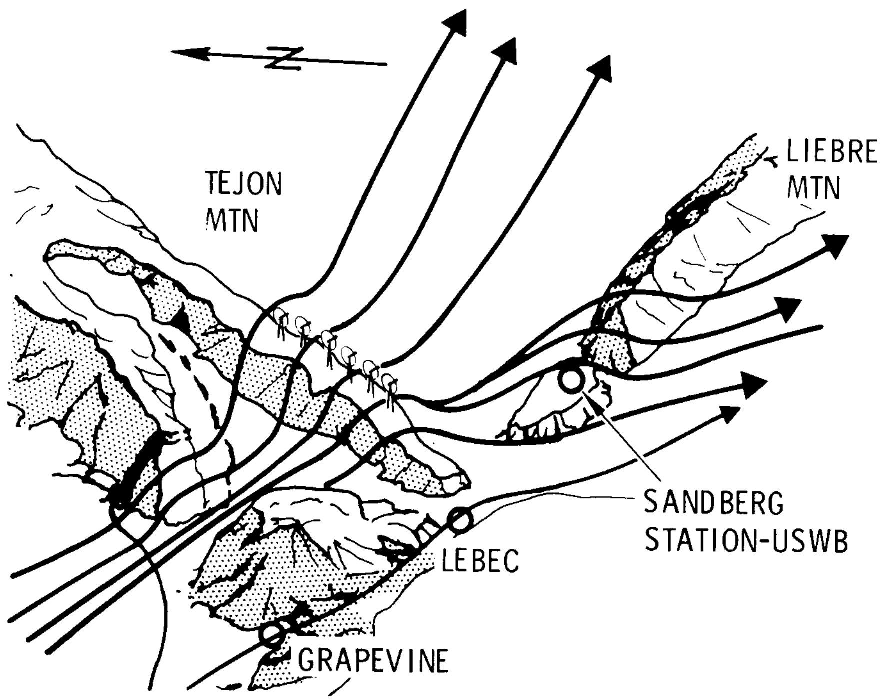


Figure 6. CLOSE-SPACED RIDGE TOP ARRAY

SYSTEM SYNTHESIS AND SIMULATIONS

A system concept was synthesized, which consists of between 100 and 1000 close-spaced WTGs in lines in the Tehachapi Mountains (Figure 5). The large number represents a full Aqueduct energy source. The small number represents a small wind energy system to augment conventional sources. The wind resource at this site was characterized by actual data from the nearby Sandberg site. Simulations in which system performance was evaluated for each hour over a full year were run to estimate the annual energy output and diurnal and long-term variations of the output. These simulations included performance simulation of the ERDA/NASA 1500 kW design and design perturbations of higher rated speed. The WECS capacity factor for the Sandberg wind site data now available is estimated to be 44% for the 1500 kW design, but sites yielding 50% can probably be found.

Since the installation of 500-1000 machines at ten diameter spacing would require 360 miles (579 km) of ridge lines, it would be necessary to use many sites of possibly lower energy resources. It appears that reduced WTG spacing is preferable. The proper choice of spacing depends upon the number of wind machines needed, the spread of energy projected for the sites available, the directional energy distribution for the actual sites, and the actual interference losses.

The energy loss due to close WTG spacing in a linear ridge top array depends on the unit spacing, the aerodynamics of the wake geometry, and the wind directional spectrum of the particular site. The wake interference loss for the Sandberg spectrum is indicated in Figure 7. There should be less interference loss at Tejon Mountain because channeling by the higher ranges to the north and south and the canyon to the west probably increase the percentages of the wind directions normal to the ridge at Tejon Mountain.

COST ESTIMATES

Energy cost estimates were made, based on the synthesized system and ERDA/NASA Model 1 WTG subsystem cost estimates. The basic capital costs are summarized in Table 1 broken down by the conventional power plant reporting categories. Transmission cost is about 5% of the capital investment, land is

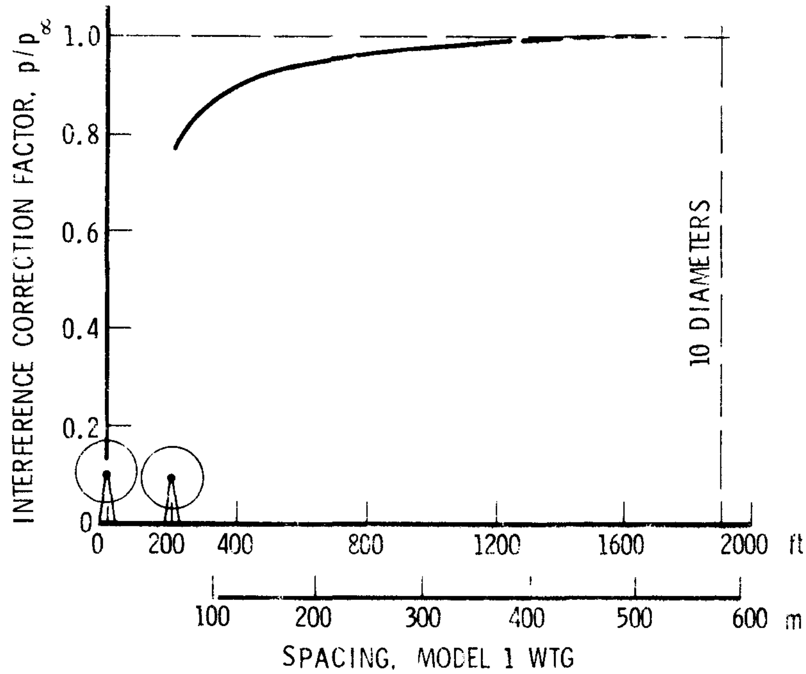


Figure 7. WECS INTERFERENCE CORRECTION; SANDBERG WIND DATA

less than 1%, and access roads are about 1/10%, too small to list separately. The total capital investment is estimated at $527/kW of rated capacity, including land, road, and transmission costs at the 150 MW size of WECS.

Estimates were made of Operations and Maintenance costs, and total system capital costs were estimated based on projected Aqueduct water bond interest rates of 7-1/2% with an assumed system life and bond maturity of 30 years. Similar estimates were made for coal-fired and nuclear baseload plants, using consistent costing techniques. The resulting unit energy costs for wind, nuclear, and coal sources are compared in Table 2 broken down by fixed charges,

Table 1. WIND MACHINE SYSTEM INVESTMENT COSTS PER UNIT CAPACITY BASELINE SYSTEM, 100 WIND MACHINES, 1.5 MW EACH

	1975 Dollars/kW
Land and Improvements	4.10
Towers	39.13
Rotor and Mech. Transmission	263.57
Electrical System	46.01
Miscellaneous Facilities	2.00
Pintle and Nacelle	22.54
Total, Basic Plant	377.35
Spare Parts	2.17
Contingency	26.49
Indirect Costs	80.40
Interest During Construction	10.25
Total Plant Investment	496.66
Transmission Facilities	30.13
Total System Cost	526.79

Table 2. ENERGY COSTS, NUCLEAR AND COAL PLANTS
MILLS/kWh, 1975 DOLLARS[4]

	WIND MACHINE SYSTEMS[1]		NUCLEAR[2]	COAL[2]
	450 MW	1500 MW	1000 MW	1000 MW
CAPACITY NO. OF MACHINES	300	1000	-	-
OPERATING COST				
Fuel	0	0	2.95	4.95
O&M	3.11	3.02	1.51	1.56
Total Operating Cost	3.11	3.02	4.46	6.51
FIXED CHARGES				
Cost of Money[3]	7.28	7.27	5.21	3.85
Depreciation	4.68	4.68	3.36	2.49
Insurance & Property Tax	.64	.64	1.52	.32
Total Fixed Charges	12.60	12.59	10.09	6.66
TOTAL BUSBAR COST	15.71	15.61	14.55	13.17
TRANSMISSION COST	.75	.68	1.27	4.12
DELIVERED ENERGY COST	16.46	16.29	15.82	17.29

1. Plant Capacity Factor, 40%.
2. Plant Capacity Factor, 65%.
3. Financing 100% debt at 7.5%, no Federal Income Tax.
4. No escalation or inflation.

operating cost, and transmission cost. All costs are figured at the rather low estimated capacity factors listed in the Table.

Figure 8 compares the various costs for various plant capacity factors, varying WECS size, and with and without reduction of WECS cost with quantity based on production and installation experience (96% experience curves). The wind resource available should give a WECS capacity factor of 0.45-0.50, resulting in unit energy costs slightly lower than the conventional alternatives.

BACKUP ENERGY COSTS

Evaluation of backup energy costs was made difficult by the fact that the Aqueduct demand is partly fixed and partly schedulable. However, an analysis reasonably approximating reality was found and used to obtain the results shown in Figure 9, based upon the 40% capacity factor WECS baseline.

The sources of backup energy examined were pumped hydroelectric storage, gas turbine generators and direct utility backup. Because six days or more of storage are required, pumped hydroelectric storage was found to be too expensive unless it was limited to 15 hrs. capacity and drew off-peak energy from the utility to replenish storage. Pumped storage with utility backup was found to be competitive with gas turbine generators and simple utility backup.

All three backup techniques are shown by Figure 9 to have very reasonable costs for the Aqueduct demand schedule of 1985 but increase to 30-40% of the basic energy cost as the schedule becomes more rigid. The spread of backup cost with varying fuel cost is shown for the gas turbine. The two utility based backup techniques have similar but slightly lesser fuel dependence because the utility generation has somewhat better fuel rates than the gas turbine and some fraction of non-petroleum fuel sources.

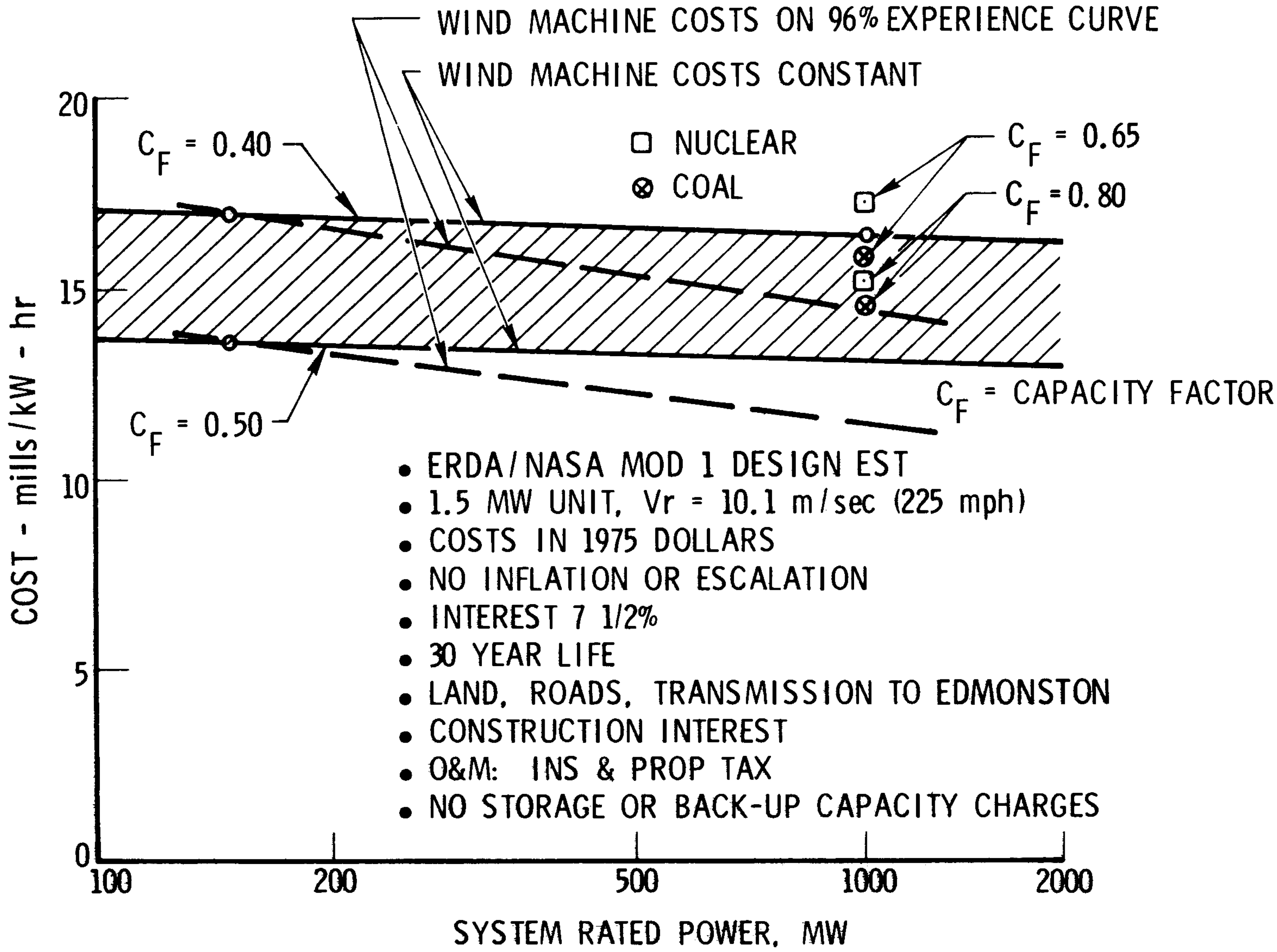


Figure 8. WIND ENERGY COST ESTIMATES (WITHOUT BACKUP)

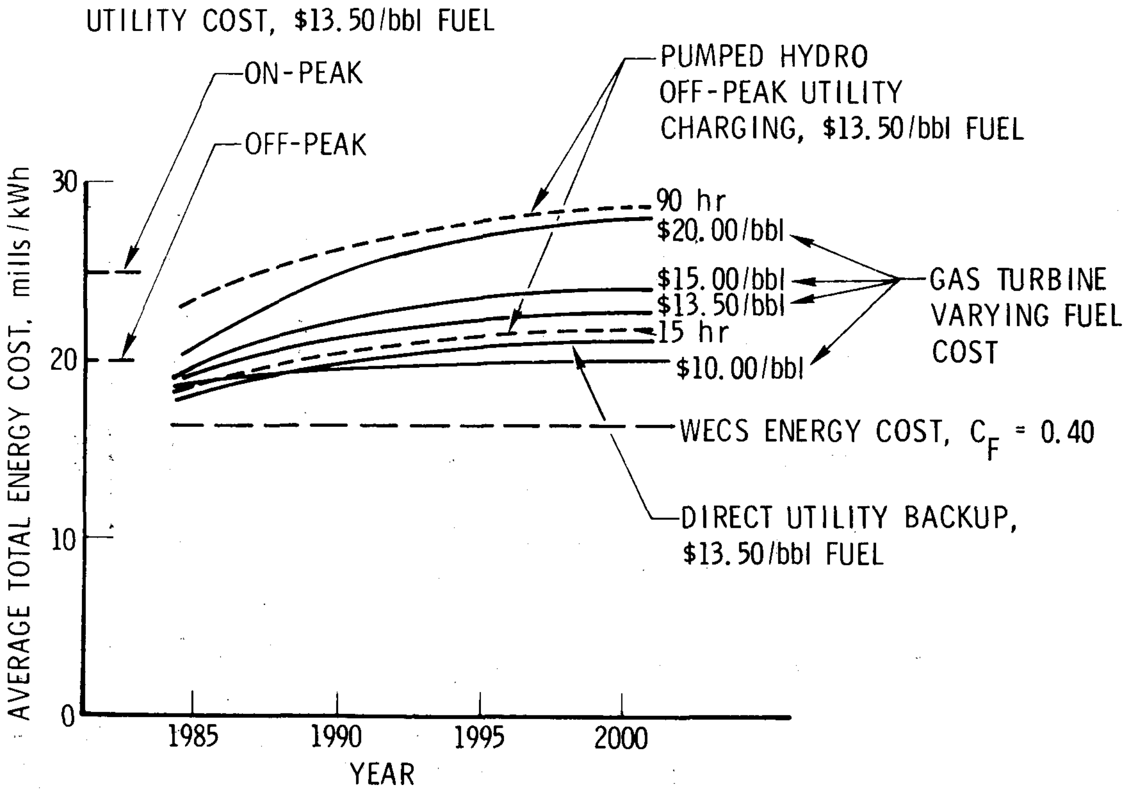


Figure 9. COMPARATIVE COSTS OF BACKUP MODES

The choice between backup modes would seem to depend on the relative valuation placed by the Aqueduct managers on self-sufficiency versus cushioning from fuel price rises. The comparative attractiveness of WECS versus a coal or nuclear plant within the Aqueduct system is reduced by the WECS backup cost, but even a coal or nuclear plant will require a lesser amount of backup for its outage time.

In practice, the backup system for any WECS or conventional generation system would incorporate the operationally limited pumped hydroelectric energy storage capability already incorporated in the Aqueduct at the Hyatt-Thermalito installation.

ENVIRONMENTAL AND RESOURCE ISSUES

The WECS system has at least one major favorable environmental impact, the displacement of about 10,000 barrels of petroleum consumption per year by each 1.5 MWe WTG. This implies corresponding reductions in air pollution, cooling water consumption, resource depletion, transportation problems, and energy import dependency.

A potential environmental concern would be the esthetic effect of many WTGs installed along the mountain horizon. However, the distance from the baseline Tejon Mountain site to the nearest point of major public access would render the WECS almost invisible. Contrasting color and lighting will be required to minimize aircraft flight hazards.

Possible effects on the California Condor, an endangered species, will be of concern, and further study of this problem is warranted.

RESULTS AND CONCLUSIONS

The following conclusions were reached:

1. Adequacy of Model 1 Design

   Based on the synthesized system and the Model 1 design data:

   (1) The design rating of the ERDA/NASA 1500 kW WTG design (8.0 m/sec or 18 mph design wind speed) gives the lowest unit energy cost for its parametric family of designs with the actual velocity spectrum of wind data used to characterize the source.

   (2) The WTG costs estimated in ERDA/NASA design studies for the 1500 kW WTG ($429/kW) and the proven wind resource at Sandberg Station, result in energy costs of 1.3 to 1.7 cents per kWh, approximately equal to coal and nuclear-fueled baseload power plants. The anticipated identification of more favorable winds nearby

would lead to lower energy costs.

(3) For this location the WTG must be capable of operating under severe icing conditions.

(4) To maximize the energy recovery from a limited mountain ridge or pass location of high wind energy, the WTG should be able to operate in the near wake of another machine.

(5) A commitment to use the 1500 kW WTG for a major portion of the Aqueduct energy demand by 1983 would involve serious schedule risk.

2. Effect of Design Variations

(1) The 500 kW WTG design (5.4 m/sec, (12 mph) design wind speed) has too high a cost per rated kilowatt to compete in this application.

(2) A significantly higher design speed than 8 m/sec does not collect enough additional energy to justify the added cost. Also, it increases the seasonal and diurnal variations in output.

(3) If a significantly higher energy wind resource were found in the region, as is expected, a higher rated speed might be preferred.

(4) Larger WTGs may be favored in mountain locations because they would extract more energy in a high energy site of limited extent, such as a limited ridge line.

3. Energy Storage Issues

(1) The Aqueduct could, at present, use wind energy when available and very little power when there is no wind. However, by the time a WECS could be installed, flow

capacity saturation and operational constraints will require a large and increasing component of backup power.

(2) Adding fifteen hours energy storage could increase the WECS investment and energy cost about 30%. A part of this capacity could come from the operationally limited pump hydroelectric capacity within the Aqueduct itself.

(3) Because of long wind outages, a hydroelectric pumped storage system without utility backup would be excessively costly.

(4) Backup by gas turbine, direct utility power, or off-peak utility filling of a pumped hydroelectric storage system, all provide acceptable cost increments of 30-40%. Costs remain approximately competitive, since conventional sources owned and operated by the Aqueduct would also require some backup.

4. Wind Resource Data

(1) Wind data from attractive mountain ridge and pass locations is very scarce.

(2) The energy resource probably varies greatly between nearby mountain tops.

(3) Detailed site surveys before installing a major WECS system in mountain terrain is likely to be moderately expensive and time consuming.

(4) Unless many sites of nearly equal energy are available, WTGs should be installed at spacings much less than 10 diameters, especially if terrain constrains the flow to a strongly prevailing direction.

Environmental Issues

(1) A WECS installation on the Aqueduct could displace petroleum fuel consumption to the extent of about 10,000 barrels per year for each 1.5 MW unit. This displacement could reduce air pollution, water consumption, resource consumption and oil imports proportionally.

(2) No significant meteorological effects or microwave and television interference problems are expected.

(3) The WTGs on mountain tops could be considered a flight hazard and will probably require clearance lights and contrasting paint.

(4) Possible impact on the California Condor, an endangered species, will be a consideration in this region.

(5) The esthetic impact of wind machines on mountain crests may be an issue. The location considered, within the 40,000 acre Tejon Ranch provides very low visibility from the nearest public access.

*U.S. GOVERNMENT PRINTING OFFICE: 1978 740-306/9406. Region 4.