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PN-AAV-125

IRN-45463

20 MAY 1986

RENEWABLE ENERGY RESOURCES
FIELD TESTING

APPLICATION REVIEW FOR FIELD TEST #6

PHOTOVOLTAIC/DIESEL POWERED ICE MAKING PLANT AT WADI EL RAIYAN

MAY 1986

FINAL

Renewable Energy Field Testing
Project
USAID 263-0123
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Prepared for

Egyptian Electricity Authority
Cairo, Egypt

U.S. Agency for International Development
USAID Mission: Cairo, Egypt

Submitted to

Louis Berger International, Inc.
Washington, D.C.
(Contract AID 263-0123C-00-4069-00)
(Meridian Task No. MC-173-396)

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FOREWARD
APPLICATION REVIEW

The Egyptian Electricity Authority (EEA), the United States Agency for International Development (USAID/Cairo), and a group of U.S. consultants form a team responsible for conducting field test demonstration projects for eleven renewable energy applications in Egypt. These demonstration projects include the use of photovoltaic, wind and solar thermal systems for water pumping, ice making, desalination, industrial process heat and grid connected electricity generation. The specific objectives of the four-year program are: (1) to demonstrate the viability of renewable energy technologies in Egypt, (2) to comprehensively strengthen Egyptian technical and institutional capabilities in the full spectrum of renewable energy planning and decision making, and (3) to establish the infrastructure necessary to ensure that renewable energy technologies, which have proven successful, are available for widespread use in Egypt.

Each of the field tests contains seven generic tasks: Technology Review, Application Review, Conceptual Design, Preparation of a Statement-of-Work for a Tender Document, Proposal Evaluation, Supervision of Hardware Installation and Performance Evaluation. Three of the eleven potential field test demonstration projects are photovoltaic (PV) energy system applications. The Application Review for one of these three field tests, a PV/Diesel Powered Ice Making Plant, is presented in this document.

The proposed system is sited near Wadi El Raiyan near El Faiyum. The system consists of a six ton per day capacity ice making plant powered by a 35 kilowatt peak (kWp) photovoltaic array, with a 22 kW diesel and 233 kilowatt hour (kWh) of battery storage. The power system is designed to operate as a PV/diesel hybrid system.

This Application Review is the key document on which a decision to proceed further with this particular field test will be based. The review summarizes an evaluation of the proposed field test location, user requirements, solar resource assessment and the technology of photovoltaics in combination with diesel energy systems to meet the load levels required of ice making.

A preliminary engineering cost estimate was completed as part of this Application Review in support of Task 2.1. This cost estimate is presented in Appendix D of this document.

This document is subtask 3.6.1 of the field test requirements under Contract AID 263-123C-00-4069-00, Task Area 3. The recommendations made in this document are based on the technical merit of the application. The results from Task 2.1, Economic/Market Assessment address other factors that may impact the potential for widespread implementation of PV/diesel powered ice making plants in Egypt. The Task 2.1 results are provided in a separate document.

Finally, general background technical information on photovoltaics has been provided in the Photovoltaic Technology Reference Notebook (TRN) under Task 2.2.4. Section 5.0 of this Application Review contain a summary of the TRN information relevant to this specific field test.

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1. EXECUTIVE SUMMARY

1.1 Criteria for Evaluation of the Field Test

The proposed field test for a photovoltaic (PV)/ diesel powered ice making system is one of the original eleven field tests under the Renewable Energy Field Testing (REFT) Project. The principal objective of this field test project is to provide the Egyptian Electricity Authority (EEA) with practical working experience with photovoltaic energy systems as a long term, least-cost remote power supply for refrigeration, and specifically for ice making. This experience includes system design, operation, maintenance, repair, and evaluation of photovoltaic systems for the purpose of assessing and implementing similar projects throughout Egypt.

There are a number of key factors that provide the context for Application Reviews and support the evaluation of the desirability to proceed with a particular field test. The first factor is the degree to which the field test contributes to the objectives of the overall REFT Project. The Project has broad objectives to investigate selected renewable energy options:

1. Comprehensively strengthen Egyptian technical and institutional capabilities in the full spectrum of renewable energy planning and decision-making for technologies and applications;

2. Develop and sustain an Egyptian renewable energy infrastructure through establishment of data bases, information systems and organizations that effectively serve both the public and private sectors;

3. Design, realize and evaluate the performance of a series of field tests which utilize commercially available technologies in applications having potential for widespread use in Egypt.

4. Complete formal managerial and technical training, both on-the-job and specialized, and an intensive information dissemination program.

An assessment of the contribution of this specific field test to the REFT Project objectives must consider the criteria necessary for a successful

demonstration of any PV/diesel power system. These criteria are comprehensively listed below, although not necessarily in the order of importance.

1. Current and future user needs
2. A viable solar and water resource
3. Proven, reliable and commercially available systems
4. Site characteristics and infrastructure for installation
5. Capability for successful operation and maintenance of the systems
6. Potential for widespread use in Egypt

The application of a PV/diesel power system for ice making at Wadi El Raiyan will serve as a demonstration of the capability of the combined technology of PV and diesel to reliably supply significant amounts of power in remote locations. Other applications that are expected to have similar load levels and characteristics are communications and centralized village electrification. It is important that this field test be designed to distinguish between the performance of the PV/diesel power system and the performance of the ice making equipment and other related equipment such as instrumentation and water treatment so that the PV/diesel power can be evaluated for other applications. This field test will also provide valuable data on the field performance of diesel generators in comparison to PV under similar levels of maintenance and operational support.

The following paragraphs summarize the findings of various studies and analyses addressing these criteria. Detailed discussions of each are provided in the respective sections of the document or in additional published documents as referenced.

1.2 Current and Future User Requirements

The location chosen for this field test is Wadi El Raiyan, an area 140 kilometers south-west of Cairo, near El Faiyum.[1] Wadi El Raiyan consists of two large man-made lakes formed by the discharge of an agricultural canal. The lakes are managed by the Fish Resources and Development Authority (FRDA) as a source of fresh fish for El Faiyum, Cairo, and neighboring market areas.

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[1]While English spellings of Arabic words are used consistently throughout this report, accepted local variants are used in cited sources.

Two site visits were made with representativees from Meridian Corporation, EEA and FRDA to collect information on fish production, ice demand, solar and water resource, relevant institutional factors, and market and economic data.

There are two principal fishing locations at the lake area. The "central location" is about 40 km west of El Faiyum on the bay of the first lake at the outlet of the agricultural drainage canal. Approximately 90 oar powered boats operate from this location bringing in about 1000 metric tonnes of fish per year. The road leading to this site from El Faiyum is the main access road to the lake area. It is unpaved and often indistinguishable from surrounding desert. The other principal fishing location has been designated the "second lake location." Forty-six boats currently operate from the second lake location providing approximately 400 tonnes of fish per year. The combined fish production from the lake is therefore estimated as 1400 metric tonnes per year.

Fish Production

Fishing is regulated by the FRDA. The season may extend from September through April with daily catches ranging from 40 tonnes per day occurring in the early part of the season and tapering off toward the spring to as little as 0.2 tonnes per day. No fishing is permitted during the summer months of June, July and August because of the spawning season. Based on discussions with FRDA personnel and evaluating the limited data available, average daily catch throughout the fishing season is estimated to be between 6 and 10 tonnes per day.

Fish are mixed with ice at the lake location. Currently ice is brought from El Faiyum in block form and crushed at the lake with a diesel powered mechanical crusher. The fish are packed and trucked to markets in El Faiyum, Cairo, and as far as Alexandria.

Ice Demand

The ratio of ice to fish determines the present use of ice. The ice/fish ratio at Wadi El-Raiyan ranges from 1/2:1 to 2:1 depending on the market

locations and the quality of ice used. Therefore the average season daily ice demand for fish preservation may range from 3 tonnes per day to 20 tonnes per day.

In addition to the ice demand for fish preservation, there is a steady ice demand in the El Faiyum area for home refrigeration. Information collected for the market/economic analysis (Task 2.1) indicates that the demand for ice in the El Faiyum area is significantly greater than the ice making capacity. Therefore, a greater utilization of the PV/diesel ice making plant throughout the year is possible if ice can be sold to non-fish specific markets. This will significantly improve the economics of the facility by maximizing the use of the capital-intensive PV power system and ice making equipment.

1.3 The Resources at Wadi El Raiyan

Insolation data were calculated based on recorded data (sunlight hours) from a meteorological station in El Faiyum. Horizontal daily global insolation ranges from 3.4 kWh per m2-day in December to 8.1 kWh per m2-day in June. Appendix A provides solar insolation, ambient temperature, and water temperature data for the site.

Ambient temperature data are based on meteorological station data from El Giza. An additional two degrees has been added to each temperature to reflect the generally higher temperatures at the site. Average daily temperatures range from 30.2 to 15.2°C over the year.

Water temperature for the lake at Wadi El Raiyan is estimated to range from 8 to 26°C in the vicinity of the central location. The water is apparently not potable based on World Health Organization (WHO) standards. Until a more thorough and accurate analysis is obtained, it is not possible to determine the extent of water treatment that may be required. For the preliminary conceptual design in this Application Review, it was assumed that the ice maker input water is potable.

1.4 Preliminary Conceptual Design

Ice Plant Capacity Sizing

An ice plant capacity of 6 tons per day (12000 pounds per day)[2] has been selected as a candidate sizing. This sizing capacity will meet a significant portion of the average daily demand for ice. It is also a reasonable size for demonstrating the design, operation and maintenance, and evaluating the complete technical and cost performance of photovoltaic and diesel power systems for making ice. The two most important factors regarding ice plant sizing are that: (1) the demand for ice is greater than the ice production capacity of the area, and (2) the cost of the largest cost component of the PV/diesel ice plant, the PV array and battery system, is relatively linear with increasing array size. Therefore a 6 ton/day capacity ice plant and power system can be regarded as a "modular design." Over the course of this field test, the performance of the system can be evaluated. Modifications in design and operation can then be made to result in self-contained ice plants (ice maker and power system) with applicability at other locations throughout Egypt.

Power System and Ice Plant Design Selection

A Technology Review (TR) for this field test is submitted to EEA as a separate document. The review includes ice making equipment, photovoltaics, battery systems, diesel generators, and related equipment relevant to the design of a power system and ice making plant for this field test. The principle findings of the Review relate to the choice of ice making technologies, power system and load current selection (AC or DC), and the sizing of the PV array and battery.

Plate or flake ice making technologies are the most suitable for fish

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[2] U.S. ice maker ratings are in "tons" (2000 pounds) as distinct from "tonnes" (2200 pounds or 1000 Kilograms)

preservation and are more energy efficient than block ice making which is currently practiced. Plate ice is formed by passing water over a refrigerated vertical surface and allowing a sheet or plate of ice to build up to a preset thickness. Plate ice can be made into block ice for commercial sale through the use of a "block press." The principal disadvantage of plate ice is that it is a cyclic process which requires that the diesel generator, battery, and all electronics be sized for peak and fluctuating loads. Flake ice technology produces ice by rotating a cutting blade or drum to shave ice off a forming surface. Flake ice has the highest surface-area-to-weight ratio of the ice making technologies and therefore is the most energy efficient. It results in a relatively continuous load which simplifies the design and operation of the power system.

The energy required to make ice by either plate or flake technology for Wadi El Raiyan ranges from 60 to 80 kWh per ton-day which includes the energy demand for ice making, storage, water supply and miscellaneous lighting loads. Based on a 6 ton/day ice demand and an average energy requirement of 70 kWh per ton of ice per day, the daily energy demand is calculated as 420 kWh per day.

The principal power system design question is the selection of either an alternating or direct current (AC or DC) system. For AC systems stand-alone inverters are required to convert DC power (from the PV array and battery) into AC power. The poor reliability, capital expense, and inherent energy conversion efficiency (80 - 90 percent) of stand-alone inverters favors a DC system design. However, because conventional ice making equipment uses AC motors, a DC system requires that AC motors be replaced by DC motors. Since the power system will integrate a diesel generator with a PV system, the diesel generator must also be capable of producing DC power either directly or through the use of a separate rectifier. These required modifications for a DC system may be justified on the basis of improved operating reliability and efficiency of the system.

An evaluation of the sizing of the PV array and battery system has resulted in a determination that the optimum renewable energy system for ice making loads is a "hybrid" power system, combining the technologies of PV and diesel generators. Hybrid power systems i.e. PV/diesel power systems, as referred to in this report, improve the performance of both diesel and PV power systems by increasing the operating capacity factor. The PV/diesel hybrid is an integrated power system that is distinct from a PV system with a diesel generator backup. In the hybrid system, both PV and diesel generate and supply power on a regular basis. The energy is dispatched from each source so that total energy costs are minimized. For example, in a PV/diesel hybrid the diesel might be used to supply power at night and the PV used as the primary source of power during the day. In contrast, a PV system with diesel backup would use PV to supply the total energy requirements of the load; the diesel would only be used in unusual circumstances such as long periods of unexpectedly low insolation. Compared to a PV only or a PV system with a diesel backup, advantages of a PV/diesel hybrid are many. For example, the diesel generator is able to operate at rated capacity which results in the best fuel to electricity conversion efficiency and reduces maintenance frequencies. The size of the PV array and battery systems can be reduced because the diesel will provide power during extended periods of low insolation and during seasonal load and insolation mismatch. This effectively increases the capacity factor of the PV array and battery system.

Comparative Cost/Analysis

Cost projections for PV prices show that PV will become competitive with diesel in the 1995 timeframe at costs of about $0.27/kWh. Based on projections to 1995 for PV, diesel, and battery energy costs, one hybrid system that could be justified is a PV array and battery system sized to provide between 30 and 40 percent of daily average load. The remaining energy would be supplied by the diesel. This sizing provides the EEA with significant operating experience with all

major components of PV/diesel hybrid systems and as such will form the design basis for optimizing PV, battery, and diesel sizing on future applications. Estimated sizing for the PV/diesel powered ice making plant described above is as follows:

PV Array	35 kW
Battery Storage	233 kWh
Diesel Generation	22 kW
Ice Making Plant	6 tons/day

This component sizing is based on a DC system design incorporating the flake ice manufacturing process resulting in a continuous, stable load and a minimum of battery storage capacity. This system design is only one of many possible configurations. For example, alternate designs features could include AC power supply, different proportions of energy being supplied by the PV and battery, or a larger ice maker operated for a shorter period during the day. These and other alternative configurations will be discussed in detail in the conceptual design (Task 3.6.3).

1.5 Status of Agreements and Responsibilities

The daily operation and maintenance associated with ice making dictate that full time operators be assigned to the location. EEA and FRDA have signed a contract, covering a two year period, for the operation, maintenance, repair and monitoring of the facility. Aspects of this agreement which are pertinent to the operation, maintenance, repair and monitoring should be made available to all involved parties (including bidding contractor) so that clear lines of responsibility will be understood.

1.6 Conclusions and Recommendations

Based on this Application Review, the following conclusions and recommendations are provided.

Conclusions

1. The Wadi El Raiyan location is an acceptable application site for

demonstrating the use of photovoltaics for ice making because there is an existing and growing demand for ice, the solar resource is exceptional, and the location represents a balance between remoteness and accessibility for monitoring and evaluation.[3]

2. The sizing of the ice plant is based on average daily ice demand because daily ice demand fluctuates over the season. A modular design using proven, reliable, and commercially available systems is considered so that additional capacity can be added in the future and the potential for other applications throughout Egypt is enhanced.

3. The most suitable ice making technologies are plate or flake because they are the most energy efficient and suitable for fish preservation.

4. The lowest cost, most reliable design choice, on a long term basis, is a PV/diesel hybrid power system.

5. The financial viability of PV/diesel remote power systems for ice making depends on the cost of photovoltaic energy compared with diesel produced energy.

6. The design, operation, maintenance, and repair experience with PV/diesel hybrid power systems that will be obtained through this field test will form a strong technical and cost data base for the design and application of PV/diesel power systems for other remote power applications.

Recommendations

The PV/diesel hybrid is an integrated power system that is distinct from a PV system with a diesel generator backup. In the hybrid system, both PV and diesel generate and supply power on a regular basis. The energy is dispatched from each source so that total energy costs are minimized. For example, in a PV/diesel hybrid the diesel might be used to supply power at night and the PV used as the primary source of power during the day. In contrast, a PV system with diesel backup would use PV to supply the total energy requirements of the load; the diesel would only unexpectedly low insolation. Compared to a PV only or a PV system with diesel backup, advantages of a PV diesel hybrid are many. For example, a 6 ton/day ice making plant, powered by a 35 kW PV/22 kW diesel hybrid power system with 233 kWh of battery storage is recommended to be field tested at Wadi El Raiyan. This recommendation is based on the following assumptions:

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[3] Assumes that potable water is available for ice making. [NOTE: Water quality data is currently insufficient to determine the extend and cost of water treatment that may be required. Depending on the results of further data collection and analysis, the conclusions presented in this Application Review may be modified.]

1. The life cycle cost of PV power is likely to be less than the life cycle cost of diesel power in Egypt within the next 10 to 15 years.

2. The timeframe of 10 to 15 years is within the energy planning and institutional perspectives of the Egyptian Electricity Authority.

Additional system configurations will be evaluated during the conceptual design phase of this field test.

2.0 OBJECTIVES AND BACKGROUND

2.1 Objectives

The primary objectives of this field test are to provide EEA with practical working experience with photovoltaic energy systems, and to provide system design and operational training for Egyptian engineers for the purpose of assessing and implementing similar projects throughout Egypt. This field test will evaluate the viability of photovoltaic energy systems and PV in combination with diesel energy systems, through the demonstration of a PV/diesel powered ice making plant.

The application of a PV/diesel power system for ice making at Wadi El Raiyan will serve as a demonstration of the capability of the combined technology of PV and diesel to reliably supply significant amounts of power in remote locations. Other applications that are expected to have similar load levels and characteristics are communications and centralized village electrification. It is important that this field test be designed to distinguish between the performance of the PV/diesel power system and the performance of the ice making equipment and other related equipment such as instrumentation and water treatment so that the PV/diesel power system can be evaluated for other applications. This field test will also provide valuable data on the field performance of diesel generators in comparison to PV under similar levels of maintenance and operational support.

2.2 Background

The site chosen for a field demonstration of this application is Wadi El Raiyan, an area 140 kilometers south-west of Cairo, near El Faiyum. Exihibit 2-1 shows the lake area of Wadi El Raiyan with reference to El Faiyum and Cairo. Wadi El Raiyan consists of two joined man-made lakes, currently totaling about 50,000 feddans, being formed by the discharge of an agricultural canal flowing from the El Faiyum area. The first lake is 12,000 feddans in area and

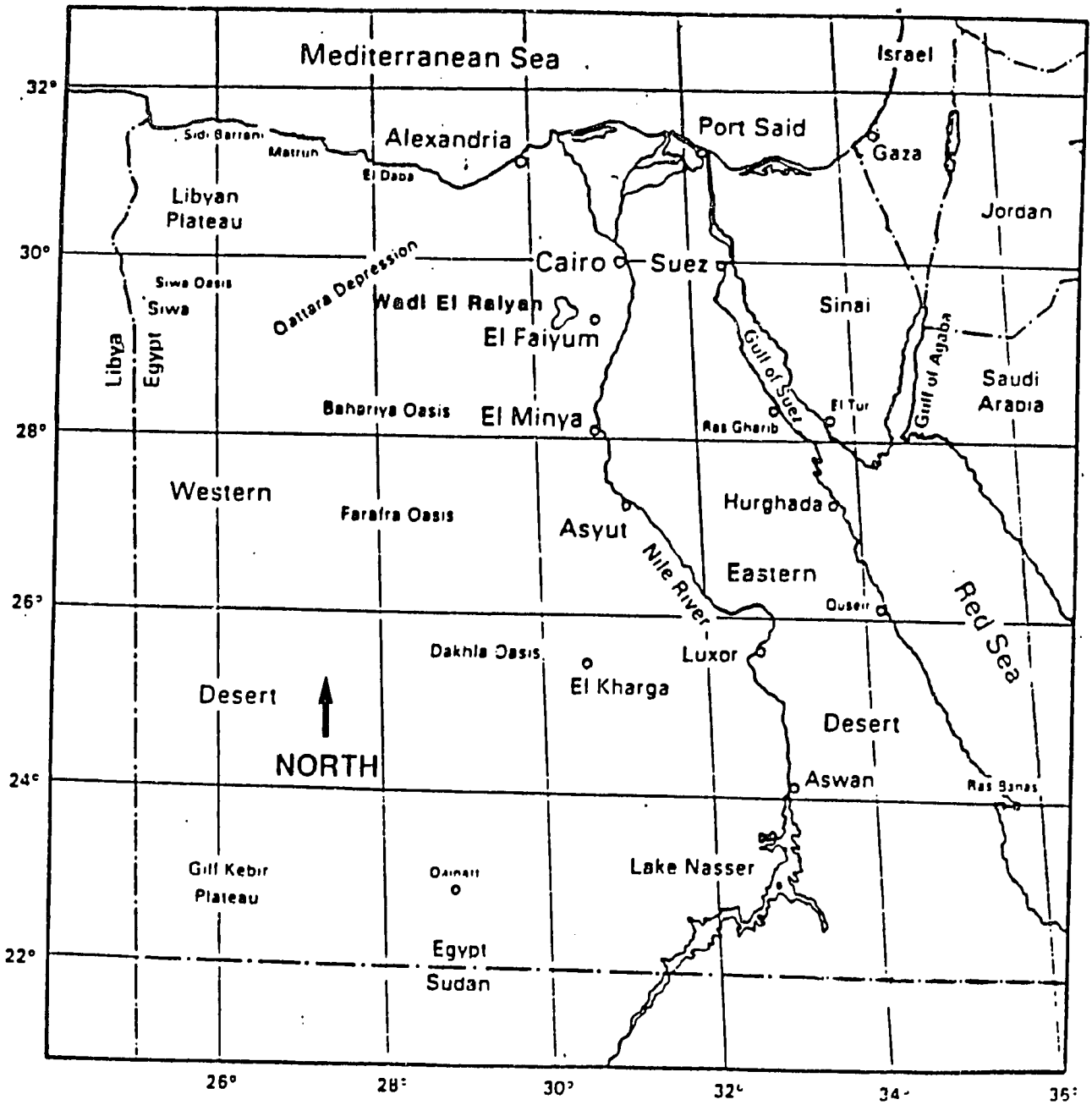

Exhibit 2-1 WADI EL RAIYAN LAKE LOCATION

the second lake area is 35,000 feddans. The two lakes are joined by a canal whose are is 3,000 feddans.

The lakes are managed by the Fish Resource and Development Authority (FRDA) as a source of fresh fish for El Faiyum, Cairo and neighboring market areas.

The Wadi El Raiyan lake area has two fishing locations, shown in Exhibit 2-2. The "central location" is about 40 km west of El Faiyum on a bay of the first lake at the outlet of the agricultural drainage canal. The road leading to the site is unpaved and often undistinguishable from the surrounding desert. Approximately 90 oar-powered boats operate from this location during the season producing about 1000 tonnes of fish per year.[4]

The "second lake location" is about 30 km south-west of the central location on a newer, larger lake. Forty-six oar-powered boats currently operate from this location bringing in approximately 400 tonnes of fish per year.[5]

Historical data on fish catch and distribution is very limited. Estimates based on two site visits and discussions with FRDA personnel indicate that the daily catch may range from as much as 40 tonnes to as little as 200 kilograms per day over the fishing season.[6] The season is set by the FRDA and may extend from September through April. No fishing is permitted from June through August because of the spawning season. Based on a total lake production of 1400 tonnes/season, and discussion with FRDA personnel, average daily catch is from 6 to 10 tonnes/day.

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[4]Data collected by Seyoum Solomon of Louis Berger International, Inc. during site visit October 1985.

[5]Ibid.

[6]Abdel-Halim, Ahmed El-Mokhtav, Fish Production December 15 to April 15, 1984, FRDA, Personal Communication

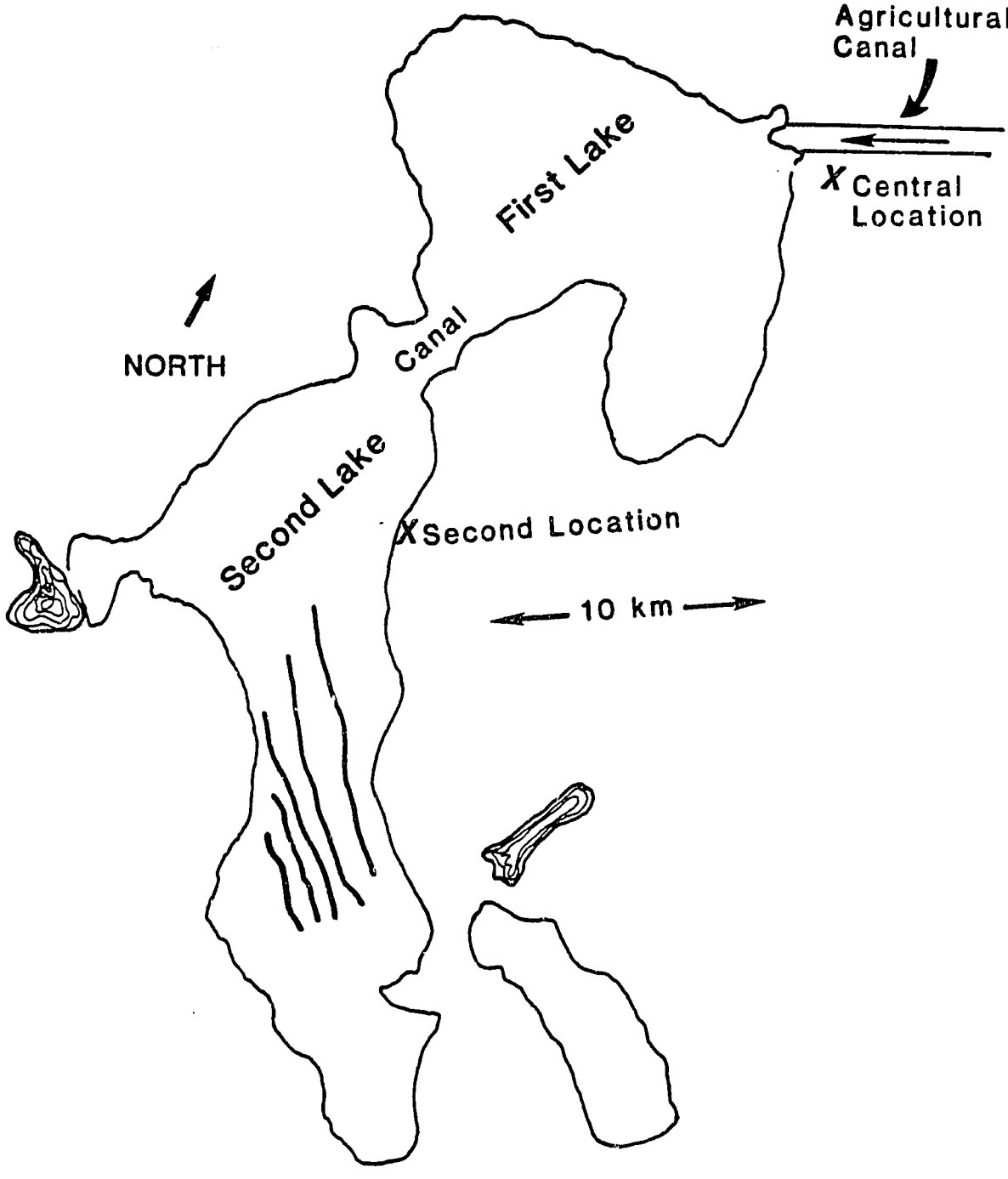

Exhibit 2-2. WADI EL RAIYAN LAKE AREA

Ice is currently transported 40 km from El Faiyum to the fishing locations where fish are packed and trucked to markets in El Faiyum, Cairo and points as far as Alexandria. Some fish are sold direct to merchants at the lake location.

The ice making capacity of the El Faiyum area is approximately 421,000 blocks per year made in grid-connected ice plants. Block weight ranges from 25 kg in the winter to 15 kg during the summer when the high demand does not permit the production of solid blocks (i.e. hollow blocks are produced). The resulting capacity tonnage is approximately 30 tonnes per day.

Based on information collected during the second site visit the demand for ice in the El Faiyum area is significantly greater than the ice making capacity. In addition to the ice needed for fish and other food preservation, there is a steady demand for block ice for private use (home refrigeration). The installation of an ice making plant at the lake to serve the fishing sector will therefore also serve the surrounding area, especially during the summer and toward the end of the fishing season when the demand for ice for fish preservation declines. The reliable availability of ice at the lake is also expected to contribute to an increase in the annual fish catch by reducing spoilage. (Data on the extent of spoilage are not available).

3.0 ASSESSMENT OF USER REQUIREMENTS

3.1 Summary of Site Visits

Site Visit - May 23, 1985

The first of two site visits was made to Wadi El Raiyan on May 23, 1985. The following people participated: EEA senior engineer Rafik Georgy, EEA staff engineers Helmy El Fotouh and Heba Gawad; Lawrence Slominski and Judy Hogan from Meridian Corporation; and Ibrahim Galla from the Fish Resources and Development Authority.

The central location and the second lake location were visited and interviews with Mr. Galla provided market, economic and technical data on current and future fishing development activity around the lake.

Two likely sites were identified at the central location for the PV/diesel power system and ice plant. The site criteria used were that it be relatively level, stable ground as close as possible to the fishing activity to reduce wiring power losses and provide for easy maintenance and security of equipment. A site layout is provided in Exhibit 3-1. One possible site is east of the fisherman's shelter, bounded on two sides by the access road and on two sides by steep, sloping sand down to the water front. The usable area is 45 meters by 60 meters requiring a minimal amount of grading.

The second possible site is northeast of the agricultural canal (Nile Canal) surface outlet. This site is relatively unbounded in area and slightly flatter than the first site. Both central location areas are easily accessible from the fisherman's shelter (100 meters) or from the roadways leading to El Faiyum and the second lake.

The second lake location was also visited. A schematic of the site is provided as Exhibit 3-2. The most likely site is within 100 meters of the water inlet where flow from the central location lake enters the second lake. The area is level and a large array could easily be sited.

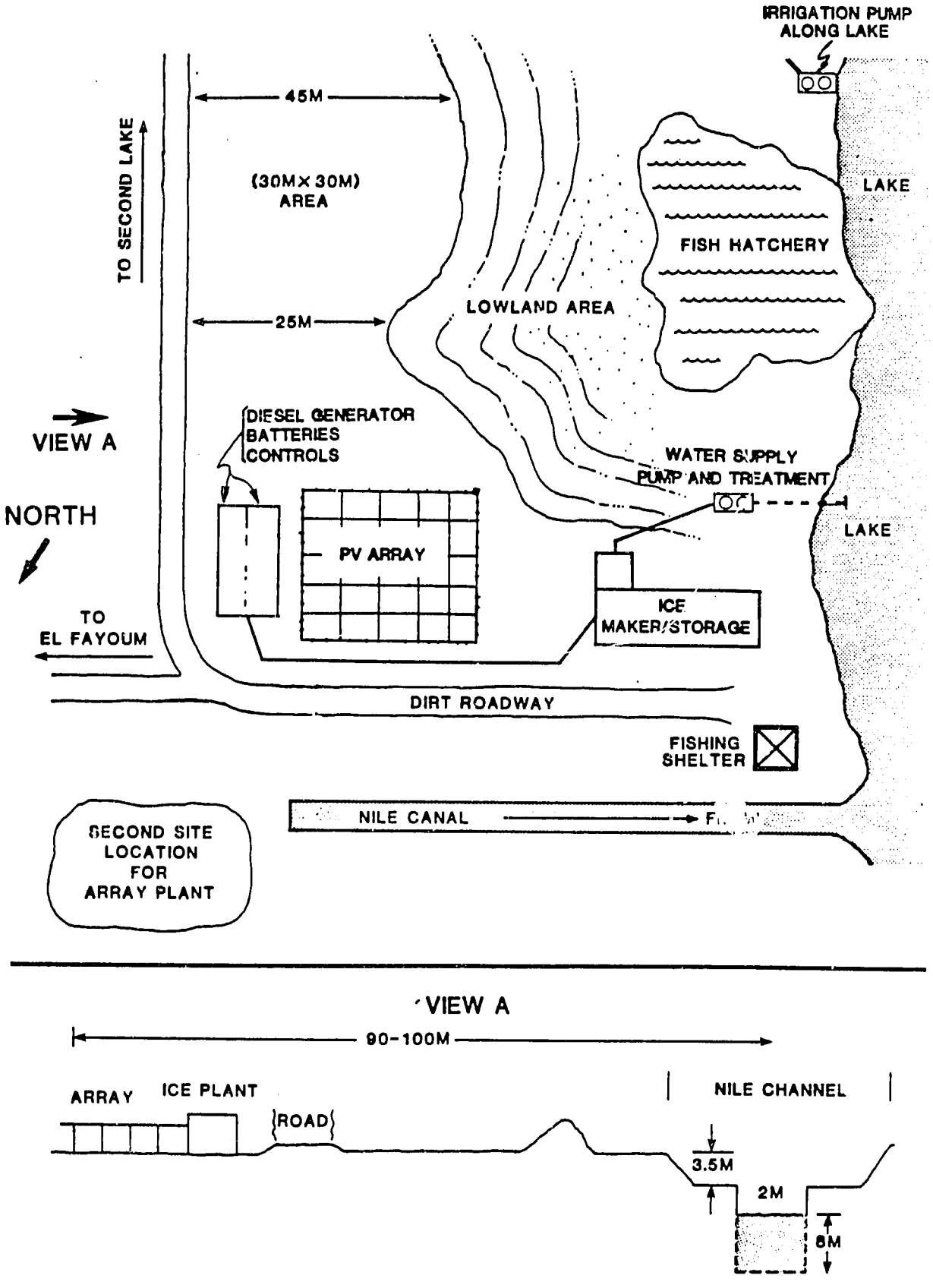

Exhibit 3-1 CENTRAL LOCATION - SITE SCHEMATIC

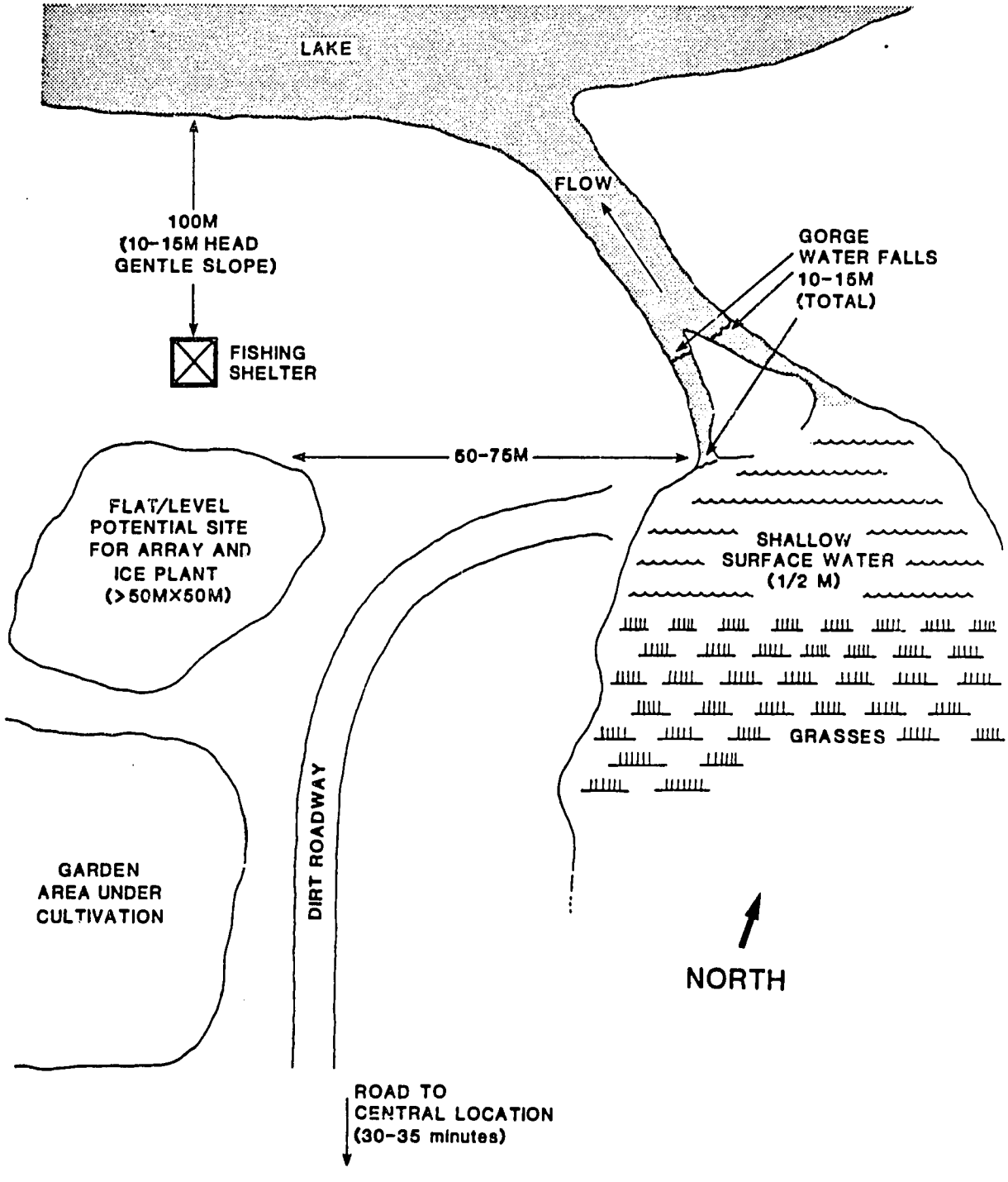

Exhibit 3-2 SECOND LAKE LOCATION - SITE SCHEMATIC

There is less fishing activity at the second lake location than at the central location lake. However, fish production is expected to steadily increase over the next few seasons and the second lake location will eventually surpass the first lake in total annual catch.

Water supply was available at both the central lake and the second lake location for making ice and for condenser cooling. Since water quality is crucial to producing potable ice and reducing equipment maintenance, a water quality analysis of both locations was requested.

Site Visit October 16-17, 1985

A second site visit was made October 16 - 17, 1985 by Dr. Seyoum Solomon of LBII; Engineers Rafik Georgy and Helmy Fotouh of EEA and a representative of the FRDA. It was observed that significant development had occurred since the first site visit at both locations. A warehouse and diesel generator had been placed at both sites to support fish packing, short term storage, and transport. Refrigerated trucks were in use and a better understanding of the existing practices of ice transport, ice crushing, fish packing and transport was gained by Dr. Solomon and EEA. Data on present ice quality, ice/fish packing ratio and current ice demand were collected. Social, institutional, and market economic data were refined. A water sample was taken from both locations and an analysis performed which is discussed in Section 4.0. Data have been collected on solar insolation, ambient temperature, and water temperature at Wadi El-Raiyan.

In summary, there is a functioning fishing industry with a strong demand for ice at the lake area.

3.2 Ice Demand Evaluation

The amount of ice required for fish preservation at Wadi El Raiyan varies throughout the year. It is a function of the daily catch, the period of the fishing season, the distribution of fish at the site, and the ice/fish ratio. Fish production data, supplied by Mr. Abdel-Halim of the FRDA, from the 1984-1985 fishing season, has been graphed in Exhibit 3-3. Boulti (Talapia) represented the principal catch. FRDA projects that the average annual daily catch will increase over the next five years. Based on two site visits and discussions with FRDA personnel, the average daily catch is estimated to be 6 to 10 tonnes per day with a range of .2 tonnes per day to 40 tonnes per day over the season. Peak production occurs in the months of December and January.

The ratio of ice to fish is used to estimate the demand for ice. The ratio is a function of the physical and thermal properties of the ice and fish, the method of transport and the location of the markets. Presently, block ice is crushed into chunks at the lake site and mixed with fish in ratios ranging from 1/2:1 to 2:1 (ice to fish) depending on the mode of transport and the market distance. Exhibit 3-4 shows an approximate relation between these factors. The use of ice specifically manufactured for fish preservation is also expected to affect the ice to fish ratio. Block ice is not an ideal technology because of the low surface area to weight ratio. The use of thinner, more uniform ice may result in lower ice to fish ratios. Setting ice demand requirement approximately equal to the average daily fish production results in a sizing of 6 to 10 tons per day[7] for the capacity of the ice maker (12000-20000 pounds).

A number of daily ice production capacities are feasible.[8] An ice plant

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[7] Note that U.S. ice maker ratings are in "tons" (2000 pounds) as distinct from "tonnes" (2200 pounds or 1000 kilograms)

[8] Modular ice production technology currently exists with daily capacities ranging from 1 to 85 tons per day (for example, North Star Ice Equipment Corporation, Seattle, Washington, U.S.A., and TURBO, Refrigerating Company, Denton, Texas, U.S.A.).

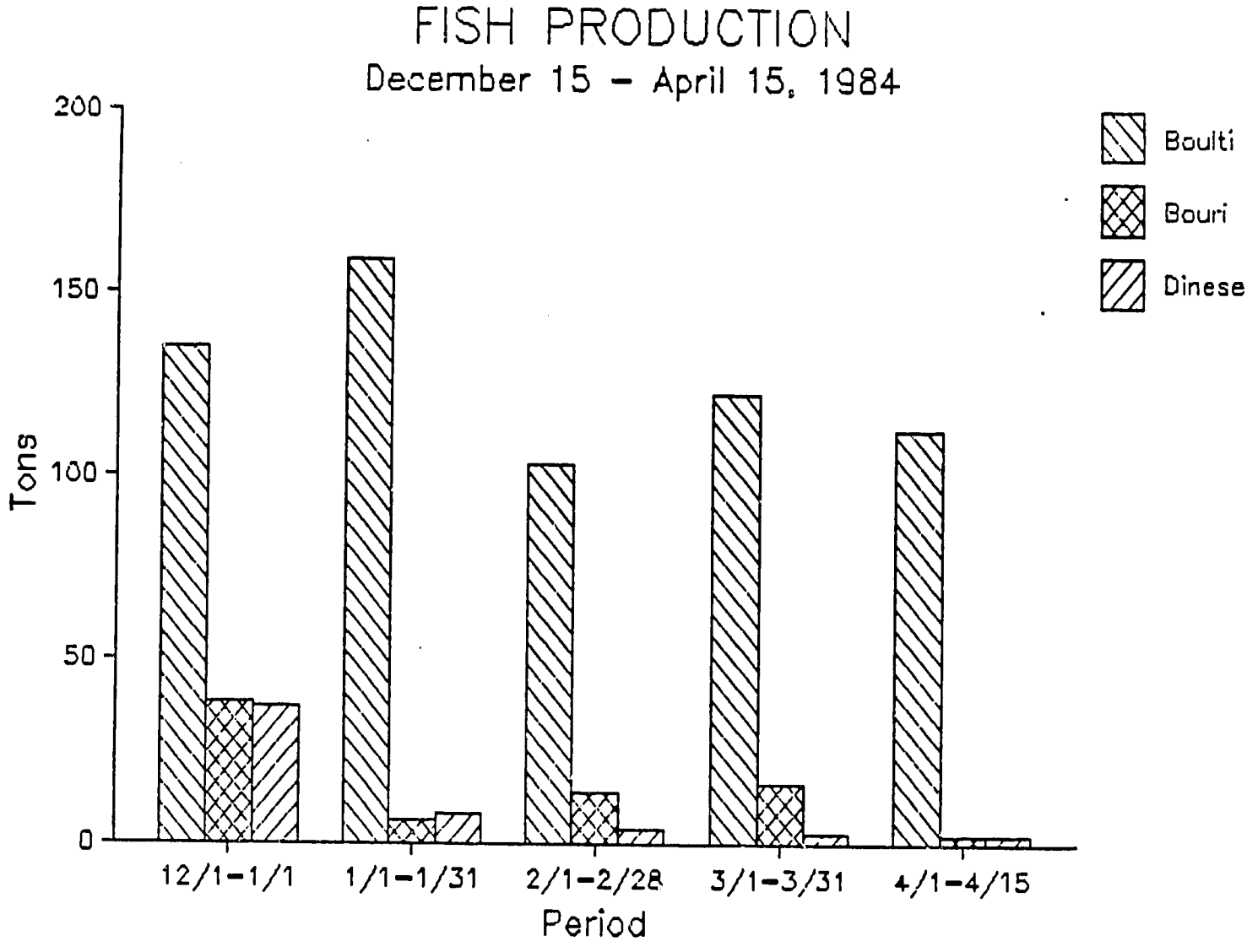

Exhibit 3-3 FISH PRODUCTION CURVE WADI EL RAIYAN

LOCATION / TRANSPORT	El Faiyum	Cairo	Alexandria
Truck	1/2:1	1:1	2:1
Train		1:1	2:1
Small Vehicle/ Hand Carry	1/2:1		

Exhibit 3-4 ICE/FISH RATIOS

capacity of 6 tons per day is selected as a candidate sizing for this application review. This sizing will meet a significant portion of the average daily demand for ice. It is also a reasonable size for demonstrating the design, operation, maintenance and evaluating the complete technical and cost performance of a photovoltaic and diesel power system for ice making. Other ice production capacities will be investigated during the conceptual design phase. Also, for this application review, flake ice will be assumed to be made since it is better for fish preservation.

3.3 Application Specific Requirements

Summer Use of Power

Full usage of the ice plant and the PV power system is necessary to optimize the economic performance of the project. Three alternative uses for the power system during the summer period were discussed with EEA and FRDA, one which includes an alternative use of the ice maker. They are as follows:

Irrigation - Use of the available power to operate dedicated irrigation pumps to cultivate a summer crop.

Ice Sale - Manufacture ice all year, selling ice on the private commercial market in El Faiyum whenever possible.

Hatchery - Use any excess energy to operate pumps to run a fish hatchery.

Because of the existing strong demand for ice and the ability to fully utilize the ice making equipment, the production of ice for sale is recommended as the alternative use of the ice plant during the spawning season.

Ice Storage

An ice storage building sufficient to hold three days of ice production capacity is recommended. This will permit ice production during periods of low or no ice demand. A larger storage size is not recommended because long term storage of ice (more than 3 to 5 days depending on ice and environmental conditions) results in large volumes of ice bonding together and maintenance difficulties.

Water Treatment

Potable water is required for ice making because the ice will come in contact with fish and it will be sold for general commercial and private use. World Health Organization standards for potable water provided in Appendix B should be used since the ice must be suitable for human consumption. Condenser cooling water treatment will be necessary to minimize maintenance of the heat exchangers. Industry requirement for condenser water quality will be followed. [NOTE: Initial water analyses suggests significant treatment may be required. This will be confirmed by more complete testing.]

Condenser Cooling Water

An open cycle cooling system using lake water for condenser cooling, with no evaporative cooling, is the simplest method for condenser cooling. For typical ice plant condenser cooling systems, about a 14 degree C temperature increase in the cooling water is expected[9]. This temperature rise is similar to the allowable discharge temperature of cooling water from thermal power plants in the U.S.[10]. Producing about 6 tons per day of ice will require about 9 cubic meters of cooling water per hour at an inlet water temperature of 27°C[11]. Given the large size of the lake (12,000 feddans), the thermal impact of discharging the condenser cooling water directly into the lake will be negligible. Also, if necessary, rapid dilution methods can be used to reduce the thermal plume of the discharge to within a short distance of the discharge point[12].

3.4 Energy Demand Evaluation

The energy required to produce and maintain ice is determined on a kilowatt-

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9 North Star, Ice Maker Specifications. North Star Ice Equipment Corporation, 1981.

10 National Academy of Sciences (NAS) and the National Academy of Engineering (NAE), Water Quality Criteria. Section III, Heat and Temperature. Report No. EPA-R3-73-033, March 1973.

11 North Star, op.cit.

12 NAS and NAE, op. cit.

hour per ton per day basis. For the purpose of the application review, a 24 hour day of operation is assumed. Other operating periods will be evaluated in the conceptual design phase. The required energy is the sum of three loads. These are shown in Equation 3-1.

Equation 3.1

$$\text{LOAD} = \text{Ice Making Load} + \text{Heat Gain to Storage} + \text{External Loads (Water Supply/Treatment)}$$

The first two loads are refrigeration or heat transfer loads. They are the work or energy required to remove heat from the incoming water and convert water to ice. The ice making load and heat gain load are a direct function of the operating efficiency of the ice maker and the amount of heat to be removed.

For all refrigeration loads, the ratio of the heat to be removed to the work required to remove it is called the Coefficient of Performance (COP). The COP is a measure of the energy operating efficiency of refrigeration processes. It is expressed by the following equation:

Equation 3-2

$COP = \frac{Ql}{W}$, where Ql is the heat transfered from a low temperature body to a high temperature body. W is the work or energy input required.

Data collected for the Technology Review showed that for commercially available hardware a COP of 1.7 is reasonably obtainable.

The ice making load and heat gain to storage load are represented in Equation 3-2 by the term W. Calculation of Ql is shown in Equation 3-3. It is a function of water inlet temperature, the amount of ice to be made and the final ice temperature. Solving Equation 3-2 for W calculates the ice making load as shown in Equation 3-3.

Equation 3-3

$$\text{Ice Making Load (W)} = \frac{Ql}{COP} = \frac{Cv,\ water \times (\Delta°C) + \text{Heat of Fusion} + Cv,\ ice \times (\Delta°C')}{COP}$$

where, Cv, water = Specific heat of water, 0.0012 kWh/kg-C
Heat of Fusion = Energy required to change water at 0°C to ice at 0°C, 0.0928 kWh/kg
Cv, ice = Specific heat of ice, 0.0005 kWh/kg-C
Δ °C = Change in temperature from average lake water temperature (assumed as 21°C) to 0°C.
Δ °C' = Change in temperature from 0 to - 4°C, final ice temperature
COP = Coefficient of Performance, 1.7 (See Section 5.1)

Ice Making Load (W) = [0.0012 x (21-0) + 0.0928 + 0.0005 x (4-0)] x 2000lb/(2.2kg/lb) ÷ 1.7 = 64kWh/ton

Multiplying 64 kWh per ton by 6 tons per day results in 384 kWh per day of energy required to produce 6 tons per day of ice. The refrigeration load due to the heat gain to the storage space is calculated from Equation 3-4. This calculation is done on a daily basis for 40 m^3 storage (three days of ice making capacity; 50 percent full storage). One complete air change per day is estimated for access time during unit operation.

Equation 3-4

$$\text{Heat Gain to Storage, } W = \frac{UA\,(To - Ti) + Cp\ air\ (Air\ Volume)\ p\ (To - Ti)}{COP}$$

where, U = thermal conductance of the storage walls, .02 wh/hr-m^2-F.
A = surface area of the storage space, 70 m^2.
To = outside ambient temperature, 73° F (yearly mean).
Ti = inside temperature, 25° F (to be maintained).
Cp air = specific heat of air at constant pressure, .075 wh/hr-m^2-F
Air Volume = Storage volume times air changes per day, 40 m^3.
p = the density of air, 1.28 kg/m^3.

$$\text{Heat Gain to Storage} = \frac{\frac{.02\ Wh(70\ m^2)(73-25)}{hr\text{-}m2\text{-}F} + \frac{.075\ Wh(40\ m^3)(1.28)(73-25)}{kg\text{-}F}}{1.7}\ \frac{24\ hr(kwh)}{day(1000\ wh)} = 3.5kWh/day$$

The external energy requirements for this field test consist primarily of water supply and treatment, operational and security lighting.[13] The energy required for water supply are those of pumping. Loads associated with water treatment are not addressed here because insufficient data currently exists to

[13] Ice crusher would be needed if plate ice is made and its energy requirements should also be taken into account.

determine the extent of water treatment that will be necessary. Operational and security lighting are estimated not to exceed 2 kWh per day. They consist of lighting around the array, diesel generator and inside the control room and ice maker.

Water must be supplied by pumping it from the lake to the ice maker. The vertical distance and pressure required can be translated to an average static head. This is estimated to be a maximum of 10 meters including piping losses and the required pressure for the ice maker.

Two volumes of water are required: one for making ice and one for condenser cooling. The combined quantity of water required per day for an ice production of 6 tons per day is estimated to be 220 m^3 using water cooling.[14] The pumping energy required for this volume is calculated using a standard pumping energy equation[15] provided in Equation 3-5.

Equation 3-5

$$\text{Pumping Energy (PE)} = \frac{9.8\ (V)\ (H)}{3600\ (Np)}$$

where, PE = pumping energy kWh/day.
V = volume of water to be pumped, m^3.
Np = pumping efficiency, 80% motor times a 50% pump.
H = head, m.

$$\text{Pumping Energy(PE)} = \frac{9.8(220)(10)}{(3600)(.4)} = 15 \text{ kWh/day}$$

Combining the energy demands for ice making (384 kWh per day), heat gain to storage (3.5 kWh per day), pumping for water supply (15 kWh per day) and operational/security lighting (2 kWh per day) results in an approximate value of 405 kWh day per for 6 tons per day or 67 kWh per ton of ice produced each day.

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[14] North Star, op. cit.

[15] Intermediate Power Inc., Handbook on Solar Water Pumping, 1984.

This value corresponds closely with reported energy requirements from manufacturers which range from 60 kWh per ton to 80 kWh per ton. For the conceptual design of this field test a value of 70 kwh per ton will be used. A 6 ton (5,500 kg or 12,000 lb) per day capacity ice plant is therefore estimated to require 420 kwh per day of energy.

4.0 ASSESSMENT OF SITE RESOURCES

4.1 Site Specific Data

Insolation data were calculated based on recorded dat. (sunlight hours) from a meteorological station in El Faiyum. Horizontal daily global insolation ranges from 3.4 kWh per m2-day in December to 8.1 kWh per m2-day in June. Appendix A provides solar insolation, ambient temperature, and water temperature data for the site.

Ambient temperature data are based on meteorological station data from El Giza. An additional two degrees has been added to each temperature to reflect the generally higher temperatures at the site. Average daily temperatures range from 30.2 to 15.2°C over the year.

Water temperature for the lake at Wadi El Raiyan is estimated to range from 8 to 26°C in the vicinity of the central location.

Appendix B provides a water quality analyses from both lakes performed in October 1985. The analyses state that the water is not potable based on World Health Organization (WHO) standards. An evaluation of the analyses has identified inconsistencies in the data that indicate another water quality analysis should be performed immediately. Until a more thorough and accurate analysis is obtained, it is not possible to determine the extent of water treatment that will be required and the effect of the water treatment activity on the primary objectives of the field test.

4.2 Additional Data Requirements

Site Survey

A site survey should be completed for inclusion in the Statement of Work. The survey should provide elevation, related topographical information and locate all current and known future buildings and roads. It should also indicate the location of the fishing boat loading and unloading and fish transfer points.

4.3 Insolation Profiles

Based on the insolation and ambient temperature data supplied by EEA an optimum tilt for the photovoltaic array has been determined. Using PV F-CHART, the daily insolation normal to a tilted surface was calculated for tilt angles of 10, 20, 29 (the latitude of the site), 40, and 50 degrees over the year. Figure 5-1 is a graph of the insolation values.

There are two system-specific conditions which affect the choice of tilt angle for the array in this application. First, the tilt angle should provide for the maximum obtainable insolation during December to provide for maximum PV power output because fish catch is highest and global radiation is lowest of any month of the year. Secondly, the array tilt should also maximize total insolation over the entire year to achieve the most output from the PV array.

A tradeoff exists with a fixed tilt array. A 10 degree tilted array results in the highest insolation during the period May through August. A 50 degree tilt maximizes the insolation in December but significantly reduces the insolation normal to a 50 degree plane during the summer. Hence there is no one fixed tilt which satisfies both of the above conditions. Exhibit 4-1 shows that there is a cross over in April and September.

One way of improving efficiency is by using a manually adjustable array. This approaches getting maximum performance from a non-tracking, quasi-fixed PV array. Exhibit 4-2 plots total yearly insolation against tilt angle. A seasonally adjusted tilt can maximize insolation in December and throughout the year. A 3.6 percent improvement over a fixed array in total yearly insolation and 8.6 percent increase in December daily insolation over a fixed array is obtained by adjusting the tilt in September to 40 degrees and in March to 10 degrees.

An adjustable tilt structure is recommended to maximize the performance of the array and to provide EEA the opportunity to evaluate different operating conditions. Most American PV manufacturers offer such an option.

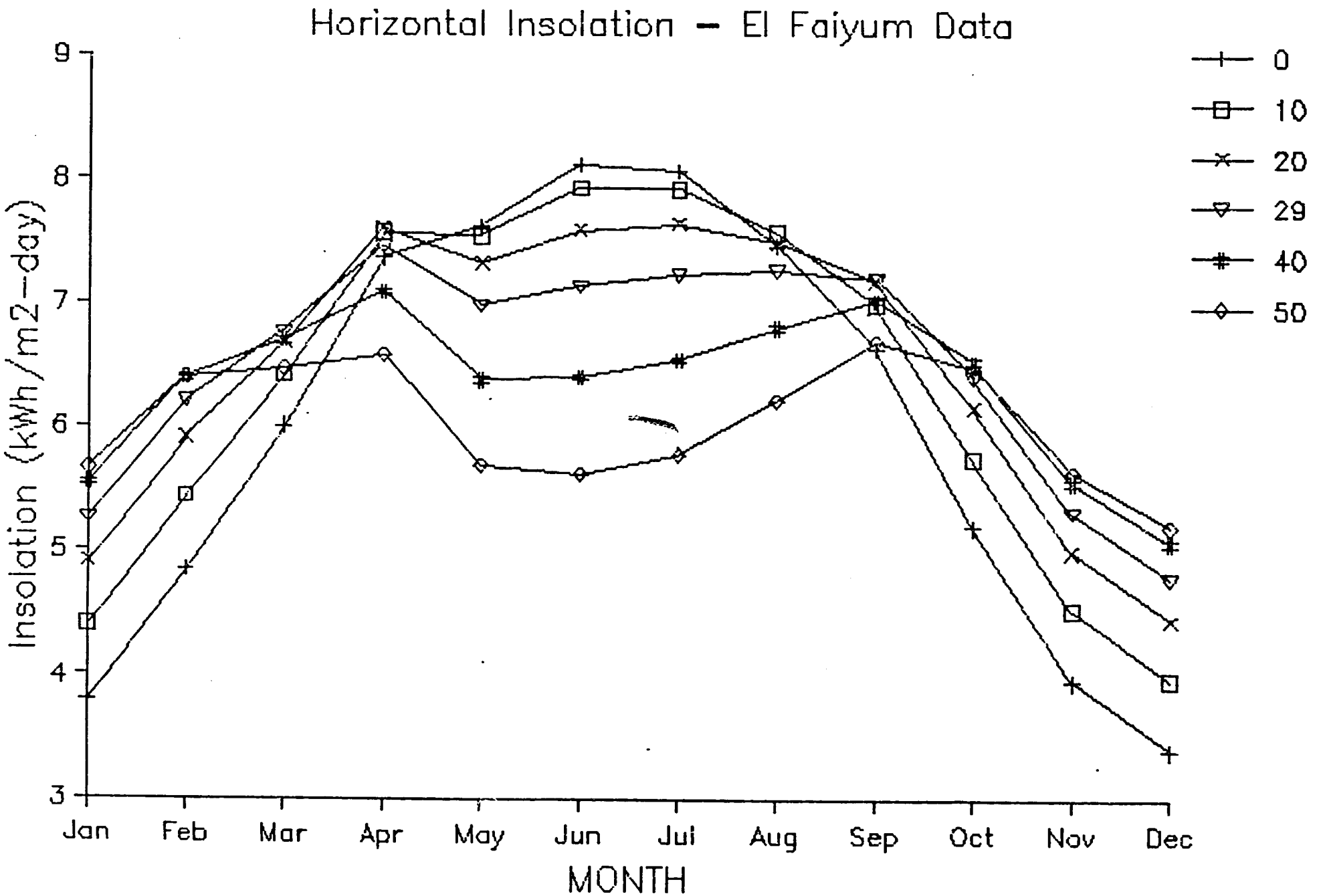

Exhibit 4-1 DAILY INSOLATION VERSUS TILT

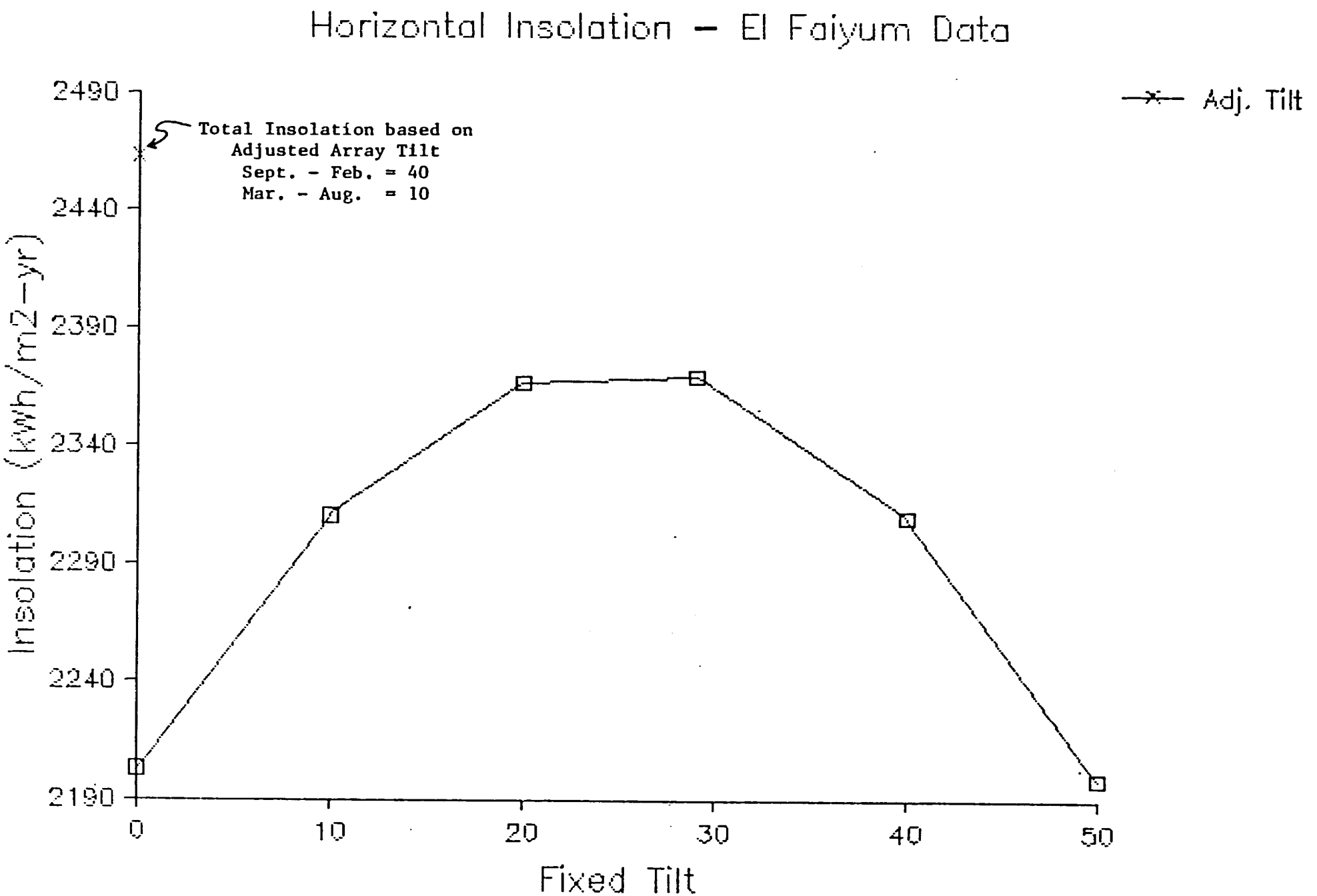

Exhibit 4-2 ANNUAL INSOLATION VERSUS TILT

5.0 TECHNOLOGY REVIEW SUMMARY

General background technical information has been provided in the Technology Reference Notebook on equipment components related to photovoltaic systems. The Technology Review for this field test, a separate document, reviews the specific equipment technologies in use in this field test with emphasis on refrigeration and diesel generators. A summary discussions of the components most critical to the design and operation of the PV/diesel ice making plant is provided here.

5.1 Technology Background

Three proven "stand-alone" energy technologies were considered as power for refrigeration and specifically ice making at Wadi El-Raiyan. These are diesel, wind and photovoltaics.

Diesel Generators

Diesel generators are considered to be the existing technology and as such PV and wind are considered viable if they are economically competitive to it. Diesel generators are available in a wide range of sizes from 2 kW up to several hundred kW rating. They operate with a thermal-to-electricity fuel conversion efficiency of 15-30 percent depending on capacity factor and the quality of maintenance.

Wind

In good wind regimes, wind power is often cost competitive with diesel. Wind energy was considered on the basis of resource availability. The nearest available wind data for Wadi El Raiyan is from El Faiyum, provided in Exhibit 5-1. If the wind resource data recorded at El-Faiyum is similar to Wadi El-Raiyan, it does not appear to be significant enough to warrant consideration of wind energy technologies for ice making at this location. In addition, wind energy technology for ice making is being evaluated as a separate project at Abu Gossoun, Egypt, through funding from the United Nations Development Program.

This project is being implemented by the Ministry of Electricity and Energy of the Arab Republic of Egypt and is in the hardware procurement phase.

Photovoltaic

Photovoltaic energy systems have been technically proven to be more reliable and require less maintenance than diesel systems for remote power supply. Photovoltaic energy, however is currently competitive to diesel generators only at low daily load levels, generally below 10 kWh per day. As the cost of photovoltaic energy continues to drop, the competitiveness of PV with diesel will improve. A detailed discussion of this is presented in Section 7.0. Under the assumptions provided, PV is likely to be competitive to diesel within the next 10 years for remote power applications such as ice making at the load levels required for this application.

PV/Diesel "Hybrids"

The characteristics of stand-alone PV energy systems indicate that competitive PV systems, with energy production capability necessary to meet ice making loads, will be "hybrid" systems. The PV/diesel hybrid is an integrated power system that is distinct from a PV system with a diesel generator backup. In the hybrid system, both PV and diesel generate and supply power on a regular basis. The energy is dispatched from each source so that total energy costs are minimized. For example, in a PV/diesel hybrid the diesel might be used to supply power at night and the PV used as the primary source of power during the day. In contrast, a PV system with diesel backup would use PV to supply the total energy requirements of the load; the diesel would only be used in unusual circumstances such as long periods of unexpectedly low insolation. Compared to a PV only or a PV system with diesel backup, advantages of a PV/diesel hybrid are many. For example, the diesel could be used to provide power for periods of low insolation and to meet peak energy demands and thereby substantially reduce the required battery storage capacity that would otherwise be necessary if PV were used

alone. Also, the use of diesel generators in combination with photovoltaics increases the reliability of the power system due to the availability of multiple energy sources. A hybrid system can also reduce the cost of delivered energy over either energy technology alone. The relative proportion of PV to diesel in a PV/diesel hybrid system is a technical and financial issue which is discussed in Section 6.0 of this Application Review.

5.2 Technology/Component Data Base

There are three ice making technologies to consider in this field test: block, plate and flake ice. Block ice is the current technology in use in the El Faiyum area. It is the least efficient of the three because of its relatively low surface area to weight ratio. However, it is best for transport and storage. Therefore it is the preferred choice for in-home use throughout Egypt.

Plate ice is commonly used in the fishing industry worldwide. It is made by passing water over refrigerated vertical metal surfaces and allowing a sheet or "plate" of ice to form. The refrigerant flow is stopped when the ice reaches a preset thickness. Warm water is used against the forming surface to dislodge the ice plate and cause it to fall into a storage bin. Ice thickness can be varied by changing the period of the refrigeration cycle. Plate ice technology is more efficient than block ice. Plate ice can also be processed into block ice, according to one manufacturer, with a "block press." The principal disadvantage of plate ice is the cyclic nature of the power demand.

The flake ice process is the most energy efficient and it results in a relatively continuous load. Flake ice is formed by a shaving process of rotating either a drum or blade to scrape thin layers of ice into flakes.

The power system to operate the ice maker and related loads consists of the PV array, diesel generator, battery bank, and power system controller. The first consideration is given to the choice of an AC (alternating current) or DC (direct current) power system. An AC system requires the use of a stand-alone

inverter to convert PV and battery energy (DC) into AC power for use by conventional AC loads. The field performance of inverters has been poor and, because inverters are a critical link between PV array and the load, their failure can prevent the use of PV produced power. In addition, inverters are at best 90 percent efficient. The alternative is to eliminate the inverter by modifying load equipment to use DC power. The use of DC loads results in the most efficient use of the PV/battery system and improves the system's reliability. The trade off is that the ice maker must be modified by changing AC motors to DC motors and a rectifier must be added to the diesel/generator to convert AC to DC power.

The choice of an AC or DC primary design will reflect individual companies experience and capabilities. There is no clear indication among industry as to the best choice for a system of this size. It is recommended that the design not be required to be either AC or DC, but that the Statement of Work insist that bidders justify their design and respond to the concerns raised in this Application Review. For conceptual design purposes, a DC design system is used.

Concerning the photovoltaic array, there are three basic PV technologies with proven field experience: single crystalline, poly-crystalline, and ribbon. Any of these should be considered as acceptable for this field test. An adjustable tilt array should be required to provide for the maximum output of the PV array in the peak demand months and also throughout the year.

The power system controller should be capable of three functions: (1) efficient power conditioning of the PV array, (2) battery protection, and (3) power distribution of the PV, battery and diesel energy to the loads. Several controllers are commercially available that can perform these functions. They range from what may be described as "smart" or programable controllers to "basic" controllers that use preset relays and minimum amounts of logic circuitry. For either controller, it is likely that some customization will be required to meet specific design,

operating and safety objectives. Specific emphasis should be placed on performance testing at manufacturer's plants and in the field and guarantees that may be offered.

Regarding the battery energy storage system, there are two basic choices: vented or sealed deep cycle batteries. Vented batteries are less expensive than sealed, however, the loss of electrolyte due to either evaporation or "gassing" can require frequent monitoring and maintenance. Vented batteries can be equipped with "recombination" caps to reduce the use of electrolyte. Sealed batteries are the preferred choice for handling, shipping, and maintenance considerations. The increased cost for sealed batteries may be justified on a life cycle cost basis if the above parameters can be quantified. Additional factors to be considered include the use of locally (Egyptian) manufactured vented batteries; availability of replacements; historical performance, reliability and life of sealed batteries in the Egyptian environment. These factors will be evaluated fully during the conceptual design phase.

Several safey factors should be considered when using lead acid batteries. These include: venting the room to prevent hydrogen gas accumulation; provision of means to prevent electrolyte spillage and emergency fresh water sources in the proximity of the batteries in case of an accidental spillage; design of battery banks to reduce/prevent the chance of shocks; provision of lifting devices for moving batteries safely; and design of facilities to prevent corrosion.

5.3 Selection of System/Component Technology

Based on a review of available equipment and technology the following recommendations are made:

1. Plate or flake ice making technology is recommended. Power system design for use with plate ice making equipment must be capable of handling inherent cyclic loading while flake ice making technology must show that block ice can be made through the use of block presses to produce ice for commercial sale.

2. The ice maker and power systems should be of either an alternating or direct current design (AC or DC). A DC power system design is encouraged in order

to maximize the efficiency and reliability of the photovoltaic power system.

3. Photovoltaic modules of single crystalline, poly-crystalline or multi-crystalline and ribbon technology are recommended.

4. An adjustable tilt array structure is recommended which permits manual adjustment of the array tilt, seasonally for at least three positions: 10, 29 and 40 degrees. Structural material should be aluminum, galvanized metal, treated wood or concrete. Designs should be encouraged which permit future fabrication in Egypt.

5. A power system controller with a field proven record of performance is recommended. The power system controller should be as simple as possible, providing the ability to easily troubleshoot problems and make component replacement and repairs. A maximum power tracking controller should be used if additional useful energy can be collected at reasonable cost. The conceptual design will explore the usefulness of a maximum power tracker more fully. Also a microprocessor-based design is acceptable for this application if field performance data shows the unit to have comparable reliability to non-microprocessor-based control equipment. Instrumentation for system performance monitoring should also be included in the field test.

6. Deep cycle, sealed or vented lead-acid batteries are recommended. Vented batteries should be equipped with recombination caps. Sealed batteries should be considered if their life cycle cost is not greater than 20 percent over comparable vented lead acid batteries (20 percent is a qualitative value attributable to the elimination or reduction of maintenance):

An example system configuration (DC design) is shown in Exhibit 5-2. The detailed conceptual design will be based on this configuration, and on a comparable AC system.

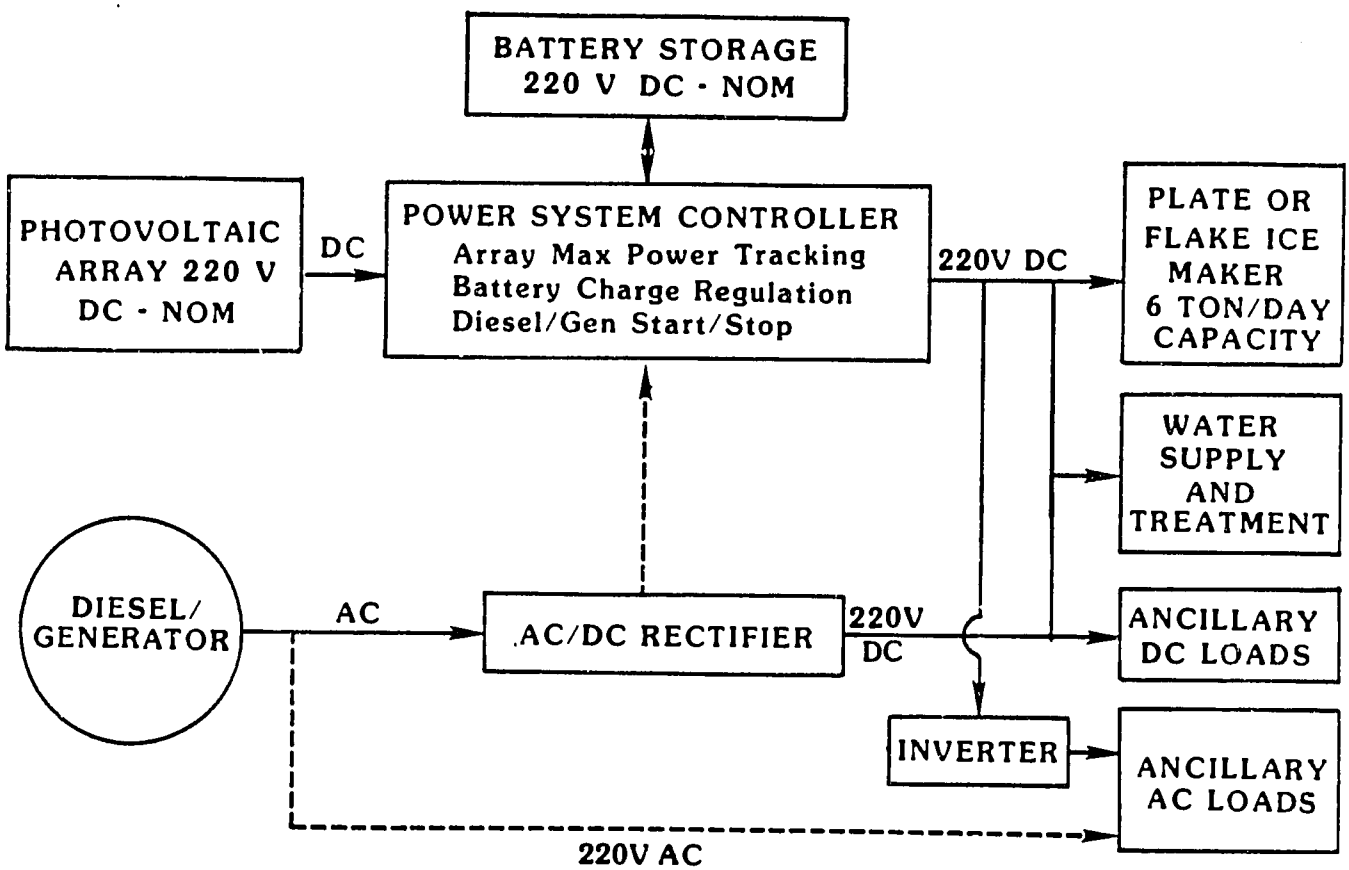

Exhibit 5-2 PV/DIESEL ICE PLANT CONFIGURATION

6.0 PRELIMINARY CONCEPTUAL DESIGN

6.1 Design Approach

A system configuration is developed based on the loads identified, the equipment technology under consideration, and the design purpose (i.e., development, demonstration, training, lowest cost option). An iterative process is conducted to determine an optimum design; specifically for this field test an optimum mix between PV, diesel generator, and battery power to operate the ice making plant. Exhibit 6-1 is a block diagram of the process.

The preliminary conceptual design of the PV/diesel hybrid energy system is based on an average hourly load equal to the total daily kilowatt hours divided by operating hours of the ice maker. In this case, the design is based on twenty-four hour operation to maximize capacity. Other operating strategies will be investigated during Task 3.6.3, Conceptual Design. A constant hourly load may not be the case in practice. A cyclic load, as with plate ice making technology would require a larger capacity diesel generator and battery but would not affect array sizing because array sizing is performed on a daily energy production basis. With plate ice, PV energy lost during periods when PV output exceeds load (i.e., defrost) can be recovered through battery storage.

6.2 Operating Concept

The operating concept behind a PV/diesel power system is to operate each power system at its highest efficiency compatible with producing the lowest levelized energy cost. This means using a minimum battery capacity and operating the diesel at not less than 40 percent of its rated capacity to achieve good efficiency and to minimize maintenance requirements.

Exhibit 6-2 is a graphical representation of the operation of a PV/battery/diesel power system supplying a twenty-four hour daily load. In general, the photovoltaic array operates the load during the day and the diesel operates the

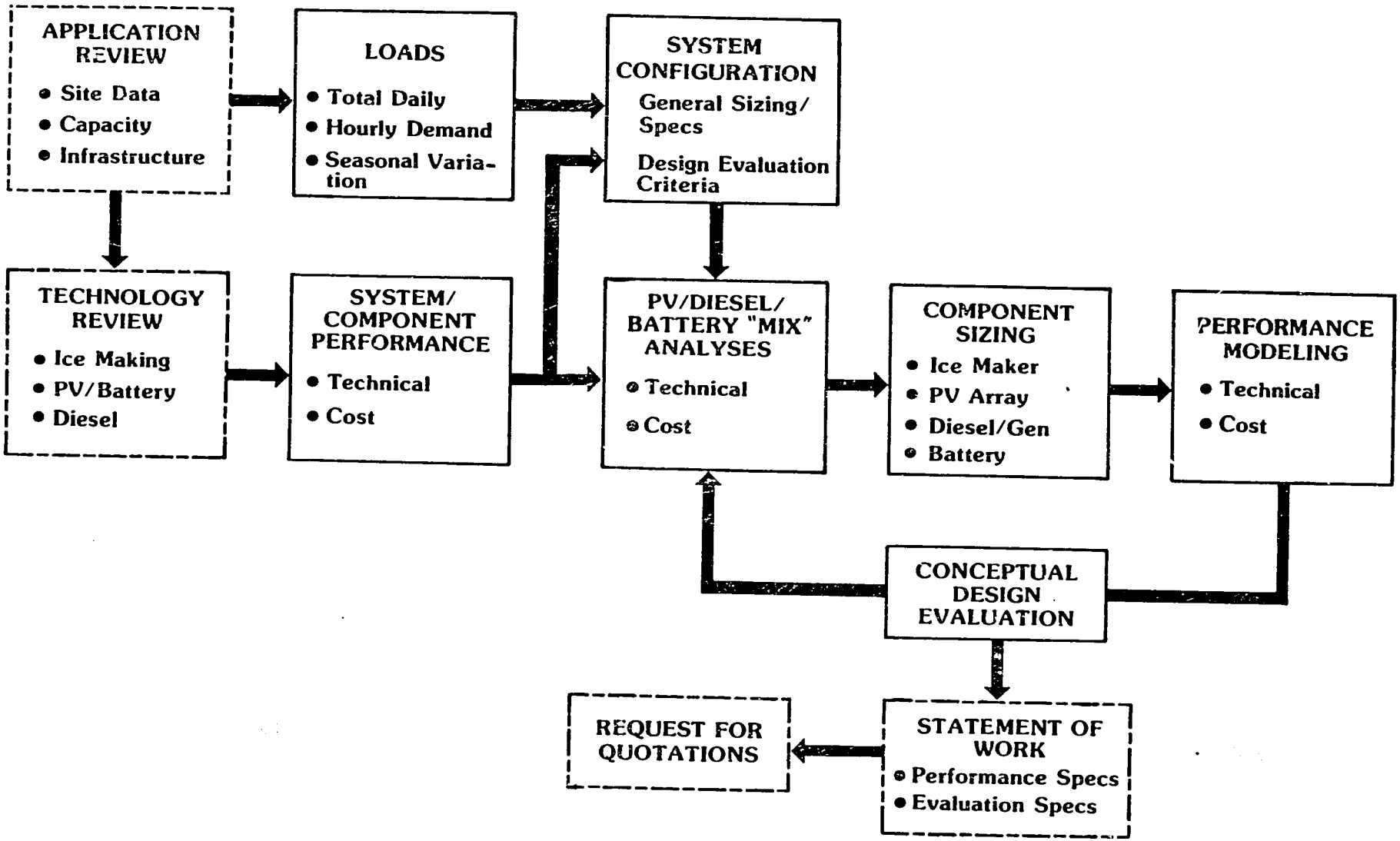

Exhibit 6-1

CONCEPTUAL DESIGN PROCESS FOR FIELD TEST 6 PV/DIESEL ICE MAKING PLANT

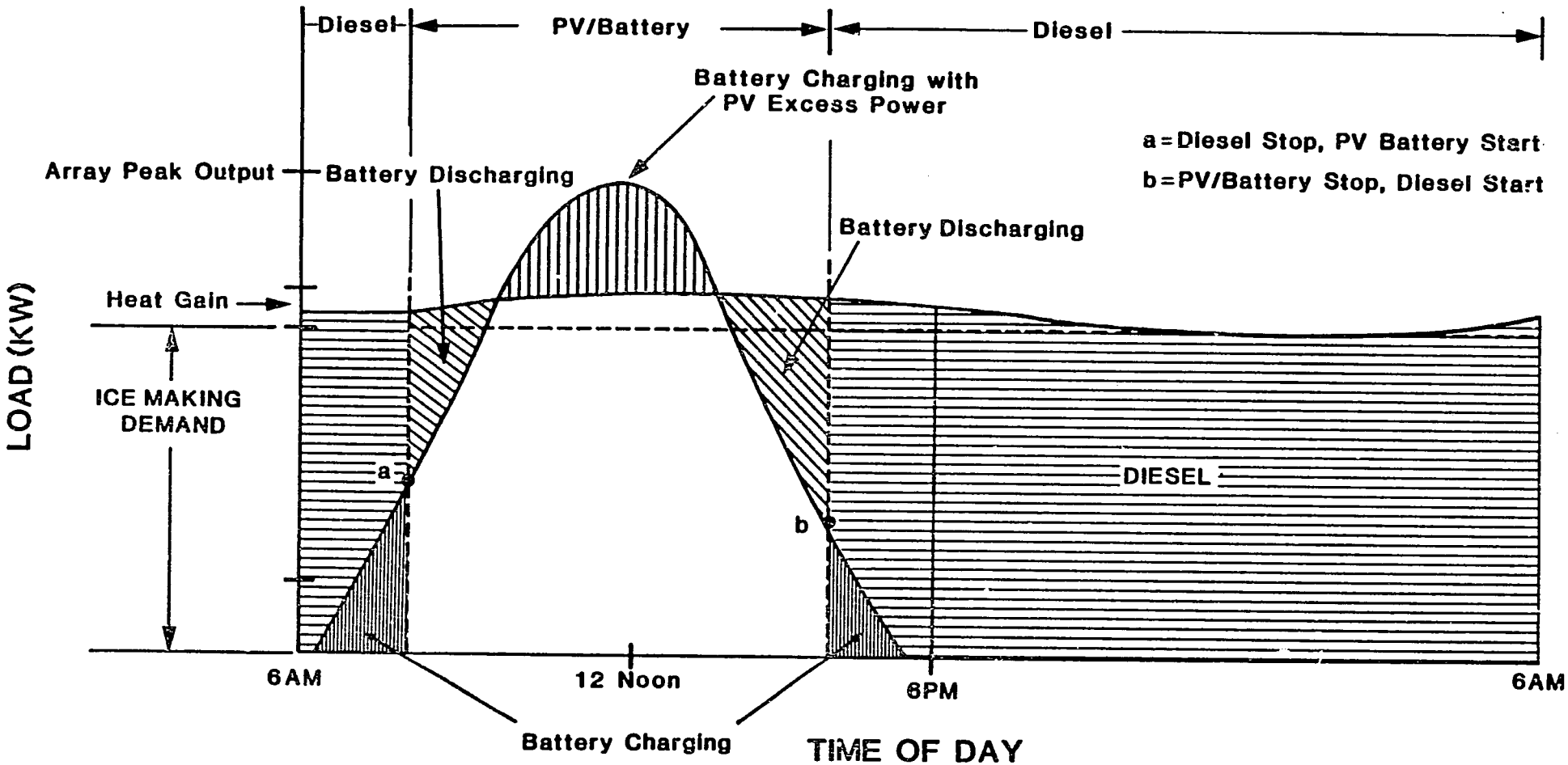

Exhibit 6-2

PV/DIESEL IDEALIZED OPERATING CURVE

load during the night. Points "a" and "b" represent changes in the principal power supply source; from diesel to PV/battery in the morning as array output increases, and from PV/battery to diesel in the evening as array power decreases. The change in power supply can be gradual by "integrating" or combining PV/battery/diesel power to supply the total load, or it can be distinct by effectively operating the equipment as separate power supplies, PV/battery and diesel. Both are reasonable operating methods, although the former method requires a more complex control system.

A fully "integrated" power system provides for the maximum flexibility in operating the system. It requires a "smart" power system controller which can identify and compare various operating parameters relative to the PV, battery and diesel power system and determine when to start the diesel, at what power level it should operate, and what is the optimum use of PV power at a given point in time. The availability of such "smart" controllers is relatively recent.

A simpler control method is to operate the PV, battery and diesel as independent power systems. The PV array and battery provide power to the loads for a specific time interval or until a specified battery charge level is reached. At this time the diesel starts and takes over the ice making load. Any remaining array power is used to recharge the battery bank. Diesel power is dedicated to the ice making load and does not concurrently charge the battery bank. Power supply is switched by power relays and can be specified to be manual or automated, to prevent load operation interruption. Commercially available controllers can perform as a "basic" power system controller with the addition of a time, current, or voltage sensor and "remote start" relay.

Issues such as proven reliability, efficiency, cost and maintainability should be considered when evaluating the power controller design. In addition, it is useful to specify that typical daily power curves be provided by the designer to enable simulating the operational concepts specific to the control design.

6.3 System Sizing and Configuration

PV/Battery Sizing Approach

The most significant design question of a PV/diesel power system is the sizing of the PV array and battery system. The PV array and battery can be sized to contribute up to 0 to 100 percent of the demand. The size of the array and battery is a function of the relative life cycle costs of the PV, battery and diesel energy. To define this relation, three different array sizing options are considered as shown in Exhibit 6-3.

The first array sizing option is Curve 1 in Exhibit 6-3, labeled "Fuel Displacement." In this sizing, photovoltaic energy serves only to displace diesel fuel when the sun shines. No battery storage is used because on the average, no excess energy is produced. The maximum size for a PV array in this instance is when peak array output at midday equals average power demand at that period. If the cost of PV produced energy equals the cost of diesel energy this "PV only" sizing is justified as a diesel fuel displacement design. PV energy will represent about 25-30 percent of the total daily energy demand, assuming 24 hour continuous loading.

The second array sizing level is shown as Curve 2 and is labeled "Partial Load Supply". The PV array produces excess energy during the day which is stored in a battery system and returned to the load during periods when the PV array output is less than the load. At night the diesel provides power to the loads. PV energy costs, in this case, must be less than diesel because battery energy costs are higher than diesel costs on a life cycle cost basis. Therefore, a PV array and battery storage size is justified to a point at which the marginal cost due to battery storage results in total PV/battery life cycle energy cost equal to diesel.

In the third sizing level, the PV/battery system is sized to supply the total daily load during the year and is shown as Curve 3 labeled "Total

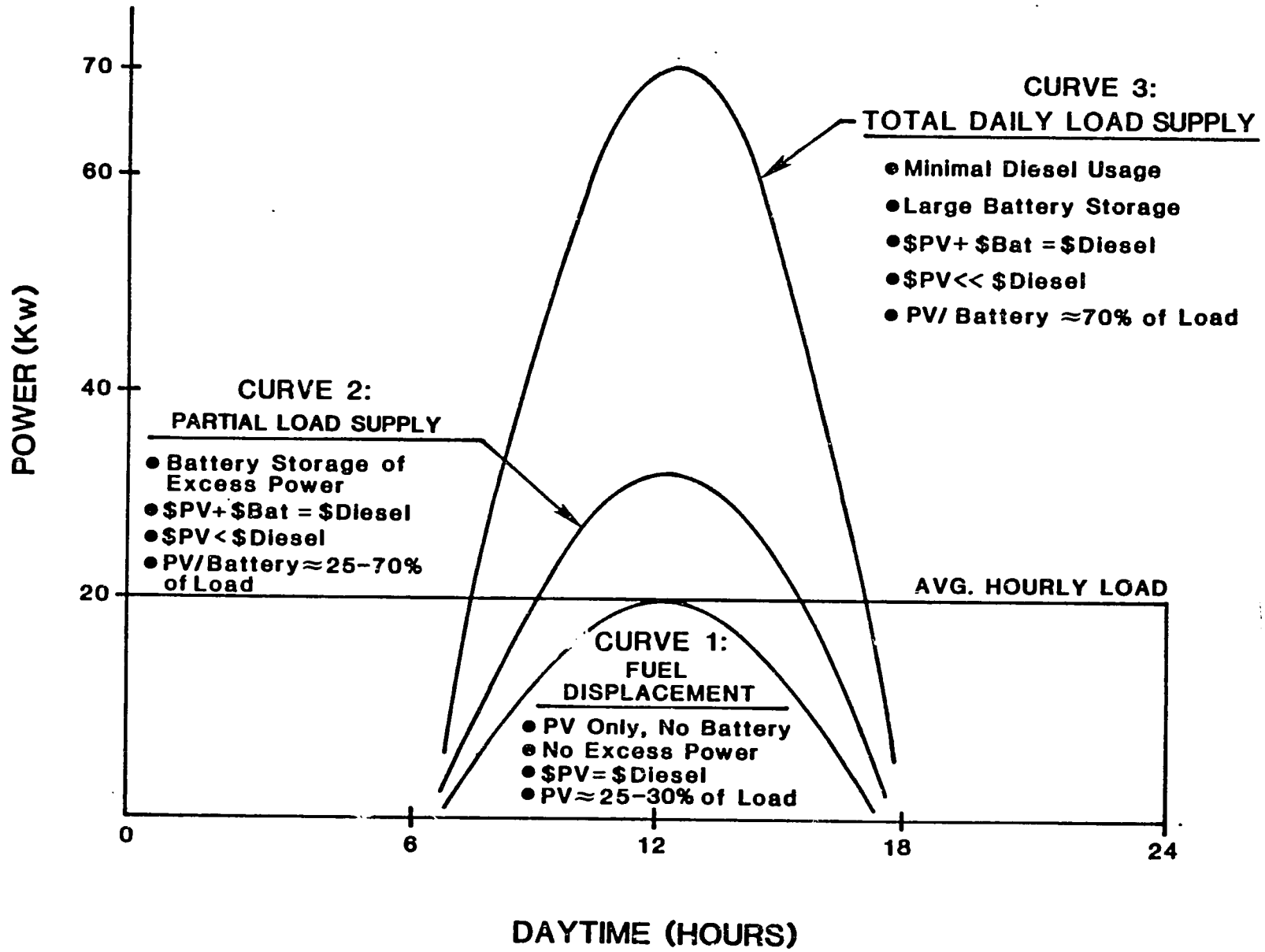

Exhibit 6-3 ARRAY SIZING OPTIONS

Daily Load Supply". As in all cases, the combined life cycle cost of PV and battery must be equal to or less than diesel. Because of the relatively large battery storage cost, PV energy costs must be significantly less than diesel.

Sizing of the array to supply the total energy demand can greatly affect financial performance of the system. If the sizing is performed based on December insolation (for assuring reliable power supply during months with low insolation), significant amounts of PV power will be "dumped" during the summer because of excess production. The amount of wasted energy is a function of the change in insolation from winter to summer and any seasonal load fluctuations. Designing for the average daily insolation over the year results in a smaller surplus in the summer but an energy deficit in the winter. Energy deficits would be supplied by a backup diesel because the battery capacity required to carry summer surplus to winter deficits would be unrealistic. A value of approximately 70 percent of the daily average load demand is considered a reasonable upper limit to the proportion of PV to diesel[16]. In this instance, diesel makes up the 30 percent deficit over the year, to a greater extent in winter and to a lesser extent in summer. The actual proportion of PV to diesel in a system depends on costs, resource availability at the site, load profiles and other factors specific to the application.

The principle conclusion regarding sizing options for the PV array is that if PV energy costs (without battery) are less than diesel, then some battery storage is justified and the PV/battery system can be sized to provide from 25 percent to 70 percent of the total yearly energy demand. The optimum percentage is a function driven by the economics of the system components, primarily the PV array, battery and diesel life cycle costs. Equation 6-1 shows a general relation.

[16] Conversation with Ken Gerken of Integrated Power Corporation in November 1985.

Equation 6-1

PV cost + X (Battery Cost) = Diesel Cost

where, PV, Battery, and Diesel Cost are Life Cycle costs in $/kWh and "X" is the ratio of the energy produced by the PV in excess of load demand during the period when the sun shines, to the total energy produced by the PV array.

PV costs can be annualized over 20 years and divided by the annual useful energy produced to achieve a dollar per kWh cost figure. Diesel cost is determined in the same manner but takes into consideration equipment replacement after 10 years.

Battery life cycle costs (BLCC) are approximated by annualizing the capital costs of battery storage and dividing that value by the effective battery capacity and 365 days/year to arrive at a dollar per kWh-day life cycle cost. Effective battery capacity is based on the allowable depth of discharge. Equation 6-2 shows the method used to calculate BLCC based on a 10 percent nominal discount rate and replacement of the battery bank after 10 years.

Equation 6-2

$$\text{Battery Life Cycle Cost (BLCC, \$/kWh-day)} = \frac{(\text{Capital Cost/kWh})(\text{Financing Factor})}{(365)(\text{Depth of Discharge})}$$ [17]

$$\text{BLCC} = \frac{(150.00)(.16275)}{(365)\ (.25)} = \$.27/\text{kWh - day}$$

Using 1995 cost estimates[18] for PV of $.26 per kWh, $.27 per kWh for battery and cost estimates of $.30/kWh for diesel [19], up to 15 percent of the energy would be cost justified to pass through the battery storage. Relating this percentage to what will be supplied by the PV array alone (25 - 30 percent)

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[17] Financing factor is equal to .11746 X (1+.3855) representing a present capital cost and a replacement cost 10 years in the future, both costs annualized at 10% over 20 years.

[18] An analysis is performed in Section 8 on the life cycle cost/kWh of PV energy versus diesel energy over the next 10 years.

[19] Based on fuel costs of $1.70/gallon, 1985 prices.

gives a total percentage of 40-45 percent of the daily energy demand being supplied by the PV/battery power system with the diesel system providing the balance.

This example points out that optimum PV array and battery sizing in hybrid power systems design is a complex task and is as much a function of economics as technical issues. More importantly, projected costs for PV, battery and diesel energy are extremely important for this field test to aid in evaluating the viability of energy supply from photovoltaic/battery systems compared to conventional diesel generator systems.

PV array, battery and related component sizings for this application review are based on supplying approximately 40 percent of the average daily energy demand of the load (420 kWh per day x .4), or 168 kWh per day. This sizing provides the opportunity for significant operating experience with all major components of PV/diesel hybrid systems and could form the design basis for optimizing PV, battery, and diesel sizing on future applications.

PV Array Sizing

The required size of a photovoltaic array to produce an average of 168 kWh/day can be estimated using the average daily insolation, average array operating efficiency over the year, the array reference efficiency, the power conditioning efficiency and losses associated with battery storage. Equation 6-3 shows the relationship betwen these factors to calculate an approximate array size.

Equation 6-3

$$\text{PV Array Size} = \frac{(\text{Load})\ (\text{PV Ref. Eff.})\ (1 + \text{Battery Loss \%})}{(\text{Av. Insol.})\ (\text{PV Oper. Eff.})\ (\text{Power Cond. Eff.})}$$

where, PV Array Size = Rated in kW peak
Load = 168 kWh/day
PV Ref. Eff. = Array reference efficiency (manufacturer supplied) equal to module peak rated output divided by gross area (9.9%)
Battery Loss % = 3%, for energy passing through 80% efficient battery storage
Avg. Insol. = Average daily insolation (kWh/day-m^2); 6.7 kWh/day m^2 for Wadi El Raiyan
PV Oper. Eff. = PV operating efficiency including power tracking efficiency and temperature effects
Power Cond. Eff. = Power conditioning efficiency including power controls and wiring losses

$$\text{PV Array Size} = \frac{(168)\ (.099)\ (1 + .03)}{(6.7)\ (.076)\ (.95)} = 35.4 \text{ kW}$$

In the above calculation, energy attributed to battery loss is estimated by multiplying 168 kWh/day by 15 percent for the amount of energy passing throug the batteries multiplied by 20 percent which must be made up due to 80 percent efficient batteries. This results in a total of 5 kWh/day battery loss or 2.5 percent of 168 kWh/day.

Insolation and array operating efficiency values were determined with the use of PV FCHART. Site specific insolation and ambient temperature data were used and the array tilt adjusted seasonally. As an example of U.S. manufacturer technology, PV array performance characteristics for a Solarex SX-146 polycrystalline module were used. Appendix C contains the results for PV FCHART.

It is important to note that calculations with single crystal and ribbon PV technologies would not result in a significant change in array rating on a peak watts basis because the factor, array reference efficiency divided by array operating efficiency, is very similar between technologies.

Lastly, array sizing may vary depending on the methods used to calculate the required array size and specific array configuration requirements to achieve efficient operating voltages and currents. An array size range of 33 - 38 kW, representing a 10 percent total variance, is considered reasonable. The technical and financial analysis portion of this Application Review is performed using a 35 kW array.

Battery Sizing

The purpose of battery storage in this project is to increase the hours of ice plant operation on PV/battery power alone. In doing so, the battery will also reduce the hours of low capacity (low efficiency) diesel operation which would otherwise be required. This is accomplished by storing PV array power in excess of that required by the load(s) at a given point in time and returning it to supplement PV and/or diesel power at required periods. The battery will also serve as a demand "buffer" to reduce the problems associated with high-motor-starting currents and voltage spikes.

At the same time, it is desirable to minimize the amount of battery storage because of the additional cost and inefficiency associated with battery storage. The amount of battery storage is determined on the basis of the minimum amount of energy to be stored and the maximum charging current to be experienced.

Considering the battery to be sized to store excess energy produced during the day, the sizing would be based on the month with the most excess energy. Results from PV FCHART, provided in Appendix C show that the month with the most excess PV array energy is April. The excess energy "XSO",for that month equals 1277 kWhrs. Dividing this by 30 days in April shows that a total of 43 kWh/day are produced in excess of the energy required by the load at a given point in time. Using a 25 percent discharge limit to achieve a 10 year battery life, one cycle per day, results in a battery storage requirement of 172 kWh.

The second and more critical sizing parameter for battery storage systems is the maximum charge rate that the battery system will experience. A review of lead-acid battery ratings show that charging current should be limited to 1.5 times the 10 hour capacity current rating. A 35 Kw - 220 volt nominal array may charge the battery bank with 159 amperes, at least for limited periods. If this represents 150 percent of the 10 hour current rating, then the required 10 hour battery capacity rating is 1060 ampere-hours (10 x 159/1.5). This figure corresponds to 233 kWh of battery storage at 220 volt nominal buss voltage. Therefore, this is the governing battery storage size compared to the minimum desired capacity of 172 kWh.

A 233 kWh battery storage will normally be discharged only 10 - 20 percent on a daily basis assuming that the battery system cycles at a level approximately equal to the excess PV energy produced. This depth of discharge corresponds to a cycle life of 4000-4300 cycles. The financial analysis part of this Application Review will be based on 10 year life of 233 kWh of battery storage.

Diesel/Generator

Assuming a steady load as with a flake ice maker, the average hourly load to provide 420 kWh/day is 17.5 kW. Dividing by a capacity factor of 80 percent results in a diesel generator rating of 22 kW. Plate ice making technology would require a rating approximately two times the average hourly load or 35 kW because a typical refrigeration cycle is 25-30 minutes. Variations in the rating of the diesel generator have very small affects on the overall power system price because the diesel generator capital cost represents only 2-5 percent of the system capital cost and a fuel to electricity conversion efficiency is used to determine operating costs.

Inverter/Rectifier

Although this conceptual design is for a DC system, a small inverter may be required to operate small conventional AC power loads. A DC/AC inverter is sized for both peak and continuous load. Specific requirements are to be left to the system contractor.

A rectifier will be required to condition the power produced by the diesel generator to operate the DC loads and charge the battery. Its size will be a function of the maximum input and output power. The rectifier may be a separate component (i.e., battery charger) or it may be part of the diesel generator set. An AC system is also feasible. It will be discussed in the detailed conceptual design in Task 3.6.3

Power Control System

The power control system will be sized to handle the maximum power to be switched and regulated. An important parameter is the system voltage since it determines the maximum current and in turn determines the rating of the integral components. A 220 volt system passing 40 kW (array output may reach 35 kW or slightly more) will need components capable of handling 180 amperes DC. Significant attention must be given to all component selection for the entire system because of the currents involved both from safety and efficiency standpoints.

Miscellaneous Equipment

Sizing for water pumps and motors, water treatment, and other small loads are not considered here because they are minimal. As explained earlier, however, the sizing and complexity of any water treatment equipment must be determined immediately after a water quality analysis is performed to identify any aspects of cost maintenance or waste disposal which may detract from the PV/diesel performance evaluation emphasis of this field test.

6.4 Performance Modeling

The technical and financial performance of the PV/diesel power system is the most important information to be obtained from this field test because the viability of such power systems for Egypt hinges on the life cycle costs per kWh of PV/diesel hybrid power systems compared to conventional remote power technology, namely diesel generators. The performance of the ice making machinery is also an important part of this field test for reliability, maintainability and energy efficiency. However, evaluation of the performance of ice making equipment is not performed here because the performance should not directly impact the decision of the viability of photovoltaic/diesel hybrid power systems for Egypt.

The technical performance of the PV/diesel power system is simulated to determine the expected monthly and annual energy production for the PV array and diesel energy.

The major components and performance assumptions for the performance modeling are as follows:

Components

PV Array	35 kW
Battery Storage	233 kWh
Diesel/Generator	22 kW
Ice Making Plant	6 ton/day

Performance Assumptions

1. Array reference performance data is for poly-crystalline silicon. Specific parameters are provided in Appendix C as input to PV FCHART.
2. PV FCHART is used to determine PV operating efficiency and average daily insolation on a monthly basis.
3. Battery losses are estimated to be 3 percent, based on 15 - 20 percent of the energy passing through 80 percent efficient batteries.
4. Power conditioning losses are 5 percent.
5. Diesel operating efficiency, i.e., fuel to electricity conversion, is 20 percent.
6. The energy content of diesel fuel is 10.8 kWh/liter (140,000 Btu/gallon).

PV FCHART has been used to determine the array performance over the year. The actual program "run" is provided in Appendix C. The average daily array operating efficiency is multiplied by the average daily insolation over each month. That value is multiplied by the number of days in a particular month to obtain total energy production from the array. Diesel generator contribution is the difference between 420 kWh per day and the kilowatt-hours produced by the PV array. Exhibit 6.4 tabulates the resulting values.

Energy Demand = 420 kWh/day

MONTH	Days/mo.	PV Oper. Eff.	Battery Losses (1-x)	Power Cond. Eff.	Insolation (kWh/day)	ENERGY PRODUCTION (KWH/DAY) 35 kW ARRAY 354 m2 Array PV	Diesel
JAN	31	.08	.97	.95	5.5	143	277
FEB	28	.079	.97	.95	6.4	165	255
MAR	31	.077	.97	.95	6.7	168	252
APR	30	.076	.97	.95	7.6	188	232
MAY	31	.075	.97	.95	7.5	183	237
JUN	30	.074	.97	.95	7.9	191	229
JUL	31	.073	.97	.95	7.9	188	232
AUG	31	.073	.97	.95	7.6	181	239
SEP	30	.074	.97	.95	7	169	251
OCT	31	.075	.97	.95	6.5	159	261
NOV	30	.078	.97	.95	5.6	142	278
DEC	31	.08	.97	.95	5	130	290
YEARLY ENERGY PRODUCTION (kWH)						61089	92211
YEARLY DIESEL FUEL (gals)						-	11237

Exhibit 6-4 PV/DIESEL ENERGY PRODUCTION DATA

The annual energy production values provided in Exhibit 6.4 are calculated based on average daily array efficiency and insolation. PV FCHART predicts a 35 kW array will provide 39.6 percent of the annual energy demand or 60707 kilowatthours (See Appendix C). The slight difference in total annual energy production is primarily due to daily average computation versus hourly average.

It is useful to plot the power output for the PV array, battery, and diesel system and the ice making load so that relative contributions, and start and stop times can be visualized. A program has been written by Meridian using SuperCalc 3, called "ICE" which provides a daily power curve for the power systems and load. Exhibit 6-5 is a set of daily power curves based on average yearly daily insolation and array operating efficiency.

Input data requirements for the program are shown in the exhibit; positive and negative power values for the battery represent charging and discharging periods, respectively. The load curve (demand) is relatively flat yet it includes heat gain during the day, water supply temperature fluctuations, and ambient temperature fluctuations. ICE is a valuable tool for determining the effects of various diesel operating constraints and visualizing the relative power levels of the PV, battery, and diesel system with respect to the load at each hour of the day. Because ICE can be easily modified, it will serve as a useful tool to evaluate the designs which will be received from bidders.

6 ton/day cap., Avg. Day Perf.

MERIDIAN CORPORATION
PV-DIESEL HYBRID ICE PLANT SIMULATOR "ICE"
VERSION 1.0
AUGUST 8, 1985

**********INSOLATION AND POWER SYSTEM INPUT DATA**********

LOCATION :	EL FAIYUM, EGYPT
LATITUDE :	29 DEGREES
GROUND REFLECTANCE :	.2
ARRAY TILT ANGLE :	29 DEGREES
ARRAY EFFICIENCY :	.0760
FRAC. ENERGY FROM ARRAY :	-) GIVE ONLY ONE
OR - ARRAY AREA M2 :	354) OR THE OTHER
BATTERY SIZE (OPTIONAL INPUT) (KWH) :	233
BATTERY EFFICIENCY :	.8
BATTERY DEPTH OF DISCHARGE :	.25
MIN. ENGINE CAPACITY (FRAC. OF MAX) :	.4
MAX. ENGINE CAPACITY (FRAC. OF MAX) :	.8
GIVE EITHER KT :	-) GIVE ONLY ONE
OR INSOL.ON ON HORIZON. KWH/M2/DAY :	6.7) OR THE OTHER
DATE INSOLATION COMPUTED AT :	9/21/85 AVG DAY
DAY IN YEAR :	264

**********ICE PRODUCTION INPUT DATA**********

PRODUCTION START TIME	100	HOURS
PRODUCTION END TIME	2400	HOURS
TOTAL DAILY PRODUCTION	6000.00	KG
PUMPING HEAD (M)	5	
PUMP EFFICIENCY	.5	
MAX AMBIENT TEMPERATURE	22.6	DEG C
MIN AMBIENT TEMPERATURE	10.1	DEG C
TIME AT MAX TEMPERTURE	13	HOURS
RELATIVE WATER TEMPERATURE	15	DEG C
ICE TEMPERATURE	-4	DEG C
ICE STORAGE TEMPERATURE	-4	DEG C
U OF ICE STORAGE	.06	W/M2/DEG C
SURFACE AREA OF CONTAINER	30	M2
COP OF ICE PLANT	1.7	

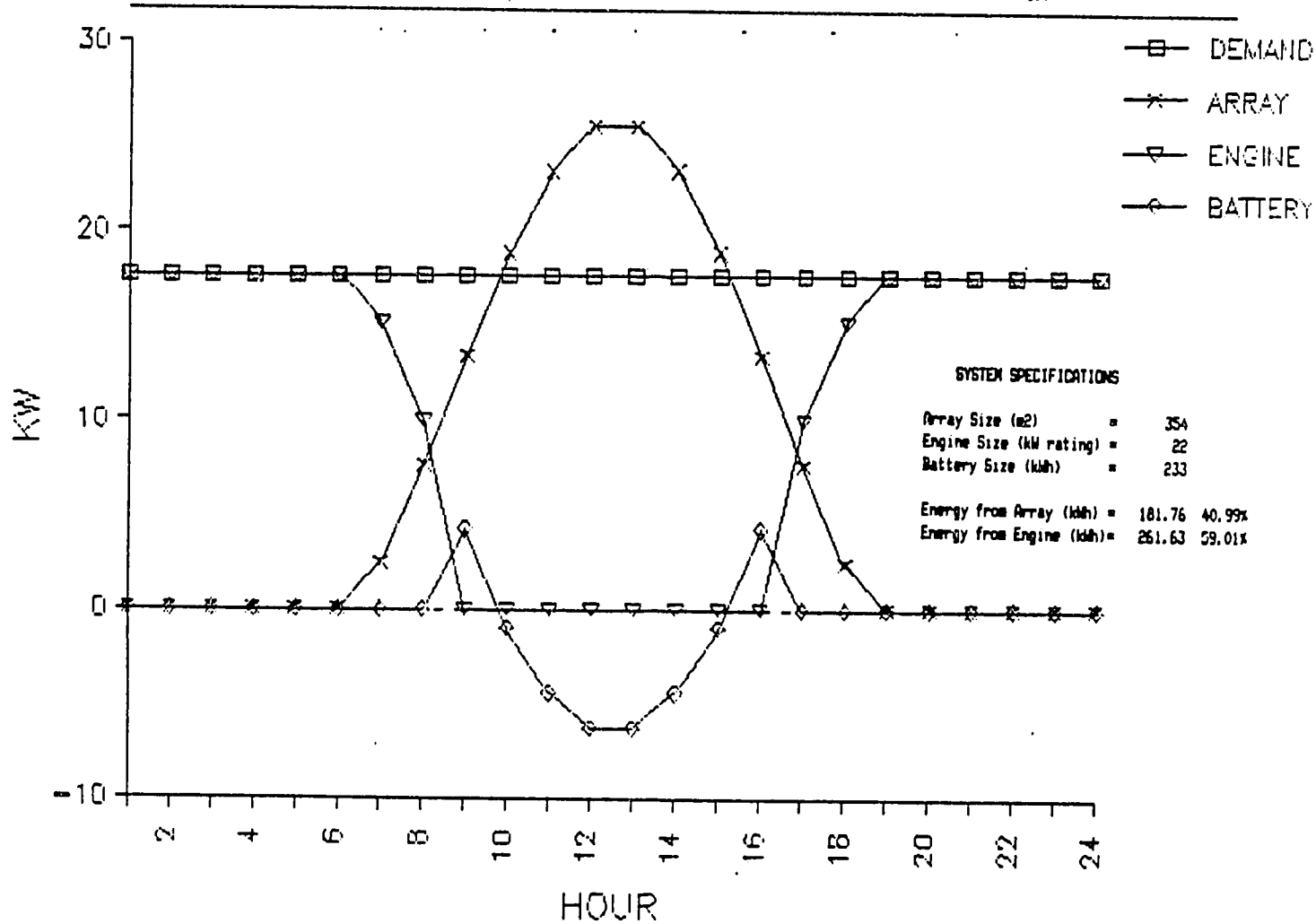

Exhibit 6-5 PV/DIESEL ICE PLANT OPERATING CURVE

7.0 STAFFING

The daily operation and maintenance associated with ice making require that full time operators be assigned to the location. EEA and FRDA have signed a contract, covering a two year period, for the operation, maintenance, repair and monitoring of the facility. Aspects of this agreement which are pertinent to the operation, maintenance, repair and monitoring should be made available to all involved parties (including bidding contractor) so that clear lines of responsibility will be understood.

Minimum staffing requirements for the first two years of operation, maintenance, repair and facility management of the PV/diesel powered ice making plant are shown in Exhibit 7-1. Long term annual stafffing requirements are expected to be reduced 70 percent of those shown.

Specific training requirements, and power system operations and maintenance staffing responsibilities between EEA, FRDA and the contractor will be detailed in the Statement of Work.

Months	Principle Activities	Required No. Staff	Total Man-months
ON-SITE STAFF			
0 - 3	Startup, testing, evaluation of system and components On the job training of EEA/FRDA technical personnel.	4	12
3 - 6	Continuous operation using distinct operating modes of PV/battery and diesel. Performance evaluation. Maintenance. Training.	4	12
6 - 9	Refine operating characteristics; evaluation.	2	6
9 - 12	Regular operation, evaluation.	2	6
12 - 18	Refine operating characteristics; evaluation.	2	12
12 - 24	Regular operation, evaluation.	2	24
	TOTAL ON-SITE STAFF-MONTHS		72
FACILITY MANAGEMENT STAFF			
0 - 6	On the job training in management of technical support and procurement of spare parts	2	12
6 - 24	Regular operation	1 (half-time)	9
	TOTAL MANAGEMENT STAFF-MONTHS		21

EXHIBIT 7-1. Staffing Requirements for the First Two Years

8.0 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are provided based on the Technology Review and Application Review.

Conclusions

1. Wadi El Raiyan location is a good application site for demonstrating the use of photovoltaics for ice making because there is an existing and growing demand for ice, the solar resource is exceptional, and the location is a balance between remoteness and accessibility for monitoring and evaluation.[20]

2. The daily ice demand fluctuates over the season. Therefore, the sizing of the ice plant is based on average daily ice demand. Since the plant is modular, additional capacity could be added in the future and the potential for other applications throughout Egypt is enchanced.

3. The best ice making technologies are plate or flake because they are the most energy efficient and are suitable for fish preservation.

4. The lowest cost, most reliable design choice, on a long term basis, is a PV/diesel hybrid power system with corresponding ice making loads.

5. The financial viability of PV/diesel remote power systems for ice making depends on the cost of photovoltaic energy compared with diesel produced energy.

6. The design, operation, maintenance, and repair experience with PV/diesel hybrid power systems that can be obtained through this field test will form a strong technical and cost data base for the design and application of PV/diesel power systems for other remote power applications.

Recommendations

A 6 ton per day ice making plant, powered by a 35 kW PV/22 kW diesel hybrid power system with 233 kWh of battery storage is recommended to be field tested at Wadi El Raiyan. This recommendation is based on the following assumptions:

1. The life cycle costs of PV power are likely to be less than the life cycle cost of diesel power in Egypt within the next 10 to 15 years.

2. The timeframe of 10 to 15 years is within the energy planning and institutional perspectives of the Egyptian Electricity Authority.

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[20] Assumes that potable water is available for ice making

BIBLIOGRAPHY

Alternate Hybrid Power Sources for Remote Site Applications. U.S. Department of Transportation report CG-D-06-81, February 1981.

Assessment and Conceptual Design of Photovoltaic Hybrid Systems. U.S. Department of Energy report DOE/NASA/0299-1, October 1983.

Buresch, Matthew. Photovoltaic Energy Systems Design and Installation. New York: McGraw-Hill, Inc., 1983.

Fan, John. "Solar Cells: Plugging into the Sun," Technology Review, 80:8 August/September 1978, 2-19.

Fundamentals and Applications of Photovoltaics Course Manual. Florida Solar Energy Center, Cape Canaveral, Florida, 1984.

Ice Maker Specifications. North Star Ice Equipment Corporation, 1981.

Handbook for Battery Energy Storage Photovoltaic Power Systems. Bechtel National, Inc., San Francisco, California, Department of Energy report SAN-2192-T1, November 1979.

Handbook on Solar Water Pumping. Intermediate Power Inc., 1984

Krauthamer, S., et al. Photovoltaic Power Conditioning Subsystem: State of the Art and Development Opportunities. Jet Propulsion Laboratory, Pasadena, California, Department of Energy report DOE/ET-20356-9, January 15, 1984.

Macomber, H. L., et al. Photovoltaic Stand-Alone Systems: Preliminary Engineering Design Handbook. Monegon Ltd., Gaithersburg, Maryland, Department of Energy report DOE/NASA/0195-1, August 1981.

Mantell, Charles. Batteries and Energy Systems. New York: McGraw-Hill, Inc., 1983.

Maycock, Paul D. and Edward N. Stirewalt. Photovoltaics: Sunlight to Electricity in One Step. Andover, Massachusetts: Brick House Publishing Co., 1981.

National Photovoltaics Program Five Year Research Plan 1984-1988. Department of Energy report DOE/CE-0072, May 1983.

Paul, Terrance D. How to Design an Independent Power System. Necedak, Wisconsin: Best Energy Systems for Tomorrow, Inc., 1981.

Photovoltaics: Electricity from Sunlight. Department of Energy report DOE/NBMCE-1075, 1984.

Photovoltaic Energy Systems Seminar. National Aeronautics and Space Administration, Cleveland, Ohio, 1978.

Polycrystalline and Amorphous Silicon Photovoltaic Cells. Solar Energy Research Institute report SERI/SP-281-1704, Golden, Colorado, June 1982.

Rosenblum, Louis. Practical Aspects of Photovoltaic Technology, Applications and Cost. National Aeronautics and Space Administration report NASA CR-168025, Cleveland, Ohio, November 1982.

Solar Photovoltaic Applications Seminar. Planning Research Corporation, McLean, Virginia, Department of Energy report DOE/CS/32522-T1, January 1980.

Water Quality Criteria, Section III, Heat and Temperature. National Academy of Sciences and National Academy of Engineering report EPA-R3-73-033, March 1973.

APPENDICES

APPENDIX A

Insolation (Source: Published research by Dr. Mossallan Shaltout of the Egyptian Meteorological Authority)

Horizontal Global Average Daily Insolation

EL FAIYUM EGYPT LAT=29

	SOLAR (kWh/day)	TEMP °C	REFLEC*
JAN	3.8	15.2	.20
FEB	4.9	16.2	.20
MAR	6.0	18.6	.20
APR	7.4	22.2	.20
MAY	7.6	26.1	.20
JUN	8.1	28.7	.20
JUL	8.1	30.2	.20
AUG	7.5	29.8	.20
SEP	6.7	27.4	.20
OCT	5.2	25.4	.20
NOV	4.0	21.2	.20
DEC	3.4	16.3	.20

* Estimated for sand

Ambient Temperature (Source: El Giza + 2 degrees Centigrade)

MONTH	MAX	MIN	MEAN
JAN	22.2	8.1	15.2
FEB	23.7	8.6	16.2
MAR	26.4	10.7	18.6
APR	30.7	13.7	22.2
MAY	34.7	17.6	26.1
JUN	36.8	20.6	28.7
JUL	37.8	22.5	30.2
AUG	37	22.5	29.8
SEP	34.4	20.4	27.4
OCT	32.6	18.1	25.4
NOV	28.2	14.2	21.2
DEC	22.6	10.1	16.3

Water Temperature (Source: Rafik Georgy, based on FRDA data)

8 - 28 Degrees Centigrade

APPENDIX B

EVALUATION OF WATER QUALITY ANALYSIS
OF WATER SAMPLES TAKEN FROM
WADI EL RAIYAN, OCTOBER 16-17, 1985

Evaluation

The results of the water quality analyses from Wadi El Raiyan, Egypt (attachment A) were compared to the World Health Organization's (WHO) guidelines for drinking water quality (attachment B). This comparison indicates that the water at Wadi El Raiyan is not potable. The WHO guidelines are the basis for Egyptian drinking water standards.

The Meridian evaluation of available the water quality data is summarized below. Meridian believes that additional analyses should be conducted before a decision is made to employ commercial water treatment technologies to purify the water at Wadi El Raiyan.

Specifically the findings are:

1) The dominant issue is the accuracy of the data. For example the level of lead (mean value of 39.25 ppm) and mercury (mean value of 71.75 ppm) suggests that there is direct industrial and/or sewage dumping into the water source. This was not observed during site visits. Additionally, the concentration of calcium carbonate (300 ppm) is higher than the conductivity value (210). This is not consistent since conductivity is a measure of total dissolved salts of which calcium carbonate is only a part. If these analyses are accurate the consumption of untreated water from the lake should be prohibited and an environmentally safe dumping area would be needed for the wastes processed out of the treated water.

2) There are several techniques to purify 1,584 gallons ($6m^3$) of water per day, the amount required to make 6 tons of ice. Three prominent procedures are: reverse osmosis of the water; passing the water

through an ion-exchange column, and, passing the water through a de-ionization column in combination with the ion exchange column (this process must be used if the cyanide concentration increases). Any one of these procedures would insure that the WHO standards for drinking water are met. They are all commercially available on a custom-design basis. The critical need for regular maintenance of these purification procedures, however, can present difficulties in remote, developing country applications.

Recommendations

Because of the uncertainty of the water analysis data, an extensive and thorough analysis of another water sample from Wadi El Raiyan should be completed. Once the data are confirmed or modified, appropriate measures can be taken to assess the cost/benefit of proceeding with water treatment for the application, if appropriate.

APPENDIX B, Attachment A

REPORT ON WATER QUALITY - FISH RESOURCE AND DEVELOPMENT AUTHORITY

Report to be submitted to the Chief,
Central Department for Production of Operations
on a trip to Wadi El Raiyan, with the Ministry of
Electricity - Renewable Energy Division

Upon the Director of the Research Department Request, and in collaboration with the Ministry of Electricity, Renewable Energy Division, a trip was made to Wadi El Raiyan, on 16-17 October 1985.

Purpose of the Trip: to investigate the possibility of establishing an ice plant on the 3rd lake at Wadi El Rayan, and to find out about the water potability.

Participated in the Trip:

1. Dr. S. Solomon, Project Economist, LBII
2. Ms. Magda Awadallah, Assistant Economist, LBII
3. Dr. Ayman Anwar M. Ammar,
   General Authority for Fish Resources Development.

Action taken: Water samples were taken to be analyzed in the Research Dept. Lab., General Authority for Fish Resources Development. In this respect, two random samples were taken from each of lakes 1/1 and 3/1.

Results: (shown in the attached tables)

1) Water samples contain Cyanide. In one sample it reached 0.06 ppm, in the other it is 0.03, with a mean of 0.04 ppm.

2) It contains lead, 50 ppm in one sample, 47.5 ppm in the other, with a mean of 39.25 ppm

Therefore, the lake 3 water is not recommended for human consumption.

We see that Wadi El Raiyan water, either lake 1 or lake 3 is not potable from a chemical point of view. It is preferable that other samples be analyzed in specified labs, to cover the microbiological side.

Signed,
Mr. Nazih Boulos
Director,
Research Dept.

Analysis done by Dr. Ayman Anwar Mohammed Anmar.

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CHEMICAL ANALYSES OF WATER SAMPLES TAKEN FROM WADI EL RAIYAN LAKE

Sample		Iron ppm	Sulphate ppm	Zinc ppm	Phosphate ppm	Nickel ppm	Silicon ppm	Cyanide ppm	Chrome ppm	Manganese ppm	Copper ppm	Hydrogen Sulphide ppm	NO_2 ppm	Nitrite ppm
Lake No. 1	Sample (1)	-	-	0.5	0.3	-	5	0.025	-	5	0.05	-	0.02	-
	Sample (2)	-	-	0.1	0.3	-	5	0.03	-	5	0.05	-	0.02	-
Lake No. 3	Sample (1)	-	-	0.1	0.3	-	5	0.06	-	5	0.05	-	0.02	-
	Sample (2)	-	-	0.1	0.3	-	5	0.03	-	5	0.05	-	0.02	-
Mean		-	-	0.2	0.3	-	5	0.036	-	5	0.05	-	0.02	-

Samples		Oxygen ppm	PH	Amonia ppm	Salinity ppm	Co_2 Co_3 ppm	Conductivity	Lead* ppm	Mercury* ppm	Cloride* ppm	Bromide* ppm	Iodine* ppm
Lake No. 1	Sample (1)	5.2	8.5	0.1	1.2	300	210	31.5	50	534	0.006	0.9
	Sample (2)	5.1	9	0.1	1.2	300	210	28	50	663	0.005	1
Lake No. 3	Sample (1)	4.5	8.5	0.1	1.2	300	210	50	90	881	0.006	1.3
	Sample (2)	3.8	8.0	0.05	1.2	300	210	47.5	97	1346	0.006	1.1
Mean		4.65	8.5	0.087	1.2	300	210	39.25	71.75	856	0.575	1.075

Chemical analysis were done by Research Dept., using the analysis instruments DR_3 - HACH, and the analysis boxes Merk. As for the items refered to with *, these were taken from a study entitled "Investigation of inorganic pollutants in El Fayoum Aquatic Environment", prepared by Dr. Mahmond Abbas, Professor, Faculty of Agriculture, Cairo University.

APPENDIX B, Attachment B

World Health Organization

GUIDELINES FOR DRINKING - WATER QUALITY

Volume 1. Recommendations

(Selected Pages)

Table 1. Microbiological and biological quality

Organism	Unit	Guideline value	Remarks
I. Microbiological quality			
A. Piped water supplies			
A.1 Treated water entering the distribution system			
faecal coliforms	number/100 ml	0	turbidity < 1 NTU, for disinfection with chlorine, pH preferably < 8.0, free chlorine residual 0.2-0.5 mg/litre following 30 minutes (minimum) contact
coliform organisms	number/100 ml	0	
A.2 Untreated water entering the distribution system			
faecal coliforms	number/100 ml	0	
coliform organisms	number/100 ml	0	in 95% of samples examined throughout the year—in the case of large supplies when sufficient samples are examined
coliform organisms	number/100 ml	3	in an occasional sample, but not in consecutive samples
A.3 Water in the distribution system			
faecal coliforms	number/100 ml	0	
coliform organisms	number/100 ml	0	in 95% of samples examined throughout the year—in the case of large supplies when sufficient samples are examined
coliform organisms	number/100 ml	3	in an occasional sample, but not in consecutive samples
B Unpiped water supplies			
faecal coliforms	number/100 ml	0	
coliform organisms	number/100 ml	10	should not occur repeatedly, if occurrence is frequent and if sanitary protection cannot be improved, an alternative source must be found if possible
C Bottled drinking-water			
faecal coliforms	number/100 ml	0	source should be free from faecal contamination
coliform organisms	number/100 ml	0	
D Emergency water supplies			
faecal coliforms	number/100 ml	0	advise public to boil water in case of failure to meet guideline values
coliform organisms	number/100 ml	0	
Enteroviruses	—	no guideline value set	
II. Biological quality			
protozoa (pathogenic)	—	no guideline value set	
helminths (pathogenic)	—	no guideline value set	
free-living organisms (algae, others)	—	no guideline value set	

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Table 2. Inorganic constituents of health significance

Constituent	Unit	Guideline value	Remarks
arsenic	mg/l	0.05	
asbestos	—	no guideline value set	
barium	—	no guideline value set	
beryllium	—	no guideline value set	
cadmium	mg/l	0.005	
chromium	mg/l	0.05	
cyanide	mg/l	0.1	
fluoride	mg/l	1.5	natural or deliberately added, local or climatic conditions may necessitate adaptation
hardness	—	no health-related guideline value set	
lead	mg/l	0.05	
mercury	mg/l	0.001	
nickel	—	no guideline value set	
nitrate	mg/l (N)	10	
nitrite	—	no guideline value set	
selenium	mg/l	0.01	
silver	—	no guideline value set	
sodium	—	no guideline value set	

Table 3. Organic constituents of health significance

Constituent	Unit	Guideline value	Remarks
aldrin and dieldrin	µg/l	0.03	
benzene	µg/l	10[a]	
benzo[*a*]pyrene	µg/l	0.01[a]	
carbon tetrachloride	µg/l	3[a]	tentative guideline value[b]
chlordane	µg/l	0.3	
chlorobenzenes	µg/l	no health-related guideline value set	odour threshold concentration between 0.1 and 3 µg/l
chloroform	µg/l	30[a]	disinfection efficiency must not be compromised when controlling chloroform content
chlorophenols	µg/l	no health-related guideline value set	odour threshold concentration 0.1 µg/l
2,4-D	µg/l	100[c]	
DDT	µg/l	1	
1,2-dichloroethane	µg/l	10[a]	
1,1-dichloroethene[d]	µg/l	0.3[a]	
heptachlor and heptachlor epoxide	µg/l	0.1	
hexachlorobenzene	µg/l	0.01[a]	
gamma-HCH (lindane)	µg/l	3	
methoxychlor	µg/l	30	
pentachlorophenol	µg/l	10	
tetrachloroethene[e]	µg/l	10[a]	tentative guideline value[b]

Table 3 (*continued*)

Constituent	Unit	Guideline value	Remarks
trichloroethene[d]	µg/l	30[a]	tentative guideline value[b]
2,4,6-trichlorophenol	µg/l	10[a c]	odour threshold concentration, 0.1 µg/l
trihalomethanes		no guideline value set	see chloroform

[a] These guideline values were computed from a conservative hypothetical mathematical model which cannot be experimentally verified and values should therefore be interpreted differently. Uncertainties involved may amount to two orders of magnitude (i.e., from 0.1 to 10 times the number).

[b] When the available carcinogenicity data did not support a guideline value, but the compounds were judged to be of importance in drinking-water and guidance was considered essential, a tentative guideline value was set on the basis of the available health-related data.

[c] May be detectable by taste and odour at lower concentrations.

[d] These compounds were previously known as 1,1-dichloroethylene, tetrachloroethylene, and trichloroethylene respectively.

Table 4. Aesthetic quality

Constituent or characteristic	Unit	Guideline value	Remarks
aluminium	mg/l	0.2	
chloride	mg/l	250	
chlorobenzenes and chlorophenols	—	no guideline value set	these compounds may affect taste and odour
colour	true colour units (TCU)	15	
copper	mg/l	1.0	
detergents	—	no guideline value set	there should not be any foaming or taste and odour problems
hardness	mg/l (as $CaCO_3$)	500	
hydrogen sulfide	—	not detectable by consumers	
iron	mg/l	0.3	
manganese	mg/l	0.1	
oxygen—dissolved	—	no guideline value set	
pH	—	6.5–8.5	
sodium	mg/l	200	
solids—total dissolved	mg/l	1000	
sulfate	mg/l	400	
taste and odour	—	inoffensive to most consumers	
temperature	—	no guideline value set	
turbidity	nephelometric turbidity units (NTU)	5	preferably <1 for disinfection efficiency
zinc	mg/l	5.0	

APPENDIX C

This appendix contains performance prediction model output for the photvoltaic array considered for this field test. The model used is PV-FCHART, purchased by LBII for the REFT project from the following vendor:

F - CHART SOFTWARE
4406 Fox Bluff Road
Middleton, Wisconsin 53560

Pages C-1 through C-5 contain actual output from PV-FCHART. Beginning on page C-6, part of the PV-FCHART manual is provided to aid in interpreting the output. Finally, pages C-13 through C-21 are the algorithms used to predict PV array output.

PV FCHART array performance output prediction

EL FAIYUM LAT= 29

	SOLAR KJ/M2	TEMP C	REFLEC
JAN	13735	15.2	.20
FEB	17672	16.2	.20
MAR	21776	18.6	.20
APR	26675	22.2	.20
MAY	27513	26.1	.20
JUN	29271	28.7	.20
JUL	29104	30.2	.20
AUG	27094	29.8	.20
SEP	23995	27.4	.20
OCT	18886	25.4	.20
NOV	14322	21.2	.20
DEC	12270	16.3	.20

1	CITY CALL NUMBER.....	125	
2	OUTPUT 1=SUM 2=DET NEG=GRAPH..	1	
3	CELL TEMP AT NOCT CONDITIONS..	49	C
4	ARRAY REFERENCE EFFICIENCY....	.099	
5	ARRAY REFERENCE TEMPERATURE...	25	C
6	ARRAY TEMP COEFFICIENT * 1000.	4	1/C
7	POWER TRACKING EFFICIENCY.....	.9	
8	POWER CONDITIONING EFFICIENCY.	.95	
9	% STANDARD DEVIATION OF LOAD..	0	%
10	EFFECTIVE BATTERY CAPACITY....	233	KW-HR
11	BATTERY EFFICIENCY.....	.8	
12	ARRAY AREA.....	354	M2
13	ARRAY SLOPE.....		DEG
	40 40 40 10 10 10 10 10 10 40 40 40		
14	ARRAY AZIMUTH (SOUTH=0).....	0	DEG

JAN

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
7- 8	2151	7.7	543	29.1	0
8- 9	4324	8.3	543	60.9	9
9-10	6492	8.2	543	79.3	76
10-11	8248	8.1	543	87.5	158
11-12	9232	8.0	543	90.5	208
12-13	9232	7.9	543	90.4	205
13-14	8248	8.0	543	87.2	151
14-15	6492	8.0	543	78.6	68
15-16	4324	8.0	543	59.6	6
16-17	2151	7.5	543	28.1	0
MONTH	60895	8.0	13020	28.8	881

FEB

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
6- 7	544	4.4	490	4.3	2
7- 8	2381	7.7	490	35.3	0
8- 9	4524	8.2	490	69.1	14
9-10	6636	8.1	490	84.9	97
10-11	8335	8.0	490	91.1	187
11-12	9283	7.9	490	93.2	239
12-13	9283	7.9	490	93.2	236
13-14	8335	7.9	490	90.8	179
14-15	6636	7.9	490	84.3	88
15-16	4524	7.9	490	67.6	9
16-17	2381	7.4	490	34.1	0
17-18	544	4.3	490	4.2	2
MONTH	63406	7.9	11760	31.3	1052

MAR

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
6- 7	837	5.2	543	7.6	0
7- 8	2944	7.5	543	38.7	0
8- 9	5333	8.0	543	72.7	13
9-10	7648	8.0	543	87.1	111
10-11	9489	7.9	543	92.2	211
11-12	10510	7.8	543	94.0	267
12-13	10510	7.7	543	93.9	263
13-14	9489	7.8	543	92.0	201
14-15	7648	7.8	543	86.5	99
15-16	5333	7.8	543	71.1	8
16-17	2944	7.2	543	37.3	0
17-18	837	5.0	543	7.3	0
MONTH	73522	7.7	13020	32.5	1172

APR

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
6- 7	1394	5.9	525	15.0	0
7- 8	3596	7.5	525	48.7	0
8- 9	5987	7.9	525	82.2	19
9-10	8235	7.9	525	93.1	128
10-11	9989	7.7	525	95.3	229
11-12	10951	7.6	525	97.3	282
12-13	10951	7.6	525	97.3	278
13-14	9989	7.6	525	96.2	216
14-15	8235	7.7	525	92.6	113
15-16	5987	7.6	525	80.4	12
16-17	3596	7.2	525	46.7	0
17-18	1394	5.7	525	14.4	0
MONTH	80304	7.6	12600	35.8	1277

MAY

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
5- 6	154	8.2	543	2.2	0
6- 7	1886	6.3	543	20.9	0
7- 8	4005	7.5	543	52.7	0
8- 9	6248	7.8	543	82.7	15
9-10	8323	7.7	543	93.0	106
10-11	9924	7.6	543	96.3	193
11-12	10796	7.5	543	97.3	239
12-13	10796	7.4	543	97.3	235
13-14	9924	7.5	543	96.1	182
14-15	8323	7.5	543	92.5	92
15-16	6248	7.5	543	80.9	9
16-17	4005	7.2	543	50.7	0
17-18	1886	6.1	543	20.1	0
18-19	154	8.0	543	2.2	0
MONTH	82674	7.5	13020	36.9	1072

JUN

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
5- 6	306	6.7	525	3.7	0
6- 7	2083	6.3	525	23.9	0
7- 8	4176	7.5	525	56.5	0
8- 9	6372	7.7	525	86.9	12
9-10	8390	7.6	525	96.1	104
10-11	9941	7.5	525	98.4	191
11-12	10784	7.4	525	99.1	237
12-13	10784	7.3	525	99.0	233
13-14	9941	7.4	525	98.3	179
14-15	8390	7.4	525	95.8	89
15-16	6372	7.4	525	84.8	5
16-17	4176	7.2	525	54.2	0
17-18	2083	6.1	525	23.0	0
18-19	306	6.5	525	3.6	0
MONTH	84105	7.4	12600	38.5	1050

JUL

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
5- 6	212	7.9	543	2.9	0
6- 7	2064	6.2	543	22.5	0
7- 8	4262	7.4	543	55.3	0
8- 9	6578	7.7	543	86.0	13
9-10	8714	7.6	543	95.6	110
10-11	10358	7.4	543	98.1	201
11-12	11254	7.3	543	98.8	248
12-13	11254	7.3	543	98.8	244
13-14	10358	7.3	543	98.0	188
14-15	8714	7.4	543	95.1	94
15-16	6578	7.4	543	84.0	6
16-17	4262	7.1	543	53.0	0
17-18	2064	6.0	543	21.6	0
18-19	212	7.6	543	2.8	0
MONTH	86883	7.3	13020	38.0	1104

AUG

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
6- 7	1626	6.0	543	17.0	0
7- 8	3846	7.3	543	49.3	0
8- 9	6231	7.7	543	81.2	14
9-10	8459	7.6	543	92.5	110
10-11	10189	7.5	543	95.9	202
11-12	11136	7.4	543	97.0	251
12-13	11136	7.3	543	97.0	247
13-14	10189	7.3	543	95.8	190
14-15	8459	7.4	543	91.9	95
15-16	6231	7.4	543	79.3	8
16-17	3846	7.0	543	47.3	0
17-18	1626	5.7	543	16.3	0
MONTH	82976	7.3	13020	35.9	1116

SEP

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
6- 7	988	5.3	525	9.4	0
7- 8	3106	7.2	525	40.5	0
8- 9	5451	7.7	525	75.0	5
9-10	7682	7.7	525	89.7	92
10-11	9434	7.6	525	94.3	184
11-12	10399	7.5	525	95.8	235
12-13	10399	7.4	525	95.7	231
13-14	9434	7.4	525	94.1	173
14-15	7682	7.5	525	89.1	79
15-16	5451	7.4	525	72.8	2
16-17	3106	6.9	525	38.9	0
17-18	988	5.1	525	9.1	0
MONTH	74120	7.4	12600	33.5	1002

OCT

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
6- 7	677	4.5	543	5.4	0
7- 8	2744	7.4	543	35.4	0
8- 9	5138	7.9	543	68.9	10
9-10	7485	7.8	543	84.8	95
10-11	9367	7.7	543	90.9	189
11-12	10416	7.6	543	93.0	243
12-13	10416	7.5	543	93.0	239
13-14	9367	7.5	543	90.7	180
14-15	7485	7.6	543	84.1	85
15-16	5138	7.6	543	67.2	6
16-17	2744	7.1	543	34.1	0
17-18	677	4.4	543	5.2	0
MONTH	71652	7.5	13020	31.4	1048

NOV

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
7- 8	2122	7.5	525	29.0	0
8- 9	4211	8.0	525	60.1	6
9-10	6288	8.0	525	78.4	66
10-11	7964	7.9	525	86.5	140
11-12	8902	7.7	525	89.6	185
12-13	8902	7.7	525	89.5	182
13-14	7964	7.7	525	86.2	133
14-15	6288	7.8	525	77.7	59
15-16	4211	7.8	525	58.8	4
16-17	2122	7.3	525	28.0	0
MONTH	58974	7.8	12600	28.5	775

DEC

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
7- 8	1897	7.7	543	25.6	0
8- 9	3914	8.2	543	55.4	5
9-10	5933	8.2	543	74.6	57
10-11	7569	8.1	543	83.8	124
11-12	8485	8.0	543	87.3	167
12-13	8485	7.9	543	87.2	165
13-14	7569	7.9	543	83.5	119
14-15	5933	8.0	543	73.9	51
15-16	3914	8.0	543	54.2	3
16-17	1897	7.5	543	24.8	0
MONTH	55597	8.0	13020	27.1	691

SUMMARY

	SOLAR KW-HR	LOAD KW-HR	F %	BUY KW-HR	XS KW-HR
JAN	60894.8	13020.0	34.2	8566.2	177.2
FEB	63406.1	11760.0	38.5	7233.3	210.6
MAR	73521.6	13020.0	39.7	7848.6	234.4
APR	80303.8	12600.0	44.0	7061.5	253.7
MAY	82673.7	13020.0	43.5	7361.9	214.7
JUN	84105.1	12600.0	45.1	6912.0	209.7
JUL	86882.6	13020.0	44.8	7186.7	220.2
AUG	82976.0	13020.0	42.7	7458.0	222.6
SEP	74119.8	12600.0	39.9	7575.2	199.7
OCT	71651.9	13020.0	37.8	8098.8	209.6
NOV	58974.4	12600.0	33.4	8390.9	155.9
DEC	55597.5	13020.0	31.3	8940.3	139.2
YR	875107.2	%153300.0	39.6	92633.4	2447.5

OCT	705.4	93.00	31.6	63.6	25.2
NOV	436.5	90.00	24.0	68.4	13.7
DEC	384.1	93.00	20.[illegible]	73.6	12.8
YR	8098.5	1095.00	32.8	736.2	264.4

SOLAR is the monthly total solar radiation incident on the collector in kW-hrs. The area used in evaluating SOLAR is the product of the array area and the collector concentration ratio.

EFF is the array efficiency defined as percent of the solar radiation incident of the collector which is converted to electrical energy. The effects on efficiency caused by the power-tracking equipment and the angular dependence of the array transmittance and absorptance of solar radiation on the collector are included in this efficiency. The array output in kW-hrs can be found as the product of SOLAR and EFF.

LOAD is the total electrical demand on the system in kW-hrs.

F is the percent of the load supplied directly by the array.

SELL is the total electrical energy which can be sold back to the utility in kW-hrs. It is the product of the excess energy produced by the array and the power-conditioning equipment efficiency.

BUY is the total electrical energy which must be purchased from the utility to satisfy the load in kW-hrs.

3.3 Battery Storage Systems

A photovoltaic system with battery storage is shown schematically in Figure 3.2. The control logic asssumed for this system is as follows. Electrical energy produced by the array is first used to supply the load. Any excess energy is then directed to the battery. Losses resulting from this transfer process to (and from) the battery are considered by specification of the battery efficiency (parameter 11). If the excess energy sent to the battery accumulates to an amount equal to the effective battery capacity (parameter 13), additional excess energy must be dissipated. Utility feedback capability is not allowed.

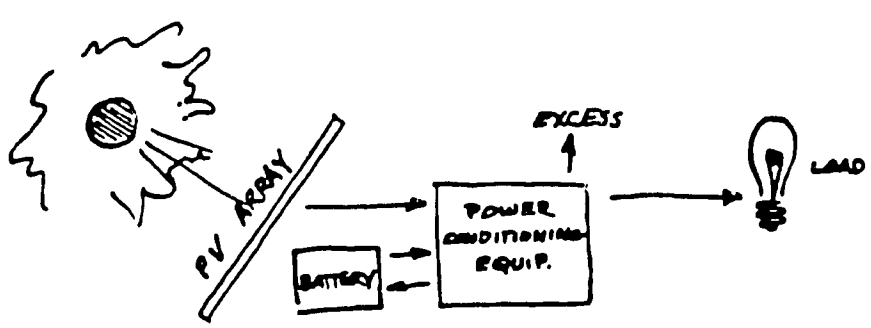

FIG. 3.2 Battery Storage System

The parameters for the battery storage system with a flat-plate tracking option are listed below with the default values in both SI and English units.

1	CITY CALL NUMBER.....	27		27	
2	OUTPUT 1=SUM 2=DET NEG=GRAPH.	2		2	
3	CELL TEMP AT NOCT CONDITIONS.	44	C	111	F
4	ARRAY REFERENCE EFFICIENCY...	.104		.104	
5	ARRAY REFERENCE TEMPERATURE..	28	C	82.4	F
6	ARRAY TEMP COEFFICIENT * 1000	4.3	1/C	2.39	1/F
7	POWER TRACKING EFFICIENCY....	.9		.9	
8	POWER CONDITIONING EFFICIENCY	.88		.88	
9	% VARIATION OF LOAD.....	0	%	0	%
10	EFFECTIVE BATTERY CAPACITY...	1.4	KW-HR	1.4	KW-HR
11	BATTERY EFFICIENCY.....	.87		.87	
12	ARRAY AREA.....	6	M2	64.6	FT2
13	ARRAY SLOPE.....	50	DEG	50	DEG
14	ARRAY AZIMUTH (SOUTH=0).....	0	DEG	0	DEG

The output for these default parameters and the load shown in section 2.3.2 is as follows.

JANUARY

TIME	SOLAR KW-HR	EFF %	LOAD KW-HR	FO %	XSO KW-HR
7 -8	10.26	8.8	3.10	17.2	0.26
8 -9	29.14	9.7	3.29	51.0	0.80
9 -10	49.04	9.7	3.50	67.1	1.83
10-11	65.58	9.6	3.75	74.6	2.73
11-12	74.97	9.5	4.00	77.1	3.19
12-13	74.97	9.5	4.25	76.0	3.03
13-14	65.58	9.5	4.46	71.0	2.33
14-15	49.04	9.6	4.65	60.6	1.32
15-16	29.14	9.5	4.77	42.3	0.42
16-17	10.26	8.7	4.84	13.3	0.14
MONTH	457.99	9.5	93.00	24.0	16.06

FEBRUARY

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SUMMARY

	SOLAR KW-HR	LOAD KW-HR	F %	BUY KW-HR	XS KW-HR
JAN	458.0	93.00	37.6	58.0	3.4
FEB	519.7	84.00	45.9	45.4	4.4
MAR	686.4	93.00	52.4	44.2	6.2
APR	741.5	90.00	56.6	39.0	6.6
MAY	828.9	93.00	60.0	37.2	6.6
JUN	853.3	90.00	62.4	33.9	6.4

JUL	871.5	93.00	61.0	36.2	6.3
AUG	820.4	93.00	57.8	39.3	6.3
SEP	792.9	90.00	58.0	37.8	7.0
OCT	705.4	93.00	52.2	44.4	6.1
NOV	436.5	90.00	36.1	57.5	2.8
DEC	384.1	93.00	31.9	53.3	2.5
YR	8098.5	1095.00	51.0	536.4	64.6

SOLAR is the monthly total solar radiation incident on the collector in kW-hrs. The area used in evaluating SOLAR is the product of the array area and the collector concentration ratio.

EFF is the array efficiency defined as percent of the solar radiation incident of the collector which is converted to electrical energy. The effects on efficiency caused by the power-tracking equipment and the angular dependence of the array transmittance and absorptance of solar radiation on the collector are included in this efficiency. The array output in kW-hrs can be found as the product of SOLAR and EFF.

LOAD is the total electrical demand on the system in kW-hrs.

FO (in the monthly output) is the percent of the load which would be supplied by the system if there were no battery.

XSO (in the monthly output) is the of the monthly total energy (for each hourly period) in excess of the load and the power-conditioning efficiency in kW-hrs. This energy is either stored in the battery for later use or dissipated if the battery is fully charged.

F (in the annual summary) is the estimated percentage of the load supplied by the system, including the contribution of the battery.

BUY (in the annual summary) is the total auxiliary energy which must be purchased from a utility to satisfy the load in kW-hrs.

XS (in the annual summary) is the monthly array output in kW-hrs which does not contribute to the load as a result of either inefficiencies in the battery or the battery being fully charged at the time the energy was produced.

3.4 Systems with No Utility Feedback or Battery Storage

The simplest photovoltaic system is one which does not have the option of utility feedback or battery storage. A schematic of this system is shown in Figure 3.3. The energy produced by the array is either used directly to supply the instantaneous load or it must be dissipated.

SUMMARY

	SOLAR KW-HR	LOAD KW-HR	F %	BUY KW-HR	XS KW-HR
JAN	458.0	93.00	24.0	70.7	16.1
FEB	519.7	84.00	28.7	59.9	18.9
MAR	686.4	93.00	32.9	62.4	24.4
APR	741.5	90.00	36.2	57.5	25.0
MAY	828.9	93.00	39.6	56.2	25.6
JUN	853.3	90.00	41.4	52.7	25.2
JUL	871.5	93.00	40.5	55.3	25.4
AUG	820.4	93.00	37.6	58.0	25.1
SEP	792.9	90.00	35.7	57.9	27.0
OCT	705.4	93.00	31.6	63.6	25.2
NOV	436.5	90.00	24.0	68.4	13.7
DEC	384.1	93.00	20.9	73.6	12.8
YR	8098.5	1095.00	32.8	736.2	264.4

SOLAR is the montnly total solar radiation incident on the collector in kW-hrs. The area used in evaluating SOLAR is the product of the array area and the collector concentration ratio.

EFF is the array efficiency defined as percent of the solar radiation incident of the collector which is converted to electrical energy. The effects on efficiency caused by the power-tracking equipment and the angular dependence of the array transmittance and absorptance of solar radiation on the collector are included in this efficiency. The array output in kW-hrs can be found as the product of SOLAR and EFF.

LOAD is the total electrical demand on the system in kW-hrs.

F is the percent of the load supplied directly by the array.

BUY is the total electrical energy which muyst be purchased from the utility to satisfy the load in kW-hrs.

XS is the total electrical energy which must be dissipated in kW-hrs.

3.5 System Parameter Descriptions

The first twelve parameters are the same for all systems. The remaining parameters will depend on the choice of system type and tracking option. A description of each system parameter is found in this section. Additional information may be found in Chapter 4 which describes how these parameters are used in the calculation of system performance.

1 CITY CALL NUMBER..... is a number between 1 and 329 indicating the city for which weather data are taken for use in the system performance calculations. A city listing appears in Appendix A. The weather data supplied with the program can be changed as described in section 2.3.13.

2 OUTPUT 1=SUM 2=DET NEG=GRAPH. is a number with absolute value of 1 or 2 which controls the amount of printed output for the thermal-electric calculations and whether graphical results are produced. All results are printed if the absolute value of this parameter is 2. Otherwise, only the annual summary is printed. If the parameter value is negative, bar graphs of monthly energy quantities are produced. These graphs appear as follows.

```
JAN !000000000000
FEB !0000000000000000
MAR !00000000000000
APR !00000000000
MAY !0000000000
JUN !0000000000
JUL !0000000000
AUG !0000000000
SEP !00000000000000
OCT !00000000000000
NOV !000000000000
DEC !000000000000
    !-----------!-----------!
     0                      93
        KW-HR/DAY
```

In these graphs, O is the monthly average daily array output; B is the monthly average daily energy which must be bought from a utility; L is the monthly average daily load; and S is the monthly average daily energy which is sold back to the utility.

3 CELL TEMP AT NOCT CONDITIONS. is the temperature which the array attains under no-load and at the nominal operating conditions of 20 C and 800 W/M2 on the aperture plane. This temperature, called NOCT, is measured in collector-array thermal tests. It can also be calculated in terms of $(ta)/U_L$ where (ta) is the transmittance-absorptance product and U_L is the array overall heat transfer coefficient. For a flat-plate array, the relationship is

$$NOCT = (800\ W/M2) * (ta)/U_L + 20\ C$$

For concentrating collectors, the assumption is made that 75% of the 800 W/M2 represents beam radiation; the remainder is diffuse and ground-reflected radiation. In this case, 800 W/M2 in the above equation is replaced with (600 * C + 200) where C is the concentration ratio. See Section 5.1 for further details.

7 ARRAY REFERENCE EFFICIENCY. . is the product of the cell packing factor and the cell reference efficiency determined at a reference array temperature (parameter 8). The packing factor should be based on the same area specified with parameter 2.

8 ARRAY REFERENCE TEMPERATURE... is a temperature at which the array efficiency (parameter 7) is known.

9 ARRAY TEMPERATURE COEFFICIENT. is the rate at which the array efficiency linearly decreases with temperature for maximum power-tracking operation. This coefficient is primarily a function of the cell material. Typical values are 0.0043 (1/C) for silicon cells and 0.0025 (1/C) for galium arsenide cells. The array temperature coefficient is insensitive to temperature for the range of cell temperatures encountered in non-concentrating arrays.

10 POWER TRACKING EFFICIENCY.... is the efficiency of the control logic and equipment used to control the array to operate at its maximum power point.

11 POWER-CONDITIONING EFFICIENCY is the efficiency of the control logic and equipment which transforms the electrical energy produced by the array into the form required by the load, utility, and battery.

12 % VARIATION OF LOAD..... is a parameter which allows a distribution to be considered in the monthly-average hourly loads. The load distribution for any hourly period is assumed to be uniformally distributed with its mean equal to the load entered for that hour and its minimum to maximum range equal to the product of this parameter and the hourly mea- load. For example, if the hourly load is 100 W and the % variation is 100%, the load is assumed to be uniformily distributed over the range of 0 to 200 W. If this parameter is set to 0, a distribution of loads in not considered; i.e.. the load at a given hour is always the fixed value entered by the user.

The following parameters may or may not appear in the system parameter set, depending on the type of system and the tracking option selected.

xx EFFECTIVE BATTERY CAPACITY... is the total energy which can be obtained from the battery when it is fully charged. It is the product of the single-cell battery capacity, the number of cells, and the allowable depth of discharge.

xx BATTERY EFFICIENCY. ..... is the ratio of the energy sent to the battery to that which can be usefully obtained from the battery. In a battery storage system, some energy is lost due to internal battery resistance and electrolyte gassing. Typical values of battery efficiency range between 0.6 and 0.9.

xx ARRAY AREA..... is the total photovoltaic cell area used in the system (FT2 or M2). The same area (gross or net) should be used to evaluate the array reference efficiency (system parameter 4) and the cost per unit area (economics parameter 2)

xx ARRAY SLOPE..... . is the angle between the plane of the array and the horizontal (DEG). A vertical array will have a slope of 90 DEG.

xx AXIS SLOPE..... is the angle between the axis of the collector and the projection of the axis into the horizontal plane (DEG).

xx ARRAY AZIMUTH (SOUTH=0)..... is the deviation of the normal to the collector surface from the local meridian (DEG) with zero indicating that the array faces directly towards the equator, west positive, and east negative.

xx AXIS AZIMUTH (SOUTH=0)..... is the angle between the projection of the axis into the horzontal plane and local meridian. An east-west axis orientation will have an axis azimuth of 90 DEG.

xx CONCENTRATION RATIO..... is the ratio of the aperture area of the solar collector to the photovoltaic array area.

xx AXIS ORIENTATION (1=EW,2=NS). is an integer, either 1 or 2, which indicates the axis orientation of the CPC collector. Specify 1 if the axis points east-west and 2 if the axis points north-south when the azimuth angle is 0. Specify 2 if the collectors ar mounted vertically with the axis pointing straight up.

xx ACCEPTANCE HALF-ANGLE..... is the maximum angle measured from the axis of the CPC for which incident beam radiation will strike the array.

CHAPTER 5
PHOTOVOLTAIC SYSTEM PERFORMANCE ALGORITHMS

PV F-CHART was developed to provide estimates of the long-term performance of photovoltaic systems. It is based on algorithms developed by the Solar Energy Laboratory at the University of Wisconsin - Madison.

PV F-CHART is not a simulation program. A simulation calculates the instantaneous (or hourly) performance of a system and then integrates it over time using as input, short-term (typically, hourly) weather records for a specific location and time period. In contrast, PV F-CHART uses long-term monthly averages of the solar radiation and ambient temperature. The effect of variations in weather parameters on the long-term average performance of photovoltaic systems is considered through the use of solar radiation utilizabilty, a radiation statistic which incorportates the distribution of solar radiation. The advantage of this approach is greatly reduced computational effort without sacrificing the accuracy of the results.

The photovoltaic system performance algorithms used in PV F-CHART are largely based on the methods developed by Siegel et al. [1] and Clark [2]. These methods were developed from simulation studies done with the TRNSYS [3] simulation program and photovoltaic component models developed by Evans et [4]. The algorithms are outlined in this chapter. Also needed in the c utions are methods of estimating the monthly-average hourly solar radiation on inclined surfaces, the solar radiation utilizability, and monthly-average hourly ambient temperatures. These methods are fully documented in the cited references.

5.1 Monthly-Average Array Output

The three photovoltaic system configurations which can be evaluated with the PV F-CHART program are described in sections 3.2-3.4. In all three configurations, power tracking equipment maintains the array output at is maximum power point. The photovoltaic array model assumes that, for maximum power tracking, the instantaneous array efficiency, n, is a linear function of cell temperature, T_c.

$$n = n_r \, [1 - b \, (T_c - T_r)] \, n_{pt} \qquad (1)$$

The array reference efficiency, n_r, is the product of the cell packing factor and the cell reference efficiency determined at a reference temperature, T_r. b is the temperature coefficient of efficiency which is assumed to be constant over the range of temperatures encountered in non-concentrating systems. The efficiency of the power tracking equipment, n_{pt}, is included in the definition of the array efficiency.

An energy balance on the array results in E, the rate at which electrical energy is produced by the array.

$$E = A\,I_c\,n = A\,I_c\,(ta) - A\,U_L\,(T_c - T_a) \qquad (2)$$

A is the cell array area upon which the cell packing factor has been calculated. I_c is the instantaneous solar radiation per unit area incident on the array. (ta) is the solar radiation transmittance-absorptance product of the array. U_L is the array overall heat loss coefficient per unit array area for losses to an environment at temperature T_a. The first term on the right hand side of equation (2) is the rate at which solar radiation is absorbed by the array. The last term in this equation is the rate of thermal energy loss. The difference between these two terms represents the rate of electrical energy production.

Eliminating the cell temperature from equation (2) and substituting into equation (1) yields

$$n = n_r n_{pt}[1 - b(T_a - T_r) - bI_c/U_L((ta)-n)] \qquad (3)$$

In the last term, (ta) is about an order of magnitude greater than n so that a relatively large error in n causes only a small error in this term. For simplicity in the computations which follow, n in the last term of equation (3) is approximated to be the product of n_r, n_{pt}, and (ta) to yield the following expression for the array efficiency.

$$n = n_r n_{pt}[1 - b(T_a - T_r) - bI_t(ta)/U_L(1-n_r n_{pt})] \qquad (4)$$

In practice, it is not necessary to determine separate values of (ta) and U_L since only their ratio appears in equation (4). This ratio can be found in terms of the nominal operating cell temperature (NOCT) defined as the cell temperature achieved by the cell under no-load conditions at 20 C and solar radiation of 800 W/m^2 on the collector aperture [5]. For flat plate arrays, equation (2) with n set to 0 results in the following re ion for the NOCT.

$$NOCT = 20\ C + 800\ W/m^2\ (ta)/U_L \qquad (5)$$

When the concentration ratio is greater than 1, a solar flux of 800 W/M2 on the collector aperture may result in a flux greater than 800 W/M2 on the array surface. To estimate the flux on the array, it is assumed that 75% of the incident solar radiation is beam radiation and the remainder is diffuse or ground-reflected radiation. NOCT is then found from equation

(5) with 800 W/M2 replaced by (600 * C + 200) W/M2 where C is the concentration ratio.

Equation (4) gives the array efficiency when the average ambient temperature is T_a and the solar radiation is I_c. Over the long-term (e.g., 10 or more years), the ambient temperature and solar radiation for a particular hourly period (e.g., 10:00-11:00 AM during all January days) vary considerably; this variation can be described by the probability distributions, $P(T_a)$ and $P(I_c)$, respectively. What is needed for long-term performance calculations is $\bar{n}$, the long-term average array efficiency for each hour and month. $\bar{n}$ is the average efficiency weighted in proportion to the solar radiation and it can be formally defined by

$$\bar{n} = \frac{\int_0^{I_{c,max}} n\, I_c\, P(I_c)\, dI_c}{\int_0^{I_{c,max}} I_c\, P(I_c)\, dI_c} \qquad (6)$$

The denominator in equation (6) is I_c, the long-term average hourly solar radiation per unit area on the array for the hour and month under consideration. I_c is calculated as the sum of three radiation components corresponding to the beam, diffuse, and ground-reflected radiation in the manner outlined in reference [6].

$$I_c = \bar{I}\,[(1-\bar{I}_d/\bar{I})R_b C + \bar{I}_d/\bar{I}\,(1+\cos B)/2 + \rho(1-\cos B)/2] \qquad (7)$$

$\bar{I}$ is the monthly-average hourly radiation per unit area on a horizontal surface which is estimated from monthly-average daily radiation data as described in section 2.13 of reference [6]. The monthly-average diffuse fraction, $\bar{I}_d/\bar{I}$, is calculated using the correlation given by equation (10) of reference [7]. R_b is the ratio of beam radiation on the aperture plane to that on a horizontal surface and C is the concentration ratio. B is the tilt of the array from horizontal and ρ is the ground reflectance. For the one and two-axis tracking options, the surface azimuth and B are computed internally using the algorithms presented in reference [8].

Substituting n from equation (4) into equation (6) and integrating to the extent possible analytically results in

$$\bar{n} = n_r n_{pt}[1 - b(T_a - T_r) - b((ta)/I_t U_L)(1 - n_r n_{pt} \int I_t^2 P(I_t) dI_t] \qquad (8)$$

T_a is the monthly-average hourly temperature which is estimated in terms of the monthly-average daily temperature and horizontal solar radiation using the correlation given by equations (13)-(15) of Erbs et al. [9].

The integral in equation (8) can be shown to depend only on geometry parameters (which are constant for a particular hour and month) and $\bar{k}_t$, the ratio of $\bar{I}$ to I_o, the extraterrestrial radiation for the hour. The integral has been evaluated numerically by estimating I_c as indicated in equation 2.15.7 of reference [6] and rearranging to produce:

$$\int I_c^2 P(I_c)dI_c = a_1 I_0^2 \int k_t^2 P(k_t)dk_t + a_2 I_0^2 \int k_t^2 (I_d/I)P(k_t)dk_t + a_3 I_0^2 \int k_t^2 (I_d/I)^2 P(k_t)dk_t \quad (9)$$

where a_1, a_2, and a_3 are constants for a given hour and month.

$$a_1 = (R_b C)^2 + pC(1-\cos B)R_b + p^2(1-\cos B)^2/4 \quad (10)$$

$$a_2 = R_b C(1+\cos B - 2R_b C) + p(1+\cos B - 2R_b C)(1-\cos B)/2 \quad (11)$$

$$a_3 = [(1+\cos B)/2 - R_b C]^2 \quad (12)$$

The dimensionless parameter, k_t, is the ratio of the horizontal solar radiation to the extraterrestrial radiation. The diffuse fraction (I_d/I) is a function of k_t; the correlation given in equation (1) of reference [7] is used here. Each of the three integrals in equation (9) can be evaluated numerically since the long-term probability distribution of k_t is a known function of $\bar{k}_t$, as shown by Liu and Jordan [10]. Least squares curve-fitting the results obtained from the numerical integration results in

$$\int_0^{k_{t,max}} k_t^2 P(k_t)dk_t = -0.1551 + 0.9226\,\bar{k}_t \quad (13)$$

$$\int_0^{k_{t,max}} k_t^2 (I_d/I)P(k_t)dk_t = 0.1456 + 0.0544\,\ln(\bar{k}_t) \quad (14)$$

$$\int_0^{k_{t,max}} k_t^2 (I_d/I)^2 P(k_t) dk_t = \bar{k}_t (0.2769 - 0.3184\bar{k}_t) \tag{15}$$

The monthly-average hourly array output, $\bar{E}$, is then given by

$$\bar{E} = A\, I_c\, \bar{n}\, K_{ta} \tag{16}$$

where K_{ta} is a factor which accounts for the dependence of the array transmittance-absorptance product with solar radiation incidence angle. This factor is calculated for a single cover and nominal surface absorption properties as described in Chapter 5 of reference [6]. The monthly-average hourly array output is referred to as OUTPUT in the printed results and the average hourly array efficiency given by equation (8) is referred to as EFF.

5.2 Monthly-Average Excess Energy

In any photovoltaic system, there may be times when the electrical energy produced by the array is greater than that needed to satisfy the electrical demand, i.e., the load. This excess energy may be fed back to the utility (section 3.1), sent to a storage battery (section 3.2), or dissipated (section 3.3). The amount of excess energy is affected by the capacity of the array relative to the load, and by the distribution of the load during daytime hours. The PV F-CHART program allows the load distribution to be entered on a monthly-average hourly basis, thus incorporating considerable generality with regard to the types of loads which can be considered.

The long-term monthly-average array output for a particular hourly period (e.g., 10:00-11:00 AM) is given by equation (16). A critical radiation level, I_{crit}, can be defined as the radiation level on the array at which the electrical energy production is just equal to $\bar{L}$, the monthly-average load for the hour.

$$I_{crit} = \bar{L}/(A\, \bar{n}\, n_{pc} K_{ta}) \tag{17}$$

where n_{pc}, the power conditioning equipment efficiency, accounts for the reduction in array output resulting from the transformation of the array electrical energy into the voltage-current characteristics needed by the load. Radiation above the critical level will result in excess energy production. The fraction of the solar radiation incident on the array which is above the critical level is referred to as ϕ, the solar radiation utilizability [11]. ϕ can be estimated for any array orientation using the correlation of Clark et al. [12].

In terms of utilizability, the monthly-average hourly energy in excess of the average hourly load is $\bar{D}$ given by

$$\bar{D} = n_{pc} \bar{E} \phi \tag{18}$$

The energy produced by the array which is used directly to supply the load is then $n_{pc}\bar{E} - \bar{D}$. The fraction of the load met by a system (without battery storage) is then

$$f_0 = n_{pc}(\bar{E} - \bar{D})/\bar{L} \tag{19}$$

The significance of the energy represented by $\bar{D}$ differs among the three system configurations. In the utility feedback system, $\bar{D}$ is the monthly-average hourly energy which is fed back into the utility grid and it is called SELL in the program output. In a battery storage system, the excess energy is sent to the storage battery and is called XSO. A portion of this energy, dependent primarily on the ratio of the daily total of $\bar{D}$ to the effective battery storage capacity, is stored in the battery for later use as described in section 5.4. In a system having neither utility feedback nor battery storage, the excess energy $\bar{D}$ must be dissipated; it is called XS for this system configuration.

5.3 Effect of Load Variability

The method of calculating the monthly-average excess energy described in section 5.2 assumed that the electrical demand for any hourly period was constant and equal to the monthly-average load for that hour. In many cases however, the demand will not be constant but will vary from minute to minute within an hour and from day to day. The variability in the load will cause an underprediction in the excess energy given by equation (18).

The variability in the load affects the excess energy calculation since the critical level at which the utilizability, ϕ, is evaluated depends on the load as evident in equation (17). When load variability is taken into account, the long-term hourly average value of ϕ, designated ϕ', is given by

$$\phi' = \int_0^{L_{max}} \phi P(L) dL \tag{20}$$

where ϕ is evaluated at a critical level corresponding to a particular load value, and P(L) is the probability distribution of the load. In the

PV F-CHART program, the probability distribution is assumed to be uniform with a mean equal to the monthly-average hourly load and a minimum to maximum range equal to the product of the mean and the value (divided by 100) entered for % VARIATION OF LOAD (thermal-electric parameter 12). If the variation is 0, ϕ' is set equal to ϕ. Otherwise, ϕ' is evaluated numerically from equation (20). ϕ' is used in place of ϕ in equation (18) to obtain D, the monthly-average excess energy.

5.4 Battery Storage Systems

The addition of battery storage to a photovoltaic system generally increases the performance of the system. This performance increase can be expressed in term of F, defined as

$$F = f - f_0 \tag{21}$$

where f is the fraction of the monthly load supplied by the system with storage and f_0 is the load fraction supplied by an equivalent system with no storage. f_0 is estimated as described in the preceding sections.

Consider the constraints which limit the possible values of F. If all of the excess energy produced by the array can be stored (and subsequently used), F would be the product of the monthly total excess energy, D_m, and the battery storage efficiency divided by the monthly total load, L_m. D_m and L_m are obtained by summing the monthly-average hourly values of D and L over all hours. This combination of parameters is designated d.

$$d = n_b D_m / L_m \tag{22}$$

If the array output is such that it is always less than the electrical demand, there will be no excess energy and consequently, F will be 0. F cannot exceed $(1-f_0)$ since the load fraction supplied by the system cannot exceed unity. (Utility feedback capability is not considered in battery storage systems.) For large values of d, all of the daytime portion of the load will be met directly by the array; the battery will then be discharged at night and F may be limited by the effective daily battery storage capacity, B_c. In general, the maximum value of F is given by

$$F_{max} = \mathrm{MIN}\,[(1-f_0),\ n_{pc} N B_c / L_m] \tag{23}$$

where N is the number of days in the month.

An equation for F which satisfies the constraints above has been derived by Clark [2].

$$F = 1/(2Z)\ [d + F_{max} - [(d+F_{max})^2 - 4ZdF_{max}]^{0.5}] \qquad (24)$$

where

$$Z = 1.315 - 0.1059\ f_0 L_m/(n_{pc} B_c N) - 0.1847/\bar{K}_t \qquad (25)$$

$\bar{K}_t$ is the monthly-average clearness index defined as the ratio of the monthly total radiation on a horizontal surface to the monthly extraterrestrial radiation.

In order to correlate Z, Clark used TRNSYS [3] in conjunction with photovoltaic array, regulator-inverter, and battery models developed by Evans [4] to obtain values of F. Equation (23) is based on 73 years of hourly simulations using 15 different load profiles in Seattle, Madison, and Albuquerque climates for a range of battery sizes between 0 and 2 times the monthly-average daily load. To allow for larger battery sizes, Z is replaced by Z' defined in the following manner.

$$Z' = Z + (1-Z) * [1-EXP(-.10*(n_{pc} B_c N/L_m)^2] \qquad (26)$$

The procedure for estimating the load fraction of battery storage system agrees with the simulation results with a standard deviation of less than 3% on an annual basis.

5.5 References

1. Siegel, M.D., Klein, S.A., and Beckman, W.A.,"A Simplified Method for Estimating the Monthly-Average Performance of Photovoltaic Systems," SOLAR ENERGY, Vol. 26, pp. 413-418, (1981)

2. Clark, D.R., "Hourly Radiation Utilizability and Its Application to Photovoltaic Systems," M.S. thesis, Mechanical Engineering, University of Wisconsin - Madison, (1982)

3. Klein, S.A. et al., "TRNSYS - A Transient System Simulation Program,", EES Report #38-11, Solar Energy Laboratory, University of Wisconsin - Madison, (1981)

4. Evans, D.L., Facinelli, W.A., and Otterbein, R.T., "Combined Photovoltaic/Thermal System Studies, SAND 78-7031, Arizona State University - Tempe, (1978)

5. Stultz, J.W. and Wen, L.C., "Thermal Performance Testing and Analysis of Photovoltaic Modules in Natural Sunlight", Jet Propulsion Laboratory, California Institute of Technology, Report 5101-31, July 29, (1977)

6. Duffie, J.A. and Beckman, W.A., Solar Engineering of Thermal Processes, Wiley-Interscience, New York, (1980)

7. Erbs, D.G., Klein, S.A., and Duffie, J.A., "Estimation of the Diffuse Radiation Fraction for Hourly, Daily, and Monthly-Average Global Radiation," SOLAR ENERGY, Vol. 28, p. 293, (1982)

8. Braun, J.E. and Mitchell, J.C., "Solar Geometry for Fixed and Tracking Surfaces", SOLAR ENERGY, Vol. 31, No. 5 (1983)

9. Erbs, D.G., Klein, S.A., and Beckman, W.A., "The Estimation of Degree-Days and Ambient Temperature Bin Data from Monthly-Average Temperatures,", to appear in ASHRAE Journal, (1982)

10. Liu, B.Y.H. and Jordan, R.C., "The Interrelationship and Characteristic Distribution of Direct, Diffuse, and Total Solar Radiation,", SOLAR ENERGY, Vol. 4, No. 3, (1960)

11. Liu, B.Y.H. and Jordan, R.C., "A Rational Procedure for Predicting the Long Term Performance of Flat Plate Solar Energy Collectors," SOLAR ENERGY, Vol. 7, p. 53, (1963)

12. Clark, D.R., Klein, S.A., and Beckman, W.A., "Algorithm for Evaluating Hourly Radiation Utilizability Function," ASME Journal of Solar Energy Engineering, (1983)

APPENDIX D

SYSTEM COST DATA

Evaluation Criteria

It has been shown that the basic criteria for PV/diesel system viability is that the life cycle energy costs from a photovoltaic power system PV must be equal to or less than diesel power life cycle energy costs. Therefore, the evaluation criteria that should be applied to this field test are as follows:

1. The life cycle cost of photovoltaic energy ($/kWh) must be equal to or less than remote diesel generator energy costs.

2. The cost projections used in any analysis must be within the energy planning and institutional perspectives of the Egyptian Electricity Authority and USAID.

The financial evaluation of this project should therefore concentrate on the comparative life cycle cost and performance projections for photovoltaics and diesel energy.

Comparative Cost Analysis of PV and Diesel Life Cycle Energy Costs.

An analysis of photovoltaic and diesel power system life-cycle energy cost has been performed using current and projected energy costs for a given installation year. The purpose of this cost analysis is to clarify the technical and cost comparison between PV and Diesel power systems as the main decision parameter in determining the viability of this field test. Attention is focused on the most influential technical and cost factors by performing three sensitivity analyses.

The parameters which most influence the life cycle cost comparison between PV and diesel technologies are as follows:

- Photovoltaic System Price ($/Wp basis)
- Finance Rate.
- Operating Efficiency of the Diesel Generator.
- Diesel Fuel Price.

The most critical cost aspect is the cost of photovoltaic modules because the price of PV energy drops as a function of lower prices for photovoltaic modules. There are strong indications that the price of PV modules will continue to drop because of recent improvements in cell efficiency and production technology related to single crystal, poly-crystalline and amorphous silicon photovoltaic cell technology. PV system cost projections by component for 1985, 1990 and 1995 are provided in Exhibit D-5.

The second most critical parameter for PV system competitiveness is financing. Photovoltaic energy has been considered the "ultimate capital" good. That is, almost all of the total life cycle cost is capitalized into the purchase cost. Therefore, the financing factors (interest rate and term) used to pay for the system bear heavily on the cost competitiveness to diesel energy systems.

The performance of the diesel generator energy system impacts the comparison to photovoltaics. Two of the most important factors are operating efficiency and fuel cost. Unfortunately these are often the most difficult to determine. Operating efficiency is predicted by manufacturers to be 25-30 percent on the basis of rated load, under specific environmental conditions and with the machine in good running condition (having been properly maintained). Field measurements of the actual operating efficiencies of diesel generators are between 15 and 25 percent. In a similar manner, the actual cost for fuel, at the site, is hard to determine, yet it is as significant an influence in the cost comparison of photovoltaics to diesel as module price.

Labor costs normally associated to diesel power systems, and specifically not associated with PV systems, are considered as a less influential parameter because labor rates are low and ice making machinery requires full time skilled operators who can concurrently operate a diesel power system.

The life cycle energy costs for a PV system and diesel power system are compared in Exhibits D-1, D-2, and D-3 on the basis of finance rate, diesel fuel

costs and operating efficiency for 1985, 1990 and 1985. Assumptions and conditions for the graphs are provided in Exhibits D-4 and D-5.

A review of the graphs reveals that PV energy will be competitive with diesel in the 1990 to 1995 timeframe. An example set of conditions which show PV to be the lowest cost option are when system prices are $4.40/Wp or less, finance rate is 10 percent or less, diesel fuel price is $1.50 or more at the site, and operating efficiency of the diesel is 20 percent or less. If either of diesel operating parameters incline toward higher cost for diesel or if lower real interest rates are used, then higher module prices are viable and therefore competiveness will be earlier than 1995.

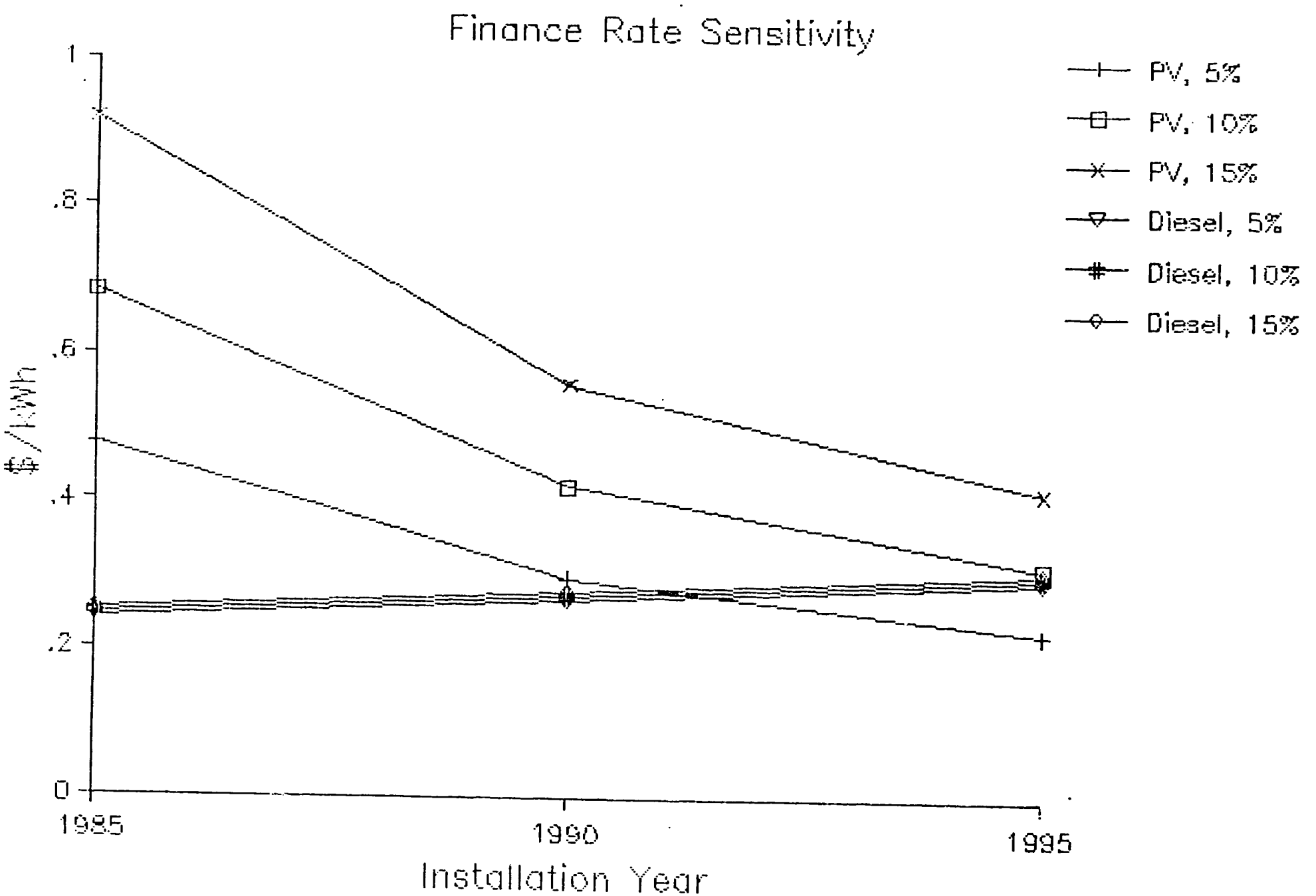

Exhibit D-1 PV/DIESEL ENERGY LIFE CYCLE COSTS - FINANCE RATE SENSITIVITY

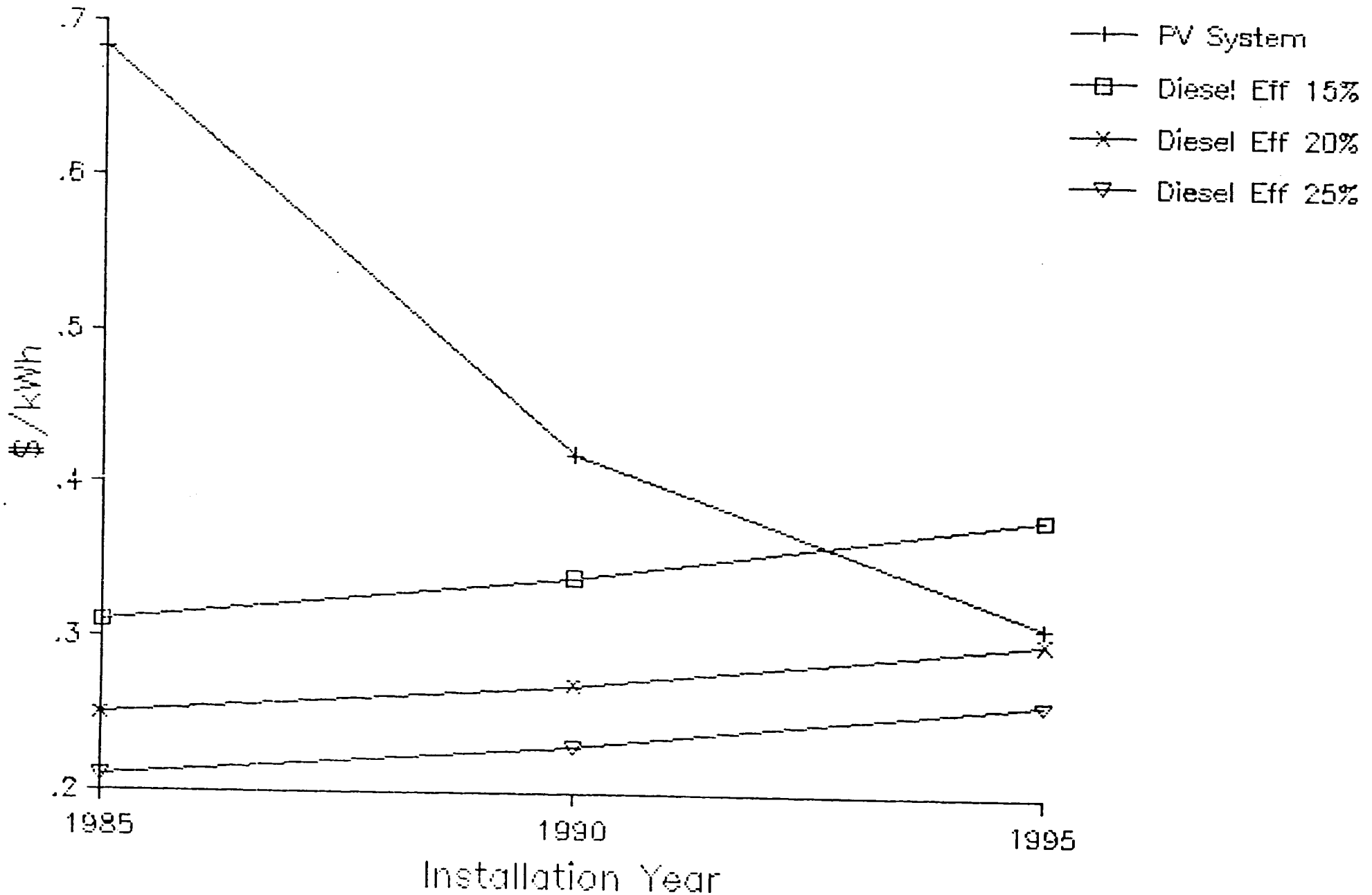

Exhibit D - 2

PV/DIESEL ENERGY LIFE CYCLE COSTS - DIESEL OPERATING EFFICIENCY SENSITIVITY

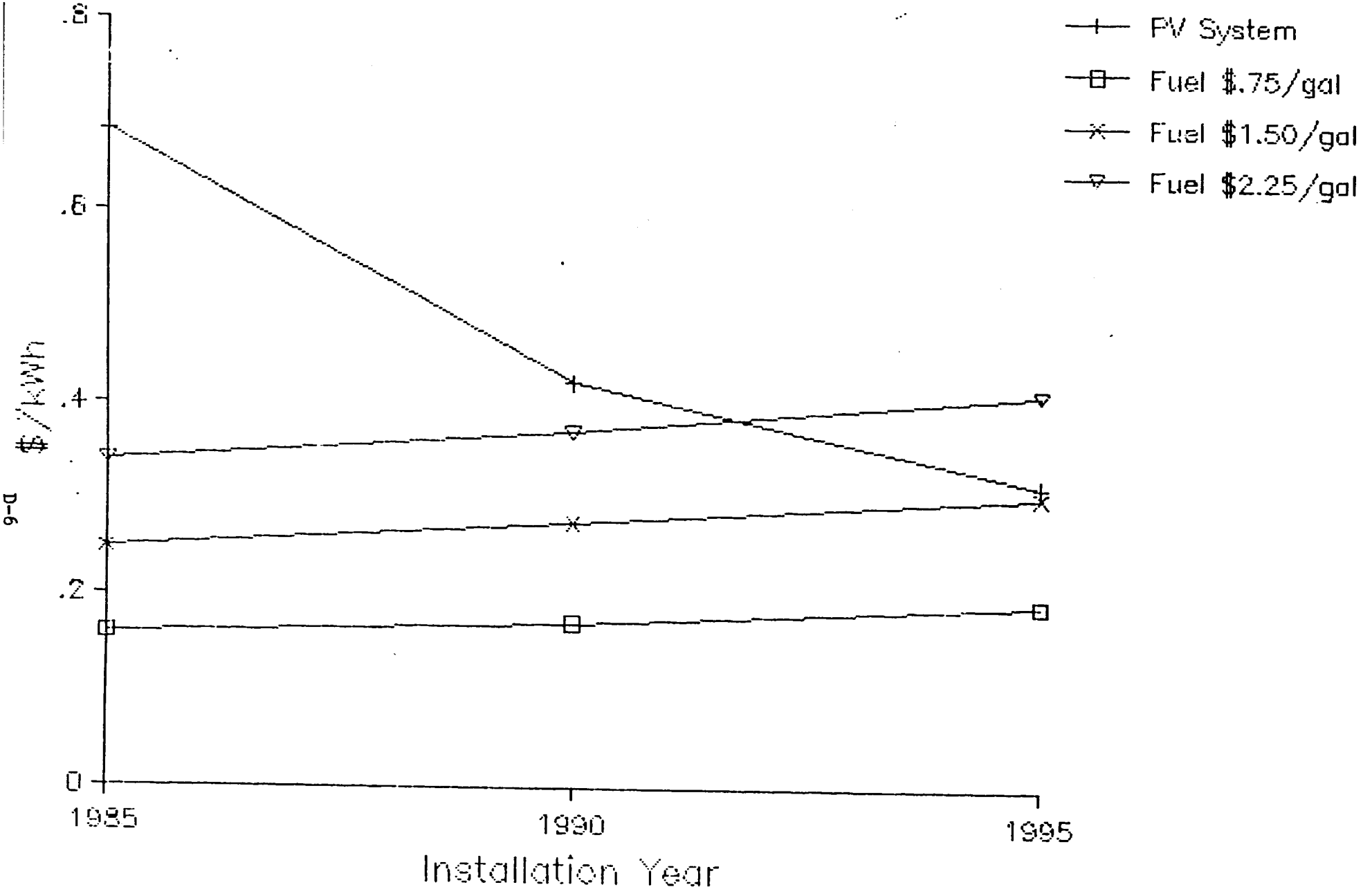

Exhibit D-3

PV/DIESEL ENERGY LIFE CYCLE COSTS - DIESEL FUEL COST SENSITIVITY

Specification (Ref.)	PV System			Diesel System		
Power System	35 Kilowatt (1)			2 - 22 kW (2)		
Energy Production (kWh/year)	62500 (3)			153300 (4)		
	1985	1990	1995	1985	1990	1995
Capital Costs	350000	210000	154000	26400	29126	32120
($/Wp), PV (5)	10	6	4.40	N/A	N/A	N/A
($/kW), Diesel (6)	N/A	N/A	N/A	600	660	730
O & M ($/year) (7)	100	100	100	4380	4836	5340
Diesel Operating Efficiency	N/A	N/A	N/A	.15	.15	.15
				.20	.20	.20
				.25	.25	.25
Fuel Costs ($/gal) (8)	0	0	0	.75	.83	.91
				1.50	1.66	1.83
				2.25	2.48	2.75
Annual Fuel Expense @ 20% Oper. Effic. Baseline Fuel Costs:						
.75				14021	15517	17013
1.50				28043	31034	34212
2.25				42064	46364	51412
Life (years) (9)	20	20	20	6.8	6.8	6.8

1. PV array size per preliminary conceptual design.
2. Diesel engine/generators sized for required rating. Two are required for reliability during maintenance periods.
3. Energy production is based on 35 Kwp PV array and average daily insolation of 6.7 kWh/day.
4. Diesel energy production based on required demand for ice making, 24 hours per day.
5. PV cost projections based on cost data provided in Figure D-5.
6. Diesel capital costs are based on study conducted for Sandia National Laboratory on the cost and performance of small diesel generator sets compared to PV systems. Projected capital costs are figured at 2% increase per year above inflation.
7. Operation and maintenance for PV are nominal, parts only. Diesel O & M are calculated on a basis of $ .50/hour operation, parts cost only. References for diesel O & M are from NASA sponsored study, Assessment and Conceptual Design of PV/Diesel Hybrid Power System and Telephone Organization of Thailand on Tandem 14.3 kW KVA Diesel Generator Set. Projected O & M costs are estimated to increase at 2% per year.
8. Fuel prices are estimated to increase at average rate of 2% per year.
9. Diesel life is 30,000 hours, or 6.8 years based on 12 hours per day average operation.
10. Battery life is 10 years based on 10 - 15% average daily depth of discharge.

Exhibit D-4 PV/DIESEL COMPARATIVE COST ANALYSIS DATA

Component	Ref.	Costs ($/Wp) 1985	1990	1995	Life
PV Modules	(1)	6.50	3.50	2.50	20
Structures, Wiring	(2)	.75	.50	.25	20
Controls	(3)	.25	.20	.15	20
Battery Storage	(4)	1.00	1.00	1.00	10
Transp/Install.	(5)	1.50	.75	.50	20
Total		10.00	5.95	4.40	

1. Photovoltaics Technology, Performance, Costs and Market Forecasts to 1995 by Paul Maycock and Dr. Vic Sherlekar 2/11/85).

2. Current cost quote from Solarex Corp. and Solavolt Int'l Inc. Estimates for 1990 and 1995 costs assume structure procured locally and installation is performed by local technicians.

3. Current costs based on quote from Solarex Corp. and Photron Inc. and does not include maximum power tracking of the array.

4. Current costs based on quote from GNB Batteries Inc. for Absolyte model deep cycle lead acid batteries. Battery storage size of 230 kWh is used.

5. Current transportation costs based on quote from Davidson Shipping. Installation costs based on field experience on 22 kWp stand-alone PV system in Guyana, South America.

Exhibit D-5 PV POWER SYSTEM COST PROJECTIONS

(based on35 kW nominal size PV system)

Field Test Specific Cost Information

Cost and performance information are provided in Exhibits D-7 through D-10 for the PV/diesel ice making plant and also for a comparative diesel powered ice making plant. Current costs and projected costs to 1995 are detailed. These data have been submitted to LBII as input for the market/economic analysis. A summary of the important system cost/ information is provided in Exhibit D-6.

These costs represent hardware installed costs and do not reflect cost for engineering, instrumentation, extensive performance testing and other "product" development related costs. The costs for formal training and on-the-job training are also not reflected. These costs reflect local construction costs in Egypt for buildings as received from Dr. Talaat El Tablawi through LBII February 7, 1985.

	Current Costs (1985)	Projected Costs (1995)	Benefit
PV/Diesel Powered Ice Plant: 35 kWp PV array, 22 kW Diesel, 233 Battery, 6 ton/day ice capacity			
Total System Capital Cost	$419,250	$237,988	
(PV/Diesel Power System Cost)	(377,250)	(186,790)	
Diesel Fuel Consumption (gals/yr)	11,237	11,237	
Total Energy Production (kWh/yr)			153,3(
(PV/Battery Energy Production)			(61,08
(Diesel Energy Production)			(92,21
Ice Production (tons/yr)			2,19
Diesel Powered Ice Plant: Two, 22 kW Diesel generators, 6 ton/day ice cap			
Total System Capital Cost	$88,400	$ 98,318	
(Diesel Power System Cost)	(46,400)	(47,120)	
Diesel Fuel Consumption (gals/yr)	18,695	18,695	
Total Energy Production (kWh/yr)			153,300
Ice Production (tons/yr)			2,190

Exhibit D-6. Equipment Cost Summary

Current Costs

Component	(Ref.)	Specs	Unit Cost ($)	Component Cost($)	Life (yrs)	O&M [1] ($/yr)
PV Array	(2)	35 kW	$ 7.25/Wp	$253750	20	100[4]
Battery	(3)	233 kWh	150.00/kWh	34950	10	100[4]
Power Conditioning		35 kW	.25/Wp	8750	20	100[4]
Diesel/Generator[5]	(5)	220kW	600.00/kW	13200	4	2634[6]
Battery Charger/ Rectifier	(7)	22 kW	300/kW	6600	10	-
Ice Making Plant	(8)	6 ton/day	7000.00/ton	42000	10	2100[9]
Buildings	(10)	100 m^2	100.00/m2	10000	20	-
Transportation	(11)	-	-	15000	-	-
Installation	(12)	-	1.00/Wp	35000	-	-
			PV/Diesel Power System Cost	$377250		
			Total System Capital Cost	419250		

PV/Battery Energy Production	61089	kWhrs/year
Diesel Energy System Production	92211	kWhrs/year
Total Ice Production	2190	tons/year
Total Diesel Fuel Usage	11237	gal/year[13]

1. Parts costs only.
2. Array costs include modules, structure and wiring (Ref. See Figure D-5).
3. Battery life time of 10 years is based on 10-15 percent depth of discharge of deep cycle batteries according to manufacturers curves.
4. Nominal maintenance expenses for cleaning supplies.
5. Diesel generator harsh service. (Ref. See Figure D-4)
6. Based on $ .50/hour operation. (Ref. See Figure D-4)
7. La Marche Manufacturing Company.
8. BACU Refrigeration Equipment Company.
9. Based on 5% of equipment capital costs/yr.
10. Data collected by Anil Cabraal for Task 2.2.2. and data provided by Dr. Talaat El Talblawi, EEA.
11. Data from Davidson Shipping for a 20 foot and 40 foot shipping container to Alexandria, Egypt.
12. Based on installation experience with 22 kWp stand alone PV power system (Development Sciences Incorporated)
13. Diesel usage is based on 20% thermal efficiency and 140000 Btu/gallon.

Exhibit D-7. PV/Diesel Powered Ice Making Plant
(1985 costs)

Component	Ref.	Specs	Unit Cost ($)	Component Cost($)	Life (yrs)	O&M [1] ($/yr)
Diesel Generator	(2)	2-22 kW	$ 600.00/kW[3]	26400	6.8	4380[4]
Ice Making Plant		6 tons/day	7000.00/ton	42000	6.8	2100[5]
Building	(6)	50 m^2	100/m2[6]	5000	20	-
Transportation		-	-	10000	-	-
Installation		-	-	5000	-	-
		Diesel Power System Cost		46400		
		Total System Capital Cost		88400		

Diesel Power System Production	153300 kWh/year
Total Ice Production	2190 tons/year
Total Diesel Fuel Usage	18695 gals/year[7]

1. Parts costs only.
2. Two diesel/generators are necessary to provide for operation during maintenance overhauls and for increased reliability. (Ref. See Figure D-4).
3. Diesel generator costs based on AC system, harsh environment.
4. Based on $.50/hour operation (Ref. See Figure D-14).
5. Based on 5% of equipment capital costs/year.
6. Data collected by Anil Cabraal for Task 2.2.2, and data provided by Dr. Talaat El Tablawi, EEA.
7. Diesel usage is based on 20% thermal efficiency and 140000 Btu/gallon.

Exhibit D-8. Diesel Powered Ice Making Plant
(1985 Costs)

Projected Costs

A system cost is projected for the PV/diesel ice making plant to 1995 based on the following parameters:

1. PV array costs will have dropped to $2.75/Wp made up of $2.50/Wp module cost and $.25/Wp structure and related wiring procured locally.

2. Power conditioning costs will have dropped to $.15/Wp based on reduced cost for controllers and improved electronics.

3. Installation costs will have dropped to $.25/Wp because of the minimal need for engineering expertise (foreign and domestic) during installation.

4. Transportation costs will have been reduced because of the larger proportion of equipment procured in-country.

5. Diesel generator, and ice making plant captial and O&M costs are assumed to escalate at an annual two percent rate above inflation and therefore are higher than for current costs. Battery costs are expected to remain constant with technological advances balancing against a 2% above inflation increase.

The cost data for a conceptual PV/diesel ice making plant in 1995 is provided in Exhibit D-9.

Component	Ref.	Specs	Unit Cost ($)	Component Cost($)	Life (yrs)	O&M [1] ($/yr)
PV Array	(2)	35 kW	$ 2.75/Wp	$96250	20	100[3]
Battery		233 kWh	150.00/kWh	34950	10	100[3]
Power Conditioning		35 kW	.15/Wp	5250	20	100[3]
Diesel/Generator	(4)	20 kW	730.00/kW	16060	4	2634[5]
Battery Charger/ Rectifier		22 kW	365.00/kW	8030	10	
Ice Making Plant		6 ton/day	8533.00/ton	51198	10	2560[6]
Buildings	(7)	100 m^2	100.00/m2	10000	20	-
Transportation		-	-	7500	-	-
Installation		-	.25/Wp	8750	-	-

PV/Diesel Power System Cost	186790
Total System Capital Cost	237988

PV/Battery Energy Production	61089 kWhrs/year
Diesel Energy System Production	92211 kWhrs/year
Total Ice Production	2190 tons/year
Total Diesel Fuel Usage	11237 gal/year[8]

1. Parts costs only.
2. Array costs include modules, structure and wiring. (Ref. See Figure D-5)
3. Nominal maintenance expenses for cleaning supplies.
4. Diesel/generator, harsh service (Ref. See Figure D-4).
5. Based on $.50/hour operation, parts costs only.
6. Based on 5% of equipment capital costs/yr.
7. Data collected by Anil Cabraal for Task 2.2.2 and data provided by Dr. Talaat El Tablawi, EEA.
8. Diesel usage is based on 20% thermal efficiency and 140000 Btu/Kwh.

Exhibit D-9. PV/Diesel Powered Ice Making Plant Projected Costs to 1995

Component	Ref.	Specs	Unit Cost ($)	Component Cost($)	Life (yrs)	O&M [1] ($/yr)
Diesel/Generator	(2)	2-22 kW	$ 730.00/kw[3]	32120	6.8	4380[4]
Ice Making Plant		6 ton/day	8533.00/ton	51198	10	2560
Building		50 m^2	100.00/m^2	5000	20	-
Transportation		-	-	5000	-	-
Installation		-	-	5000	-	-
			Diesel Power System Cost	47120		
			Total System Capital Cost	98318		

Diesel Energy Production	153300 kWh/year
Total Ice Production	2190 tons/year
Total Diesel Fuel Usage	18680 gals/year

1. Parts costs only.
2. Two diesel/generators are necessary to provide for operation during maintenance overhauls and for increased reliability.
3. Diesel/generator costs based on AC system, harsh environment.
4. Based on $.50/hour operation.

Exhibit D-10. Diesel Powered Ice Making Plant
Projected Costs to 1995