# Sizing of Stand-Alone Photovoltaic Systems
## WORKSHEET

**Application** Stand-Alone Home 5 miles from Utility Line
**Location** Tallahassee, FL **Latitude** 30.38

### A. Loads

| | | | |
|---|---|---|---|
| **A1** | Inverter efficiency (decimal) | .85 | |
| **A2** | Battery bus voltage | 24 | volts |
| **A3** | Inverter ac voltage | 110 | volts |

| Component | **A4** Rated Wattage | **A5** Adjustment Factor 1.0 for dc (A1) for ac | **A6** Adjusted Wattage (A4/A5) | **A7** Hours Per Day Used | **A8** Energy Per Day (A6 x A7) |
|---|---|---|---|---|---|
| 5 lights 30 W ea. | 150 | .85 | 176 | 2 | 352 |
| Refrigerator | 500 | .85 | 588 | 5 | 2940 |
| 3 ceiling fans 45 W ea. | 135 | .85 | 159 | 8 | 1272 |
| Dishwasher | 600 | .85 | 706 | 2 | 1412 |
| Washer | 1500 | .85 | 1765 | 6 hrs/wk = .86 day | 1518 |
| Toaster | 1500 | .85 | 1765 | .25 | 441 |

| | | | |
|---|---|---|---|
| **A9** | Total energy demand per day (summation of A8) | 7935 | watt-hours |
| **A10** | Total amp-hour demand per day (A9/A2) | 331 | amp-hours |
| **A11** | Peak ac power requirement (summation of A4) | 4385 | watts |
| **A12** | Peak dc power requirement (summation of A6) | 5159 | watts |

### B. Battery Sizing

**Design Temperature** 25°C

| | | | |
|---|---|---|---|
| **B1** | Days of storage desired/required | 7 | days |
| **B2** | Allowable depth-of-discharge limit (decimal) | .8 | |
| **B3** | Required battery capacity (A10 x B1/B2) | 2896 | amp-hours |
| **B4** | Amp-hour capacity of selected battery * | 478 | amp-hours |
| **B5** | Number of batteries in parallel (B3/B4) | 6 | |
| **B6** | Number of batteries in series (A2/battery voltage) | 2 | |
| **B7** | Total number of batteries (B5 x B6) | 12 | |
| **B8** | Total battery amp-hour capacity (B5 x B4) | 2868 | amp-hours |
| **B9** | Total battery kilowatt-hour capacity (B8 x A2/1000) | 68.8 | kilowatt-hours |
| **B10** | Average daily depth of discharge (.75 x A10/B8) | .09 | |

** Use amp-hour capacity at a rate of discharge corresponding to the total storage period, B1.*

## C. Photovoltaic Array Sizing  Design Tilt 40°  Design Month December

| | | | |
|---|---|---|---|
| C1 | Total energy demand per day (A9) | 7935 | watt-hours |
| C2 | Battery round-trip efficiency (0.70 - 0.85) | 0.85 | |
| C3 | Required array output per day (C1/C2) | 9335 | watt-hours |
| C4 | Selected PV module max power voltage at STC x 0.85 | 13.6 | volts |
| C5 | Selected PV module guaranteed power output at STC | 42.3 | watts |
| C6 | Peak sun hours at design tilt for design month | 3.77 | hours |
| C7 | Energy output per module per day (C5 x C6) | 159.5 | watt-hours |
| C8 | Module energy output at operating temperature. Use derating factor, DF = 0.80 for hot climates and critical applications; DF = 0.90 for moderate climates and non-critical applications (DF x C7) | 143.6 | watt-hours |
| C9 | Number of modules required to meet energy requirements (C3/C8) | 65 | modules |
| C10 | Number of modules required per string (A2/C4) rounded to next higher integer | 2 | modules |
| C11 | Number of strings in parallel (C9/C10) rounded to next higher integer | 33 | strings |
| C12 | Number of modules to be purchased (C10 x C11) | 66 | modules |
| C13 | Nominal rated PV module output | 47 | watts |
| C14 | Nominal rated array output (C13 x C12) | 3102 | watts |

## D. Balance-of-System (BOS) Requirements

1. A voltage regulator is recommended unless array output current (at 1000 W/m² condition), less any continuous load current, is less than 5% of the selected battery bank capacity (at the 8-hour discharge rate).
2. Wiring should be adequate to ensure that losses are less than 1% of the energy produced.
3. In low voltage (i.e., less than 50 volts) systems, germanium or Schottky blocking diodes are preferred over silicon diodes.
4. Fuses, fuse holders, switches, and other components should be selected to satisfy both voltage and current requirements.
5. All battery series branches should contain fuses.
6. Fused disconnects are strongly recommended to isolate the battery bank from the rest of the system.

APPLICATION : Stand-alone home 5 miles from utility line

LOCATION : Tallahassee, FL LATITUDE : 30.38° North

A. LOADS

(A1): Inverter efficiency (decimal). This quantity is used as a power adjustment factor when current is changed from dc to ac. The efficiency of the inverter selected for this application is assumed to be **0.85.**

(A2): Battery bus voltage. This is the nominal operating voltage of the battery. The battery bus voltage for this application is **24 volts**, which corresponds to the required input voltage for the dc side of the inverter.

(A3): Inverter ac voltage. The output voltage of the inverter selected for this application is **110 volts.**

The components (appliances) that the system will power are:

5 lights (30W ea.), combined rated wattage 150, used 2 hrs/day.
Refrigerator, rated wattage 500, used 5 hrs/day.
3 ceiling fans (45W ea.), combined rated wattage 135, used 8 hrs/day.
Dishwasher, rated wattage 600, used 2 hrs/day.
Washer, rated wattage 1500, used 6 hrs/wk or 0.86 hrs/day.
Toaster, rated wattage 1500, used 0.25 hrs/day.

The components are listed under the column heading **Component.**

(A4): The rated wattage is listed for each component in column (A4).

| Component | (A4) Rated Wattage |
|---|---|
| 5 lights (30W ea.) | 150 |
| Refrigerator | 500 |
| 3 ceiling fans (45W ea.) | 135 |
| Dishwasher | 600 |
| Washer | 1500 |
| Toaster | 1500 |

(A5): Adjustment factor. The adjustment factor increases wattage to compensate for wattage loss due to the inefficiency of the inverter. For ac loads the value (A1) is inserted in column (A5). For this application the adjustment factor is **0.85.**

(A6): Adjusted wattage. Dividing rated wattage (A4) by the adjustment factor (A5) adjusts the wattage to compensate for the wattage loss due to inverter inefficiency. (A4)/(A5).

| Component | (A4) / (A5) | = | Adjusted Wattage (A6) |
|---|---|---|---|
| 5 lights (30W ea.) | 150 / 0.85 | = | 176 |
| Refrigerator | 500 / 0.85 | = | 588 |
| 3 ceiling fans (45W ea.) | 135 / 0.85 | = | 159 |
| Dishwasher | 600 / 0.85 | = | 706 |
| Washer | 1500 / 0.85 | = | 1765 |
| Toaster | 1500 / 0.85 | = | 1765 |

(A7): Hours per day used. The number of hours each component is used per day is listed in column (A7).

(A8) : Energy per day. The amount of energy each component requires per day is determined by multiplying each component's adjusted wattage (A6) by the number of hours it is used per day (A7). (A6) x (A7).

| Component | (A6) x (A7) | = | Energy per day (A8) |
|---|---|---|---|
| 5 lights (30W ea.) | 176 x 2 | = | 352 |
| Refrigerator | 588 x 5 | = | 2940 |
| 3 ceiling fans (45W ea.) | 159 x 8 | = | 1272 |
| Dishwasher | 706 x 2 | = | 1412 |
| Washer | 1765 x 0.86 | = | 1518 |
| Toaster | 1765 x 0.25 | = | 441 |
| | Total | = | 7935 |

(A9): Total energy demand per day. The sum of the quantities in column (A8) determines the total energy demand required by the components per day. For this application the total energy demand per day is **7935 watt-hours.**

(A10): Total amp-hour demand per day. The battery storage subsystem is sized independently of the photovoltaic array. In order to size the battery bank the total electrical load is converted from watt-hours to amp-hours. Amp-hours are determined by dividing the total energy demand per day (A9) by the battery bus voltage (A2). (A9) / (A2).

7935 watt-hours / 24 volts = **331 amp-hours.**

(A11): Peak ac power requirement. The sum of the rated wattages (A4) for all components is equal to **4385 watts.** Note that this is the maximum continuous power required and does not include surge requirements.

(A12): Peak dc power requirement. The sum of the adjusted wattages (A6) for all components is equal to **5159 watts.**

## B. BATTERY SIZING

DESIGN TEMPERATURE: The location where batteries are stored should be designed to minimize fluctuations in battery temperature. For this application the design temperature is assumed to be **25°C.**

(B1): Days of storage desired/required. The loss of electricity for the residence in this application, although undesirable, would not be catastrophic. Consequently, the battery storage system is designed to provide the necessary electric energy for a period equivalent to **7 days** without any sunshine. This time period is considered a moderate level of storage for the southeastern U.S. for non-critical applications.

(B2): Allowable depth-of-discharge limit (decimal). The maximum fraction of capacity that can be withdrawn from the battery is specified by the designer. Note that the battery selected must be capable of this or greater depth of discharge. For this application the allowable depth of discharge is **0.8.**

(B3) : Required battery capacity. The required battery capacity is determined by first multiplying the total amp-hours per day (A10) by the daily allowable depth of discharge (B1), 331 x 7 = 2317, and then dividing this number by the allowable depth of discharge limit (B2). [(A10) x (B1) / (B2)].

2317 / .8 = **2896 amp-hours.**

(B4): Amp-hour capacity of selected battery. Once the required number of amp-hours has been determined (B3), batteries or battery cells can be selected using manufacturers' information. Exide 6E95-11 industrial grade batteries were selected for this application because of their long cycle life and rugged construction. Figure 6.2 shows that Exide 6E95-11's capacity (over seven days) is **478 amp-hours.**

## To 1.90 Volts Per Cell

| TYPE | VOLTS PER UNIT | NOMINAL A.H. CAP. | 20 DAY (480 HR) A.H. | 20 DAY (480 HR) AMPS | 10 DAY (240 HR) A.H. | 10 DAY (240 HR) AMPS | 5 DAY (120 HR) A.H. | 5 DAY (120 HR) AMPS | 3 DAY (72 HR) A.H. | 3 DAY (72 HR) AMPS | 32 F (0 C) 500 HR A.H. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6E95-5 | 12 | 180 | 192 | 0.40 | 192 | 0.80 | 192 | 1.60 | 192 | 2.67 | 184 |
| 6E95-7 | 12 | 270 | 288 | 0.60 | 288 | 1.20 | 288 | 2.40 | 288 | 4.00 | 276 |
| 6E95-9 | 12 | 360 | 383 | 0.80 | 383 | 1.60 | 383 | 3.19 | 383 | 5.32 | 368 |
| 6E95-11 | 12 | 450 | 478 | 1.00 | 478 | 1.99 | 478 | 3.98 | 478 | 6.64 | 459 |
| 6E120-9 | 12 | 500 | 538 | 1.12 | 538 | 2.24 | 538 | 4.48 | 538 | 7.47 | 516 |
| 6E120-11 | 12 | 625 | 673 | 1.40 | 673 | 2.80 | 673 | 5.61 | 673 | 9.35 | 646 |
| 6E120-13 | 12 | 750 | 808 | 1.68 | 808 | 3.37 | 808 | 6.73 | 808 | 11.22 | 776 |
| 6E120-15 | 12 | 875 | 942 | 1.96 | 942 | 3.93 | 942 | 7.85 | 942 | 13.08 | 904 |
| 3E120-17 | 6 | 1000 | 1077 | 2.24 | 1077 | 4.49 | 1077 | 8.98 | 1077 | 14.96 | 1034 |
| 3E120-19 | 6 | 1125 | 1212 | 2.53 | 1212 | 5.05 | 1212 | 10.10 | 1212 | 16.83 | 1163 |
| 3E120-21 | 6 | 1250 | 1346 | 2.80 | 1346 | 5.61 | 1346 | 11.22 | 1346 | 18.69 | 1292 |
| 3E120-23 | 6 | 1375 | 1481 | 3.09 | 1481 | 6.17 | 1481 | 12.34 | 1481 | 20.57 | 1422 |
| 3E120-25 | 6 | 1500 | 1616 | 3.37 | 1616 | 6.73 | 1616 | 13.47 | 1616 | 22.44 | 1551 |
| 3E120-27 | 6 | 1625 | 1750 | 3.65 | 1750 | 7.29 | 1750 | 14.58 | 1750 | 24.31 | 1680 |
| 3E120-29 | 6 | 1750 | 1885 | 3.93 | 1885 | 7.85 | 1885 | 15.71 | 1885 | 26.18 | 1809 |

**Figure 6.2 Exide battery specifications**

(B5): Number of batteries in parallel. The number of batteries or battery cells needed to provide the required battery subsystem capacity is determined by dividing the required battery capacity (B3) by the amp-hour capacity of the selected battery (B4). (B3) / (B4).

2896 amp-hours / 478 amp-hours = **6.**

(B6): Number of batteries in series. The number of batteries needed to provide the necessary voltage is determined by dividing the battery bus voltage (A2) by the selected battery or battery cell voltage (taken from manufacturer's information). (A2) / battery voltage.

24 volts / 12 volts = **2.**

(B7): Total number of batteries. Multiplying the number of batteries in parallel (B5) by the number of batteries or battery cells in series (B6) determines the total number of batteries needed. (B5) x (B6).

6 x 2 = **12.**

(B8): Total battery amp-hour capacity. The total rated capacity of selected batteries is determined by multiplying the number of batteries in parallel (B5) by the amp-hour capacity of the selected battery (B4). (B5) x (B4).

6 x 478 amp-hours = **2868 amp-hours.**

(B9): Total battery kilowatt-hour capacity. Based on the selected batteries, the energy capacity is determined by first multiplying the total amp-hour capacity (B8) times the battery bus voltage (A2), and then dividing this number by 1000. [(B8) x (A2)] / 1000.

[2868 amp-hours x 24 volts] / 1000 = **68.8 kilowatt-hours.**

(B10): Average daily depth of discharge. The actual daily depth of discharge to be expected on the average for the selected battery subsystem is determined by first multiplying 0.75 by the total amp-hour demand per day (A10), and then dividing this number by the total battery amp-hour capacity (B8). [0.75 x (A10)] / (B8).

[0.75 x 331] / 2868 = **0.09.**

## C. PHOTOVOLTAIC ARRAY SIZING

The size of the photovoltaic array is determined by considering the available solar insolation, the tilt of the array and the characteristics of the photovoltaic modules being considered. The array is sized to meet the average daily load requirements for the month or season of the year with the lowest ratio of daily insolation to the daily load.

The available insolation striking a photovoltaic array varies throughout the year and is a function of the tilt angle of the array. If the load is constant, the designer must consider the time of year with the minimum amount of sunlight (in the Northern hemisphere, typically December or January). Knowing the insolation available (at tilt) and the power output required, the array can be sized using module specifications supplied by manufacturers.

Using module power output and daily insolation (in peak sun hours), the energy delivered by a photovoltaic module for an average day can be determined. Then, knowing the requirements of the load and the capability of a single module, the array can be sized.

The array is sized to meet the average daily demand for electricity during the worst insolation month of the year, which is December in Tallahassee. The array will face south and because the sun is low in the sky during December will be tilted at an angle of 40° from horizontal in order to maximize the amount of insolation received during December.

DESIGN MONTH: December

DESIGN TILT : 40° for maximum insolation during the design month.

(C1): Total energy demand per day. (A9). **7935 watt-hours.**

(C2): Battery round-trip efficiency. A factor between 0.70 and 0.85 is used to estimate battery round-trip efficiency. For this application **0.85** is used because the battery selected is relatively efficient and because a significant percentage of the energy is used during daylight hours.

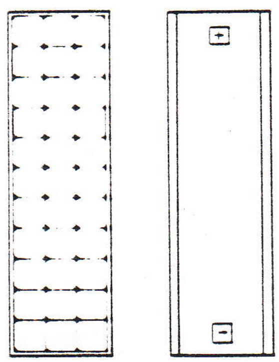
(C3): Required array output per day. The watt-hours required by the load are adjusted (upwards) because batteries are less than 100% efficient. Dividing the total energy demand per day (C1) by the battery round-trip efficiency (C2) determines the required array output per day. (C1) / (C2).

7935 watt-hours / 0.85 = **9335 watt-hours.**

(C4): Selected PV module max power voltage at STC x 0.85. Maximum power voltage is obtained from the manufacturer's specifications for the selected photovoltalic module, and this quantity is multiplied by 0.85 to establish a design operating voltage for each module (not the array).

ARCO Solar M75 modules are used in this application. According to figure 6.3, the maximum power voltage at STC for the ARCO Solar M75 is 16.0 volts.

16.0 volts x 0.85 = **13.6 volts.**



**Power Specifications***

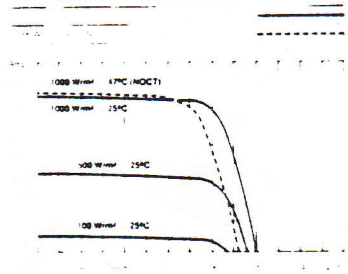
| Model | M75 |
|---|---|
| Power (typical ± 10%) | 47.0 Watts |
| Current (typical at load) | 2.94 Amps |
| Voltage (typical at load) | 16.0 Volts |
| Short Circuit Current (typical) | 3.27 Amps |
| Open Circuit Voltage (typical) | 19.9 Volts |

**Physical Characteristics**

| | |
|---|---|
| Length | 48 in/1219 mm |
| Width | 13 in/330 mm |
| Depth | 1.4 in/36 mm |
| Weight | 11.6 lb/5.2 kg |

*Power specifications are at standard test conditions of 1000 W/M², 25°C cell temperature and spectrum of 1.5 air mass.

**Performance Characteristics**




The IV curve (current vs. voltage) above demonstrates typical power response to various light levels at 25°C cell temperature and at the NOCT (Normal Cell Operating Temperature), 47°C

**Figure 6.3 ARCO Solar M75 module specifications**

(C5): Selected PV module guaranteed power output at STC. This number is also obtained from the manufacturer's specifications for the selected module. Figure 6.3 shows that the nominal power output at 1000 watts/m² and 25°C is 47 watts. The guaranteed power output is 90% of this value, or **42.3 watts.**

(C6): Peak sun hours at optimum tilt. This figure is obtained from solar insolation data (shown in figure 6.4) for the design location and array tilt for an average day during the worst month of the year. Peak sun hours at 40° tilt for Tallahassee in December equals **3.77** hours.

| City | Tilt | Insolation (kWh/m²-day) JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tallahassee, FL Latitude 30.38 | Horizontal | 2.77 | 3.59 | 4.67 | 5.75 | 6.11 | 5.94 | 5.52 | 5.29 | 4.71 | 4.16 | 3.18 | 2.56 | 4.52 |
| | 15 | 3.32 | 4.07 | 4.98 | 5.83 | 5.97 | 5.72 | 5.36 | 5.27 | 4.90 | 4.62 | 3.77 | 3.15 | 4.75 |
| | 20 | 3.47 | 4.20 | 5.04 | 5.81 | 5.87 | 5.60 | 5.25 | 5.22 | 4.93 | 4.74 | 3.93 | 3.31 | 4.78 |
| | 25 | 3.61 | 4.30 | 5.08 | 5.76 | 5.74 | 5.88 | 5.12 | 5.14 | 4.93 | 4.83 | 4.07 | 3.46 | 4.79 |
| | 30 | 3.72 | 4.38 | 5.09 | 5.67 | 5.58 | 5.26 | 4.97 | 5.04 | 4.90 | 4.89 | 4.19 | 3.59 | 4.77 |
| | 35 | 3.82 | 4.44 | 5.07 | 5.56 | 5.39 | 5.05 | 4.79 | 4.91 | 4.85 | 4.92 | 4.28 | 3.69 | 4.73 |
| | 40 | 3.89 | 4.47 | 5.02 | 5.41 | 5.17 | 4.82 | 4.59 | 4.76 | 4.77 | 4.93 | 4.35 | 3.77 | 4.66 |

**Figure 6.4 Insolation data for Tallahassee, Florida**

(C7): Energy output per module per day. The amount of energy produced by the array per day during the worst month is determined by multiplying the selected photovoltaic power output at STC (C5) by the peak sun hours at design tilt (C6). (C5) x (C6).

42.3 x 3.77 = **159.5 watt-hours.**

(C8) : Module energy output at operating temperature. A derating factor of 0.90 (for moderate climates and non-critical applications) is used in this application to determine the module energy output at operating temperature. Multiplying the derating factor (DF) by the energy output per module (C7) establishes an average energy output from one module. DF x (C7).

0.90 x 159.5 watt-hours = **143.6 watt-hours.**

(C9) : Number of modules required to meet energy requirements. Dividing the required output per day (C3) by the module energy output at operating temperature (C8) determines the number of modules required to meet energy requirements. (C3) / (C8).

9335 watt-hours / 143.6 watt-hours = **65 modules.**

(C10): Number of modules required per string. Dividing the battery bus voltage (A2) by the module design operating voltage (C4), and then rounding this figure to the next higher integer determines the number of modules required per string. (A2) / (C4).

24 volts / 13.6 volts = 1.8 (rounded to **2 modules**).

(C11): Number of strings in parallel. Dividing the number of modules required to meet energy requirements (C9) by the number of modules required per string (C10) and then rounding this figure to the next higher integer determines the number of strings in parallel. (C9) / (C10).

65 modules / 2 modules = 32.5 (rounded to **33 strings**).

(C12): Number of modules to be purchased. Multiplying the number of modules required per string (C10) by the number of strings in parallel (C11) determines the number of modules to be purchased. (C10) x (C11).

2 x 33 = **66 modules.**

(C13): Nominal rated PV module output. The rated module output in watts as stated by the manufacturer. Photovoltaic modules are usually priced in terms of the rated module output ($/watt). The ARCO Solar M75's rated module power is **47 watts.**

(C14): Nominal rated array output. Multiplying the number of modules to be purchased (C12) by the nominal rated module output (C13) determines the nominal rated array output. This number will be used to determine the cost of the photovoltaic array.

66 modules x 47 watts = **3102 watts.**

## 6.3 Example 2: Sizing of a Stand-Alone Engine Generator System

The application for this example is the same as for example 1 — a residence in rural Tallahassee, Florida, with the same electrical appliances. Rather than using a photovoltaic system, however, this example considers a gasoline-powered engine generator. To minimize the run-time of the engine and to utilize it efficiently, battery storage is provided. Because the electrical output of the generator is alternating current, a battery charger is needed to convert the ac signal to dc to charge the batteries.

Because the appliances use ac power, an inverter is required between them and the battery subsystem. A smaller battery subsystem than that required in the stand-alone photovoltaic system can be used because available sunshine is not a factor for this system. Exide industrial grade batteries are used with different capacities than those used in example 1.

For this application the average operating efficiency of the inverter is assumed to be 0.85. The required nominal input voltage for the selected inverter is 24 volts dc, thus establishing the battery bus voltage at this level.

The following is a copy of the completed sizing worksheet for stand-alone generator systems. Detailed explanations on the completion of each step follow the worksheet.

# Photovoltaic Water Pumping System Design
## WORKSHEET

Design period December  Design tilt 40°
Design location Orlando, FL  Latitude 28.55°N

### Insolation Availability

P1 Daily insolation = 4.24 [kWh/(m²-day)]

P2 Usable insolation = P1 4.24 x derating factor 0.95 = 4.03 [kWh/(m²-day)]

P3 Peak sun hours available = P2 = 4.03 (hrs/day)

### Pumping Flow Requirements

P4 Daily quantity of water required = 4000 (gal/day)

P5 Peak flow rate = P4 4000 / (P3 4.03 x 60) = 16.5 (gal/min)

P6 Pipe inside diameter = 1 (in) Type Steel

P7 Peak velocity = P5 16.5 / (P6 1)² x .408 = 6.73 (ft/s)

### Pumping Head Requirements

Static Head

P8 Suction lift (or Head) * = -15 (ft)

P9 Discharge head = 115 (ft)

P10 Pressure head = 0 (PSIG) x 2.31 = 0 (ft)

P11 Total static head = P8 -15 + P9 115 + P10 0 = 100 (ft)

Dynamic Head

P12 Velocity head = (P7 6.73)² x 0.0155 = 0.7 (ft)

| Friction Head Fitting | Quantity | | Equivalent Length Factor | | Equivalent Length |
|---|---|---|---|---|---|
| 90° | 1 | x | 2.7 | = | 2.7 (ft) |
| | | x | | = | (ft) |
| | | x | | = | (ft) |
| | | x | | = | (ft) |
| | | x | | = | (ft) |
| | | | Actual pipe length | = | 125 (ft) |
| P13 | | | Total equivalent length | = | 127.7 (ft) |

* *Enter a negative number for suction head.*

P14 Friction head = P13 127.7 /100 x loss per 100 ft 17.8 = 22.7 (ft)

P15 Total dynamic head = P12 0.7 + P14 22.7 = 23.4 (ft)

P16 Total system head = P11 100 + P15 23.4 = ≈124 (ft)

## Pumping Energy Requirements

P17 Hydraulic energy =

P16 124 (ft) x P4 4000 (gal/day) x 0.0031 = 1538 (Wh/day)

P18 Hydraulic power =

P5 16.5 (gal/min) x P16 124 (ft) x 0.188 = 385 (watts)

## Pump Selection

Flow rate = P5 16.5 (gal/min)

Total system head = P16 124 (ft)

Select a pump/motor combination capable of meeting flow and head requirements with high efficiency.

Pump/motor model Jacuzzi SJ1-D10

Efficiency 44 (%)

P19 Motor voltage = 55 (volts)

P20 Electric power = 920 (watts)

P21 Daily electrical energy = P20 920 x P3 4.03 = 3708 (Wh/day)

## Photovoltaic Array Sizing

Selected PV Module Solarex SX-146

Standard tests conditions (STC): 1 kW/m², 25°C

M1 Module voltage at max power (STC) 18 (volts)

M2 Module current at max power (STC) 2.67 (amps)

M3 Module guaranteed power output at 1 kW/m² (STC) = M1 x M2 46 (watts)

M4 Total energy demand = P21 3708 (Wh/day)

M5 Impedance mismatch and non-linear effects for direct coupled systems = (0.7 - 0.9) 0.9

M6 Required array output =M4/M5 4120 (Wh/day)

M7 PV module operating voltage = M1 x (0.8 - 0.9) 15.3 (volts)

M8 Daily energy output per module = M3 x P3 185 (Wh/day)

M9 Temperature derating factor = (0.80 - 0.90) 0.90

M10 Derated module energy output = M8 x M9 166 (Wh/day)

M11 Number of modules to meet daily energy requirements =M6/M10 25 (modules)

M12 Number of modules per string rounded to the next higher integer = P19/M7 4 (modules)

M13 Number of strings in parallel rounded to the next higher integer = M11/M12 7 (strings)

28 (modules)

## 6.5 Example 4: Sizing a Photovoltaic Water Pumping System

The following example illustrates a systematic methodology for designing stand-alone photovoltaic water pumping systems.

The application presented calls for a direct-coupled pumping system capable of delivering 4000 gallons of water per day in the Orlando, Florida, vicinity. A submersible pump is to be used at a depth of 65 feet below ground level. The water table level is assumed to be 40 feet below ground level on the average. The pump is required to lift the water to a height of 60 feet above ground level for storage, thus eliminating the need for battery storage. Steel pipe with an inside diameter of 1 inch is to be used. Figure 6.14 illustrates this pumping example.

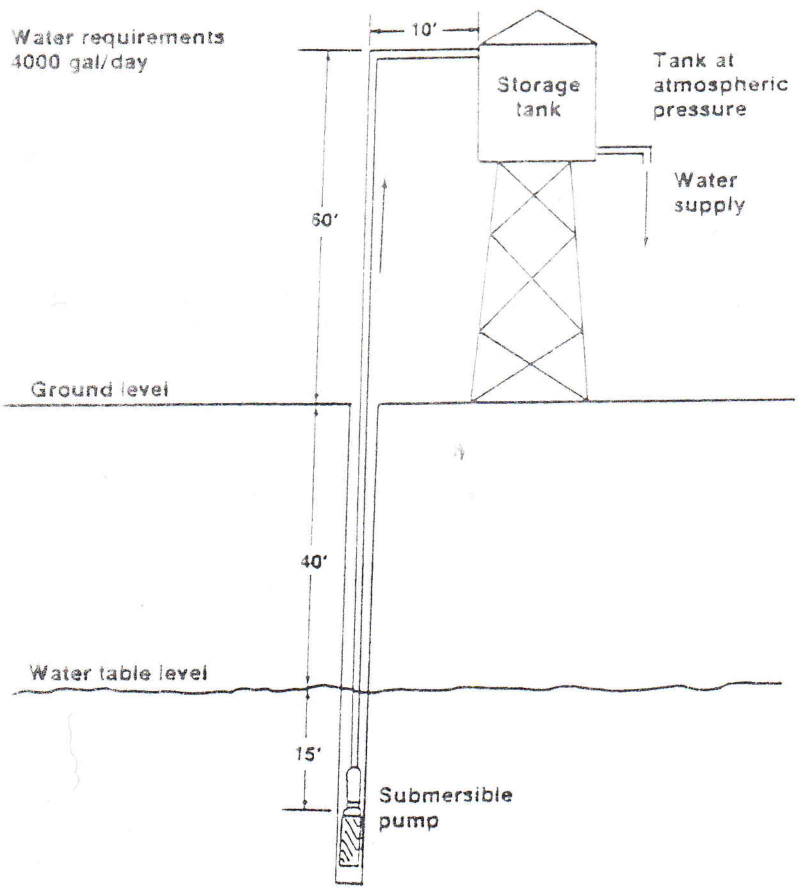



Figure 6.14 Pump system illustration

The following is the completed sizing worksheet used for this application. Detailed explanations of each step follow the worksheet.

## INSOLATION AVAILABILITY

The location of the application is Orlando, Florida, which is at 28.55° North latitude. The array is designed to meet the average daily load during the worst insolation month. For December in Orlando, an average tilt of 40° from horizontal is nearly optimum.

Design Period: December

Design Tilt: 40°

Design Location: Orlando, FL

Latitude: 28.55° North

P1 : Daily insolation. The amount of insolation occurring at the design location (Orlando, FL) during the design period (December) at design tilt (40°) is obtained from daily insolation data shown in figure 6.15. The daily insolation for this application is 4.24 kWh/($m^2$-day).

| City | Tilt | Insolation (kWh/m²-day) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | Annual |
| Orlando, FL | Horizontal | 3.14 | 3.92 | 4.99 | 5.99 | 6.27 | 5.78 | 5.68 | 5.28 | 4.72 | 4.11 | 3.46 | 2.92 | 4.59 |
| Latitude 28.55 | 15 | 3.75 | 4.43 | 5.30 | 6.05 | 6.10 | 5.54 | 5.49 | 5.24 | 4.39 | 4.53 | 4.06 | 3.56 | 4.71 |
| | 20 | 3.92 | 4.56 | 5.36 | 6.01 | 5.99 | 5.41 | 5.37 | 5.18 | 4.90 | 4.63 | 4.23 | 3.74 | 4.74 |
| | 25 | 4.07 | 4.67 | 5.39 | 5.95 | 5.85 | 5.26 | 5.23 | 5.10 | 4.89 | 4.70 | 4.37 | 3.90 | 4.75 |
| | 30 | 4.19 | 4.75 | 5.39 | 5.85 | 5.67 | 5.07 | 5.06 | 4.99 | 4.86 | 4.75 | 4.49 | 4.04 | 4.73 |
| | 35 | 4.29 | 4.80 | 5.36 | 5.72 | 5.47 | 4.87 | 4.37 | 4.35 | 4.79 | 4.77 | 4.58 | 4.15 | 4.38 |
| | 40 | 4.37 | 4.82 | 5.31 | 5.56 | 5.24 | 4.63 | 4.66 | 4.69 | 4.71 | 4.76 | 4.64 | 4.24 | 4.30 |

**Figure 6.15 Insolation data**

P2 : Usable insolation. Pump/motors directly-coupled to a photovoltaic array require a minimum current before starting. Because the irradiance on the photovoltaic array must reach a threshold before the pump starts, some of the insolation (integrated irradiance) is not usable. Figure 6.16 illustrates pump/motor turn-on and turn-off points and the resulting unusable insolation.

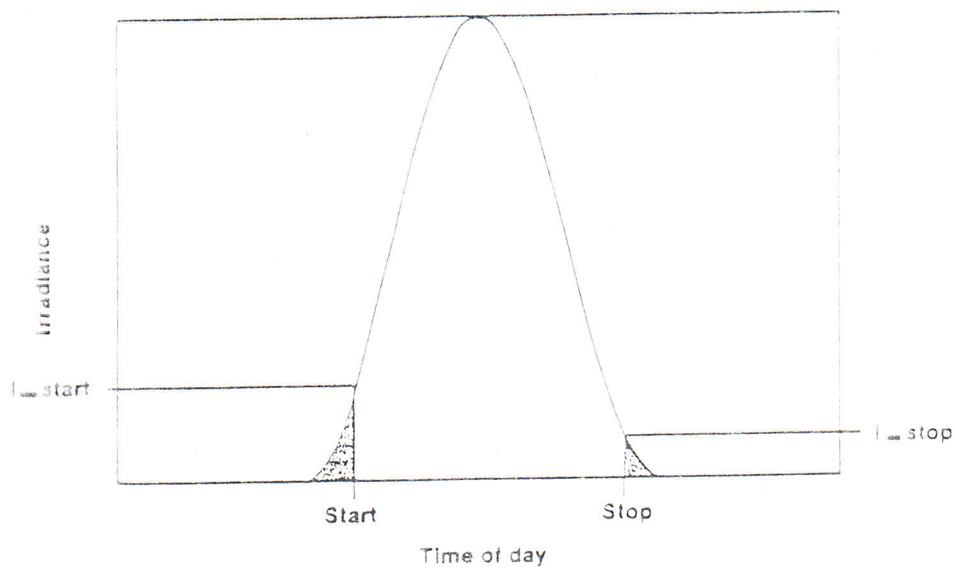



Figure 6.16 Photovoltaic pumping start/stop characteristics

The approximate amount of insolation that is usable per day is determined by multiplying the daily insolation (P1) by a derating factor. This derating factor is an estimated value determined by comparing pump turn-on and turn-off points with insolation data for a given photovoltaic array. For this application a derating factor of 0.95 is used.

Usable insolation = 4.24 x 0.95 = **4.03 kWh/(m²-day).**

P3: Peak sun hours available. The peak sun hours available are numerically equal to the amount of insolation that is usable per day (P2).

(P2) = **4.03 hrs/day.**

PUMPING FLOW REQUIREMENTS

P4: Daily quantity of water required. This quantity is determined by the pumping system application. For this application the amount of water required per day is **4000 gallons.**

P5: Peak flow rate. The peak velocity at which water is delivered by the pump, assuming that the daily quantity of water is pumped with the sun at peak intensity during the usable peak sun hours, is determined by dividing the daily quantity of water required (P4) by the usable peak sun hours (P3). (This measurement is converted from gal/hr to gal/min by multiplying usable sun hours by 60.)

$$\text{Peak flow rate} = \frac{4000}{4.08 \times 60} = 16.5 \text{ gal/min.}$$

P6: Pipe inside diameter. The inside diameter of the pipe size used in this application is 1 **inch**, and the pipe is made of **steel**.

P7: Peak velocity. To determine the peak flow velocity of the water moving through the pipe, the peak flow rate (P5) is divided by the inside pipe diameter squared. This number is then multiplied by a conversion factor of 0.408 to convert to ft/sec.

$$\text{Peak velocity} = \frac{16.5}{(1)^2} \times .408 = 6.73 \text{ ft/sec.}$$

## PUMPING HEAD REQUIREMENTS

### STATIC HEAD

P8: Suction lift (or head). Suction lift is the vertical distance (ft) from the surface of the water source to the center of the pump. Figure 6.17 illustrates the pump configuration. Because the pump is located 15 feet below water level the suction lift is a negative value. This negative value is referred to as a suction head.

Suction head = **15 ft** (or suction lift = -15 ft).

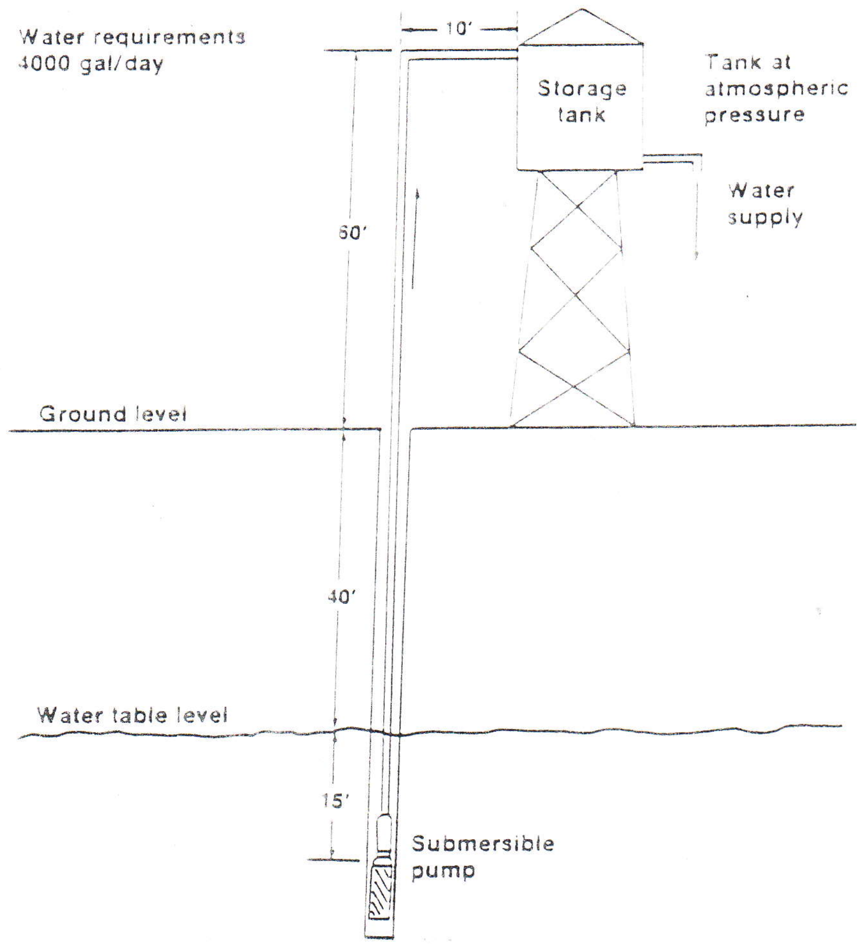



Figure 6.17 System sized in example

P9: Discharge head. Discharge head is the total vertical distance (ft) from the center of the pump to the point of free discharge. As illustrated in figure 6.17 the vertical distance from the center of the pump to the water table is 15 ft. The vertical distance from the water table to ground level is 40 ft, and the vertical distance from ground level to the storage tank is 60 ft.

Discharge head = 15 ft + 40 ft + 60 ft = 115 ft.

P10: Pressure head. If a final discharge pressure other than atmospheric pressure is desired, the pump must be able to supply the extra needed energy. The pressure head is the equivalent feet of head required to overcome these losses. A factor 2.31 is used to convert units of psig to ft. Since the tank in this application is at atmospheric pressure, the pressure head is 0.

P11: Static Head. The measure of the total head required to lift the water to a desired level and to store it in a tank at a prescribed pressure is the sum of the suction lift or head (P8), the discharge head (P9), and the pressure head (P10).

Static head = -15 ft + 115 ft + 0 ft = 100 ft.

DYNAMIC HEAD

P12: Velocity head. The equivalent head that a pump must supply to move a fluid through pipe at a given velocity is determined by squaring the peak velocity (P7) and multiplying this number by the factor 0.0155 to convert to ft. This number is usually small and can often be neglected.

Velocity head = $(6.73)^2 \times 0.0155 = 0.7$ ft.

P13: Total equivalent length. In addition to the energy required to lift and store the water, energy is also required to overcome losses due to pipe friction. Friction head is the head required to overcome the energy losses that occur as a fluid flows through the pipe.

In this application there is one 90° fitting of 1 inch diameter. The equivalent length factor of this fitting (obtained from the chart shown in figure 6.18) is 2.7.

| Size of Fitting, Inches | ½" | ¾" | 1" | 1¼" | 1½" | 2" | 2½" | 3" | 4" | 5" | 6" | 8" | 10" |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 90° Ell | 1.5 | 2.0 | 2.7 | 3.5 | 4.3 | 5.5 | 6.5 | 8.0 | 10.0 | 14.0 | 15 | 20 | 25 |
| 45° Ell | 0.8 | 1.0 | 1.3 | 1.7 | 2.0 | 2.5 | 3.0 | 3.8 | 5.0 | 6.3 | 7.1 | 9.4 | 12 |
| Long Sweep Ell | 1.0 | 1.4 | 1.7 | 2.3 | 2.7 | 3.5 | 4.2 | 5.2 | 7.0 | 9.0 | 11.0 | 14.0 | |
| Close Return Bend | 3.6 | 5.0 | 6.0 | 8.3 | 10.0 | 13.0 | 15.0 | 18.0 | 24.0 | 31.0 | 37.0 | 39.0 | |
| Tee—Straight Run | 1 | 2 | 2 | 3 | 3 | 4 | 5 | | | | | | |
| Tee—Side Inlet or Outlet | 3.3 | 4.5 | 5.7 | 7.5 | 9.0 | 12.0 | 14.0 | 17.0 | 22.0 | 27.0 | 31.0 | 40.0 | |
| Glove Valve Open | 17.0 | 22.0 | 27.0 | 36.0 | 43.0 | 55.0 | 67.0 | 82.0 | 110.0 | 140.0 | 160.0 | 220.0 | |
| Angle Valve Open | 8.4 | 12.0 | 15.0 | 18.0 | 22.0 | 28.0 | 33.0 | 42.0 | 58.0 | 70.0 | 83.0 | 110.0 | |
| Gate Valve—Fully Open | 0.4 | 0.5 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.7 | 2.3 | 2.9 | 3.5 | 4.5 | |
| Check Valve (Swing) | 4 | 5 | 7 | 9 | 11 | 13 | 16 | 20 | 26 | 33 | 39 | 52 | 65 |
| Check Valve (Spring) | 4 | 6 | 8 | 12 | 14 | 19 | 23 | 32 | 43 | 58 | | | |

Figure 6.18 Equivalent number of feet of straight pipe for different fittings

Multiplying the equivalent length factor for each fitting type by the quantity of that type determines the equivalent length.

Equivalent length = 1 x 2.7 = 2.7 ft.

Actual Pipe Length. The actual length of straight pipe used in this application is 125 ft.

The total equivalent length of pipe for the application is determined by adding the equivalent lengths of the fittings to the actual pipe length.

2.7 ft. + 125 ft. = 127.7 ft.

P14: Friction Head. The equivalent head required to overcome the loss of energy that occurs as fluid flows through a pipe is determined by dividing the total equivalent pipe length (P13) by 100 and multiplying this number by the friction loss per 100 ft. Friction loss per 100 ft is dependent on the type of piping used and, for this application, is obtained by finding peak flow rate on the chart shown in figure 6.19.

$$\text{Friction head} = \frac{127.7}{100} \times 17.8 = 22.7 \text{ ft.}$$

| GPM | GPH | ¼" Ft. | ¼" Lbs. | ½" Ft. | ½" Lbs. | ¾" Ft. | ¾" Lbs. | 1" Ft. | 1" Lbs. | 1¼" Ft. | 1¼" Lbs. | 1½" Ft. | 1½" Lbs. | 2" Ft. | 2" Lbs. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 50 | 4.30 | 1.85 | 1.86 | .80 | .26 | .11 | | | | | | | | |
| 2 | 120 | 15.00 | 6.45 | 4.78 | 2.06 | 1.21 | .52 | .38 | .16 | | | | | | |
| 3 | 180 | 31.80 | 13.67 | 10.00 | 4.30 | 2.50 | 1.08 | .77 | .33 | | | | | | |
| 4 | 240 | 54.90 | 23.61 | 17.10 | 7.35 | 4.21 | 1.81 | 1.30 | .56 | .34 | .15 | | | | |
| 5 | 300 | 83.50 | 35.91 | 25.80 | 11.09 | 6.32 | 2.72 | 1.93 | .83 | .51 | .22 | .24 | .10 | | |
| 6 | 360 | | | 36.50 | 15.70 | 8.87 | 3.81 | 2.68 | 1.15 | .70 | .30 | .33 | .14 | .10 | .04 |
| 7 | 420 | | | 48.70 | 20.94 | 11.80 | 5.07 | 3.58 | 1.53 | .93 | .40 | .44 | .19 | .13 | .06 |
| 8 | 480 | | | 62.70 | 26.96 | 15.00 | 6.45 | 4.54 | 1.95 | 1.18 | .51 | .56 | .24 | .17 | .07 |
| 9 | 540 | | | | | 18.80 | 8.08 | 5.65 | 2.43 | 1.46 | .63 | .69 | .30 | .21 | .09 |
| 10 | 600 | | | | | 23.00 | 9.89 | 6.86 | 2.95 | 1.77 | .76 | .83 | .36 | .25 | .11 |
| 12 | 720 | | | | | 32.60 | 14.02 | 9.62 | 4.14 | 2.48 | 1.07 | 1.16 | .50 | .34 | .15 |
| 15 | 900 | | | | | 49.70 | 21.37 | 14.70 | 6.32 | 3.74 | 1.61 | 1.75 | .75 | .52 | .22 |
| 20 | 1,200 | | | | | 86.10 | 37.02 | 25.10 | 10.79 | 6.34 | 2.73 | 2.94 | 1.26 | .87 | .37 |
| 25 | 1,500 | | | | | | | 38.60 | 16.60 | 9.65 | 4.15 | 4.48 | 1.93 | 1.30 | .56 |
| 30 | 1,800 | | | | | | | 54.60 | 23.48 | 13.60 | 5.85 | 6.25 | 2.69 | 1.82 | .78 |
| 35 | 2,100 | | | | | | | 73.40 | 31.56 | 18.20 | 7.83 | 8.37 | 3.60 | 2.42 | 1.04 |

16.5 gpm (beside rows 15 and 20) = 17.3

Figure 6.19 Friction loss per 100 ft of steel pipe

P15: Dynamic head. The measure of pressure required to move liquid at a given velocity and to overcome effects due to friction is determined by adding the velocity head (P12) to the friction head (P14).

Dynamic head = 0.7 + 22.7 = **23.4 ft.**

P16: Total system head. The total system head is the sum of the total static head and total dynamic head. The system head and the flow rate determine the power requirements for pumping. The total system head is determined by adding the total static head (P11) to the total dynamic head (P15).

Total system head = 100 + 23.4 = approx. **124 ft.**

## PUMPING ENERGY REQUIREMENTS

P17: Hydraulic energy. The mechanical energy required to deliver a prescribed volume of water at a given head is determined by multiplying the total system head (P16) by the daily quantity of water required per day (P4). This figure is multiplied by the factor 0.0031 to convert units to watt-hours per day.

Hydraulic energy = 124 ft x 4000 gal/day x 0.0031 =
**1538 watt-hours/day.**

P18: Hydraulic power. This figure is determined by multiplying the peak flow rate (P5) by the total system head (P16). This quantity is then multiplied by the factor 0.188 to convert units to watts.

Hydraulic power = 1.65 gal/min x 124 ft x 0.188 = **385 watts.**

## PUMP SELECTION

The criterion for pump selection for any pumping application is that the pump/motor combination be capable of meeting flow and head requirements with high efficiency.

The pump/motor selected for this application is the **Jacuzzi SJ1-D10.** At the prescribed peak flow conditions (i.e., total head of 124 ft and a peak flow rate of 16.5 gpm), this pump has an efficiency of approximately **44%.**

P19: Motor voltage. The motor voltage is determined by interpolating the manufacturer's data in figure 6.20.

Motor voltage = 55 volts (approximately).

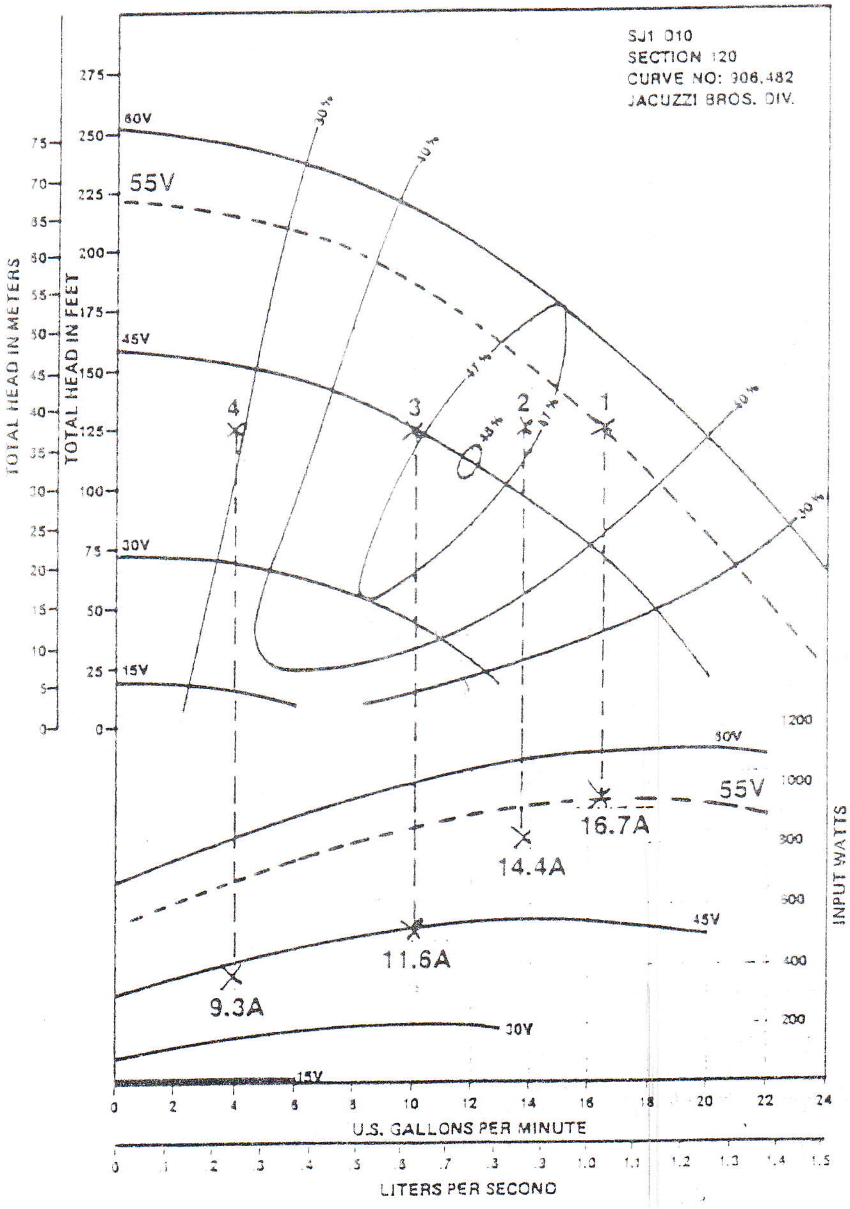



Figure 6.20 Efficiency graph for Jacuzzi SJ1 D10 pump

P20 : Electric power. The electric power required to drive the pump motor is also obtained from figure 6.20. For a peak flow rate of 16.5 gpm at approximately 55 volts, one can interpolate between the 45V and 60V curves (using the lower family of curves) to estimate the input watts.

Electric Power = **920 watts** (approximately).

P21: Daily electrical energy. The amount of electrical energy required to provide the daily water requirements at a given head is determined by multiplying the electric pump power (P20) times the peak sun hours available (P3).

Daily electrical energy = 920 watts x 4.03 hrs/day =
**3708 watt-hours/day.**

## PHOTOVOLTAIC ARRAY SIZING

A Solarex photovoltaic module, model **SX-146**, was selected for this application. Figure 6.21 provides the manufacturer's specifications for the SX-146 module.

**TYPICAL ELECTRICAL CHARACTERISTICS**

| | Nominal Wiring Configuration | |
|---|---|---|
| | 12-volt | 6-volt |
| Guaranteed minimum peak power | 46W | 46W |
| Typical peak power (Pp) | 48W | 48W |
| Voltage at peak power (Vpp) | 18V | 9V |
| Current at peak power (Ipp) | 2.67A | 5.34A |
| Current at specified voltage | 2.73A @ 15V | 5.46A @ 7.5V |
| Short-circuit current (Isc) | 2.9A | 5.8A |
| Open-circuit voltage (Voc) | 22V | 11V |
| Temperature coefficient of I | 2.7 mA/°C | 5.4 mA/°C |
| Temperature coefficient of V | -88 mV/°C | -44 mV/°C |
| Approximate effect of temperature on power | -0.4%/°C | -0.4%/°C |

Note:
These data represent the performance of typical modules as measured at their output terminals, and do not include the effect of such additional equipment as diodes and cabling. The data are based on measurements made at Standard Test Conditions (STC), which are:

- Illumination of 1 kW/m² (1 sun) at spectral distribution of AM 1.5 (1 ½ atmospheres)
- Cell temperature of 25 °C ± 3 °C or as otherwise indicated (on curves).

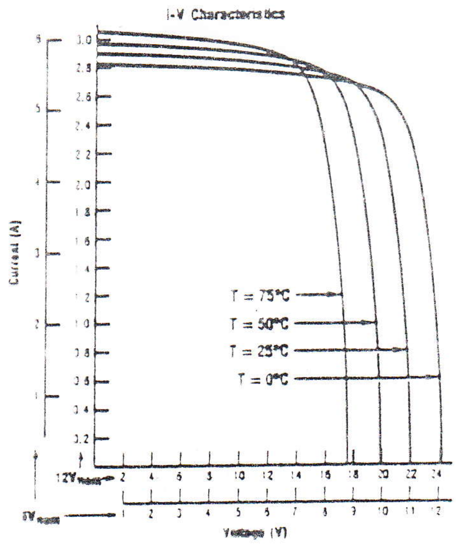



**Figure 6.21 Solarex SX-146 module specifications**

M1: Module voltage at max power (STC). The photovoltaic module voltage is obtained from the manufacturer's specifications, as in figure 6.21. The voltage at maximum power for the SX-146 is **18 volts.**

M2: Module current at max power (STC). The photovoltaic module current at maximum power is also obtained from the manufacturer's specifications. Current for the SX-146 at maximum power is **2.67 amps.**

M3: Module guaranteed power output at 1 kW/m² (STC). Module guaranteed power output at standard test conditions is obtained from the manufacturer's specifications shown in figure 6.21. The guaranteed power output for this module, indicated by the manufacturer's specification data, is **46 watts.**

M4: Total energy demand. The total energy demand that the photovoltaic array must meet is equal to the daily electrical energy required by the pump/motor to provide the daily quantity of water at a given head (P21).

Total energy demand = **3708 watt-hours/day.**

M5: Impedance mismatch and nonlinear effects for direct-coupled systems (0.7 - 0.9). Because the modules do not operate at the maximum power point throughout the day, a derating factor is used to adjust the energy demand. In addition, the pump/motor may not operate at the design efficiency for all irradiance levels. For this application a factor of **0.9** is used.

M6: Required array output. The required array output is the adjusted total energy demand. To determine the required array output, the total energy demand (M4) is divided by the derating factor (M5).

Required array output =
3708 watt-hours/day / 0.9 = **4120 watt-hours/day.**

M7: PV module operating voltage. The module voltage at maximum power (M1) is multiplied by an adjustment factor (between 0.8 and 0.9) to establish a module operating voltage that is, on an I-V curve, to the left of the maximum power voltage. A derating factor of 0.85 is used for this application.

PV module operating voltage = 18 volts x 0.85 = **15.3 volts.**

M8: Daily energy output per module. The daily energy output per module at STC is determined by multiplying the guaranteed module power output at $1 kW/m^2$ (M3) times the peak sun hours available (P3).

Daily energy output per module =
46 watts x 4.03 hr/day = **185 watt-hours/day.**

M9: Temperature derating factor. A temperature derating factor (between 0.80 -0.90) is used to compensate for the difference between actual operating conditions and standard test conditions. For this application a temperature derating factor of **0.90** is used.

M10: Derated module energy output. The derated module energy output is determined by multiplying the daily energy output per module (M8) times the temperature derating factor (M9).

Derated module energy output = 185 watt-hour/day x 0.90
= **166 watt-hours/day.**

M11: Number of modules to meet daily energy requirements. To determine the number of modules needed to meet the daily energy requirements, the required array output (M6) is divided by the derated module energy output (M10).

Number of modules to meet daily energy requirements =
4120 watt-hours/day / 166 watt-hours/day = **25 modules.**

M12: Number of modules per string. To determine the number of modules needed for each string, the motor voltage (P19) is divided by the photovoltaic module operating voltage (M7). This number is then rounded to the next higher integer.

Number of modules per string = 55 volts / 15.3 volts = **4 modules.**

M13: Number of strings in parallel. The number of strings in parallel required to supply the needed energy is determined by dividing the number of modules needed to meet the daily energy requirements (M11) by the number of modules per string (M12). This number is rounded to the next higher integer.

Number of strings in parallel = 25 modules / 4 modules = **7 strings.**

M14: Total number of modules required. The total number of modules required for this application is determined by multiplying the number of modules per string (M12) by the number of strings in parallel (M13).

Total number of modules required =
4 modules x 7 strings = **28 modules.**