

Photovoltaic System Design

Photovoltaics are a fuel free energy technology with no moving parts, made from common bulk materials, albeit by a complex process. Raw materials used in manufacture are Quartz rock, coal, charcoal and some exotic trace materials. Process chemicals include halogens (as chlorosilanes) and modules include common glass and (usually) aluminium sections.(See appendix 1) Theoretical energy payback ratio for PV is about 9 (Boyle et al.2003,p.559), but varies according to type of silicon, siting, control and use of output, and is improving with incremental gains in new technologies. Once installed a PV system delivers energy for decades with minimal maintenance.

Economic payback depends on relative costs of grid connection and comparison with other off grid solutions; and for grid connected systems the relative tariffs are a critical factor. PV module prices are perceived to be high, but major efforts are in hand to reduce costs to one dollar/euro per watt peak at factory gate. This represents a breakout price at which the costs of PV become more acceptable (Pearce,2005). Sunshine is available across the planet in varying amounts depending on latitude and local weather. PV is particularly suited to regions with high levels of direct sun. In cloud prone areas design requires care to ensure that installations are fit for purpose within budgets, often requiring use of supplementary sources.

All renewable energy installations producing electricity may be connected to a grid if available. High costs of making grid connections to remote sites make standalone a viable option. To cover times of no available energy, a standalone system must include some form of storage, most often batteries but could include pumped storage of fluids (water at height, compressed air) or inertial mass (flywheel). In PV systems this means at night and on days of severely adverse weather. A grid connected system uses the grid as the reserve so needs no storage, but must provide electricity to grid standards, using complex (i.e. expensive) inverters and must shut down (for safety) if the grid fails. For this reason, a grid connected system is not suitable for critical applications with an unreliable grid unless additional storage, switching and control systems are installed. Such a system would have to be sized to ensure supply for the duration of grid failure, at a level decided by appropriate risk assessments. (Note1)

Factors impacting on PV system design.

Essentially a standalone system is sized according to a matrix of variables defined by the site and the clients needs. (see appendix 2)

- Clients needs or expected loads both peak and average.
 - A system must be capable of delivering the clients peak demand. (Wp)
 - The system must be able to deliver the expected daily output. (Wh)
- Economic issues usually dictate that the client accept occasional loss of supply in order to reduce the capital cost of the system. This is defined according to two factors,

- the number of days the system will deliver power when there is no input, (days of autonomy) and
 - the probability of loss of power(LOL expressed as %).
- The relationship between loads, autonomy and LOL factors combine to define storage required for any off-grid system, regardless of power source. The higher the days of autonomy the larger the storage system needs to be, and the smaller the LOL value the larger the total system needs to be.
- The size of array needed to provide the energy is determined by available solar energy which in turn depends on latitude, site specific variables (shading) and weather.
 - Latitude impacts are inter seasonal variations on day length and sun path, so for example PV at the poles is useless for 6 months on the year, whilst at equator will perform at relatively high efficiency all year. There are also energy losses due to absorption by the atmosphere, which will be greatest at low sunpath angles.
 - Weather factors determine the amount of direct or beam light available at the site. At a cloudy site a greater proportion of light will be diffuse yielding lower energy than a sunnier site at the same latitude.
 - Suitable data is best taken from many years local records, which may be hard to obtain, so data is often taken from nearest available reliable meteorological recording station. (Note 2)
 - Weather data suitable for PV design are available online with varying degrees of granularity and local relevance depending on source. PVSyst uses highly granular data, for example the nearest data point to the study site is Birmingham, separated by a meteorologically significant mountain range. PhotoVoltaic Geographical Information Service (PVGIS) however has many more data points, Aberystwyth being much more like the site in question.
- The weather data combine with latitude to yield average figures for irradiance, which can now be found online for many territories.
 - Because of wide seasonal variations in temperate latitudes it is essential to avoid using annual average values for daylight hours, insolation, temperature. Monthly figures will give more useful results.
 - Because a system is often designed to meet demand at low energy availability it will inherently produce surplus beyond use and storage at peak times (high summer). This allows flexibility in terms of siting, array pitch etc. to maximise for winter output. (but reduces energy payback ratio).
 - Alternatively a system for inter seasonal storage could utilise any summer surplus for winter use, but may not be monetarily cost effective.
- Site specific shading is determined in the field using surveying tools (compass and inclinometer, or more simply by using a graphical Solar Horizon Estimator tool). In both cases shading objects are drawn onto a sun path diagram to show when the site is in shade from direct sunlight. This could then be used in conjunction with data for average beam and diffuse light to reduce estimates of available power according to season and time of day.

THE BRIEF

The eco-cabin is used to accommodate groups of school students at times during the school year and other groups during school holidays. The learning experience involves learning to use the resources, especially energy, in appropriate ways. The client has requested a design for a PV system with controls and battery system to supply the cabin with a given daily average amount of electricity; to permit two days of autonomy, and to price equipment for various expected loss of load scenarios. In addition the client has asked for an assessment of the merits of using a tracker device.

The factors bearing on the design are;

1. **Client's requirements;** expected peak and daily average loads, days of autonomy, LOL permitted.
2. **Available solar energy;** location, weather.
3. **System losses.**
4. **Siting of array** in relation to cabin/storage. Cable runs, voltages, sizing. Engineering issues of mounting.
5. **Possible use of tracker mounting.** Less array for same power?
6. **Budget;** are the proposed elements cost effective?

1. A survey of the cabin produced an estimate of loads. See table (appendix 3) for a detailed breakdown. In essence loads are divided into;

- Critical loads, safety systems, building services (pumps) IT hub.
- Routine use services eg lights, supply for consumer electronics.
- Occasional high power uses; cleaning equipment, maintenance tools.
- Also some loads are already configured as DC, eg lighting. whilst others run from existing inverters.

The client specified the daily load at 13 kWh (from the table). (Note 3)

The client specified the required autonomy as two days; and asked for prices for systems giving LOL at 10%, 25% and 50%.

2. Primary data for expected solar radiation were derived from PV GIS; a free resource maintained by the EC and covering the whole of the Union. The nearest data point to the site is Aberystwyth. By taking data for the month of lowest available energy and applying the "Rule of thumb" PV array size equation a ball -park idea of the required array was derived.

$$\text{PV Array (peak)} = \frac{\text{Loads}}{\text{Irradiation} \times \text{Efficiency factors}}$$

Giving a system size of 27 kW p before considering size reductions for various LOL factors. A system this size is both capital intensive and presents an engineering challenge to install at the selected site, which would have knock – on costs.(See 4 below).

The design software package PVSyst was then used to model various versions of the proposed installation and produce comparative costings for the LOL variable. The final proposed design is detailed in Appendix 4.

The final design uses a 7 kWp array.

3. System losses are principally attributable to four factors; temperature losses in the PV array, losses due to cable resistance between array and battery, losses in the battery (Note 4) and inverter losses. Inverter losses are included in loads (*Appendix 3*). The siting of the array at a distance from the point of use makes ohmic losses (proportional to the square of current) in the transmission cables a major factor in this particular case, resulting in a requirement for higher than usual voltage output from the array, and for a significantly more versatile voltage control unit (able to cope with higher input voltages). Other losses are guesstimated by using a fudge factor in sizing calculations.

Wherever possible loads are taken as DC direct from the battery, such as for lighting. In addition, overall system efficiency can be optimised by using a low power inverter for background critical tasks, and a high power inverter available for occasional use of electrical appliances.

4. The site selected for the PV array is believed to be optimal in terms of incident solar radiation. (Note 5).The distance from the proposed array site to the existing control room is determined as 61m. Two issues arise. Firstly, the voltage loss across the length of the cable, and secondly the power loss due to ohmic resistance. To deal firstly with power loss, it is most sensible to arrange for the output from the array to be at as high a voltage as is practicable, which reduces the current and hence power losses. For this reason, given the length of cable run it was decided to set the array operating voltage as 120V DC; a consequence of which was the need for an unusually sophisticated charge controller able to accept this voltage and output to the battery at 24V.

For a known maximum current and acceptable voltage drop cable sizing is determined from standard tables.(BS 7671, 17th Edition currently)

5. To examine the potential use of either a single or twin axis tracker system a block of comparative data from an existing trial were analysed. The available data covered the period from 29th June to 10th July 2008 and yielded totals for energy received by each system.

Table 1; Comparative accumulated energy for three trial mounting configurations

System	Fixed Array	Single Axis Tracker	Twin axis Tracker
Total Wh	6452	7832	7779
Ratio	1	1.214	1.206

It is immediately obvious that for the trial conditions the tracker systems both outperform the fixed system, but that the impact of a twin axis system is negligible. (Note 6) There is merit in examining the cost and engineering implications of using a single axis tracker optimised for early and late winter given the *possible* 20% improvement in yield. Tracker systems give economic returns in locations of high beam radiation as the array can

be constantly optimised to maximise yield. In this site however, *in no month does average beam radiation exceed diffuse*. (Synthetic meteorological data for 1990 Aberystwyth converted for CAT site)

6. The client requested costings for given loads, days of autonomy and loss of loads at 10%, 25% and 50%. Ballpark figures from PVSyst software simulation (indicative to within an order of magnitude) allow an examination of relative cost of the three designs. In addition Wind and Sun Ltd. (Wind and Sun.2007 p.22) give a price indicator of £5 - £6 thousand per kW installed.

Table 2; System size and cost estimate for various LOL factors

LOL %	10	25	50
Array size kWp	9.8	5.7	3.4
PVSyst	59855	38991	26678
Wind and Sun (6k£/kWp)	58800	34200	20400

The cost implications of using a single axis tracker in these scenarios are based on the assumption that the 20% performance improvement from the data in Table 1 are valid.

Table 3; Comparative effects of using tracker to reduce array size against extra modules

LOL %	10	25	50
Array area m2 (-16.7 %)	71.8 (59.5)	42.8 (35.7)	27.7 (23.1)
Array output Wp (-16.7%)	9.8 (8.17)	5.7 (4.75)	3.4 (2.83)
No of mounts (large) plus (small)	1 + 0	0 + 3	0 + 2
Cost (ex VAT) (£)	7343	5079	3386
Equiv modules Wp (BP3170)	1678 (10)	1360 (8)	774 (4.5)

The large mount is the DEG 7000 NT able to carry a 60m2 array.
The small mount is the ETA 1500 able to carry a 15m2 array
(Wind and Sun)

WARNING; These are ball park figures only. From the box highlighted it is clear that the adjusted array size only just fits on the available mounting, so this solution may in practice result in a reduced yield than expected. From the bottom line it is also clear that spending the equivalent capital on additional modules would yield the same or more power without the engineering issues of footing such a large moving array. None of these costs include associated civil engineering.

Conclusions

This was overall a useful exercise in PV system design, pitting a challenging site and client brief against the aspirational values associated with this technology. It became clear during the iterative design process that possibly the most important initial factor in a real project is re-negotiating the clients perceived demand for power and enabling realistic expectations of financial and energy returns.

A particularly challenging aspect of this site is the relatively high proportion of total solar energy received as diffuse rather than direct light, a suboptimal condition for benefiting from PV in general and tracker mounted systems in particular.

There is clearly no economic solution to providing all year electricity for this project from PV alone, raising the issue of the winter lack of supply and selection of a replacement system. This interseasonal replacement may then be able to supply a greater proportion of the demand during other months, and hence allow a smaller PV system.

The exercise presented valuable opportunities to grasp the fundamentals underlying the sophisticated modelling and design software. This is strongly enabling in terms of advocacy for the technologies and in terms of discussion with potential clients for projects. There is however no substitute for repeated practice of a design methodology under various conditions in order to become fully competent.

The group working on this task brought a wide range of competences in terms of practical skills and knowledge and also use of IT. This enabled sub division of the group into task focussed units each of which contributed important design decisions or analysis. There is a risk that some tasks being undertaken by those with prior knowledge will have reduced the learning opportunity for others. The huge range of raw data and analysis produced during the practical (symptomatic of availability of IT) deserved a longer period for group report back and appraisal than was available (I later found some data input errors in my own contribution for example). Overall the group benefited from group process gains in sharing insights and talents.

NOTES

1. The experimental site is within a complex which has been historically off-grid, and so has an existing off grid system which is being considered for upgrading; specifically to determine the viability of a larger array using a solar tracking mounting. (But - see notes on loads below). The present system uses 8 modules in two arrays as a PV source, with a micro-hydro system powered by overflow from the funicular railway head stock as a supplement. No data are in hand regarding seasonal variations in output from this system. All power generated is run through controllers into a battery bank at 24 v, from which power is fed directly to DC loads, and through inverters to AC loads.

2. The site at issue is renowned as a cool temperate rainforest, so may enjoy a very localised micro-climate which would not be accurately reflected in " nearest best approximation" based on data from sunnier locations. In all cases data must be taken from the longest period possible to minimise effects of annual variations. Available synthetic (ie computer generated from nearest suitable weather station-Aberystwyth) data reveals that in no month does beam radiation exceed diffuse radiation, which has significance in considering use of a tracking device. There is no reason to believe that more energy will be available at the site and good reason to suppose it will be less. (ie temperate rainforest)

3. It should be noted that most of the consumer electronics loads represent a power loss in converting from the DC supply through an inverter to mains equivalent AC and then in the

appliance being used back to a low voltage DC. It is suggested that these applications could be served by a regulated DC power supply system run directly from the battery instead. This should reduce conversion losses as well as provide users with a valuable lesson in the waste inherent in their devices. In addition, some means of energy production using human power, such as pedal generators, could be added to the input system with strong educational effects.

4. Battery losses arise as a result of energy lost as heat during electrochemical processes. These are inevitable, but steps can be taken to keep them to a minimum by sizing and by managing the battery use. For example rapid draining of power from the battery will tend to result in larger losses than trickle discharge. Regular monitoring of electrolyte levels and quality is vital to ensure good performance.

5. Being a spit of quarry waste the capacity of the ground to carry significant shear and turning forces (such as may be caused by wind load on either a fixed or pole mounted tracker array of the size under consideration) may need to be examined. In either case the costs of civil engineering mounting points for the array(s) may become significant.

6. Owing to data collection errors it was not possible to determine if this is due to energy lost in seeking for optimum orientation of the twin array. It would be wrong to draw too strong conclusions from this trial as it uses such a short time period in high summer the effect of twin axis tracking is lost.

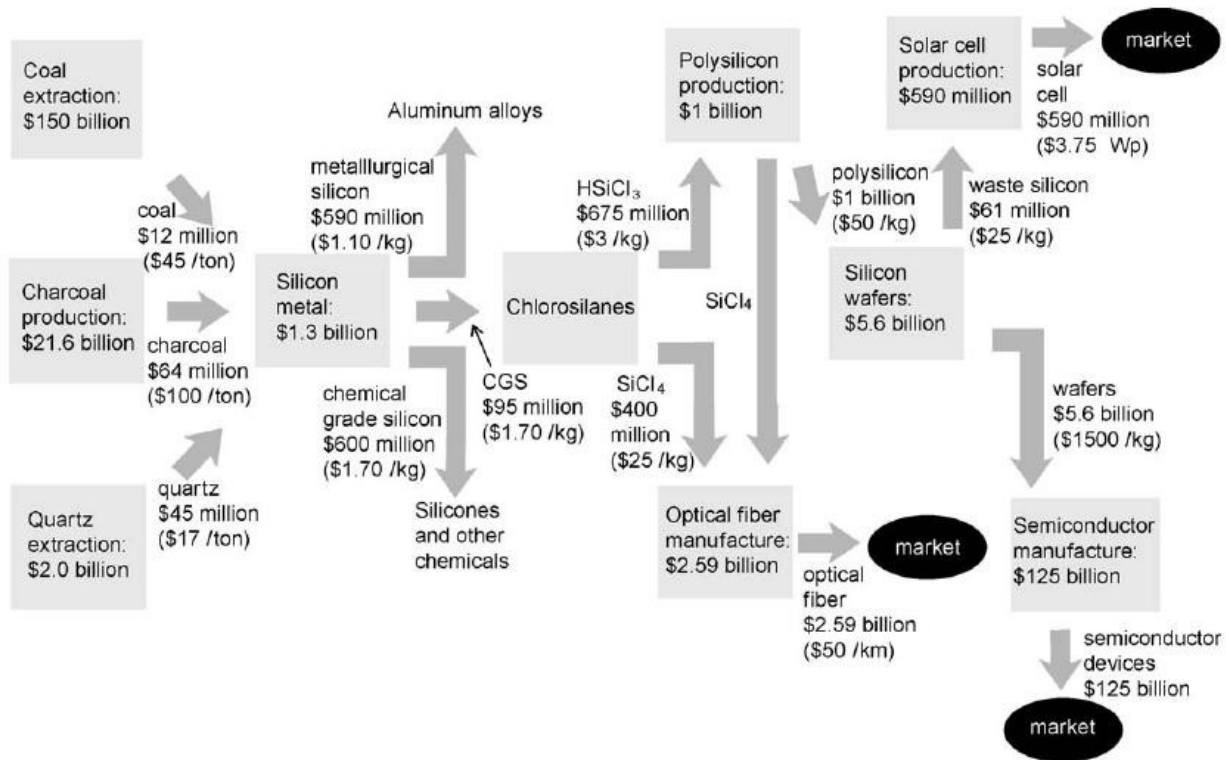
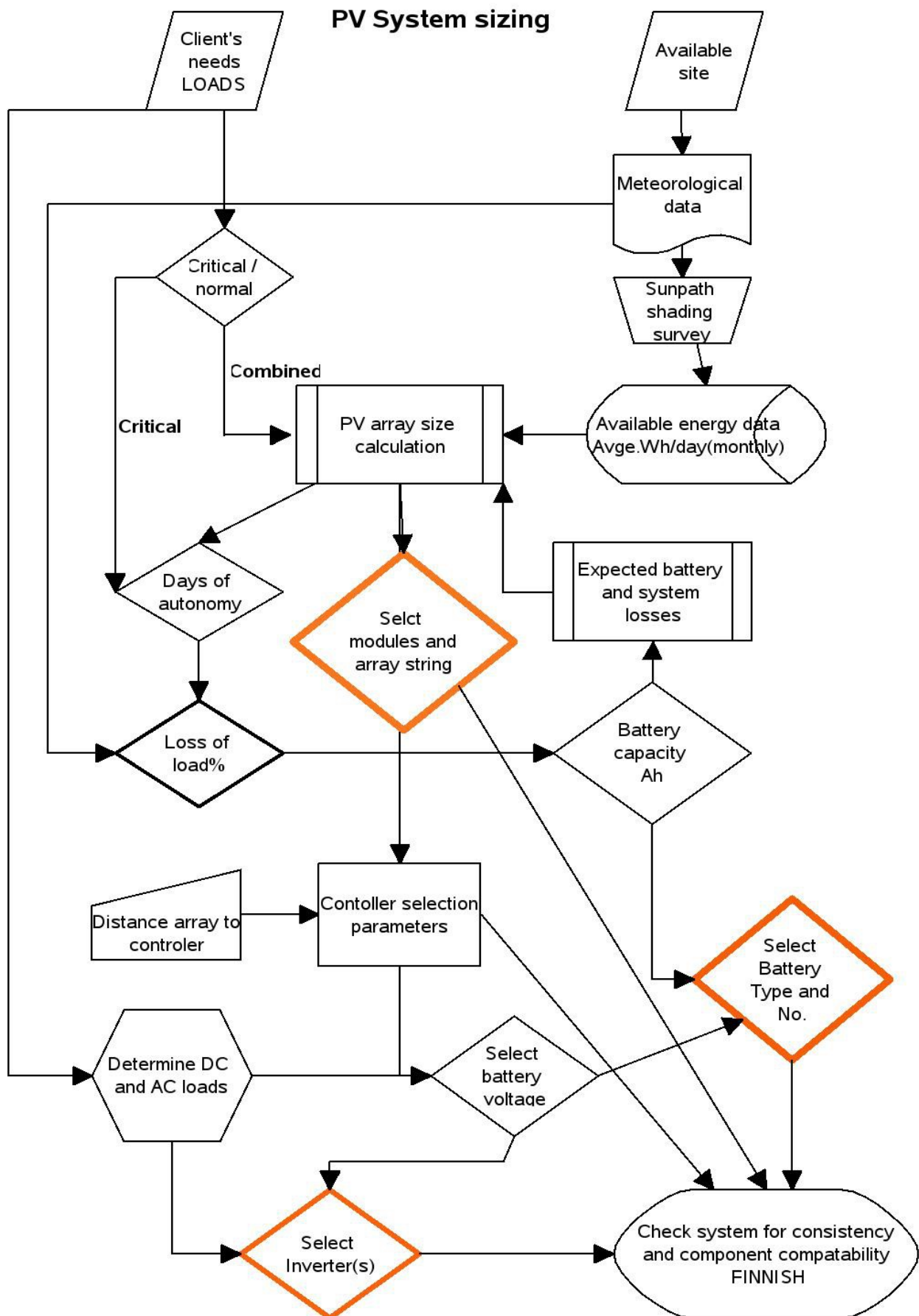


Fig. 2. 1998 economic scale and flows in the global production chain for silicon.

(Williams, E. 2003 fig 2)

Note that at the time this chart was describing ten years ago the supply of silicon for PV manufacture was almost all from waste from the semi-conductor industry. As the quality of silicon required for PV is lower than for micro-electronics an entire new industry producing silicon exclusively for PV has emerged in the intervening time, (such as PVCrystalox plc in the UK and Solar Grade Silicon in the USA). In the same article projections for the year 2020 are below market size and installed capacity at present day. A large effort under way in China to build capacity for PV production will impact on global supply and prices in the near term future. (ENF,2007)

Appendix 2; Draft of proposed system sizing flow chart



Appendix 4

The system recommended.

Criteria;

Loads average daily use 13 kWh
Maximum power 2kW
Days of autonomy 2
Loss of load (annual average) 20%

PV array;

40 no. BP3170N
Mounted in 8 strings each of 5 modules.
Array nominal power (peak) 6.8 kW
Voltage 120 DC
Current (Mpp) Per string; 4.8A; Array total 38.4 A
Current (sc) Per string 5.2A; Total 41.6 A
Price each; £633 or £ 25,320 total

Cable to charge controllers,

cables in pairs of strings 10.4 A
Voltage 120 DC
Length 122m
Cable size 10mm²
Voltage drop 5.37 v (4.48 %)
Power loss 54.8 W
Selected 4 core SWA to BS5467 90 degrees C ; 4 No.
4 x 122 m @ £3,45/m Total £ 1,684

Charge controllers

4 No. Outback MX 60 (one per two strings)
Output to battery nominal 24V at Sc_c 52 A (max possible- will be less in practice!)
Note; this controller uses maximum power point tracking to get optimum performance from the array.
Price each; £366 or £ 1,464 total

Battery pack

4 no. Rolls Solar 4000 (6V each)
Voltage 24 V
Capacity 1840 Ah
Price each; £ 193 or £772 total

Inverters

Low load 200W modified sine wave
1 off Studer AJ350-24
250 W continuous, 350 W @ 30mins, 500W surge (5s)
Price; £177

High load 2kW modified sine wave
1 off Studer SI2324
2300W continuous, 8kW surge
Price; £1373

Total main element cost (Ex VAT) £ 30, 790 excluding labour and sundries. All prices from Wind and Sun 2007 Catalogue apart from cable which is priced from Electric Cable Co. (GB) Ltd. website.

Given the clients request for costings for loss of load scenarios of 10%, 25% and 50%; as detailed in the table above, this designer believes that a LOL of 20% is the optimal for the task. The chart for battery state of charge and monthly LOL given by the PVSyst software shows that from April to October LOL probability is at *or below* 20%, whilst only for December and January does it exceed 50%. Given that the sunpath/ horizon survey for this site shows significant loss of beam radiation for those months it was never going to be economic to build a system to supply such a large load at that time of year.

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