RIGHT SIZING AN OFF-GRID SOLAR HOUSE

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ABSTRACT

Power reliability is one of the biggest concerns for people living off-grid. Current practice in off-grid solar house tends to either oversize solar power system or oversize the backup generator to ensure available electricity at all times, which often leads to a high system capital cost. Research has shown that right-sizing is essential to achieve a more efficient system with reduced energy consumption. Sound, responsible system sizing can only happen when liability issues become part of the design methodology, i.e. actively communicating with prospective owners/occupants regarding the risk that the thermal comfort, and full time use of appliances cannot be fully guaranteed. The risk of non-fulfilments may be related to extraordinary environmental conditions for a certain amount of time of the year, the chance that certain components will fail for some reason, and the fact that predictions of the operation of houses are based on design idealizations, whereas its real operation is to some degree uncertain.

This paper presents a value-based approach to find the balancing point between the acceptable reliability level and the affordable system capital cost. The value-based approach is illustrated through a sizing practice of an existing off-grid solar house in Atlanta, GA.

INTRODUCTION

Sizing in an off-grid solar residential home design mainly includes PV array sizing, battery sizing, domestic hot water system sizing, and home heating, ventilation, and air conditioning (HVAC) system sizing. Nowadays every system or sometimes even every single main component of a system has its own well-established sizing methodology. For instance a PV system is commonly sized either according to worst case scenarios (usually in the winter when there is limited solar resources) or according to the typical local weather data (Bhuiyan and Ali Asgar 2003; Celik 2003). HVAC systems are usually sized according to a worst case scenario or extreme design day. The requirements of specializations in specific areas result in rather isolated sizing procedures at pre-defined stages of the building design. This reduction of relationships among different components during design stage is contrary to their multiple, real time interactivities that occur in the operation stage.

From the operation perspective none of these system parts should be sized in isolation, as their performances are highly interrelated and need to be studied through holistic assessment based on dynamic simulations. In off-grid solar house design energy self-sufficiency is one of the key performance aspects. All involved design components and building loads, the HVAC system, weather dynamics, battery or other type storage system, and solar power system are interacting with each other every second. Many of the interactions are not well accounted for by the current disjointed and often individual system design tasks. This often leads to mismatches among different components and systems and eventually causes under performance, in particular unnecessary energy waste. Celik (2007) investigated the effects of different load profiles on the performance of stand-alone PV systems and his research results show that the reliability of a PV power system varies considerably when it works with different load profiles, especially for small battery capacities. Anis and Nour (1995) studied energy losses in PV system and results show that the mismatch between the array and the load or battery capacity could cause big energy losses. The main reason is that the PV array is usually sized to meet the load during the winter season when solar irradiation is low. As a result the system is oversized for the summer and energy loss from the PV system can be as high as 40%. These results reveal the importance to integrate building load, renewable power generation system, battery bank and their instantaneous interaction together in the design, system balancing and performance evaluation processes of off-grid solar houses.

Another common issue that confronts the off-grid solar house design is that designers in each field tend to oversize their components. This is due to the liability issue which demands full responsibilities from designers to ensure that their design meets the performance requirements under all conditions. In response to the increasing need to provide liability protection designers have to either oversize the system or add an extra parallel system to ensure system reliability, which in off-grid solar house design, often results in purchasing huge backup electricity generators or oversized PV power generation systems. This justifies the question whether the extra costs incurred by customers to "buy" reliability guarantees is really cost effective.

This paper advocates a holistic approach which brings the house, its mechanical system, and the supportive renewable power system into one computational model for an overall performance evaluation regarding energy self-sufficiency, system costs, and the sophistication of system sizing. A value-based approach is then proposed to evaluate the reliability cost of the off-grid solar house design and to help potential off-grid residents make the most economic investment in terms of their power reliability. A case study on an existing off-gird solar house, in which both the mechanical system and solar power generation system were designed using traditional sizing techniques, is used to illustrate the importance and flexibility of the proposed approach. It is argued that the value-based approach helps make the most cost economic sizing selection in off-grid houses.

A VALUE-BASED SIZING APPROACH

A performance evaluation cannot be done without a corresponding evaluation criterion. A well-known performance parameter used to evaluate the reliability of off-grid solar power systems is the so-called loss-of-load probability (LOLP). It is defined as the ratio between energy deficit (the energy need that cannot be met by the system) and energy demand over the total operation time of the installation (El-Maghraby, Abed et al. 1985). The LOLP connects a PV power system with its electricity consumers. It should be noted that in current practice, most building (electricity) load simulations are conducted separately from the LOLP evaluation of a PV system. This disconnection leads to the neglect of energy reliability impacts that result from system sizing mismatches.

The value-based approach was first proposed in the power planning industry to help utility companies make the most promising investments in their utilities service business (Rau 1994). This approach combines customer-value with the cost to design the power transportation and distribution system at various levels of reliability and "power quality" and then uses it to identify the optimum balance between service reliability and utility company's investments (Willis, Welch et al. 2001). The customer value of reliability and service quality is often measured by the cost that customers pay for the damage due to a lack of perfect reliability and service quality. Customer interruption cost has been used to represent the customer value since 1994 (Rau 1994; Chowdhury and Koval 2001; Kaur, Singh et al. 2004). Figure 1 shows the concept of value-based planning in the power industry. The total cost of a power system configuration is the sum of utility investment cost, operating cost, and customer interruption cost. The point of minimum of total cost is the balancing point that power planners look for.

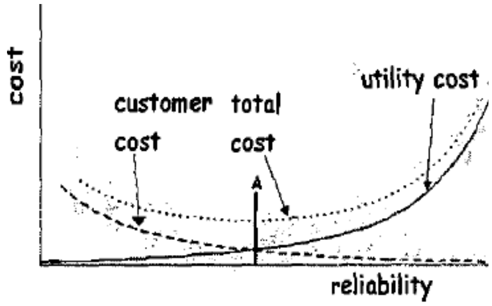

Figure 1 The concept of value-based planning (Kaur, Singh et al. 2004)

The value-based sizing approach adopts the concept of value-based planning described above. In fact an off-grid solar house could be considered as a small scale power plant with multiple (internal) electricity consumers. However the operating cost in an off-grid solar house is close to zero and the total cost becomes a sum of customer interruption cost and system investments. The design objective is to find the most economic system sizing match which corresponds to the minimum total cost.

A CASE STUDY

Building description

The solar house used in this case study is the Georgia Tech entry in the Solar Decathlon 2007 (SD07) competition. Figure 2 and Figure 3 show a front and rear views of the house. The house has a floor plan of 60 m^2, including a bedroom, a bathroom, and a living room/open kitchen. The vertical house envelope has two types of materials: part of the southern wall and eastern wall (transparent area in Figure 2) are duo-guard which is made of polycarbonates filled with aerogel; the rest are SIP walls (red area in Figure 3). The roof is made of ETFE membrane filled with aerogel in the middle. Both the roof and duo-guard walls are translucent. More details on this design can be found in (Choudhary, et al. 2007).

Figure 2 A front view of the GT solar house

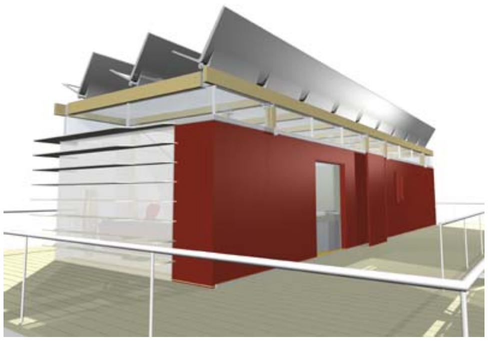

Figure 3 A rear view of the GT solar house

The electricity supplied to this house is produced by its PV system that includes 27 PV panels on the roof providing a total power of 6.5 kW and 12 PV panels mounted to the southern wall (black area in Figure 2) providing an additional 2 kW of electricity. The corresponding battery has a maximum capacity of 98.4 kWh. The domestic hot water (DHW) is a separate evacuated tube solar collector system. In terms of mechanical system this solar house has a mini-split air-source heat pump working together with an energy recovery ventilator.

Building models

A finite element based simulation model has been developed in Matlab for this project, serving as an tool for both energy analysis and sensitivity analysis (Choudhary, et al. 2007). The model has been calibrated against onsite measurements to identify those parameters that were difficult to estimate from experience, such as the extra thermal mass contributed by interior furniture and the level by with the thermal insulation is affected due to several types of thermal bridges in building envelope.

Although this solar house was primarily designed for the SD07 competition it is furnished and technically fully functional as a residential house to accommodate a couple without kids. The electricity consumption data of all the appliances and mechanical equipments have been collected from their product handbooks and are fed into the Building America analysis tool (Hendron 2007) and a series of users profiles, intended to represent the behaviour of "standard" occupants, are created and used in the simulations performed in this study. The standard TMY2 weather file for Atlanta, GA has been used in the following full year energy simulations and the time step has been chosen to be 3 minutes.

System efficiency models

This case study includes modelling of two important efficiency parameters: the coefficient of performance (COP) for the air source heat pump and the efficiency of the installed PV modules.

1. COP of heat pump

The COP of the installed heat pump has been evaluated in test conditions and Table 1 shows its specification. The operating condition is often different from the test condition. The corresponding correction factors (f_{cor}) under different operating conditions can be read from the included heat pump manual. A corrected COP can be calculated using equation 1.

$$COP_c = COP_0 \times f_{cor} \qquad (1)$$

Table 1
Performance data of the installed heat pump

	CAPACITY RANGES (BTU/HR)	POWER INPUTS (W)
Heating	12600~28400	1000~3250
Cooling	11400~36000	740~2880

The performance data shown in Table 1 are measured at full capacity but in reality, heat pumps are often operated at partial loads that degrade the system efficiency. This part load influence can be taken care of by another correction factor called partial load factor (PLF) as shown in equation 2. While building load falls within the range shown in Table 1 a linear relationship will be used to estimate its corresponding power input as implemented in earlier studies (Ishida and Mori 2005).

$$COP_{hp} = COP_c \times PLF \qquad (2)$$

The ARI standard suggests a generalized equation to estimate PLF (ARI 1989), as shown in equation 3.

$$PLF = 1 - c_d \times (1 - PLR) \qquad (3)$$

where the c_d is a degradation coefficient that takes the default value as 0.25; the PLR represents partial load ratio and is calculated as the ratio of the building requirement supplied by the system in the considered time interval to the maximum energy that could be supplied in the same time interval if the system would continue to work at full capacity.

2. Efficiency of PV modules

Modelling of the PV module efficiency is difficult as it depends on many factors, including ambient temperature, wind condition, installation method, module type, etc. Extensive researches have been conducted to develop implicit and/or explicit methods of modelling PV efficiency. Equation 4 represents the traditional simple linear expression for the PV electrical efficiency.

$$\eta_c = \eta_{T_{ref}} \times [1 - \beta_{ref}(T_c - T_{ref})] \qquad (4)$$

where $\eta_{T_{ref}}$ is the PV module efficiency at temperature T_{ref} and at solar radiation flux of 1000 W/m^2. β_{ref} is the efficiency correction coefficient for temperature that is included in the manufacturer data sheet. T_c is the PV operating temperature.

It has been well known that operating temperature has a significant influence on the PV module efficiency. However the estimate of PV operating temperature could be complicated due to the complex surrounding thermal environment of a PV system. Numerous researches and experiments have been conducted to investigate the correlation between air temperature and PV operating temperature. Skoplaki and Palyvos (2009) conducted extensive review on the estimate of operating temperatures. Equation 5 shows a simple semi-empirical explicit correlation for the PV operating temperature (Skoplaki, Boudouvis et al. 2008) which is used in this study.

$$T_c = T_a + \omega\left(\frac{0.32}{8.91 + 2.0V_f}\right)G_T \qquad (5)$$

where

T_a is the ambient air temperature;

ω is a mounting coefficient, estimated to be 1.2 for flat roof situation and 2.4 for a façade integrated condition;

G_T is the incident solar radiation;

V_f is the free stream wind speed in the windward side of the PV array. It is a difficult parameter to estimate especially when experimental data are not available. Our study uses wind speed data measured at meteorological station to estimate V_f as shown in equation 6 and 7 (ASHRAE 2001).

$$V_f = \gamma U_{pot} \qquad (6)$$

where

U_{pot} is the potential wind speed, i.e. (hourly average) wind speed measured at an ideal meteorological station at 10m above ground level;

γ is wind reduction factor, estimated in equation 7.

$$\gamma = \frac{V_f}{U_{pot}} = \left(\frac{\delta_{pot}}{H_{pot}}\right)^{\alpha_{pot}} \left(\frac{H}{\delta}\right)^{\alpha} \qquad (7)$$

where

U_{pot} is the wind speed measured at local reference height; δ_{pot} is wind boundary layer thickness for the meteorological station; α_{pot} is wind exponent for the meteorological station; δ is wind boundary layer thickness for the local building terrain; α is wind exponent for the local building terrain.

Uncertainty estimates in material properties

A variety of uncertainty sources in both PV system and building systems have been investigated but for the current study only a limited set of variables with uncertain is chosen. Table 1 shows the uncertain variables involved in the study and their corresponding reference values, varying ranges, and distribution functions:

- pv_env: the overall PV derate factor from power losses in cable, mismatch, wiring, diodes and connections, etc. (Detrick, Kimber et al. 2005; Marion, Adelstein et al. 2005);
- ts_etfe: the solar transmittance of the ETFE roof. The roof is a customized design and its specific solar transmittance has not been tested in the lab. The reference value is based on the best estimate and ±20% adjustment has been given to define its range of uncertainty.
- ts_kw: the solar transmittance of duo-guard walls. The reference value is based on experts' best estimate and ±20% adjustment has been given to define its range of uncertainty

Table 2
Uncertain variables – reference values, varying ranges and probability distribution functions (PDFs)

	REFERENCE VALUES	RANGES	PDF
pv_env	0.927	[0.698,1.014]	Normal
ts_etfe	0.175	[0.14,0.20]	Uniform
ts_kw	0.08	[0.05,0.12]	Uniform

Performance criteria

The objective of the case study is to investigate the relationship between the sophistication of system sizing, energy consumption, power reliability, and the house first cost. The following performance parameters are introduced to fit this need:

1) yearly electricity consumption ($E_{consume}$)

This represents the total electricity consumption by the solar house in the course of a year.

2) yearly electricity wasted (E_{waste})

It represents the total electricity "wasted" (available but unable to use) due to limitation of the installed battery capacity during a year.

3) yearly electricity unmet (E_{need})

It represents the total electricity need unmet by the installed PV system during a year.

4) yearly total interruption cost

In the off-grid solar house case power will not be available all the time and certain inconveniences or even damages will result. The damage that an electricity interruption causes is quantified to represent a valuation of power availability. The interruption cost is taken from the customers' perspective leading to a detailed cost function that will be discussed below.

5) PV system cost

The annualized life cycle cost (ALCC) of the installed PV system is calculated as the yearly cost related to PV power system investments. The ALCC spreads the total life cycle cost of the installed PV power system to its life span and is the same for every year operation (Dakkak, Hirata et al. 2003).

6) The yearly total cost (C_{total})

The total cost is the sum of expected interruption cost and the ALCC of the designed PV system.

The following three system sizing parameters are considered:

1) battery capacity;
2) the number of PV modules mounted in the roof;
3) the number of PV modules mounted to the southern wall.

The evaluation technique

The Monte-Carlo (MC) approach has been implemented as a shell around the building simulation model in Matlab to evaluate power reliability. The classic Latin Hypercube Sampling (LHS) technique is used to improve the efficiency of MC simulations. The convergence criterion of LHS, proposed by Billinton and Li (1994), suggests a sample size of 50 for this study.

Interruption cost

Power interruption reflects one aspect of power quality. The damage a power interruption causes is mostly physical but may have different consequences for different customers depending on how badly they are affected by a power interruption. Figure 4 shows typical interruption cost characteristics for the residential class (Willis, Welch et al. 2001). The interruption cost includes a fixed cost caused when an interruption occurs, and a variable cost that increases as the interruption continues.

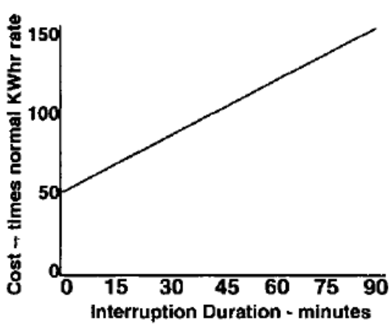

Figure 4 Typical interruption cost characteristics for residential customers (Willis, Welch et al. 2001)

RESULT ANALYSIS

The studied off-grid house currently has 27 PV modules installed on the roof with a rated power of 203.2 W each and 12 more modules mounted to the southern wall with a rated power of 197.6 W each. It uses eight batteries with an individual capacity of 12.6 kWh. Table 3 lists all the investigated design values. All the design variables are integer variables.

Table 3
Design variables – reference values, varying ranges

	INSTALLED ORIGINAL DESIGN	DESIGN OPTIONS
$N_{battery}$	8	7,8,9
$N_{pv,roof}$	27	24, 27
$N_{pv,south}$	12	8,12

The design options are generated with different combinations of three design variables at different discrete values. Table 4 shows the design variable values of each design option.

Table 4
A list of investigated design options

	$N_{BATTERY}$	N_{PV_ROOF}	N_{PV_SOUTH}
Option1	7	24	12
Option2	7	27	12
Option3	8	24	12
Option4	8	27	12
Option5	9	24	12
Option6	9	27	12
Option7	7	24	8
Option8	7	27	8
Option9	8	24	8
Option10	8	27	8
Option11	9	24	8
Option12	9	27	8

The cost of a PV power system includes costs of the PV modules, inverters, batteries, balance of system (BOS) components, and the installation labour costs (Table 5).

Table 5
Cost information about the PV systems

	PRICES	SOURCES
PV modules on the roof	$1056/module	Project data
Inverter for roof PV modules	$0.56/$W_{ac}$	Project data
PV modules on the SW	$1032/module	Project data
Inverter for SW PV modules	$0.67/$W_{ac}$	Project data
BOS	$2000	Project data
Installation	$1.66/$W_P$	(DOE 2007)
Batteries	$4200/module	Internet
Maintenance	0.5% of gross cost	(DOE 2007)

The inflation rate is assumed to be 2.5%. Based on the product specs, the batteries are assumed to be replaced once every 5 years and market discount for batteries is taken as 6% (Dakkak, Hirata et al. 2003). The PV power system is assumed to have a life time of 20 years in this study.

Table 6 shows the expected values of all three energy related performance parameters. Option 9 has the lowest electricity consumption and waste but meanwhile has the highest unmet need. In contrary Option 4 has the highest electricity consumption and waste but with the lowest unmet need. This contrariness indicates that it is impossible to find a sizing match which leads to the most desirable performance to all three energy performance criteria at the same time unless a battery with infinite capacity comes with the installation. A compromise will have to be reached in the final design decision. The economic factor can be helpful for this. It is often used as another performance aspect designers look at before reaching a design decision.

Table 6
Simulation results – energy aspect

	$E_{CONSUME}$ (KWH/YR)	E_{WASTE} (KWH/YR)	E_{NEED} (KWH/YR)
Option1	6768	872	210
Option2	6562	428	280
Option3	6834	1088	185
Option4	6862	1491	167
Option5	6757	560	227
Option6	6793	811	210
Option7	6367	154	392
Option8	6765	1038	212
Option9	5870	11	722
Option10	6829	1261	186
Option11	6552	355	291
Option12	6751	722	228

Figure 5 shows the comparison of cost parameter C_{total} for all selected design options. The Option 7 has the lowest ALCC and Option 4 has the lowest interruption cost. Option 2 has the smallest total cost among all the design options. Therefore the most cost effective investment will be: 7 batteries, 27 PV modules on the roof, and 12 PV modules mounted to the southern wall.

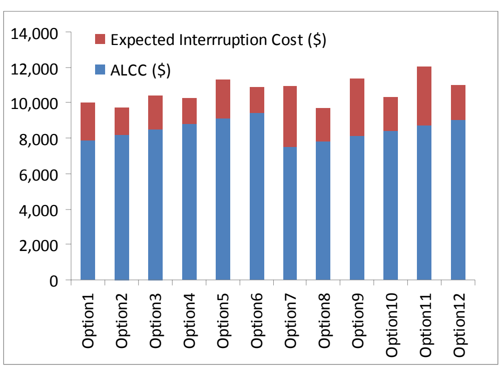

Figure 5 The comparison of C_{total} of all investigated design options

DISCUSSION

Predictive controller

The Georgia Tech SD07 solar house has implemented a model-based optimal controller integrated in the house control system. This controller predicts energy production and consumption levels for the coming week and helps occupants manage their electricity allocation to multiple house activities based on their preferences. Willis and Welch (2001) pointed out that if given sufficient time to prepare for a power interruption most of the momentary interruption cost (the fixed part) and a major part of the variable cost can be eliminated. Figure 6 shows the cost impact that a 24-hour notice could reduce.

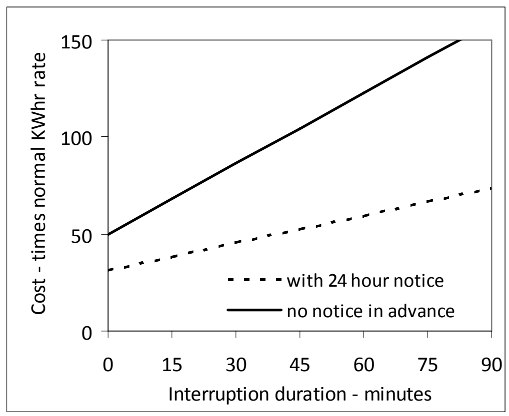

Figure 6 The reduced cost impact if power interruption is noticed to customers 24 hours ahead (Willis, Welch et al. 2001)

Although the implemented predictive controller is designed to predict the power interruption more than 24 hours ahead this paper will use an interruption cost function represented by the dotted line in Figure 6 due to the intrinsic uncertainty in performance prediction behavior (Lorenzo and Narvarte 2000) for longer periods.

Figure 7 shows the comparison of the total costs for all investigated design options. The optimal design option now changes from Option 2 to Option 8 due to the reduced cost impact from power interruption.

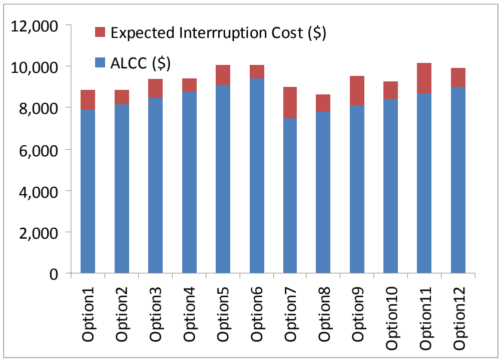

Figure 7 The C_{total} of different investigated design options – with 24-hour advance notice

Degradation of a PV power system

The efficiency of a PV module degrades with time. The yearly degradation rate depends on the type of PV modules, PV operating environment, the effectiveness of the system maintenance, etc. This study uses a degradation rate of 1% per year (DOE 2007). Figure 8 shows a comparison of total costs of all design options in the 10^{th} year. The most cost effective design option turns to be Option 2 which is consistent with the design decision based on efficiency data in the first year. Option 2 remains to the most cost effective when a cost impact of the 24 hour advance notice is considered.

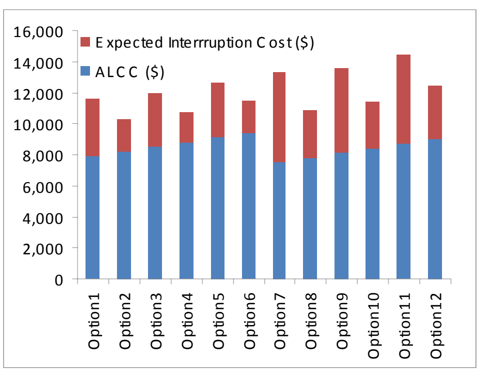

Figure 8 The C_{total} of different design options – in the 10^{th} year

Energy smart board

In all previous estimates of interruption cost, all electricity consumers in the off-grid solar house are assumed to require the same level of electricity quality, which is not true in reality. For instance the hot water temperature will not be influenced much even if the DHW system suffers from an (small) electricity shortage. However occupants may suffer critical data loss if their home computers encounter a power shortage. Moreover, subjectively occupants have different preferences to individual house functions. Therefore the consequence of a power shortage for an individual electricity consumer may be varying for different occupants. Figure 9 shows the varying quality requirement by different house electricity consumers.

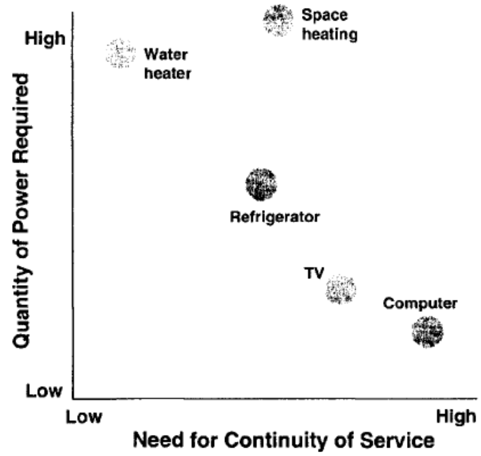

Figure 9 Electrical appliances vary in the amount of electricity they demand, and the level of continuity of service they require to perform their function adequately (Willis, Welch et al. 2001)

An elicitation based on rational decision-making theory will be conducted to conclude the most appropriate cost function regarding the power interruption for the specific residents. An energy smart board could be implemented to distribute electricity (in times of shortage) to different house electricity consumers according to their preset priority rank. The prioritized energy distribution network will help maximize occupants' satisfaction level with a fixed amount of available electricity.

CONCLUSIONS

This paper presents a value-based approach to designing a cost effective PV power system for off-grid residences. The design objective is to find the balancing point between the acceptable power reliability level and affordable capital cost. The quality of a value-based sizing of systems in off-grid solar residences depends on how accurately the power quality service could be represented. An appropriate power service value function should accurately reflect occupants' value of service quality, especially in off-grid residence situation. The ideal way of pricing power service will be through a survey of the future occupants.

This paper introduces the value-based approach and illustrates a novel sizing practice applied to the PV system in an existing off-grid solar house. The final design decision was reached using a generic cost function of power interruption for customers in residential class that is concluded in power industry practice. A PV power system comprised of 7 batteries, 27 PV modules on the roof, and 12 modules mounted to the southern wall is the most cost effective design option for the studied off-grid solar house.

It should be noted that only the expected mean values of the uncertain outcomes have been used in this stuidy. Future work will include the uncertainty range of the outcomes and provide a sizing strategy that not only optimizes performance but balances it with acceptable risks stemming from systemic parameter uncertainties.

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