PARTIAL SHADOW IMPACT ON LOSS-OF-LOAD PROBABILITY OF PHOTOVOLTAIC POWER SYSTEM

M. H. El-Maghraby M. A. El-Sayes.

All in the Electrical Power and Machines Department,
Faculty of Engineering, El-Mansoura Univ.

1 . ABSTRACT

This paper studies the shadow impact on the loss-of-load probability, the most significant reliability indices, of the photovoltaic power system (PVPS). A suggested index is derived to reflect the shadow impact, denoted by the "Reductive Index". Novel mathematical model is excecuted to estimate the reduction in the daily output energy of PVPS according to this index and the period of shadow continuity. This reduction results in an equivalent reduction in the solar cells array size. So, the maximum permissible reduction in the solar cells array size can be determined on having an arbitrary loss-of-load probability level with its change with the installed solar cells array size .

2 . INTRODUCTION

In spite of widespread installation of the photovoltaic power system (PVPS) with different scales throughout the world and again despite of the significant impact of shadow, few articles have been published in this topic. The use of non-regular interconnection scheme of solar cells to electrically distribute the impact of the shadow is discussed in reference [1]. This method is impractical and adds a new complexity to the system operation.

Shadow influence on the system loss-of-load probability (LOLP), the most significant reliability indices, had't be assessed and discussed. This issue is of great importance since one of the essential requirements of such renewable system is to be competitive with conventional ones.

In many applications of small and medium scale of PVPS envisaged for SCA, the array will be located in a restricted area, such as the roofs of the buildings at urban or agricultural regions. So, the elimination of bordering wires, poles or trees is neither practical nor desirable. The shadow impact is investigated experimentally in real circumstances with various simulated configurations of shadow. Using a small but real solar cells array installed at the site considered, the experimental work is carried out.

A proposed index is derived here named as "Reductive Index" by means of which the shadow effect of any configuration is represented and quantitatively analyzed.

A suggested mathematical model is developed to estimate directly the reduction in the daily output energy with different shadow configurations. On other hand, this reduction can be represented by an equivalent reduction in the SCA size which strongly influences the loss-of-load probability of the PVPS. Therefore the LOLP is assigned for several conditions.

The problem can easily be generalized for any other site.

3 . EXPERIMENTALLY - BASED ESTIMATION OF THE SHADOW EFFECT.

3 . 1. Experimental Work

3.1.1. Experimental set - up.

The experimental work is carried out for a real 100 - W_p solar cells array (SCA) of a single - crystal silicon type installed at the Direct Conversion of Solar Energy (DCOSE) Laboratory, Electrical Power and Machines Department, Faculty of Engineering, El-Mansoura University, El-Mansoura, EGYPT. This array contains ten modules, 36 series connected solar cells of each. The I-V measurements of its performance are carried out with different solar radiation levels. They constitute a profile similar to that remarked for most year days of El - Mansoura site taken for study.

3.1.2. Shadow Simulation.

The shadow is simulated by the use of many special configuration strips. They are shaped to represent the shadow with various features as displayed in Fig. 1. Thus, the effect of its shape, size and location on the performance of SCA is investigated. It is meant by the location of the shadow that its position on the front surface of the panel examined throughout the experimental work. In addition, the global insolation received by a horizontal surface directed toward the equator at the site considered is listed in Table 1.

Table 1 : The Global Insolation Received by a Horizontal Surface Facing South in k Wh/m^2 .

Period	SR^{+} to 81/2	81/2 to 9	9 to 91/2	91/2 to 10	10 to 101/2
Insolation	0.0192	0.1654	0.2198	0.2683	0.3124
Period	101/2 to 11	11 to 111/2	111/2 to 12	12 to 121/2	
Insolation	0.3461	0.3803	0.4100	0.4189	
Period	121/2 to 1	1 to 11/2	11/2 to 2	2 to 21/2	21/2 to 3
Insolation	0.4192	0.4147	0.3992	0.3791	0.3500
Period	3 to 31/2	31/2 to 4	4 to 41/2	41/2 to SS^{++}	
Insolation	0.3138	0.2680	0.2226	0.0982	

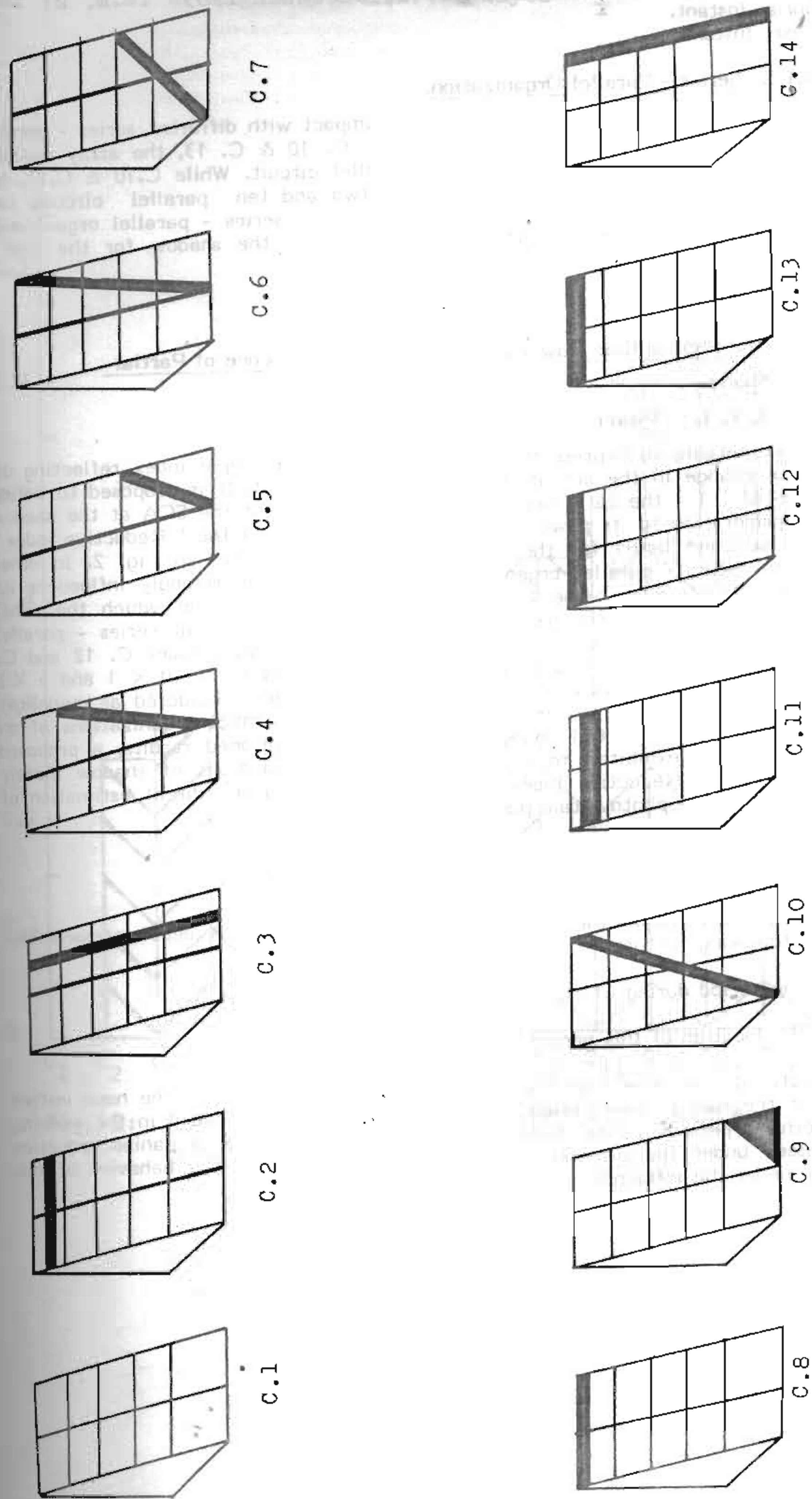

Fig. 1: SIMULATION OF PARTIAL SHADOW CONFIGURATIONS

\+ Sunrise Instant.
++ Sunset Instant.

3.1.3. Series - Parallel Organization.

It is intended, here, to find the shadow impact with different series - parallel organization. For all the case studies, except C. 10 & C. 13, the array modules are connected in series constituting one parallel circuit. While C.10 & C.13, the whole modules are arranged in the form of two and ten parallel circuits respectively. This will help us to determine the worst series - parallel organization at which its performance is pronouncly affected by the shadow for the site considered .

3.2. The Photovoltaic Power and Energy in the Presence of Partial Shadow .

3. 2. 1. Power

It is suitable to express the shadow impact by a simple index reflecting directly the change in the output PV power at any instant. It is proposed to define the value of (1 - the ratio between the output power of the SCA at the shadow under consideration to its power with full illumination) as the " Reductive Index " It is derived and listed for the configurations demonstrated in Fig. 2. In other hand , the series - parallel organization of the SCA used strongly influences its operating characteristics. The C. 6 & C. 10 are the cases at which the panel is exposed to the same shadow configuration but with different series - parallel organizations of 10 X 1 and 1 X 10 respectively. Similarly, cases C. 12 and C. 13 have other shadow configurations but with organizations of 10 X 1 and 5 X 2 respectively. The " Reductive Index " of these cases are considered as guidelines for the designers to use the most adequate series - parallel organizations of an array subjected to a partial shadow. From the prementioned results, a proposed method has been exhibited to deal with other configurations of shadow merely by knowing the " Reductive Index " . So , this enables the direct estimation of the reduction in the photovoltaic power .

3. 2. 2. Energy .

The reduction in the daily output energy of the SCA depends essentially upon the following factors :

(1) The period during which the shadow continues in its effect .

(2) The location of this period among the daytime hours .

To estimate the effect of the first factor , we consider that the noon instant locates at the half of this period. That is , it is equally extended in the morning and afternoon periods . The daily output energy and the accompanied reduction are assessed under the previous conditions . Fig. 3 depicts the behavior of this reduction under the influence

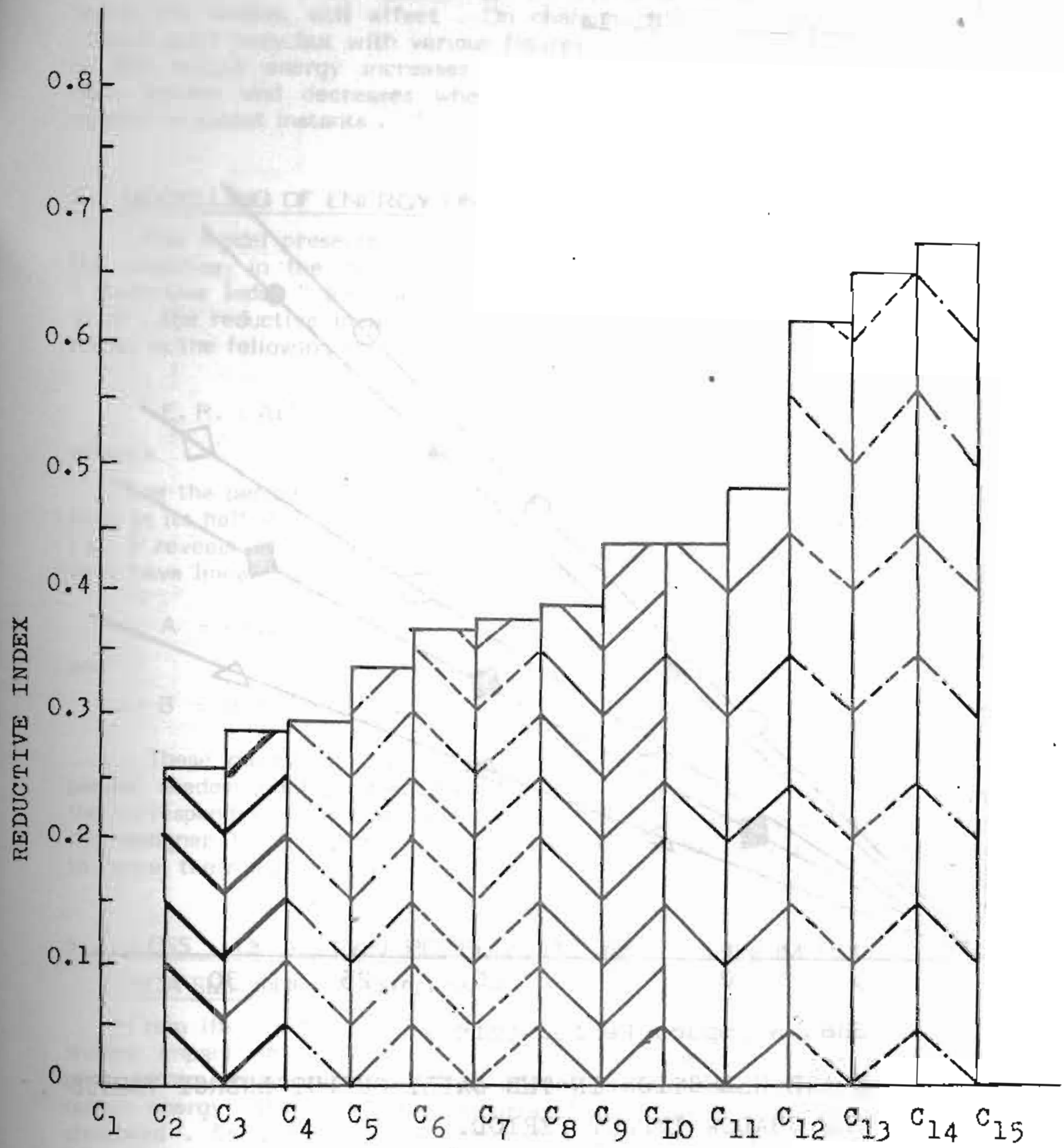

Fig. 2: REDUCTIVE INDEX FOR THE SIMULATED SHADOW CONFIGURATIONS.

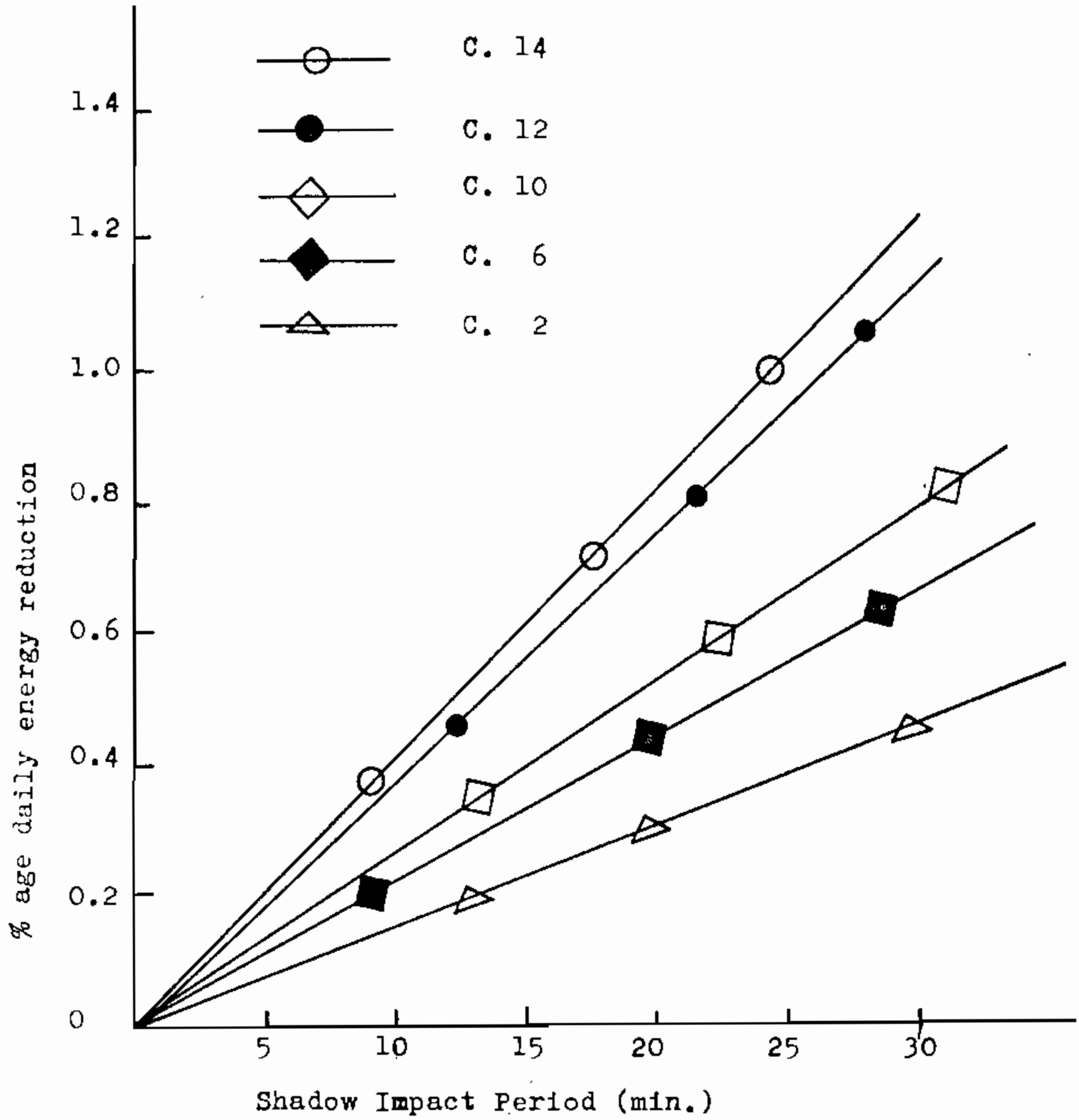

Fig. 3: % AGE REDUCTION IN THE DAILY OUTPUT ENERGY VERSUS THE SHADOW IMPACT PERIOD.

of the shadow parameters. Moreover , Fig. 4 reveals the impact of a purtial shadow on the output energy occurred at different instants throughoot the daytime hours . In this figure , half an hour is taken as a unit of time during which the shadow will affect . On changing this time , the resultant conclusion will't vary but with various figures . It is noticeable that the reduction in the output energy increases when the shadow position approaches the noon instant and decreases when the position travels in the direction of sunrise or sunset instants .

4 . MODELLING OF ENERGY UNDER SHADOW IMPACT .

This model presents a simple and accurate method to calculate dirctly the reduction in the daily output energy (E. R.). Dependent upun the " Reductive Index " associated with the shadow configuration under consideration , the reductive in the daily output energy may be expressed by a novel model in the following way :

$$E.\,R. = At^2 + Bt \qquad (1)$$

where :

t is the period during which the shadow is continued and the noon instant sites in its half A & B are coefficients dependent upon the " Reductive Index " Fig. 5 reveals the behavior of A and B versus the Reductive Index (R.I.) They have linear relations with the following forms :

$$A = -\,0.4872 \times R.\,I. \qquad (2)$$

and

$$B = 16.8666 \times R.\,I. \qquad (3)$$

These models facilitate the estimation of these coefficients for any partial shadow configuration for the geographical site under study . So , the corresponding reduction in energy will then be assessed. This will enable the designer to forecast the additional SCA area used as a compensator to cancel the shadow impact .

5 . LOSS - OF - LOAD PROBABILITY AND MAXIMUM REDUCTION IN SCA SIZE DUE TO SHADOW .

From the practical point of view , it is important to evaluate a partial shadow impact on the LOSS - OF - LOAD probability (LOLP) of the photovoltaic power system . This impact is found by estimating the daily output energy with its solar cells array being fully illuminated and partially shadowed . So , the resultant reduction and the corresponding change in SCA size is thus calculated . The LOLP is then estimated for these two cases and plotted against the respective sizes . Fig . 6 demonstrates this behavior for a daily load demand of 300 wh . As a maximum permissible limit for LOLP , a ratio of 1 % is taken as an appropriate ratio . It is line results in two regions of accepted and rejected ones .

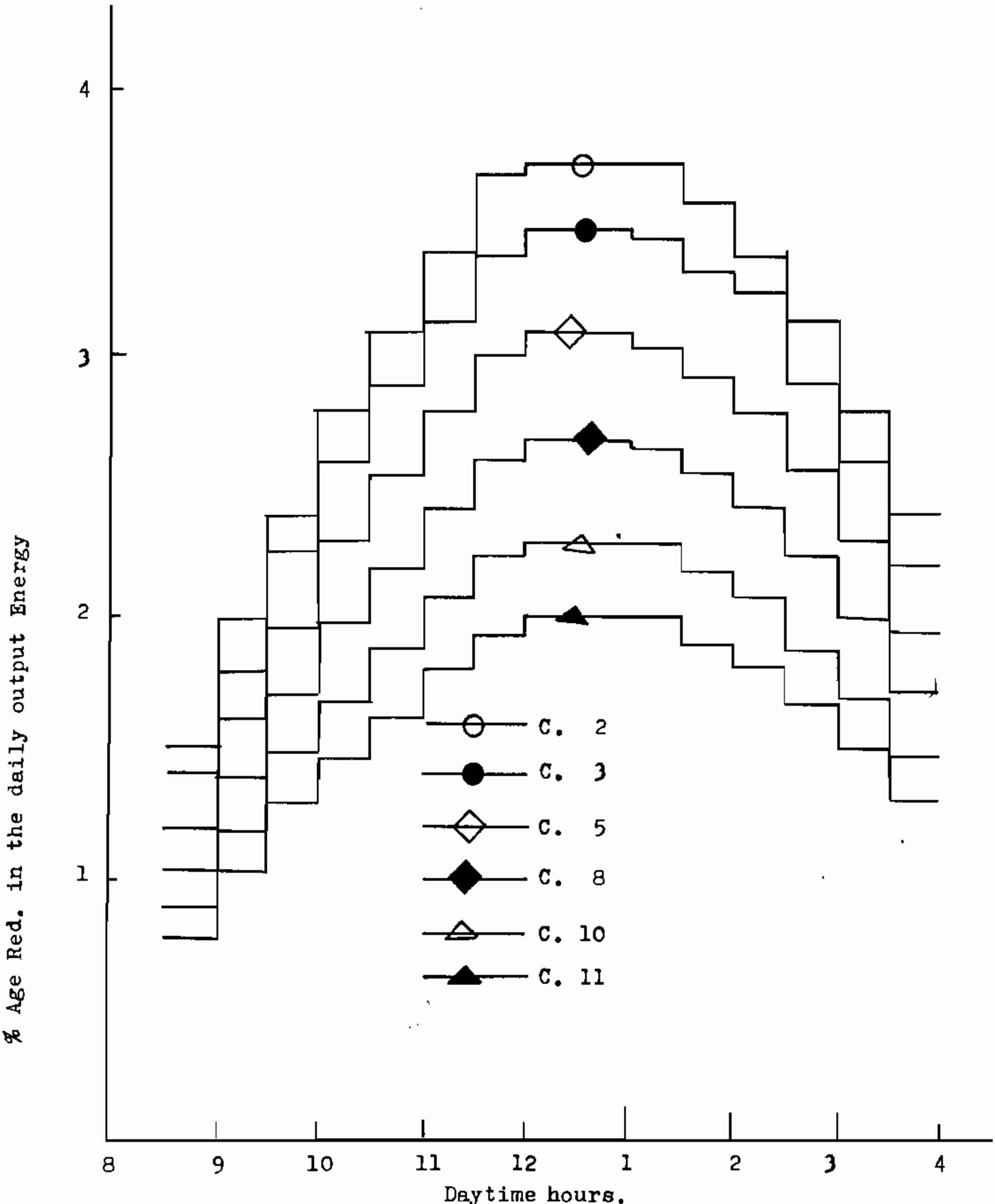

Fig. 4: THE VARIATION IN THE % AGE REDUCTION IN THE DAILY OUTPUT ENERGY DUE TO THE LOCATION OF THE SHADOW AMONG THE DAYTIME HOURS.

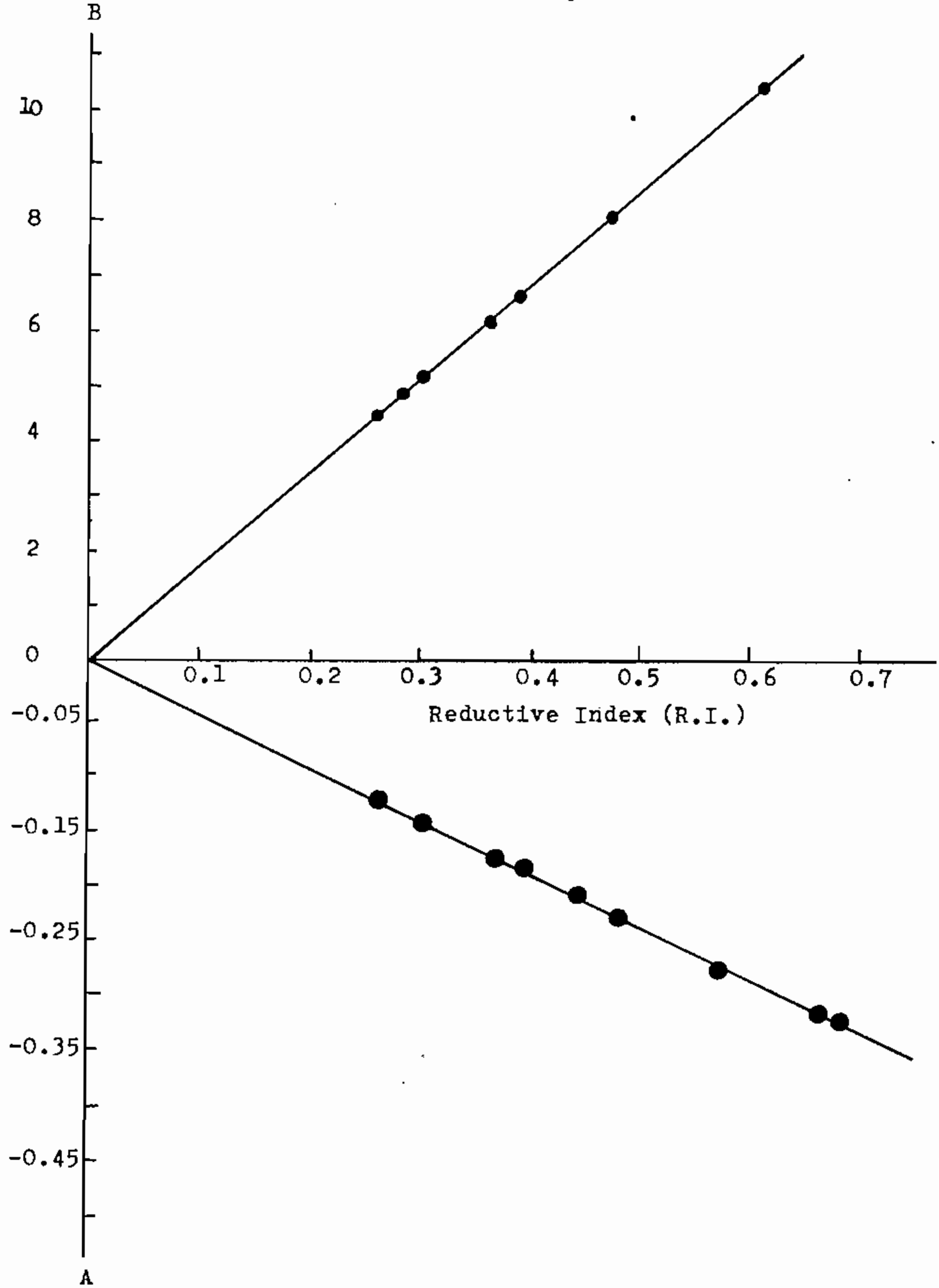

Fig. 5: THE COEFFICIENTS A & B VERSUS THE REDUCTIVE INDEX (R.I.).

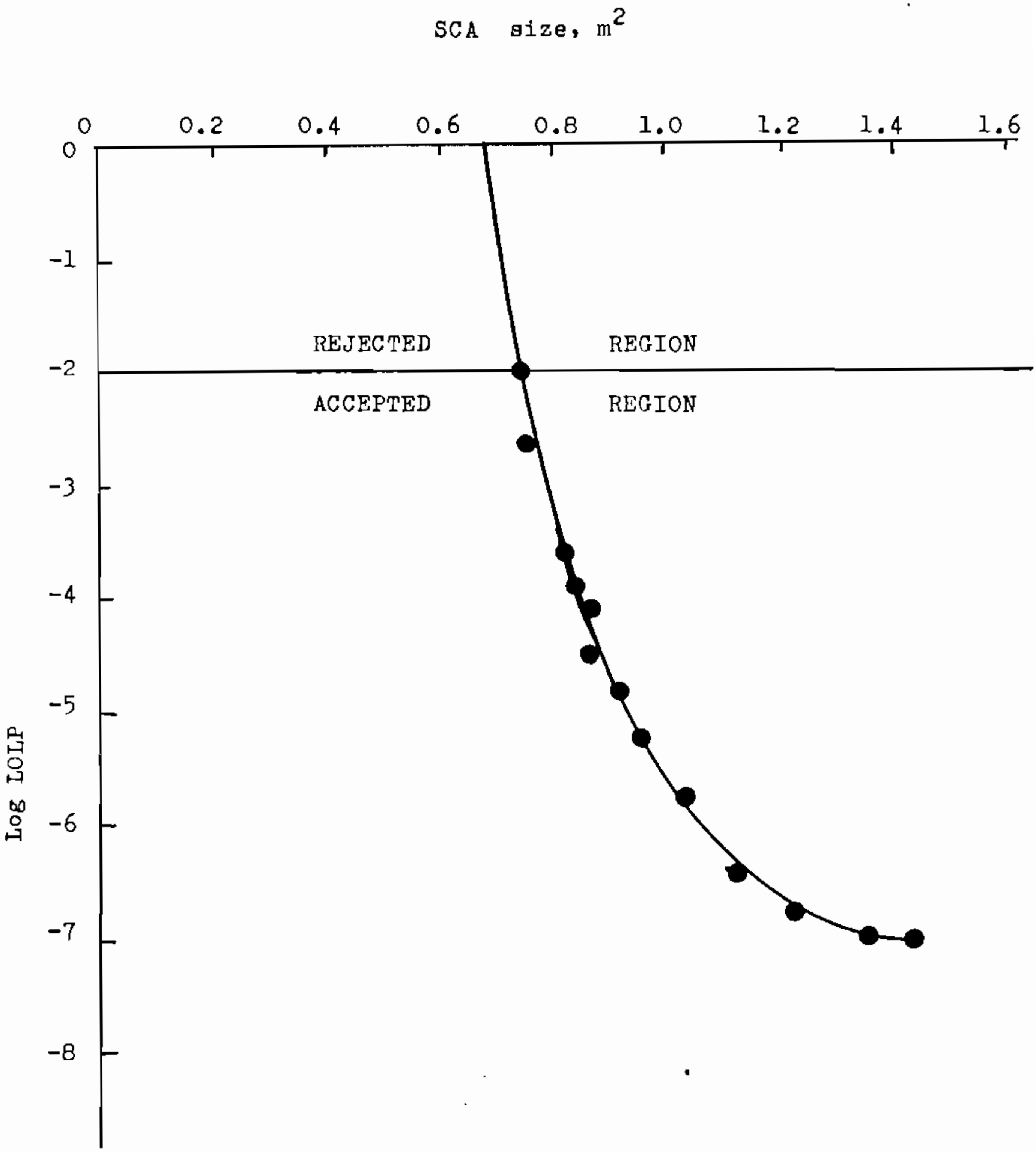

Fig. 6: THE RELATION BETWEEN THE INSTALLED SCA SIZE AND THE LOG LOLP FOR CERTAIN DAILY LOAD DEMAND. (A BATTERY STORAGE OF A CAPACITY OF 1440 WH IS USED WITH THE SCA TO SUPPLY THE LOAD).

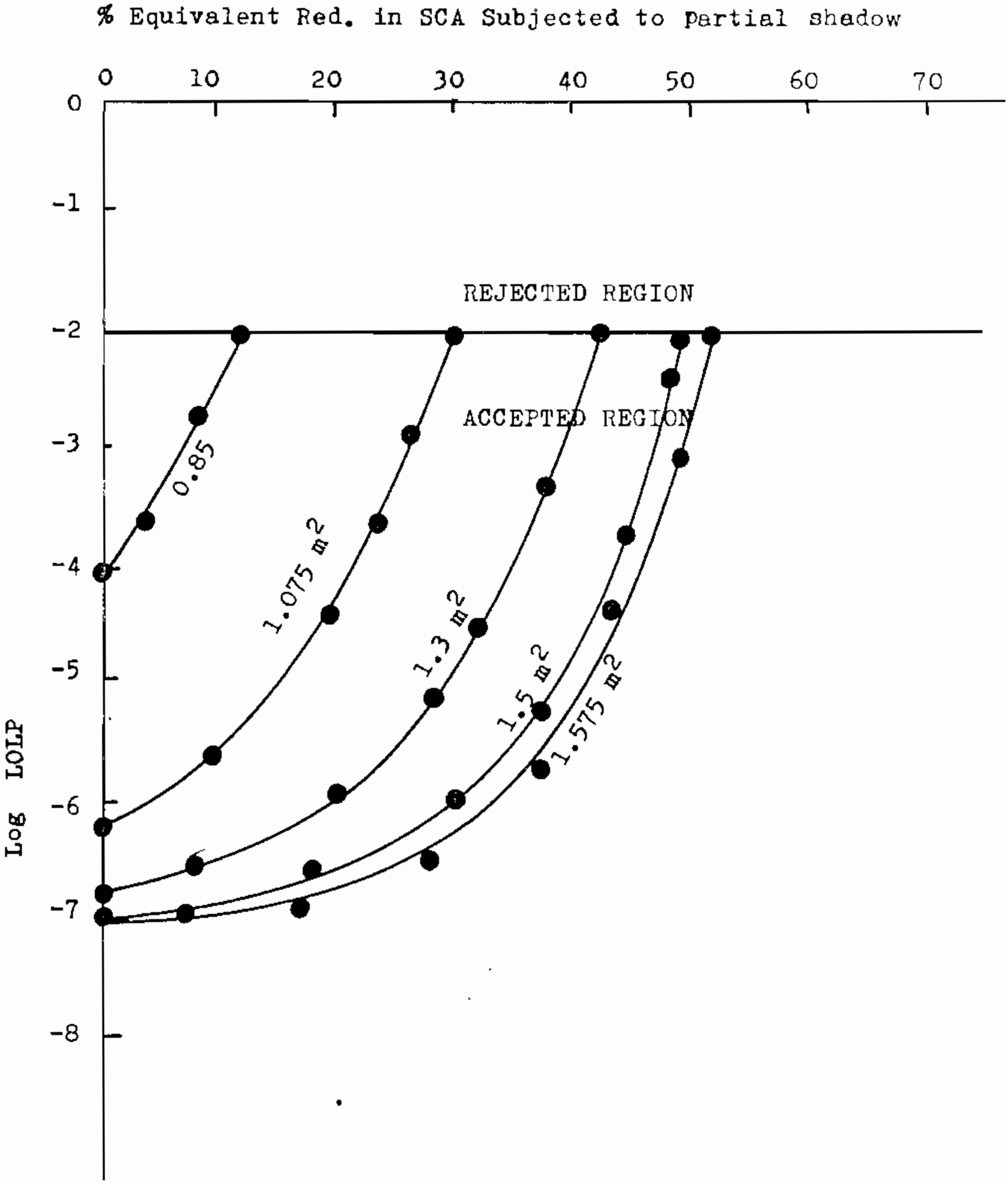

Fig. 7 : PERCENTAGE EQUIVALENT REDUCTION IN THE SCA SIZE SUBJECTED PARTIAL SHADOW AGAINST LOLP.

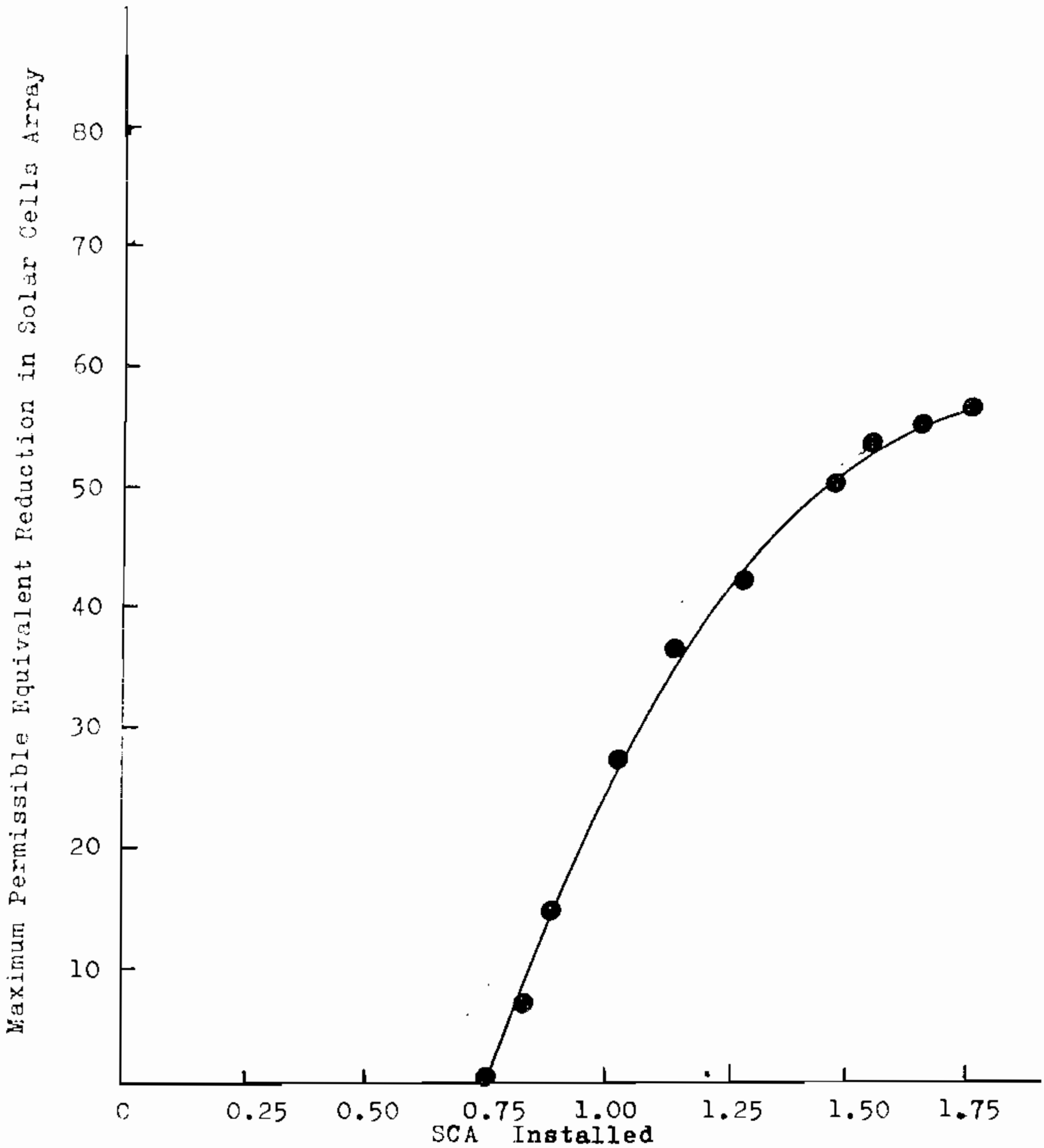

Fig. 8: THE MAXIMUM PERMISSIBLE EQUIVALENT REDUCTION IN SCA SIZE WITH LOLP OF 1 % .

So , any negative change in SCA size results in a respective increase in LOLP . This change has a maximum size given by the following relation referred to the installed SCA size :

$$MPR \% = \frac{SCA_i - SCA_m}{SCA_i} \times 100 \qquad (4)$$

where

SCA_i is the installed SCA size .

SCA_m is the SCA size corresponding the maximum permissible LOLP (0.01) .

Fig. 7 shows the variation of the maximum permissible reduction (MPP) in SCA size for different installed ones with a maximum permissible LOLP ratio of 0.01 . From this figure . the maximum equivalent reductions in SCA size have ratios of 12 , 30 , 42.5 , 50 and 52 % with installed sizes of 0.85 , 1.075 , 1.3 , 1.5 and 1.575 m^2 respectively . The intersections of these curves with the constant LOLP - line yield the corresponding maximum permissible equivalent reductions in the array size . So , these maximum reductions are plotted against its corresponding installed SCA size in Fig. 8 . Its intersection with the abscissa gives the minimum size required to have a LOLP of 0.01 [2] .

6 . CONCLUSIONS

Due to the expected widespread applications of PVPS in remote , rural and urban regions , shadow problem will arise and need stependous attention for solution . The following significant conclusions , regarding this issue , can be drawn out of this paper :

a - The partial shadow impact is essentially dependent upon the following factors :

(1) The shape , size and location of the shadow with respect to the SCA surface , and the period of its continuity .

(2) The location of this period among the daytime hours .

(3) The solar cells array series - parallel organization .

b - The proposed " Reductive Index " plays an important role in evaluating and estimating the shadow impact . It is firstly derived to assess the reduction in the output power and daily energy . The related equivalent reduction in the SCA size can then be computed . So it enables the PVPS designers to determine the additional SCA size required to cancel or lessen the shadow impact .

c - Novel mathematical model is suggested to give directly the reduction in the daily output energy under the effect of the site and most common shadowconfigurations . So , grading the shadow configurations according to their impact can be assigned .

d - The LOSS - OF - LOAD probability of the PVPS is evaluted and quantitatively analyzed under the shadow impact . The maximum permissible equivalent reduction in the SCA size is thus estimated on having an arbitrary LOLP level and its change with the installed SCA size .

7 . REFERENCES

1 JAMES FELDMAN , S. SINGER and A. BRAUNSTEIN , " Solar cell interconnections and the Shadow Problem " , Solar Energy , Vol . 36 , PP 419 - 428 , 1981 .

2 H. L. Macomber , J. B. Ruzek , F. A. Castello and Staff of Bird Engineering Research Associates , " Photovoltaic Stand - Alone Power System " , Handbook Prepared for NASA , Le RC , Contract Den 3 - 195 , August 1981 .