Sizing Method of an Autonomous Photovoltaic Generator

M.Bencherif, A.Chermitti, A.Chikhaoui, and B. Benyoucef

***Abstract*—For a given site and known weather parameters, the sizing of an autonomous photovoltaic generator consists to seek the power which it should develop to satisfy the power consumption imposed by the load. The number of the PV modules and the capacity of the accumulators of storage to be installed are optimized so as to have the most economic generator with acquisition and the maintenance and which is capable to fill up the conditions of the contract. We expose into this paper, a model of energy supplied by the photovoltaic generator followed by the model of the provided average energy and a simplified method of sizing the PV system by introduction a production factor in order to determine the optimal surface of the PV collector to install, which answers the constraints imposed by the consumption profile of the load for a residential photovoltaic installation completely autonomous, while minimizing the cost. Finally for the numerical validation of the suggested method, we chose the data of the Tlemcen site.**

***Index Terms*—Modelling, solar irradiation, PV generators, output, sizing.**

I. INTRODUCTION

Renewable energies, of natural origin, are inexhaustible and do not harm the environment. They are in general transformed in suitable forms then standardized to adapt them to the conditions of use. Among these transformations, the photovoltaic conversion, intended mainly for the electricity supply of industrial equipment and domestic apparatuses, is very widespread. It is implemented in autonomous photovoltaic projects at a weak consumption and in the achievements of electro-solar power stations adapted to the isolated sites or connected to the local electrical supply network.

II. THE POWER MODEL OF THE PHOTOVOLTAIC GENERATOR

A. Power Model provided by the PV Array

The photovoltaic modules are delivered with a peak value of power. This power represents the power delivered by the modules under the standard test conditions, i.e., with an illumination G0 of 1kW/m2 and the modules reference temperature Tr at 25°C, it is defined by:

$$Pc = \eta_r .S.Go \quad \text{(W)} \tag{1}$$

S is the active surface of the module and hr its nominal output.

A photovoltaic array is a group of elementary modules associated in series and in parallel; so that *Ns* the number of modules in series per branch and *Np* the number of parallel branch. The instantaneous power output *Ps* of the PV arrays is given by [1, 2, 3, 4,5]:

$$Ps = \eta_G GsSNop \tag{2}$$

Nop: the global number of modules forming the field

Dividing the parts of the equation (2) by the parts of the equation (1), we find the following relation:

$$Ps = \frac{\eta_G}{\eta r}\frac{GsNop}{G_O}Pc \tag{3}$$

The cells junction temperature affects the instantaneous efficiency η_G of photovoltaic arrays according to the following relation [3], [4], [5], [6], [7]:

$$\eta_G = \eta r(1 - \alpha(T_M - Tr)) \tag{4}$$

α is the thermal losses coefficient due to the variation in the modules temperature.

B. Model of the Average Power Delivered by the PV Array

The averages of the physical parameters η_G and Gs of the equation (4), they allow us to define the average power output of the PV arrays, which is given by:

$$\overline{Ps} = \frac{\overline{\eta}_G}{\eta r}\frac{\overline{G}sNop}{G_o}Pc \tag{5}$$

$\overline{G}s$ is the average solar radiation received by the PV arrays and $\overline{\eta}_G$ is the average efficiency. $\overline{\eta}_G$ depends of the average modules temperature TM. The temperature TM is related to the monthly ambient temperature Ta by the Evans relation given by the following expression [6], [8], [9]:

$$TM - Ta = (219 + 832\overline{K})\frac{NOCT - 20}{800} \tag{6}$$

NOCT: nominal operating cell temperature.

The equation (6) is valid only if the tilt of the photovoltaic arrays is equal to the latitude less the solar declination; but for others inclinations the part of right-hand of the equation (6) has to be multiplied by a correction factor, defined by the following equation [6, 8, 9]:

$$Fc = 1 - 1.17.10^{-4}\left(\phi - (\delta + \beta)\right)^2 \tag{7}$$

ϕ : Site Latitude

δ : Solar declension

β: Real Angle Inclination PV surface

ϕ,β, δ are expressed in degrees

For the estimate of the average temperature of the modules, we thought to introduce the monthly average value of the

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solar declension into Eq (7); we get the Eq (8) of the temperature TM and the Eq (9) for the average efficiency:

$$TM - Ta = Fc(219 + 832\overline{K})\frac{NOCT - 20}{800} \tag{8}$$

$$\overline{\eta}_G = \eta r\left(1-\alpha\left(Ta - Tr + Fc(219+832\overline{K})\frac{NOCT-20}{800}\right)\right) \tag{9}$$

$\overline{K}$ is the monthly average clearness index, calculated by the following relation [6, 9, 10, 11, 12]:

$$\overline{K} = \frac{\overline{GH}}{\overline{GHo}} \tag{10}$$

$\overline{GH}$ is the monthly average of the daily solar radiation on a horizontal plane and $\overline{GHo}$ is the monthly average of the daily solar radiation outside the atmosphere on the same horizontal plane.

We substitute the ratio $\frac{\overline{\eta}_G}{\eta r}$ given in the equation (9) in the equation (5), we obtains:

$$\overline{P}s = (1-\alpha(F_C((219+832\overline{K})A + T_a - T_r))\frac{\overline{G}s}{Go}PcNop \tag{11}$$

With:

$$A = \frac{Noct - 20}{800}$$

Furthermore, a set of various losses associated with various considerations can be represented by a single loss coefficient η_p, the final relation of the output power is:

$$\overline{P}s = (1-\eta_p)(1-\alpha(F_C((219+832\overline{K})A + T_a - T_r))\frac{\overline{G}s}{Go}PcNop \tag{12}$$

With: $\eta_p = k_1 + k_2$

k1 : Power transport losses.

k2 : The losses coefficient due to:

The dispersion of the modules characteristics

Weather uncertainty

Output loss due to dust and ageing, shade etc....

From the equation (12), we deduce the average power and the average energy delivered by a module, which are given by the following equation:

$$\overline{P}s_M = K\frac{\overline{G}s}{Go}Pc \text{ And } \overline{E}s_M = K\frac{\overline{G}s}{Go}Pc \tag{13}$$

$$K = (1-\eta_p)(1-\alpha\left(Fc\left((219+832\overline{K})\frac{Noct-20}{800}\right)+T_a-T_r\right)$$

The formula of the average power and the average energy supplied by the photovoltaic arrays are reduced to the following relations:

$$\overline{P}s = \overline{P}s_M Nop \text{ And } \overline{E}s = \overline{E}s_M Nop \tag{14}$$

$\overline{E}s$ and $\overline{E}s_M$ present respectively the average energy provided by the photovoltaic arrays and a module.

The units of the $\overline{G}s$ sunning are respectively in Wh/m^2 or KWh/m^2 for the energy and W/m^2 or KW/m^2 for the power.

C. Power Delivered at the Outlet of the Regulator

The average power and energy delivered at the outlet of the regulator are given by:

$$\overline{P}sreg = \overline{P}s.\eta reg \text{ and } \overline{E}sreg = \overline{E}s.\eta reg \tag{15}$$

ηreg : Efficiency of the regulator.
ηreg

III. Calculation of the Solar Radiation on a Tilted Surface

A. Calculation of the Sunniness on a Tilted Surface

The solar radiation on a tilted surface is obtained by using the simple isotropic model of Liu & Jordan. It is not the most precise model but this is amply sufficient at the pre-feasibility study. Global irradiation Gs on a tilted plane surface is made up of three sorts of radiations [6,10, 11, 12]:

$$Gs = RDir + Rdif + Rref$$

With *RDir, Rdif* and *Rref* are the solar radiation due respectively to the radiations, beam, diffuse and reflected by the ground. The three components of the total radiation are given by:

$$RDir = RD.Rb \tag{17}$$

$$Rdif = Rd\left(\frac{1+\cos\beta}{2}\right) \text{ and } Rref = \rho Gh\left(\frac{1-\cos\beta}{2}\right) \tag{18}$$

where *RD, Rd and Gh* present the solar radiation due to the radiations, beam, diffuse and total on a horizontal plane and ρ presents the diffuse reflectance of the ground (also called ground albedo).

Rb presents the geometric factor, which is defined by the ratio of the beam solar radiation on the tilted surface to that the horizontal surface at any time, can be calculated exactly by appropriate use of the following equation [2, 3, 6]:

$$Rb = \frac{\cos\theta}{\cos\theta z} \tag{19}$$

θ is the incidence angle of the beam solar radiation on the tilted surface and θz the solar zenith angle [2, 3]:

$$\cos\theta = \cos\beta\sinh - \sin\beta\cosh\cos(\alpha - a) \tag{20}$$

Or by the following equation [2] , [3]:

$$\cos\theta = \cos(\varphi-\beta)\cos(\delta)\cos(\omega) - \sin(\varphi-\beta)\sin(\delta) \tag{21}$$

where φ is the site latitude and β, α, are the inclination angle and the azimuth angle of the collector oriented in full south towards the equator (northern hemisphere). The solar angle, h and a are respectively the altitude angle and the azimuth angle, which are defined by the following equations [1, 2, 3]:

$$\sinh = \cos\theta z = \cos\delta\cos\varphi\cos\omega + \sin\delta\sin\varphi \tag{22}$$

$$\sin a = \frac{\sin\omega\cos\delta}{\cosh} \tag{23}$$

ω is the hour angle defined by[1,3]:

$$\omega = 15(TSV - 12) \tag{24}$$

$$TSV = TL - GMT + \left(\frac{Et + 4\lambda}{60}\right) \tag{25}$$

$$Et = 9.87\sin 2N - 7.35\cos N - 1.5\sin N \tag{26}$$

$$N = \frac{360}{365}(n - 81) \tag{27}$$

GMT: time shift in relation to the Greenwich meridian
TSV: real solar time
TL : legal time (the time given by the watches)
Et : the correction equation of time
λ : the site Longitude
δ is the solar declination given at the equation [1,2,3, 10]:

$$\delta = 23.45 \sin\left(\frac{360\,(n+284)}{365}\right) \text{ Degrees} \tag{28}$$

Consequently the total radiation received on tilted surface is calculated by the following equation [2, 3, 6, 12]:

$$Gs = RD.Rb + Rd\left(\frac{1+\cos\beta}{2}\right) + \rho G_H\left(\frac{1-\cos(\beta)}{2}\right) \tag{29}$$

IV. SIZING METHOD

The sunstroke duration is the moment the sun is observable in the sky, corresponds to the number of hours of the day, between the sunrise and the sunset. Its measurement is made by means of the Campbell-Stokes heliograph, Thus, only the moments when the sun is visible are recorded; we speak then of the real sunstroke duration or effective sunstroke duration. The periods when the sun is masked by the clouds are not counted.

Sizing method of the photovoltaic arrays

For the sizing of photovoltaic field, we propose a simplified method in order to determine the optimal number of modules constituting the photovoltaic arrays allowing the cover of the energy needs for the load. For that we define a factor called production factor *fp in* order to obtain the optimal surface of the photovoltaic field which fills up the load conditions. To determine the production factor, we distributed the daily energy consumed by the load in number of hours of the sunstroke duration and out of the sunstroke duration.

A. The figure

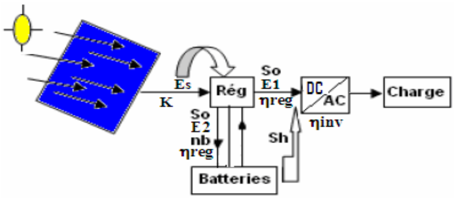

Fig. 1. General diagram of the system

B. Estimate of the Average Horary Energy at the Inverter Entry

We suppose a service map requiring an inverter (figure 1) and we consider the average horary of energy delivered at the entry of the inverter:

$$Ehinv = \frac{Ech}{Hj\eta inv} \tag{30}$$

Hj: number of hours of the day (24 hours).
ηinv: Efficiency of the inverter.
Ech : Daily energy consumed by the load

The energy supplied to the inverter (DC/AC), during the number of hours So of the sunstroke duration for a given site is estimated by the following relation:

$$\overline{E}^1 sreg = \eta reg.\overline{E}_1 \quad \text{and} \quad \overline{E}^1 sreg = Ehinv.So \tag{31}$$

C. Estimate of the Reload Power of the Batteries

The excess of the energy delivered by the PV arrays during the sunstroke duration reloads the park of storage**:**

$$\overline{E}_2 = \overline{E}s - \overline{E}_1 \tag{32}$$

The energy $\overline{E}st$ stored by the batteries for a null discharge during the number of hours of sunstroke So is given by
[6, 14]:

$$\overline{E}^2 sreg = \eta reg.\overline{E}_2 \tag{33}$$

$$\overline{E}st = \eta b \overline{E}^2 sreg \quad \text{So} \quad \overline{E}st = \eta reg.\eta b.\overline{E}_2 \tag{34}$$

ηb is the efficiency of the accumulator battery to the load, which depends on the state of load of the battery.

The delivered energy to the load profile during the number of hours outside the sunstroke duration Sh is given by the following relations:

$$E'st = Ehinv.Sh \qquad E'st = f.\overline{E}^2 sreg \tag{35}$$

$$E'st = \eta reg.f\eta b\overline{E}_2 \tag{36}$$

These assumptions give us the relation of $\overline{E}_2$.

$$\overline{E}_2 = \frac{Ehinv.Sh}{\eta reg.f.\eta b} \tag{37}$$

f indicates the fraction of the energy stored by the batteries park transferred to the load during the number of hours outside sunstroke duration *Sh,* which depends on the number Jaut of the autonomy days and the number Jr of the days necessary to completely reload the batteries park after Jaut days in autonomy. This is calculated by the following relation:

$$f = \frac{JrSh}{((Jaut+Jr)Hj - JrSo)} \quad \text{or} \quad f = \frac{JrSh}{(JautHj + JrSh)} \tag{38}$$

D. Definition of the Production Factor

The power production factor presents the ratio between the necessary energy, which must be provided by the PV arrays for the daily consumption plus a fraction to make up for losses energy exhausted during the days of bad weather, which are defined by:

$$fp = \frac{\overline{E}s}{Ech}\eta inv.\eta reg \tag{39}$$

From the relations (31), (37) and (39), we deduce the form of *fp*:

$$fp = \frac{1}{Hj}\left(So + \frac{Sh}{f\eta b}\right) \tag{40}$$

$$\text{or} \quad fp = \frac{So}{Hj} + \frac{Jaut}{Jr.nb.(1-f)} \tag{41}$$

The average energy supplied by the photovoltaic field is written:

$$\overline{E}s = NopK\frac{\overline{Gs}}{Go}Pc \quad \text{and} \quad \overline{E}s = fp\frac{Ech}{\eta reg.\eta inv} \tag{42}$$

From the Eq (38), we deduct the optimal number *Nop* of modules:

$$Nop = fp \frac{Ech.Go}{K.\overline{G}s.\eta reg.\eta inv.Pc} \tag{43}$$

E. Calculation of the Number of Modules in Series and Parallel Branches

In order to determine the number of modules series and the parallel number of branches of the photovoltaic arrays, we resort to the following equations:

$$\begin{cases} Usyst = NsUn \\ Isyst = IMNp \\ IM = \dfrac{P_M}{Un} \end{cases} \tag{44}$$

Usyst and Isyst are respectively the tension wished at the exit of the photovoltaic arrays, and the current which it produces and IM is the current generated by one module operating at its nominal voltage.

F. The Storage Park Sizing

The determination of the batteries is obtained by the taking into account of a given number of days of autonomy to be ensured during prolonged unproductive duration of the photovoltaic field (covered sky). This number of days varies according to the designers but also according to the applications and the geographical situation of the place (between 3 days and 3 weeks). During this duration the energy production is quasi null, the battery is alone to provide power to the inverter and load DC; it should not exceed the allowed discharge. The storage capacity can be appreciated by the following expression [6], [15], [16]:

$$C = \frac{\text{Jaut}.Ech}{n_b D} \quad \text{Or} \quad Cah = \frac{C}{U} \tag{45}$$

The number of batteries is calculated by [3]:

$$\text{Nbat} = \frac{C}{CnUn} \tag{46}$$

Nbat can be also calculated by the following relation, which is deduced of the previous assumptions:

$$Nbat = Ec \frac{Jrsh(1-f)}{f\eta bUnCnDHj} \tag{47}$$

The number of batteries connected in series is calculated by [3]:

$$\text{N}_{\text{Sbat}} = \frac{Ubus}{Un} \tag{48}$$

The number of parallel branches of batteries is given by:

$$\text{N}_{\text{Pbat}} = \frac{Nbat}{N_{Sbat}} \tag{49}$$

Cah: Storage capacity in ampere hour (Ah)
U: Tension of the batteries (V).
C: Storage capacity in (KWh),
Ech: Daily energy consumed by the load (kWh).
Jaut: days number of autonomy
D: Maximum depth of discharge
Un: Nominal voltage of a battery
Cn: rated capacity of a battery

G. Regulator

The regulator is an essential element for a photovoltaic installation having batteries; it is laid out between the photovoltaic field and the batteries. It ensures the load of batteries and stabilizes the tension of the system and maintains the load in a suitable way. It protects it from high voltage and under voltage and guarantees lifespan to the maximum.

Regulator characteristics

Nominal voltage: it must support the tension of open circuit of photovoltaic modules series-connected that is approximately twice its own nominal voltage.

$$Vn = Ns.Vco \tag{50}$$

Current of entry: It is the maximum current provided by the parallel branches of the photovoltaic field and that the regulator can control under a given tension. The current at the entry is calculated by:

$$\text{I}_E = 1.3.NpIcc \tag{51}$$

The output current: It is the maximum current, extracted by the apparatuses connected simultaneously and the charging current of batteries.

Icc: the short circuit of the pv arrays
Vco: Tension of the open circuit of the PV arrays

Regulator Choice

Three factors are significant in the choice of a regulator of load: it is about the tension of the system, the temperature of operation and the maximum current.

V. NUMERICAL VALIDATION

A. Meteorological and Radiometric Data

The selected site is that of the Tlemcen town, which is located at north-west of Algeria. These data radiometric and meteorological are given to the following table.

Latitude	Longitude	ground albedo
$34^{0}56^{'}$	$-1^{0}19$	0.2

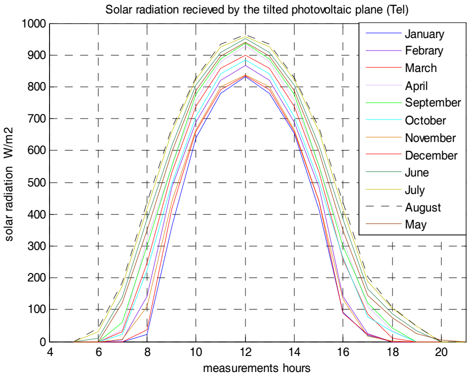

Fig. 2. The average horary of illumination received on the tilted panel surface (average day)

Starting From the meteorological hourly data of the total solar radiation and beam solar radiation collected on a three years (2005 to 2007 weather station of Zenâta Tlemcen) on a horizontal surface, we calculated the average horary of energy and the daily average energy of each month by the expressions (29) on the tilted surface (Tel) defined by Duffie and Beckmann with yearly angle of inclination equal to latitude of the place. These results are illustrated by fig. 2 and

3 describing the evolution of the radiation during hours of the day and the months of the year.

B. *Electric Characteristic of the Photovoltaic Module*

For sizing the generator necessary for the cover of the request for load we chose module PWX500 powerful and available to the URMER laboratory. The PWX500 is a module with silicon poly-crystalline Bi-glass adapted perfectly to the conditions climatic and environmental severe and this thanks to the quality of glass with which it is equipped on the front and back faces and which confers an electric insulation and increased reliability. The PWX500 is composed of 36 cells series-connected according to the configuration of four garlands of 9 solar cells. Its electric dimensions and its characteristics, under the standard conditions, are indicated on the notes and the maker badges:

1) *Electrical module characteristics*

Icc (A)	Vco (V)	Im (A)	Vm (V)	Un (V)	Pc (W)	ηr%
3.45	21.7	3.2	17.2	12	55	11. 42

2) *Temperature coefficients*

β1 mA/^{0}C	β mV/^{0}C	βp% /^{0}C	α%/^{0}C	NOCT
0.95	-79	0.43	0.40	45 ^{0}C

3) *Size of the module*

Length (mm)	Width (mm)	Thickness (mm)
1042	462	39

C. *Tables of the Results*

In table I, we recorded the monthly averages of the ambient temperature and the clearness index; table II groups the daily average energy collected on the tilted PV arrays of each month, the average temperature of the modules and the variation of their efficiency at this temperature. While the table III groups the monthly average of the day and the monthly average of the number hours of sunstroke.

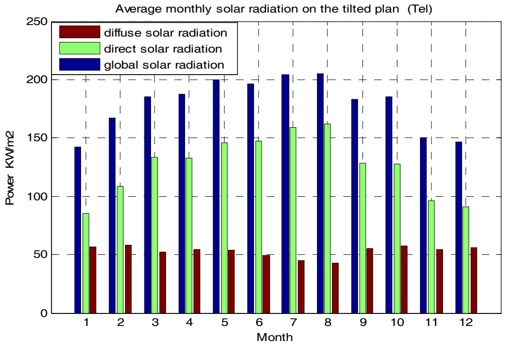

Fig. 3. The monthly average of total illumination on the tilted panel surface (average moth)

TABLE I

Month	average Ta ^{0}C	Monthly average $\overline{K}$
Jan	16.40	0.523
Feb	17.80	0.584
March	18.97	0.600
April	19.19	0.612
May	21.65	0.620
June	24.75	0.652
July	27.11	0.660
August	27.35	0.680
sept	24.90	0.697
Oct	21.56	0.620
Nov	18.33	0.560
Dec	17.20	0.546

TABLE II

Month	$\overline{Gs}$ (KWh/m^2/j)	T$_M$ (^{o}C)	$\overline{\eta}_G$ (T) %
Jan	4.590	35.79	10.92
Feb	5.749	39.81	10.74
Mach	5.985	41.40	10.67
April	6.240	42.00	10.64
May	6.445	44.66	10.52
June	6.534	48.54	10.34
July	6.586	51.11	10.22
August	6.624	51.87	10.19
sept	6.109	49.86	10.28
Oct	5.974	44.52	10.53
Nov	5.019	39.73	10.74
Dec	4.718	38.23	10.81

TABLE III

Average duration of the day in hour	10.06
The number of hour of the average sunstroke duration So	7.15

D. *Calculation of the Number of Modules*

The data used are grouped in the table IV below, which are:

- The average of the daily illumination on a solar collector of the most unfavourable month (January)
- The loss factor 1- η_P
- The output of battery to the load ηb corresponds approximately to its depth of discharge D.
- Average duration out of sunstroke Sh = (H-So)
- The efficiency of the inverter DC / AC, ηinv
- 5 days of autonomy and the number of days of refill of batteries is estimated according to the site at 9.5 days.
- The selected lead battery: nominal voltage 12V and of capacity C 10 of 100A/h

TABLE IV

$\overline{G}s$	1-η_p	ηinv	ηb	ηreg	*Hj*	Sh	D	K
4590	85 %	95%	85%	95%	24	16.85	70%	0.812

The results of the number of photovoltaic modules necessary to the cover of the energy demand of the various AC loads and the reload of the batteries and the number of accumulators are given in table V:

TABLE V

Ech (KWh/day)	1.8	2.2	2.5	2.7	3.0	4.0
Modules number	17	21	24	26	29	38
fp Factor	1.74	1.74	1.74	1.74	1.74	1.74
f Factor	0.57	0.57	0.57	0.57	0.57	0.57
Batteries number	14	17	19	20	23	30
Capacity of batteries (kWh)	16	19.4	22	24	26.5	35

E. *The Modules and Batteries Connections*

According to the optimal number of modules calculated, which fill up the conditions of load, we chose two different tensions configurations of the system. This led us to the results given to the following tables:

F. *The Modules Connections*

Configuration 36 volts

Ech (KWh/day)	1.8	2.2	2.5	2.7	3.0	4.0
Number of parallel branches	6	7	8	9	10	13
Number of modules series	3	3	3	3	3	3

Configuration 48 volts

Ech (KWh/day)	1.8	2.2	2.5	2.7	3.0	4.0
Number of parallel branches	5	6	6	7	8	10
Number of modules series	4	4	4	4	4	4

G. Batteries Connections

Configuration 36 volts

Ech (KWh/day)	1.8	2.2	2.5	2.7	3.0	4.0
Number of parallel branches	5	6	7	7	8	10
Number of batteries series	3	3	3	3	3	3

Configuration 48 volts

Ech (KWh/day)	1.8	2.2	2.5	2.7	3.0	4.0
Number of parallel branches	4	4	5	5	6	8
Number of batteries series	4	4	4	4	4	4

The difference between the total cost of the photovoltaic installation and the cost of the other devices and other expenses is a linear function of the number of batteries and the modules, according to the results mentioned in the tables above of the two configurations of tension, this last depends also on the configuration of the tension chosen. We recapitulate according to the two tensions of the system the optimal number of modules and batteries at a minimal cost of the installation.

Photovoltaic modules

	36 volts					48 volts	
Ech (KWh/day)	1.8	2.2	2.7	3.0	4.0	2.5	2.7
Parallel branches	6	7	9	10	13	6	7
Batteries series	3	3	3	3	3	4	4

Batteries

	36 volts					48 volts	
Ech (KWh/day)	1.8	2.2	2.7	3.0	4.0	2.5	2.7
Parallel branches	5	6	7	8	10	6	7
Batteries series	3	3	3	3	3	4	4

VI. CONCLUSION

In this study, we presented a model of energy supplied by a photovoltaic generator followed by the model of the provided average energy, which allow us to calculate the number of modules necessary to the cover request for load. The average energy is function of the parameters characteristic of the state of the sky, which is defined by the monthly average value of the clearness index and the monthly average of the solar declination, which are connected to the average temperature values of the modules and the average ambient temperature of the month of the considered site using the relation given by Evans and we define a factor called production factor, which connect the average energy produced by photovoltaic field and the daily energy consumed by the load in order to obtain the optimal surface of the photovoltaic array, which fills up the load conditions for a residential photovoltaic installation completely autonomous. For the numerical application we chose the data of the site of Tlemcen by the introduction of various energies of consumption to two different tensions configurations of the system, the obtained results are gathered in the tables above.

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