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Contribution des mini-centrales électriques photovoltaïques raccordées au réseau électrique dans le développement des fermes agricoles et l'amélioration du réseau électrique de la région de Chlef

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Abstract

Generating electricity from renewable energies offers significant benefits for the environment and the sustainable development. Solar energy is tremendously more abundant than any other renewable energy source on the planet and locally available. Electrical energy transport from the production site to the customers is done through the grid system which contains transformers and power lines. Unfortunately, it generates large electrical losses due to the joule effect and knows several problems such as disturbances in distribution and sudden cuts especially during the summer period when there is a high demand on electricity. The objectives of this work are multiple and concern the self-powering of farms and the injection into the grid the surplus of the PV electricity produced by the solar photovoltaic system. Thus, the use of photovoltaic systems makes it possible to reduce the dependence of these farms on the electricity grid, which has experienced high demand and disturbances in distribution in recent years. The system used is a solar photovoltaic system connected to the low voltage electrical grid and does not use electrochemical storage. During the sunny periods, the farm is fed by the PV system and during the absence of the sun, the power is taken directly from the electricity grid. The present work provides a review of a sample of articles that have studied grid-connected PV systems supplying agricultural farms by electricity and assessed their energy performance. The case study was cattle farms in the Chlef district (North-West of Algeria). A typical farm was chosen for this region in order to establish load profile according to monthly electrical bills. The results showed that 60 % of its total electricity consumption was from PV energy. Furthermore, an economic and environmental analysis was performed in order to investigate the performance of the on-farm PV system introduction. A sensitivity analysis was realized by changing some economic parameters such as the PV electricity sellback price and the project lifetime. The study demonstrates the economic viability and the environmental sustainability of the proposed system. The generalization of the proposed systems to all the Algerian farms will play an important role in the national electricity generation and greenhouse gas mitigation.

Résumé

La production d'électricité à partir d'énergies renouvelables offre des avantages importants pour l'environnement et le développement durable. L'énergie solaire est énormément plus abondante que toute autre source d'énergie renouvelable sur la planète et localement disponible. Le transport d'énergie électrique du site de production aux clients se fait par le biais du réseau électrique de distribution qui contient des transformateurs et des lignes électriques. Malheureusement, il génère de grandes pertes électriques dues à l'effet de joule et connaît plusieurs problèmes tels que des perturbations dans la distribution et des coupures soudaines surtout pendant la période estivale où il y a une forte demande en électricité. Les objectifs de ce travail sont multiples et concernent l'auto-alimentation des fermes agricoles par l’électricité produite par le système solaire photovoltaïque et l'injection au réseau électrique son excédent. Ainsi, l'utilisation de systèmes photovoltaïques permet de réduire la dépendance de ces fermes au réseau électrique, qui a connu une forte demande et des perturbations dans la distribution au cours des dernières années. Le système utilisé est un système solaire photovoltaïque connecté au réseau électrique basse tension et n'utilise pas de stockage électrochimique. Pendant les périodes ensoleillées, la ferme est alimentée par le système photovoltaïque et, en cas d'absence de soleil, la puissance est prise directement à partir du réseau électrique. Le présent travail passe en revue un échantillon d'articles qui ont étudié des systèmes photovoltaïques raccordés au réseau alimentant des fermes agricoles par l’électricité et évalué leur performance énergétique. L'étude de cas s’est basée sur des fermes bovines dans le district de Chlef (nord-ouest de l'Algérie). Une ferme typique a été choisie pour cette région afin d'établir une charge horaire selon les factures d'électricité mensuelles. Les résultats ont montré que 60 % de sa consommation totale d'électricité provenait de l’énergie solaire photovoltaïque. En outre, une analyse économique et environnementale a été effectuée afin d'étudier la performance de l'introduction du système PV à la ferme agricole. Une analyse de sensibilité a été réalisée en modifiant certains paramètres économiques tels que le prix de vente de l’électricité PV et la durée de vie du projet. L'étude démontre la viabilité économique et la durabilité environnementale du système proposé. La généralisation des systèmes proposés dans toutes les fermes agricoles algériennes jouera un rôle important dans la production nationale d'électricité et l'atténuation des gaz à effet de serre.

ملخص

توليد الكهرباء من الطاقات المتجددة له فوائد كبيرة للبيئة والتنمية المستدامة. الطاقة الشمسية هي أكثر وفرة بشكل كبير من أي مصدر آخر للطاقة المتجددة على كوكب الأرض ومتوفرة محليا. نقل الطاقة الكهربائية يتم من موقع الإنتاج إلى الزبائن من خلال شبكة التوزيع الكهربائية التي تحتوي على محولات وأسلاك الكهرباء. لسوء الحظ، فإنه يولد خسائر كهربائية كبيرة بسبب تأثير جول ويواجه العديد من المشاكل مثل اضطرابات في التوزيع وانقطاع التيار الكهربائي المفاجئ خصوصا خلال فترة الصيف عندما يكون هناك طلب كبير على الكهرباء. أهداف هذا العمل كثيرة وتتعلق بتزويد المزارع الفلاحية بالكهرباء التي ينتجها نظام الطاقة الشمسية وارسال الفائض منها الى الشبكة الكهربائية. وبالتالي، فإن استخدام الأنظمة الكهروضوئية يجعل من الممكن تقليل اعتماد هذه المزارع على شبكة الكهرباء التي شهدت ارتفاعا في الطلب والاضطرابات في التوزيع في السنوات الأخيرة. النظام المستخدم هو نظام الطاقة الشمسية الضوئية المتصلة بالشبكة الكهربائية ذات الجهد المنخفض ولا يستخدم التخزين الكهروكيميائي. خلال الفترات المشمسة، يتم تزويد المزرعة من قبل النظام الكهروضوئي، وخلال غياب الشمس، تؤخذ الطاقة مباشرة من الشبكة الكهربائية. ويقدم هذا العمل مراجعة لعينة من المقالات التي درست أنظمة الكهروضوئية المتصلة بالشبكة الكهربائية التي تزود المزارع بالكهرباء وقامت بتقييم أداءها في مجال الطاقة. هذه الدراسة كانت حول مزارع الابقار في منطقة الشلف (شمال غرب الجزائر). وقد تم اختيار مزرعة نموذجية من هذه المنطقة من أجل تحديد جدول زمني لاستهلاك الكهرباء وفقا لفواتير الكهرباء الشهرية. وأظهرت النتائج أن 60٪ من إجمالي

استهلاك الكهرباء كان من الطاقة الكهروضوئية. وإضافة الى هذا، تم إجراء تحليل اقتصادي وبيئي من أجل التحقيق في أداء النظام الكهروضوئي داخل المزرعة. تم أيضا إجراء تحليل اقتصادي اضافي عن طريق تغيير بعض العوامل الاقتصادية مثل سعر بيع الكهرباء الكهروضوئية وطول عمر المشروع. وتبين الدراسة الجدوى الاقتصادية والاستدامة البيئية للنظام المقترح. وسيؤدي تعميم النظم المقترحة إلى جميع المزارع الجزائرية دورا هاما في توليد الكهرباء الوطنية والحد من غازات الدفيئة. وقد تحقق عن طريق تغيير بعض العوامل الاقتصادية مثل سعر بيع ا الفائض الدي ينتجه نظام الطاقة الشمسية الى الشبكة الكهربائية وعمر المشروع. وتبين الدراسة الجدوى الاقتصادية والاستدامة البيئية للنظام المقترح. وسيؤدي تعميم نظام الطاقة الشمسية الدي ينتج الكهرباء الكهروضوئية في جميع المزارع الجزائرية دورا هاما في توليد الكهرباء الوطنية والحد من الغازات المتسببة في الاحتباس الحراري.

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Acronyms

AC	Alternative current
BTP	Bâtiment-travaux publics (building public works)
CdTe	Cadmium Telluride
CF	Capacity Factor
CSP	Concentrated Solar Power
CTs	Combined Tabber Stringer
DC	Direct current
FAO	United Nations Organization of Food and Agriculture
GaAs	Gallium Arsenide
GPL	Gaz de Pétrole Liquéfié (Liquefied petroleum gas)
HOMER	Hybrid Optimization Model for Electric Renewable
ITELV	Institut Technique des Elevages (Institution for farming technical)
MARD	Ministry of Agriculture and Rural Development
ONS	National Office of Statistics
PR	Performance ratio
PV	Photovoltaic
STC	Standard test conditions
toe	Tonne of oil equivalent
FY	Final yield
RY	Reference yield

List of symbols

A	Ideality factor	
AF_A	Airflow required by animal	m^3/h
AF_F	Fan air flow	m^3/h
C_{acap}	Annualized capital cost	\$
$C_{ann,tot}$	Total annualized cost	\$
$C_{aO\&M}$	Annual operation & maintenance cost	\$
C_{arep}	Annualized replacement cost	\$
C_{cap}	Initial capital cost	\$
$C_{O\&M}$	Operation & maintenance cost (O&M cost)	\$
C_{rep}	Replacement cost of the component	\$
CRF	Capital recovery factor	\$
C_{sal}	Salvage cost	\$
E_{AC}	Daily power consumption	Wh/d
E_{an}	Annual energy production	Wh/yr
E_g	bandgap energy of the semiconductor	eV
E_{grid}	Yearly grid energy purchased	Wh/yr
$E_{grid,h}$	Hourly PV energy purchased from the grid	Wh
E_L	Energy consumption of lighting	Wh
$E_{load,h}$	Hourly energy consumption	Wh
E_M	Energy consumption due to milking	Wh
E_{MC}	Energy consumption due to milk cooling	Wh
E_P	Energy consumption of pumping	Wh
E_{PV}	Yearly PV energy production	Wh/yr
$E_{PV,h}$	Hourly PV energy production	Wh
E_R	Energy consumption of the cold rooms	Wh
$E_{sold,h}$	Hourly PV energy injected into the grid	Wh
E_V	Mechanical ventilation load	Wh
f_F	Fan operating frequency	h
f_P	Time required to pumping water	h
f_{PV}	PV derating factor	

f_{rep}	Factor arising because the component lifetime can be different from the project lifetime	
G	Irradiance	W/m^2
G_g	Global solar radiation	kWh/m^2/d
G_T	Solar radiation incident on the PV array in the current time step	kW/m^2
$G_{T,STC}$	Incident radiation at standard test conditions	kW/m^2
I	Illumination required per animal	lux
i	Interest rate	%
I_{cell}	output current	A
I_{ph}	photon current	A
$I_{ph,ref}$	Photocurrent at STC	A
I_s	saturation current	A
$I_{sc,n}$	Short circuit current at STC	A
$I_{s,n}$	Saturation current at STC	A
K	Boltzmann constant	
L	Total luminous flux required	lumen
ℓ	Flux emitted by one lamp	Lumen
N	Number of years	
N_A	Animals number	
N_{CM}	Cooling machine number	
N_F	Fans number	
N_L	Lamps number	
NPC	Net Present Cost	$
N_{pp}	Number of PV modules connected in parallel	
N_s	Series-connected cells	
N_{ss}	Number of PV modules connected in series	
P	Peak power of the PV system	KWp
P_F	Power of the fan	W
P_{inv}	Power of the inverter	kW
P_L	Power of the lamp	W
P_M	Milking machine power	W
P_P	Pump power	W

P_{RP}	Cooling machine power	W
P_T	Tank power	W
Q	Total water requirement per day	l/d
q	Electron charge	C
q_A	Water required amount per animal per day	l/d
Q_{irr}	Amount of water for irrigation	l/d
Q_V	Pump flow rate	l/mn
R_{comp}	Lifetime of the component	yr
RF	Renewable fraction	%
R_{proj}	Project lifetime	yr
R_{rem}	Remaining life of the component at the end of the project lifetime	yr
R_{rep}	Replacement cost duration	yr
R_s	Series resistance	Ω
R_{sh}	Shunt resistance	Ω
S	Surface required per animal	m^2
T	Cell temperature	K
T_c	PV cell temperature in the current time step	°C
$T_{c,STC}$	PV cell temperature under standard test conditions	°C
t_L	Lighting time	h
t_M	Milking time	h
t_{MS}	Milk storage time	h
T_n	Nominal temperature	K
T_{ref}	Cell temperature at STC	K
t_{RS}	Agricultural products storage time	h
V_{cell}	Output voltage	V
$V_{oc,n}$	Open circuit voltage at STC	A
$V_{t,n}$	Voltage at STC	
Y_{PV}	Rated capacity of the PV array, meaning its power output under standard test conditions	kW

List of Greek symbols

μ_{SC}	Coefficient temperature of short circuit current provided by the manufacturer	A/K
η_{inv}	Inverter yield	
α_P	Temperature coefficient of power	%/°C

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GENERAL INTRODUCTION

Since the industrial revolution, energy plays the most vital role in the economic and social development of any country. Today, production and consumption of energy have become a major challenge to supply the energy needs of billions of people who are constantly increasing. Nevertheless, the question that arises is whether this production and consumption of energy allow sustainable development. Unfortunately, the current energy production that is due to the consumption of fossil products is highly polluting, leading to the depletion of fossil resources and environmental degradation. Electrical energy transport from the production site to the customers is done through the grid system which contains transformers and power lines. Unfortunately, it generates large electrical losses due to the joule effect and knows several problems such as disturbances in distribution and sudden cuts especially during the summer period when there is a high demand on electricity. Renewable energies like solar energy, wind energy, biomass energy, geothermal energy and hydro-electric energy are the ecological solution, they provide substantial benefits for our climate, our health, and our economy. The major advantage of using renewable energies is that they are renewable, so they are sustainable and will never be depleted. One of the most widely developed renewable energy sources is solar energy. Solar energy applications are constantly increasing in the last few years, and they are considered the most promising that can significantly contribute to the total electricity generation. There are two main technologies involved in the exploitation of solar energy, which differ in the way that solar radiation is harvested and converted to electricity. These are the solar photovoltaic (PV) and the concentrated solar power (CSP) technology. Solar Photovoltaic technology differs from concentrated solar power (CSP) technology, it does not use the sun’s heat to generate power. Instead, it uses sunlight through the "photovoltaic effect" to generate direct electric current (DC) in a direct electricity production process. The DC is then converted to AC, usually with the use of inverters. The problem treated in this work is the existence of an insufficient supply of electricity in Algeria (shedding, sudden cuts, etc.) especially during the summer period when there is a great demand on electricity while there is a great sunshine. The objectives of this work are multiple and concern the self-powering of farms and the injection into the grid the surplus of the PV electricity produced by the solar photovoltaic system.

Thus, the use of photovoltaic systems makes it possible to reduce the dependence of these farms on the electricity grid, which has experienced high demand and disturbances in distribution in recent years. The system used is a solar photovoltaic system connected to the low voltage electrical grid and does not use electrochemical storage. During the sunny periods, the farm is fed by the PV system and during the absence of the sun, the power is taken directly from the electricity grid. This study presents the usefulness of the use of grid-connected PV systems in family farms and their contribution to improving the grid in Chlef district. These systems do not require batteries to store energy, so they are simpler, cheaper and more profitable (less energy losses) than stand-alone solar systems. The PV electricity that is consumed locally or sold to the grid allows reducing the electricity bills. This thesis is organized as follows:

- General introduction.
- Chapter 1 gives a review of the classification of grid-connected PV systems and their applications in farms.
- Chapter 2 presents conventional energy situation and potential renewable energy and applications in Algeria. At the end of this chapter we gave the renewable energy program up to 2030 and the legislative framework governing the use of renewable energies.
- Chapter 3 covered the modeling of the PV generator, the topology of inverters connected to the grid and the conversion field topologies.
- Chapter 4 gives a presentation on family farms and their electricity consumption, and then a family farm was chosen as a reference to know the impact of the use of the PV system on the energy balance using the Homer software.
- Chapter 5 examines the impact of using the grid-connected PV system on all family farms from an energy and economic point of view, then the environment impact.
- General conclusion and recommendation.

CHAPTER 1: BIBLIOGRAPHICAL STUDY

1.1 Introduction

A grid-connected PV system is a solar photovoltaic energy production system that is connected to the utility grid. It consists of PV modules, one or several inverters, a power conditioning unit and grid connection equipment. The power capacity of the grid-connected PV system ranges from small residential and commercial rooftop systems to large utility-scale solar power plants. Unlike a grid-connected PV system without battery backup, a grid-connected PV system with an integrated battery backup includes more components and batteries. In addition to that, the batteries require maintenance and will add significantly to the final cost of this power system. The grid-connected PV system can contribute strongly to reduce the electrical energy purchased from the grid by suppling the PV excess power, beyond consumption by the connected load, to the utility grid especially when weather conditions are favourable. It can also reduce the energy losses of the grid and avoid or delay upgrades to the transmission and distribution grid where the average daily output of the PV system corresponds with the utility's peak demand period **[1,2].** Furthermore, the main advantage of a grid-connected PV system compared to stand alone PV system is the absence of storage batteries that decreases significantly the unit cost of the PV energy produced **[3–5].** This chapter discusses the classifications of grid-connected PV systems and academic works carried out in each classification. It has been completed on the application of PV systems in agricultural farms, which has positive effects by reducing the energy taken from the grid during the day and injecting the surplus of the PV energy under favorable climatic conditions.

1.2 Classification of grid-connected PV systems

The authors of **[6]** gave an overview on the PV systems capacity connected to the grid installed worldwide, they concluded that the worldwide market tended to classify the grid-connected PV systems in three main categories. Small PV systems (1–5 kW) for private homes, medium PV systems integrated in commercial, industrial and office buildings (usually 10–250 kW) and centralized PV power plants (100 kW up to 5 MW). In the literature, several researchers focused on the investigation of the different categories of the grid-connected PV system. Concerning the small PV system size, Missoum et al **[7]** investigated two ways to improve the energy performance of a typical rural house in the district of Chlef. The first way consists of using the passive solar by integration the adequate orientation of the house, insulation of the envelope house, efficient glazing and increased windows size with the use of shading device in summer. Second way consists of using the active solar by integration of PV systems to supply the house with electricity. The study analyzed the energy performance of 1 kW grid-connected PV system in a typical rural house in the Chef district. The results showed that 219 GWh of electricity and 26,508 t of butane gas could be saved annually in rural housing built. Dragana et al **[8]** estimated the performance and energy efficiency of the 2 kW (rooftop) solar PV plant installed on the building of the Faculty of Sciences and Mathematics (FSM building) in Niš (Republic of Serbia) for the period from January 1, 2013 to January 1, 2014. Based on the experimental determination results, the solar PV plant works efficiently on the real climate conditions. The measurement data showed that the greatest amount of electrical energy (291.47 kWh) was generated in August when the global solar energy was 206.19 kWh/m^2. However, in the same period, the greatest amount of electrical energy (11.787 kWh/day) was generated on April 17, 2013. They concluded that the integration of PV systems into the transmission network was considered satisfactory. Okello et al **[9]** presented a comparison between measured and simulated performance parameters of a 3.2 kWp grid-connected PV system in the Nelson Mandela Metropolitan University, Port Elizabeth, South Africa. The PV system consists of14 poly crystalline silicon modules connected in two strings of 7 series-connected modules. The performance of the system was simulated using PVsyst software using measured and Meteonorm derived climate data sets. The measured data showed that the PV system supplied 5757 kWh to the local electric utility grid in the year 2013. They conclude that simulation results gave good approximation to measured energy output. Hartner et al **[10]** present the theoretical approach to assess an optimal size based on the internal rate of return of the investment and define the most relevant parameters and variables. This study has done for various scenarios on prices, tariffs, cost curves, and subsidies. They assessed the optimal PV system size for a sample of more than 800 households in Austria and estimated that for a minimum system size of 5 kW total investment costs for subsidized residential photovoltaic systems from 2008 to 2013 could have been 2.2% lower for the same amount of installed capacity. In **[11]**, Kim et al presented the characteristics of the voltage rise, voltage unbalance and the voltage flicker on the network. As a result of their research, they concluded that the growth of PV system in low voltage (LV) distribution network has the potential to raise several technical issues including voltage rise and voltage unbalance. They have set up to study the voltage issues at the point of common coupling of a 7.2 kW grid connected PV system on a radial LV distribution network, they analyzed the impacts of voltage issues on the LV distribution network and feasible methods for voltage stabilization. For medium PV system size, Fantidis et al **[12]** examined the potential of a 20 kW photovoltaic (PV) power plant connected to the grid at each of the 46 locations in Greece to predict energy production, cost of energy and reduction of greenhouse gasses (GHGs) emissions by using HOMER software. The study demonstrated that the PV power plant connected to the grid can play an important role in Greek energy generation and considerable quantity of CO2 is not released into the local atmosphere each year. The financial analysis showed that the PV power plant could operate profitably in these 46 locations. Kumar et al **[13]** studied a grid connected 20 kWp solar photovoltaic installed on a flat rooftop and connected to the grid in Tiruchirappalli (India). The 20 kWp system is divided into four strings with an average PV output voltage of about 600 V in loaded condition. They highlight the operational performance and economic calculations of a grid connected solar photovoltaic. The results showed that the efficiency of the PV module varied between 10.14% and 12.6% and the inverter efficiency varied between 88.90% and 96.54%. The economic analysis shows that solar PV installation is a good investment. In **[14]**, Kymakis et al calculate the final yield (FY), the reference yield (RY), the performance ratio (PR) and the capacity factor (CF) in order to evaluate the performance of PV park system of 171.36 kWp connected to the local power grid on the island of Crete. The PV park supplied 229 MWh to the grid during 2007, ranging from 335.48 to 869.68 kWh. The final yield (FY) ranged from 1.96 to 5.07 h/d, and the performance ratio (PR) ranged from 58 to 73%, giving an annual PR of

67.36%. The study gave the following results, the average annual PV park energy output in 2007 was 1336.4 kWh/kWp, the average annual performance ratio of the park was 67.36% and the average annual capacity factor was 15.26%. For centralized PV power plants, Padmavathi et al **[15]** conducted an investigation on the performance of a 3 MWp grid connected PV plant located in Karnataka State (India) using monitored data for the year 2011. The 3 MWp PV plant has three independent segments of 1 MWp. The following conclusions could be drawn: The annual average energy generated by the plant was 1372 kWh per kWp of the installed capacity and the performance ratio (PR) was found to be less than 0.6 from August to November due to high inverter failure losses estimated to be 818 MWh. Sundaram et al **[16]** studied the performance characteristics of a 5 MWp grid connected PV system located in South India during 2011–2012. The comparison between the measured annual average energy generated by a 5 MWp system which is 24116.61 kWh/d, and the predicted annual average energy by employing a RETscreen software which was found to be 24055.25 kWh/d showed that they are appropriately close. The study showed also the following results: The module efficiency (6.08%), inverter efficiency (88.20%) and system efficiency (5.08%). In other works, power plants with power greater than 5 MW have been studied. Cheikh et al **[17]** presented and evaluated the performance of the grid-connected PV power plant of 15 MWp, which was implemented to supply 10% of the electrical needs of Nouakchott (The capital of Mauritania (18.15° N, 15.98° W)). The PV plant, which is composed of seventeen arrays connected to inverters, supplies the 33 kV electricity grid through nine transformers. The results showed that Spring, Summer and Autumn months had highest values of daily average energy output, while the lowermost ones correspond to Winter months. In **[18]**, Kumar et al studied performance results of a 10 MW photovoltaic grid connected power plant at Ramagundam (India) and compared them with the simulation values obtained from PV syst and PV-GIS software. The plant operates with a seasonal tilt. They concluded that the actual performance closely matches with the simulated performance of PV syst and Solar GIS over the entire year. The study found that the total amount of energy injected in to the grid for the entire year is 16 047 MWh. The maximum energy is generated in the month of December (1589 MW h) and minimum energy is in the month of July (926

MWh). The final yield (FY) of plant ranged from 1.96 to 5.07 h/d, and annual performance ratio (PR) of 86.12%. Zafar et al **[19]** explored the economic and technical impact of 750 MW PV power plant connected to the national grid of Pakistan. The results positively confirm that connection of this PV plant does not cause any load flow violations and the recommended short circuit current levels of the system is preserved.

1.3 Grid-connected PV system application in farms

Grid-connected PV system application in farms has been treated in few works. Nacer et al **[20]** proposed a feasibility analysis of grid-connected photovoltaic energy systems in ITELV farms in the north Algerian region. ITELV is an institution for farming technical. The size of the farms studied was ranging from 10 to 30 milking cows. The study indicated that it is able to achieve the energy balance between forecasted photovoltaic generation and energy demand in these farms. The optimal grid-connected photovoltaic system was found 4.8 kWp in three regions, 4.32 kWp in two regions and 3.84 in one region. Bey et al **[21]** studied the performances of a PV array of 43 kWp designed to supplying a typical dairy farm and the grid in a rural environment in the south of Tlemcen (west of Algeria). The studied dairy farm cultivates 3.2 ha and contains 30 dairy cows. The results showed that the consumed energy of the farm from the grid decreased with 67%, the injected energy was estimated at 30.9 MWh/year. The produced milk increased with 8% and the CO_2 emission decreased with 68%. Nacer et al compared various power systems (stand-alone PV system, stand-alone wind system, stand-alone hybrid PV/wind system, grid-connected PV system, grid-connected wind system, and grid-connected hybrid PV/wind system) to supply an experimental farm in the Mitidja region (Algeria). The farm electricity consumption was required for animal housing, feeding, milking, and milk refrigeration. They concluded that the optimal system was the optimal grid-connected systems **[22]**. Nadjemi et al tested cuckoo search (CS) and swarm sizing optimization (PSO) algorithms for both a residential load and an agricultural farm load located in the city of Ghardaia, Algeria. The first algorithm had better accuracy, faster convergence and less computation time compared to the second algorithm **[23]**. Tudisca et al **[24]** evaluated the economic convenience of four PV systems of 20 kW on farm buildings located in four different farms of the north-western coast of Sicily (Italy) and realized during the second and fourth Italian feed-in schemes. For each feed-in scheme, it has been considered a PV plant that sells the electricity to the grid and another in which the energy generated is consumed entirely by the farm. The results showed a clear convenience to the realization of investments both with the current market conditions and at the variation of the feed-in tariff or the investment costs. Houston et al evaluated the energy efficiency and renewable energy generation opportunities for small scale dairy farms. This paper uses a case study of a small dairy farm in Oyster Bed Bridge (Canada) to better understand the use of energy in the small farms. The energy requirements were lighting, refrigeration, and ventilation. Renewable energy sources findings to satisfy the farm power demand are anaerobic digester and wind **[25]**.

1.4 Conclusion

Through this literature review, we found that PV systems number in farms is very few compared to habitats, while farms have very large roofs and other factors that facilitate Installation of PV systems as the absence especially problems with shading. These advantages make it possible to install high powers, which help to reduce the load and the frequent problems of the electrical network.

CHAPTER 2: ENERGY SITUATION IN ALGERIA

2.1 Introduction

In recent years, demand for electricity has evolved significantly, particularly during summer periods, reaching significant peaks in consumption. This sharp increase in demand is a direct consequence of the change in consumer habits and the improvement of the quality of life, as well as the impulse given to the economic and industrial sectors. It is therefore necessary to ensure long-term coverage of electricity needs to diversify energy sources, including renewable energy sources.

2.2 Conventional energy

2.2.1 Energy consumptions

According to the BP Statistical Review of World Energy [26], the consumption of oil products and natural gas in Algeria is continuously increasing. The consumption of natural gas reached 39 billion m^3 and that of oil 19.3 Mt in 2015 as shown in Fig 2.1. The carbon dioxide emissions due to these fossil fuels consumption that have negative impacts on climate and people's health [27-29] increased from 89.3 Mt in 2007 to 137.1 Mt in 2015.

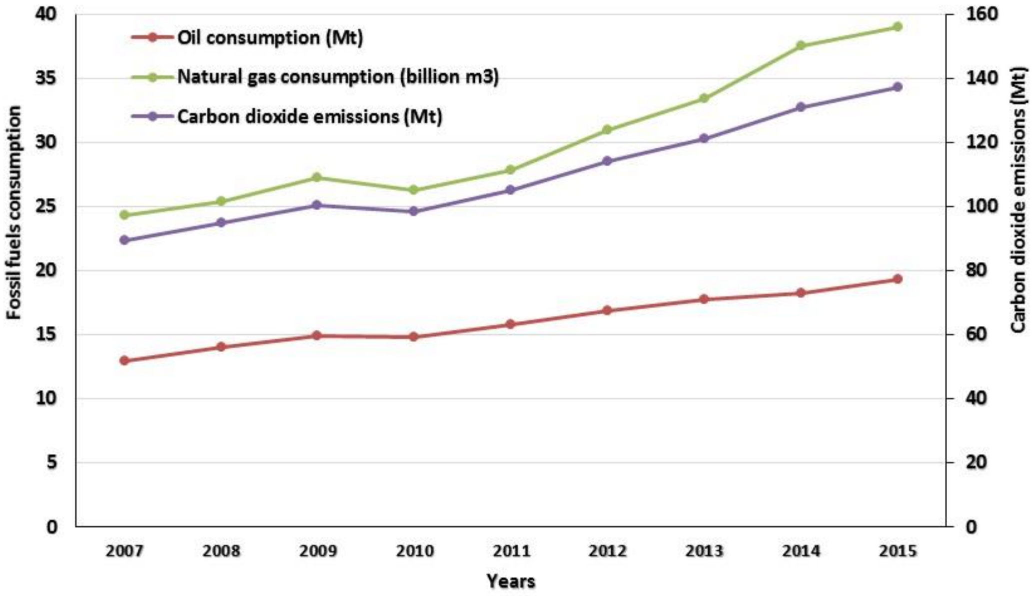

Fig. 2.1 Evolution of fossil fuels consumption and carbon dioxide emissions in Algeria

In 2014, the energy consumption reached 39.4 Mtoe, reflecting an increase of 1.9 Mtoe over 2013. This consumption could be divided into two types, energy consumption by product and energy consumption by activity sector [30].

2.2.1.1 Energy consumption by product

As sown in Fig 2.2, oil products are still the first form of energy consumed, with 38.1% of final energy consumption. Natural gas and electricity are the second and third forms of energy consumed respectively with 28,5 and 27.7 %. These energy forms recorded an increase compared to 2013 respectively with 5.6, 6.5 and 6.1%.The last form is the GPL with 5.7%, down by (-7.4%) compared to 2013 [30].

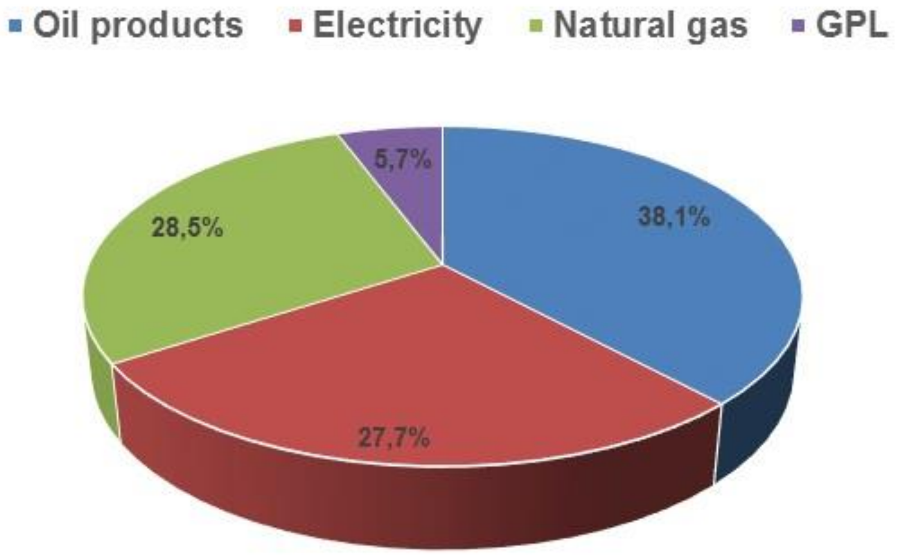

Fig. 2.2 Structure of final energy consumption by product

2.2.1.2 Energy consumption by activity sector

The evolution of final energy consumption by sector of activity in 2014 is given in Fig 2.3 [30].

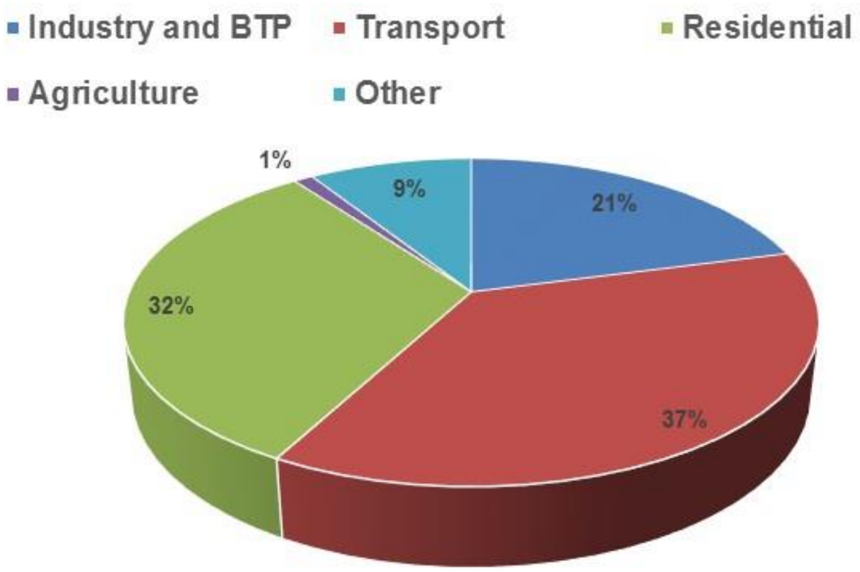

Fig. 2.3 Structure of final energy consumption by sector of activity

- Consumption in the industry and BTP sector showed a slight increase (+ 2.8%) compared with the year 2013.
- Consumption in the transport sector increased by + 5.7% in 2014 compared with the year 2013, reaching 14.6 Mtoe .
- Residential and agriculture consumptions increased respectively by 456 and 183 Ktoe compared to 2013 to reach 12.6 Mtoe and 421 Ktoe by 2014. Agriculture consumption represents 1% of the final energy consumption and residential consumption 32%.

2.2.2 Electrical energy production

Grid system in Algeria is powered by various power plants, which are interconnected through a transmission network of 60 kV, 220 kV and 400 kV, allowing the transfer of energy from production sites to energy consumers. Fig 2.4 presents the contribution of each power plant to cover the increasing national demand of electrical energy between 2007 and 2015, it will be as follows [31] :

- Almost all of the electric power production comes from thermal steam plant, thermal gas plant and combined cycle plant (between thermal steam and thermal gas).
- The contribution of hydraulic plant, diesel plant and hybrid plant in the electric power production is very low.
- The contribution of renewable energies to the improvement of the power grid remains almost nil. In 2015, electrical energy production from photovoltaic energy and wind energy reached 0.019 and 0.014 TWh respectively.

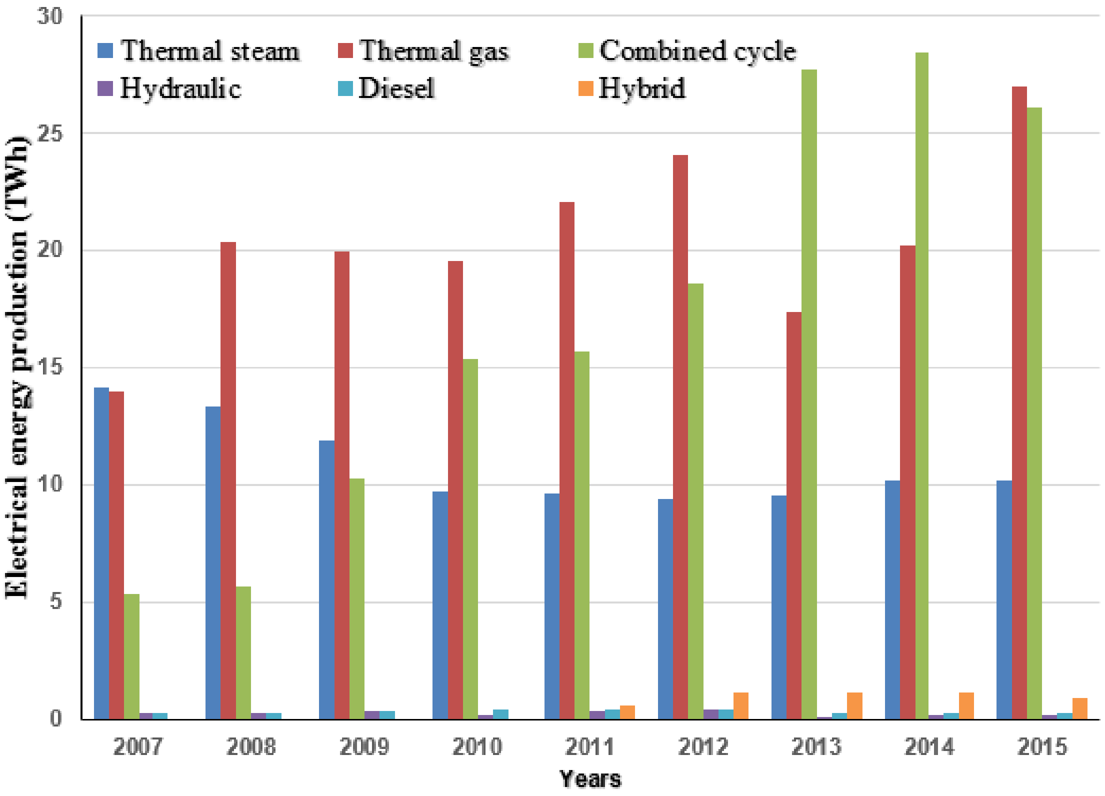

Fig. 2.4 Electrical energy production by power plants in Algeria

2.2.3 Electrical energy evolution

The electrical energy production in Algeria is constantly increasing due to the growth of the population and the development of various industrial sectors. The number of customers using the electrical energy has grown from 6.04 millions in 2007 to 8.45 millions in 2015 (Fig. 2.5) [32]. During this period, the electrical energy production has increased from 33.95 TWh in 2007 to 64.66 TWh in

2015. We note that between 2007 and 2008, there was a greater increase in electrical energy production (18 %), and after then it varies between 6 and 11% between 2008 and 20015. Unfortunately, the electrical energy losses have grown from 6.75 TWh to 10.93 TWh during the same period. The rate of the electrical energy losses was ranging from 18 to 21 % during 2007 to 2015, so it is very high in comparison with other countries. In the European countries, the rate of the electrical energy losses ranges between 4 and 8 % during 2009 to 2013 [33].

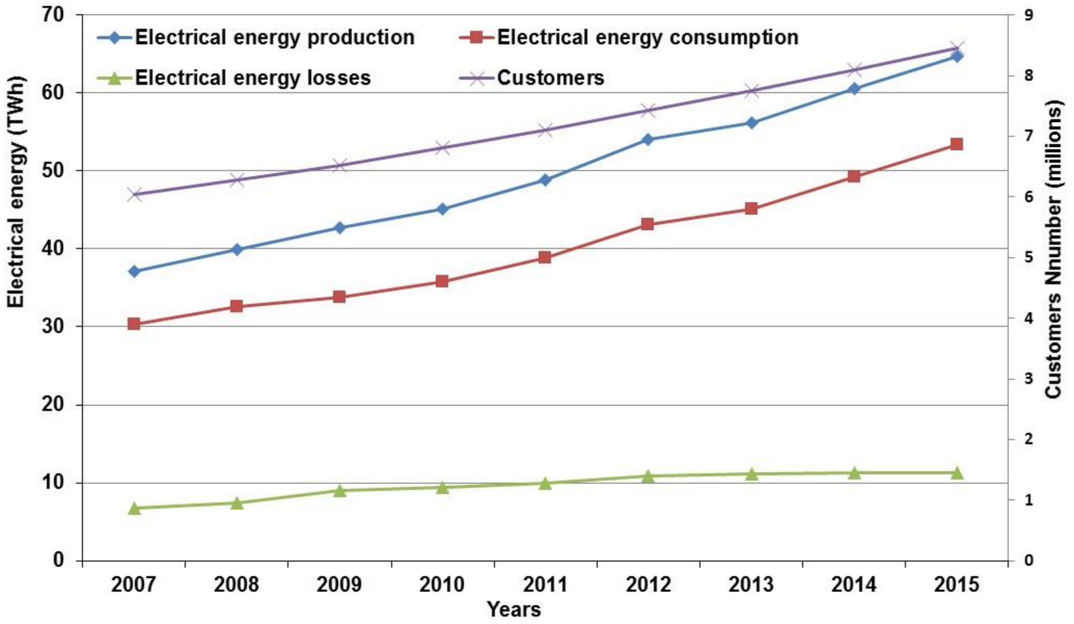

Fig. 2.5 Electrical energy production and consumption vs customers number in Algeria

The electricity sale in Algeria is made in three voltage forms, high voltage (60, 220 and 400 kV), medium voltage (30 kV) and low voltage (220/380 V). Fig. 2.6 shows the sales percentage for each voltage form between 2007 and 2014. It can be seen that the sale percentage of electricity in the form of low voltage increased and varied from 48.5 to 54%. While the electricity sale in the form of medium and high voltage decreased. Their sale percentages varied from 29.5% to 27% and from 21.6% to 19%, respectively. These data encourage the investment of renewable energies in the production of electric power in the form of low voltage [32].

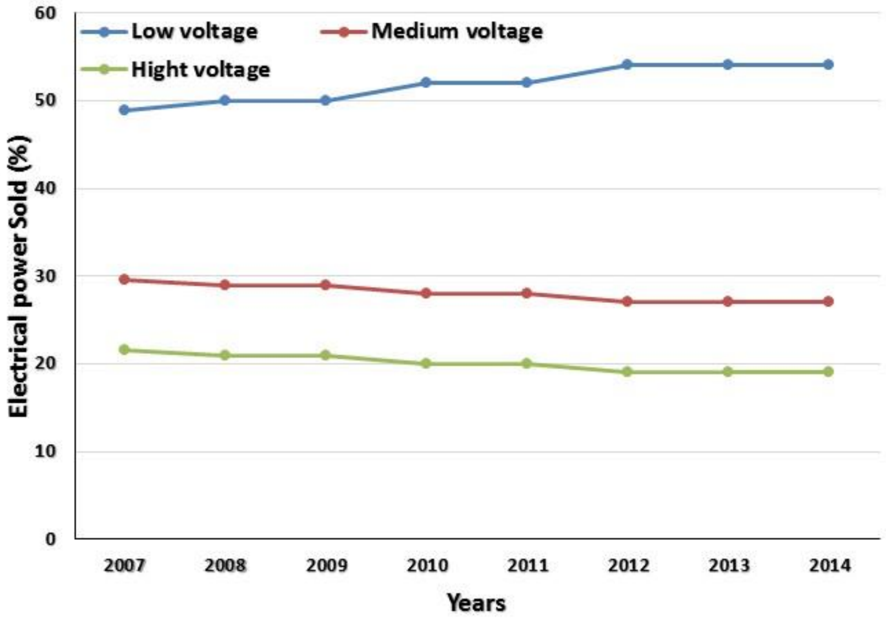

Fig.2.6 Sale of electricity forms in Algeria

2.3 Renewable energies potential

Incorporating renewable energies in the energy mix is a major challenge for Algeria in order to preserve fossil resources, to diversify the power generation and to contribute to the sustainable development. The domestic potential for renewable energies being highly dominated by the solar, Algeria regards this energy as an opportunity and a lever of economic and social development particularly through the setting up of industries that generate wealth and employment. This does not rule out the launching of numerous projects for the realization wind power stations and implementation of projects in biomass, geothermy and cogeneration.

2.3.1 Solar energy

Fig. 2.7 shows Algeria's annual average of global horizontal irradiation, seven distinct solar radiation zones can be identified in this figure [34]. The minimum annual average of global horizontal irradiation value (1 700 kWh/yr) appears in the first zone, and the maximum value (2 300 kWh/yr) in the seventh zone. The sunshine duration over the quasi-totality of Algeria's territory exceeds 2 000 hours annually and may reach 3 500 hours annually in the Sahara [35].

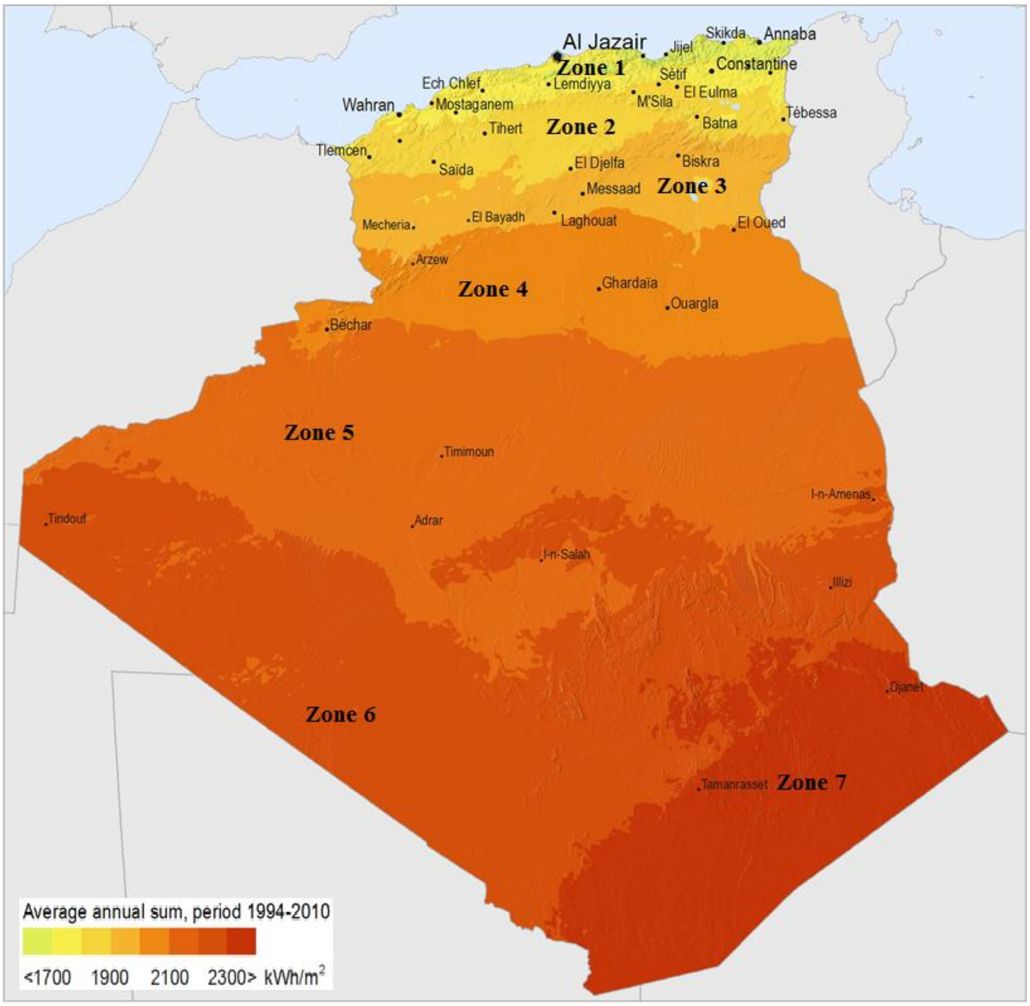

Fig. 2.7 Annual average of Algeria’s Global Horizontal Irradiation (GHI).

2.3.2 Wind energy

The wind energy potential in Algeria varies greatly from one place to another. This is mainly due to their diverse topography and climate. The map shown in Fig. 2.8 shows that the South is characterized by higher speeds than the North, particularly in the Southeast, with speeds exceeding 7 m/s and exceeding the value of 8 m / s in the Tamanrasset region (In Amguel). Concerning the North, we note overall that the average speed is low. There are microclimates on the coastal sites of Oran, Bejaïa and Annaba, on the high plateaus of Tebessa, Biskra, M'sila and Elbayadh (6 to 7 m / s), and the Great South (> 8m / s) [36].

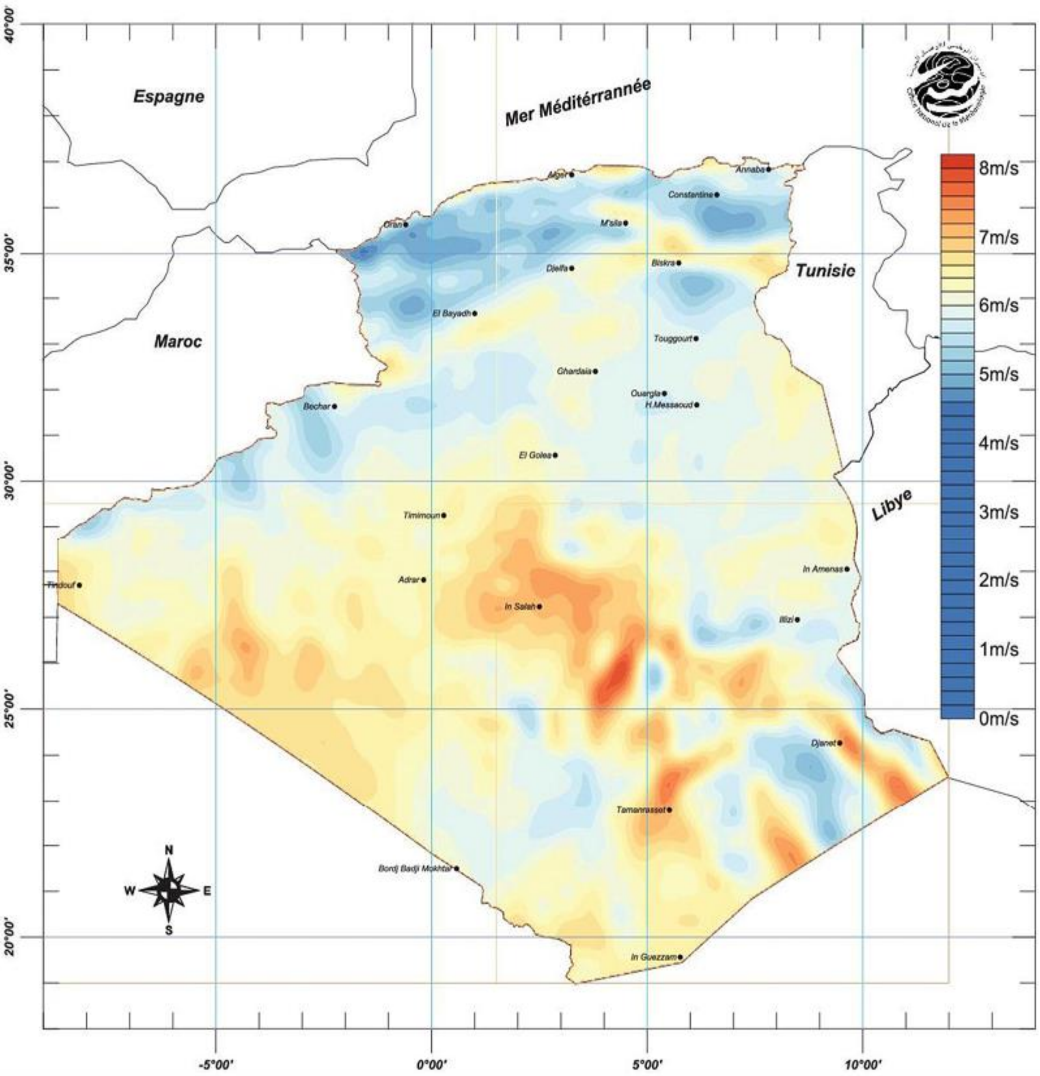

Fig. 2.8 Average annual wind speeds at 50m in Algeria (2001 à 2010).

2.3.3 Geothermal energy

The compilation of geological, geochemical and geophysical data identified more than 200 hot springs that were inventoried in the northern part of the country. 33% of them have temperatures above 45 °C. There are high-temperature sources reaching 118 ° C in Biskra. Thermal gradient studies have identified three zones with a gradient exceeding 5 °C/100m [36]:

- Relizane and Mascara
- Aïne Boucif and Sidi Aïssa
- Guelma and Djebel El Onk

2.3.4 Hydro-electric energy

In Algeria, 103 water dam sites have been identified. Table 2.1 gives the power of 13 hydropower plants [36].

Table 2.1: Power of 13 hydropower plants.

Hydropower plant	Power MW
Darguina	71.5
Ighil Emda	24
Mansouria	100
Erraguene	16
Souk El Djemaa	8.085
Tizi Meden	4.458
Ighzernchebel	2.712
Ghrib	7.000
Gouriet	6.425
Bouhanifia	5.700
Oued Fodda	15.600
Beni Behde	3.500
Tessala	4.228

2.3.5 Biomass energy

A- Forest potential

The current potential is estimated at about 37 million toe. The current recovery rate is around 10% [36].

B- Waste potential

05 million tonnes of urban and agricultural waste are not recycled. This potential represents a deposit of the order of 1.33 million toe/year [36].

2.4 Renewable energies program

Through its renewable energies program, Algeria intends to produce electricity from solar, wind, biomass, cogeneration and geothermal energy. The Table 2.2 gives combined capacities of the renewable energies program, per type and phase, over 2015 – 2030 period [37]:

Table 2.2: Capacities of the renewable energies program.

Renewable energies capacities (MW)	1st phase 2015-2020	2nd phase 2021-2030	Total
Photovoltaic	3000	10575	13575
Wind	1010	4000	5010
CSP		2000	2000
Cogeneration	150	250	400
Biomass	360	640	1000
Geothermal	05	10	15
Total	4525	17475	22000

This program involves a large-scale development of photovoltaic, wind and incorporating the concentrated solar power (CSP). Biomass, cogeneration and geothermal industries shall take place gradually. This ambitious program consists of installing a renewable power source of nearly 22 000 MW between 2011 and 2030, 12 000 MW will be dedicated to cover the national demand for electricity and 10 000 MW for export. Power generation is deemed to reach 90 TWh in 2020 and 170 TWh in 2030. By 2030, about 40% of the electricity produced for domestic consumption will be from renewable energies. This represents both a great saving in fossil energy and a significant reduction in the quantity of CO_2 gas emitted to the atmosphere as shown in Table 2.3.

Table 2.3 : CO_2 emissions to be avoided by 2030 [36].

	2015	2020	2025	2030
Reduction in the amount of CO_2 emitted (Mt)	1,1	32,1	95,9	193,3

2.5 Solar energy realizations

2.5.1 Rural electrification

During the period 1995-1999, 906 households in 18 villages isolated from the south in the wilayas of Tamanrasset, Adrar, Illizi and Tindouf were electrified by PV solar energy.

2.5.2 PV power plants

The criteria for selecting sites eligible for the implementation of solar photovoltaic projects are solar potential, accessibility to the site, availability, the topography, the vocation of the land (agricultural, forest, tourism, quarries, military, etc.). Table 2.4 shows the projects carried out [36].

Table 2.4 : Solar photovoltaic projects realizations

Implantation site	**Puissance (MWc)**	**Date of commissioning**
Ghardaïa	1,1	June 2014
Djanet (Illizi)	03	February 2015
Adrar	20	October 2015
Kabertene (Adrar)	03	october 2015
Tamanrasset	13	November 2015
Tindouf	09	December 2015
Z.Kounta (Adrar)	06	January 2016
Timimoune (Adrar)	09	February 2016
Reggane (Adrar)	05	january 2016
d’In-Salah (Tamanrasset)	05	February 2016
Aoulef (Adrar)	05	March 2016
Ain El-Ibel (Djelfa)	20	April 2016
Khnag (Laghouat)	20	April 2016
Oued El-Kebrit (Souk Ahras)	15	April 2016
Sedrate Leghzal (Nâama)	20	May 2016
Ain-Skhouna (Saida)	30	May 2016

2.6 Legislative framework (cadre législatif)

Algeria has incorporated the renewable energies development in its energy policy by adopting a legal framework in favor of their promotion and realization of relevant infrastructures. Renewable energies development is supervised by whole legislative texts [37], incentive and encouragement measures are particularly provided for in the law pertaining to energy control (financial, tax and customs duties benefits) for actions and projects that contribute at improving energy efficiency and promoting renewable energies. Among these legislative texts, there are:

- Law No. 99-09 dated 28th July, 1999 regulates the energy control
- Law No. 04-09 dated 14th August, 2004, is about the promoting renewable energies under sustainable development
- Ministerial orders dated 02nd, February 2014 setting the purchase list prices guaranteed for power generating from facilities using the photovoltaic industry and the terms of the enforcement thereof.

The goal of the aforementioned measures is to encourage local products and provide favorable conditions, particularly tax, for investors who are willing to involve in different renewable energies and energy efficiency industries.

2.7 Conclusion

The continuous increase in consumption of oil and natural gas leads to the depletion of their sources and causes ecological damage linked to their extraction and use. This negatively affects the land and the environment by emitting greenhouse gases and driving climate change. The development and use of renewable energies will reduce the ecological damage of fossil fuel consumption and contribute to the preservation of land for future generations. Through its renewable energies development program, Algeria longs to minimize its fossil energy consumptions, protect the environment and preserve this wealth for the future generations as part of a sustainable development.

CHAPTER 3: PHOTOVOLTAIC SYSTEMS CONNECTED TO LV GRID

3.1 Introduction

Photovoltaic solar energy is energy collected from sunlight and transformed directly into electricity by means of a photovoltaic cell. Photovoltaic cells are manufactured with semiconductor materials (silicon, CdTe, GaAs,….), which emit electrons when they are subjected to the action of light. The released electrons are ejected from the material and circulate in a closed circuit, thus producing electricity. The electricity produced is available in the form of direct electricity or stored in batteries (decentralized electrical energy) or electricity injected into the grid. The PV energy production releases a very small amount of greenhouse gases. In addition, solar modules can be connected to the grid and installed in locations far from any electricity distribution network. This paper presents a mathematical modeling to describe photovoltaic PV module and PV array systems, taking into account the radiation and temperature effects on output voltage, current and power.

3.2 Modeling of photovoltaic system (PV)

The photovoltaic system modeling depends on the choice of the equivalent electrical circuit of a photovoltaic cell. It is therefore necessary to understand the physical configuration of the elements making up this cell and their electrical characteristics in order to choose the appropriate mathematical model. The mathematical models that are based on the Shockley diode equation represent a non-linear behavior resulting from semiconductor junctions. These models are differentiated by the mathematical procedures and the parameters number involved in the calculation of the voltage and current of the photovoltaic module. In the literature, several mathematical models exist to describe photovoltaic cells, from simple to more complex models ranging that account for different reverse saturation currents. The single diode model is used in this study to represent a photovoltaic cell, which offers a good compromise between accuracy and simplicity **[38-42]**.

3.2.1 Mathematical model of a photovoltaic cell

The photovoltaic cell is a P-N semiconductor junction that directly converts solar radiation into DC current using the photovoltaic effect. The most common model used to predict I-V characteristics of PV cell is the single diode model as shown in Fig. 3-1. The PV cell model is represented by an equivalent circuit composed of a light-generated current source, a single diode representing the nonlinear impedance of the P-N junction, and series and parallel intrinsic resistances accounting for resistive losses **[43]**.

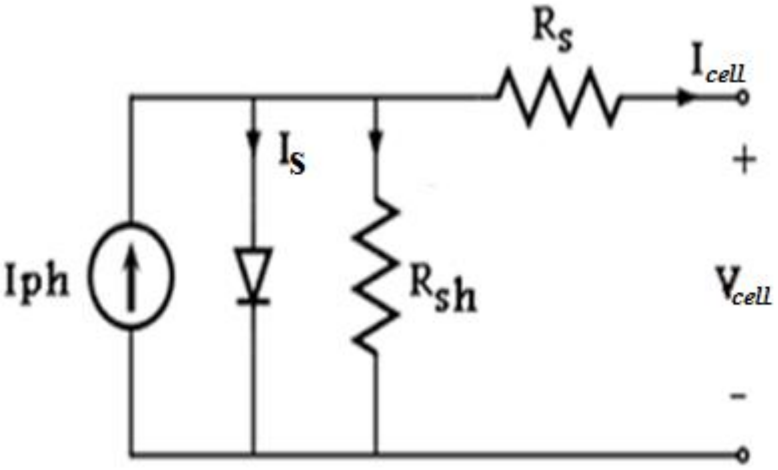

Fig. 3.1 Equivalent circuit of a PV cell

The mathematical model of a PV cell is expressed as follow:

$$I_{cell} = I_{ph} - I_s\left[e^{\left(\frac{q(V_{cell}+I\,R_S)}{K\,T\,A}\right)} - 1\right] - \frac{V_{cell}+I\,R_S}{R_{sh}} \tag{3.1}$$

Where :

I_{cell}: output current

V_{cell}: output voltage

q: electron charge

K: Boltzmann constant

T: Cell temperature

I_{ph}: photon current

I_S: saturation current

R_S: series resistance

R_{sh}: shunt resistance

A: is the ideality factor and depends on as shown in Table 1 **[44]**.

Table 3.1: Ideality factor according to PV cell technology.

Technology	Ideality factor
Si-mono	1.2
Si-poly	1.3
a-Si-H	1.8
a-Si-H tandem	3.3
a-Si-H triple	5
CdTe	1.5
CTs	1.5
GaAs	1.3

3.2.2 Mathematical model of a photovoltaic module

In the reality, PV cells are grouped in series together in larger units called modules. The mathematical model of a PV module composed of Ns series connected cells is expressed as follow **[45-48]** :

$$I = I_{ph} - I_s \left[e^{\left(\frac{q(V+I\,R_S\,N_S}{N_S\,K\,T\,A} \right)} - 1 \right] - \frac{V+I\,R_S\,N_S}{N_S R_{sh}} \tag{3.2}$$

3.2.3 Mathematical model of a photovoltaic array

PV modules are grouped together in larger units known as PV arrays (PV generator), which are combined in series and parallel to provide the desired output voltage and current. The PV array model accepts irradiance and temperature as variable parameters and outputs I-V and P-V characteristics. The mathematical model of a PV array is expressed as follow **[49-51]**:

$$I = N_{pp} I_{ph} - N_{pp} I_s \left[e^{\left(\frac{q(V+I\,R_S\,N_S\;(N_{SS}/N_{pp}))}{N_S\,K\,T\,A^{N_{SS}}} \right)} - 1 \right] - \frac{V+I\,R_S\,N_S\,(N_{SS}/N_{pp})}{N_S R_{sh}\,(N_{SS}/N_{pp})} \tag{3.3}$$

Where :

N_{pp} is the number of PV modules connected in parallel.

N_{ss} is the number of PV modules connected in series.

3.3 Estimation of the PV array parameters

For a given temperature and solar irradiation intensity, the five parameters of this model are: I_{Ph}, I_s, R_s, R_{sh} and A. these parameters are determined by using the open-circuit voltage V_{OC}, the short-circuit current I_{SC}, the voltage V_m and the current I_m at the maximum power point and the slopes of curve near V_{OC} and I_{SC}. Several methods are based on single exponential model of solar cell and assume that R_{sh} is infinite and presume R_s to be independent of the intensity of illumination, which may not be valid. The value of R_{sh} is generally high and some authors **[52-58]** neglect this resistance to simplify the model. The value of R_s is very low, and sometimes this parameter is neglected too **[59-61]**.

3.3.1 Determination of I_{ph}

The light-generated current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation **[62]**:

$$I_{ph} = \frac{G}{G_{T,STC}} \left(I_{ph,ref} + \mu_{SC}\, \Delta T\right)$$
(3.4)

G: Irradiance (W/m^2), $G_{T,STC}$: Irradiance at STC = 1000 W/m^2, $\Delta T = T - T_{ref}$ (Kelvin), T_{ref} : Cell temperature at STC = 25 + 273 = 298 K, μ_{SC} : Coefficient temperature of short circuit current (A/K), provided by the manufacturer, $I_{ph,ref}$: Photocurrent (A) at STC.

3.3.2 Determination of I_s

The diode saturation current I_s and its dependence on the temperature may be expressed by as shown **[62]**:

$$I_s = I_{s,n}\left(\frac{T_n}{T}\right)^3 exp\left(\frac{qE_g}{AK}\left(\frac{1}{T_n}-\frac{1}{T}\right)\right) \qquad (3.5)$$

Where :

E_g is the bandgap energy of the semiconductor (E_g = 1.12 eV for the polycrystalline Si at 25 ◦C) and $I_{s,n}$ is the nominal saturation current:

$$I_{s,n} = \frac{I_{sc,n}}{\exp\left(\frac{V_{oc,n}}{AV_{t,n}}\right)-1} \qquad (3.6)$$

Where $V_{t,n}$ is the thermal voltage of N_s series-connected cells at the nominal temperature T_n.

3.4 Topology of inverters connected to the grid

PV photovoltaic energy is used in two application domains, isolated PV and PV connected to the grid. These two applications have functions and implement very different conversion strings. In the following, the functions and topologies of PV fields connected to the network will be presented more particularly.

3.4.1 Photovoltaic systems features

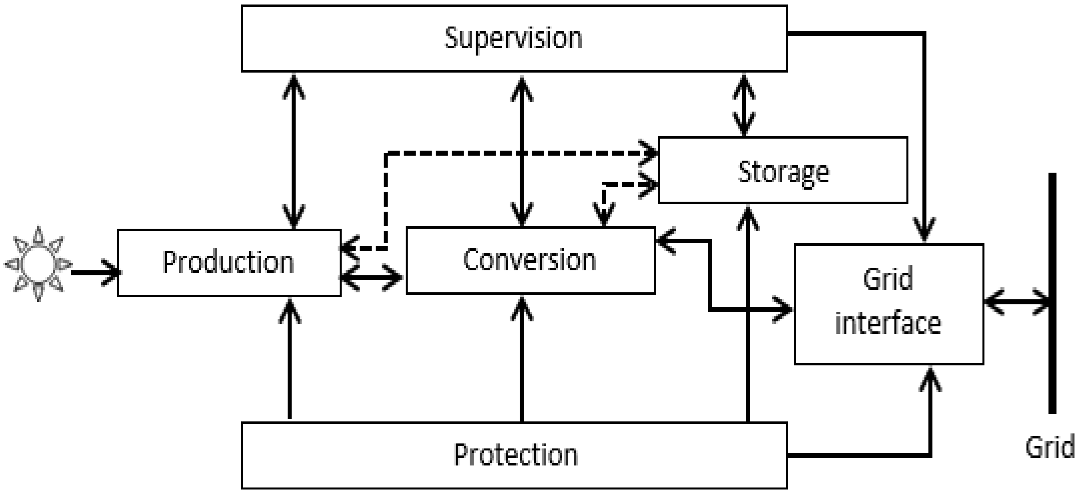

Fig. 3.2 General features of photovoltaic systems connected to the grid

A photovoltaic installation requires a chain of conversion of the light energy into electrical energy based on the photovoltaic effect. This conversion chain can be broken down into several subsystems delimited according to their functionalities. The conceptual diagram of the photovoltaic systems connected to the grid identifying the main functional subsystems and their general functions is given in Fig. 3.2. Basic functions (production, conversion, grid interface) and ancillary functions (protection, supervision and storage) can be identified in this figure **[63]**.

3.4.2 Conversion Types

3.4.2.1 Single-Stage Conversion

The conversion is done in a single step (Fig. 3.3), there is no voltage amplifier stage. It is therefore necessary that the voltage of the field PV is sufficient for the inverter to reconstitute the voltage of the grid. In this configuration, the converter must perform all the functions required by a PV application connected to the network (MPPT, anti-islanding, etc.) **[63]**.

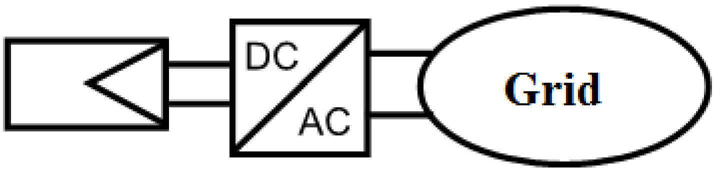

Fig. 3.3 Block diagram of a single-stage conversion chain

3.4.2.2 Two-Stage Conversion

The conversion can also be done in two steps (Fig. 3.4), a first DC/DC conversion followed by a DC/AC conversion. In this configuration, the DC/DC converter generally has the role of increasing the voltage so that the inverter can produce a sinusoidal current at the mains voltage. The converters are connected by a DC bus. In this case, the functions required by the PV applications can be divided between the two converters **[63]**.

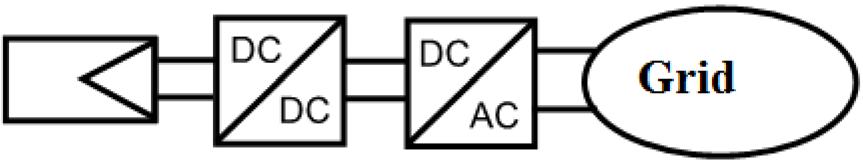

Fig. 3.4 Block diagram of a two-stage conversion chain

3.4.3 Conversion field topologies

A wide variety of PV field topologies exists, the PV field architectures enabling the connection to the distribution grid are:

3.4.3.1 Central inverter

The oldest and most traditional topology is composed of a single inverter that makes the interface between the grid and the photovoltaic array, where strings of modules are connected in parallel (Figure 3.5). This installation is generally used for installations of high power (20-400 kW) in which protections against current back-up are installed per row **[63]**.

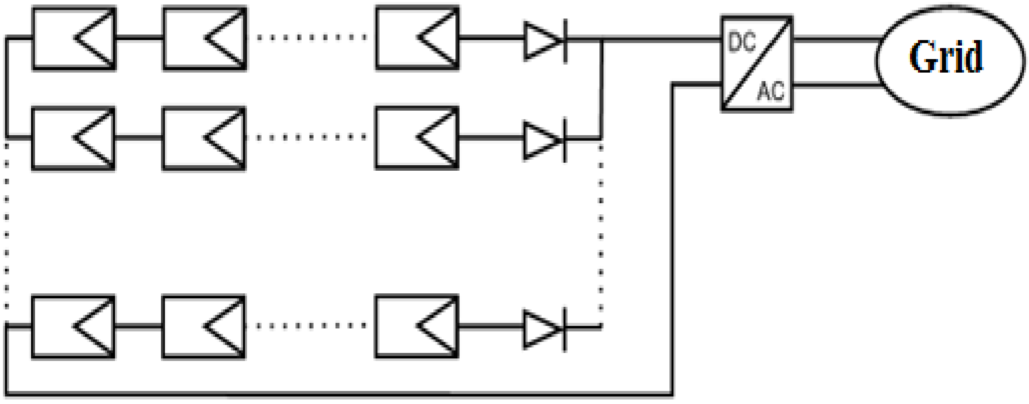

Fig. 3.5 Central inverter topology

The advantage of the central inverter topology is its simplicity of implementation, a single inverter connected to the photovoltaic field is necessary. In addition, the central inverter requires a low investment cost while allowing for simple maintenance. The simplicity of the assembly also allows a better efficiency of the conversion of the tension. Indeed, the series connection of several modules makes it possible to obtain a low transformation ratio, which increases the efficiency of the converter.

On the other hand, this assembly has several defects:

- Solar conversion losses (only one MPPT for a set of modules).
- Electrical losses and risks in DC wiring.
- No scalability.

- No continuity of service in case of inverter failure.

Despite the numerous defects of this configuration, this solution is still widely used in high power PV power plants.

3.4.3.2 Row inverter

One of the topologies most commonly used today is that of the inverter row (Fig. 3.6), which consists in implanting an inverter at the end of each chain. The inverters are then connected in parallel to the power grid, which requires coordination between the inverters (of the master - slave type) to prevent stand - alone operation and to avoid power exchanges between the inverters **[63]**.

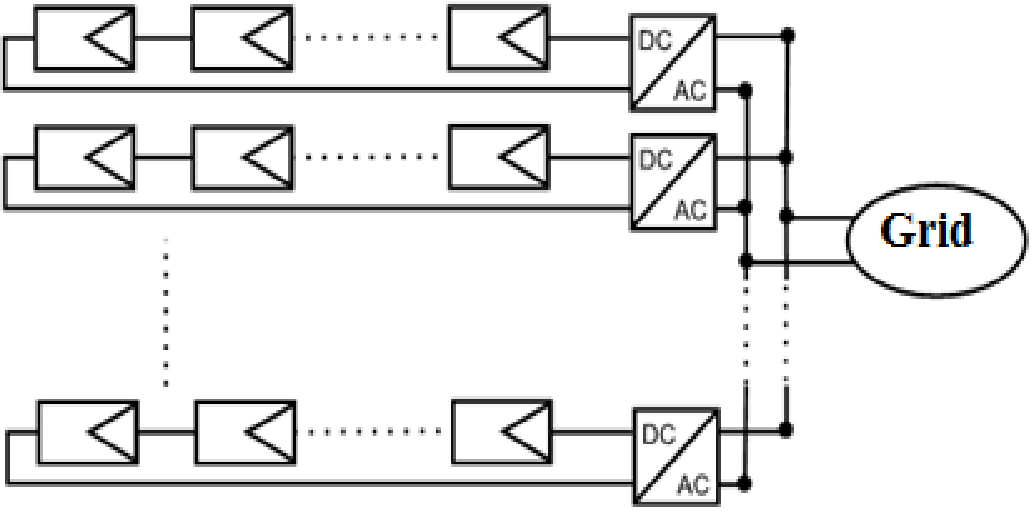

Fig. 3.6 Row inverter topology

The "row inverter" topology allows to improve the control of the power available by string thanks to the MPPT of each inverter. In addition, the continuity of service is increased because the failure of a converter does not result in total shutdown of the installation. Finally, this architecture is evolutionary since each string constitutes an independent subset. In case of power increase of the installation, only the AC connection must be replaced.

A comparison of the inverter structure "row" and "central" inverter, carried out by Italian researchers, showed that these two assemblies are similar, as regards losses in power electronics and in cables. According to the study, in both cases the energy lost accounts for about 10% of the total energy produced, the centralized structure being slightly less dissipative. On the other hand, in the case of shading of the PV system, the centralized architecture produces 12% less energy than the row structure. In conclusion, the study shows that the inverter row has an overall efficiency (which takes into account the losses as well as the number of sunny and shady days) higher efficiency of 1.5%. These conclusions are nevertheless to be balanced by the great difficulty in characterizing shading. This gain depends strongly on the shading considered. However, there are losses by serial coupling of the modules within a single string. The efficiency of the inverters remains variable depending on the power supplied by the photovoltaic chain (poor efficiency of the inverter with low power modules). An evolution called "Team concept" of the inverter row consists in introducing disconnectors downstream of the inverters. Since inverters have low efficiency at low input power, this structure proposes to modify the number of inverters used to carry out the conversion as a function of the power supplied by the PV field. Thus, the inverters operate close to their nominal power and therefore close to the zone of optimum efficiency. This evolution would make it possible to gain at least 4% of energy per year compared to the conventional structure.

3.4.3.3 Row chopper

The use of multiple conversion stages can improve the conversion efficiency and reliability of the system, by separating the functionalities of the inverter. Often presented as an intermediate solution between the central inverter and the row inverter, the row chopper, also called a multi-string converter, uses a chopper at the end of each PV system string (Fig. 3.7) **[63]**.

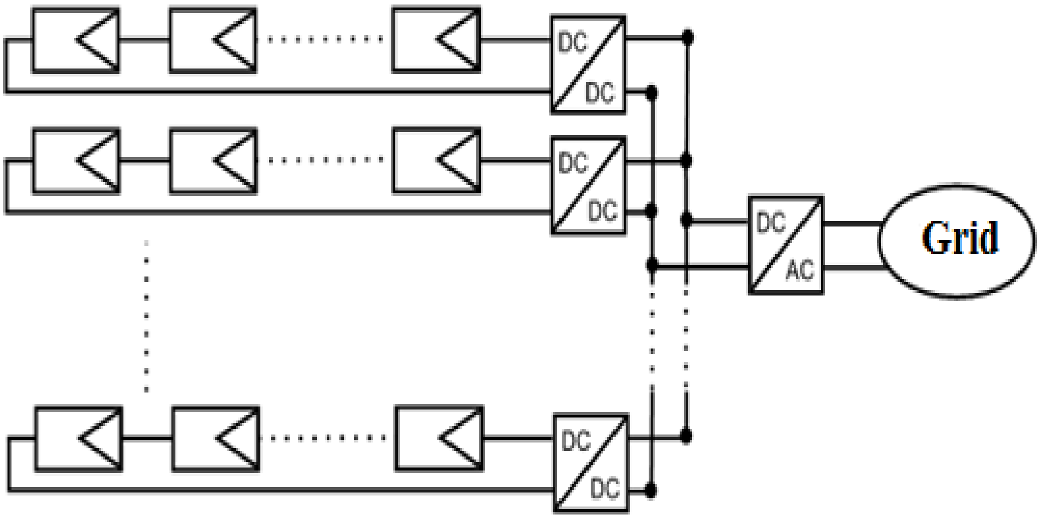

Fig. 3.7 Row chopper topology

Furthermore, the use of a single inverter as an interface with the grid reduces the number of interactions between the network and the PV plant. Participation of the facility in system services is therefore facilitated. The MPPT is done for each string, which limits the influence of the modules between them. The assembly remains evolutionary, but the continuity of service is not assured in case of failure of the inverter. Compared to the row inverter, costs are likely to be reduced because each chopper does not need to integrate voltage and current measurement and monitoring functions, control of the alternative part and Detection of residual direct current on the grid.

3.4.3.4 Parallel modular chopper

An evolution of the row chopper topology is the parallel modular chopper topology shown in Fig. 3.8. The chopper is no longer connected to a PV module chain but directly to the output of the PV module. This evolution keeps all the advantages of the chopper row, while increasing the level of discretization of the MPPT. Thus, it is no longer a chain of PV modules that works with its MPPT but each PV module. A productivity gain is therefore to be expected compared to the row chopper. In addition, this higher discretization allows finer monitoring and deeper fault detection **[63]**.

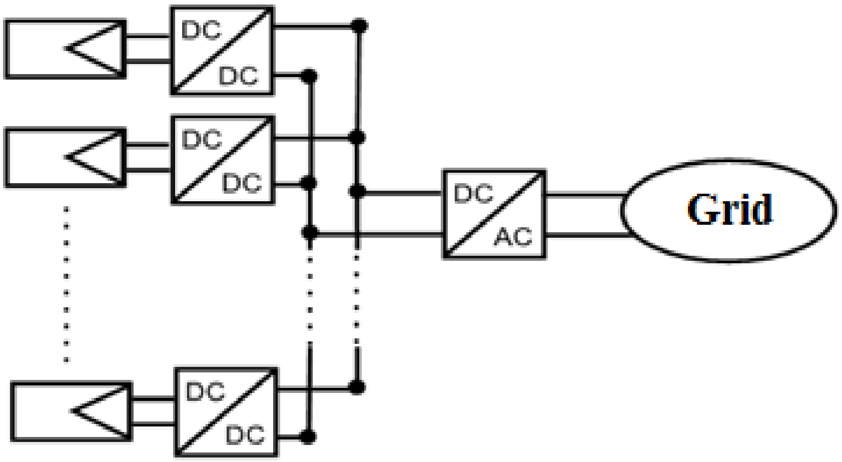

Fig. 3.8 Parallel modular chopper topology

The main hard point of this structure is the high lift ratio between the output voltage of the PV module and the voltage required for the injection on the distribution network. Indeed, for an uninsulated chopper and when the elevation ratio increases, the losses become significant. When this ratio is too large (> 8 in general), it is necessary to use isolated structures or cascades of converters.

3.4.3.5 Series modular chopper

One of the solutions to reduce the ratio of elevation of the choppers required for the parallel modular chopper topology is to put the output of the choppers in series. Thus the ratio of elevation is decreased as the number of choppers in series is increased. This topology, called a series modular chopper, is shown in Fig. 3.9 **[63]**.

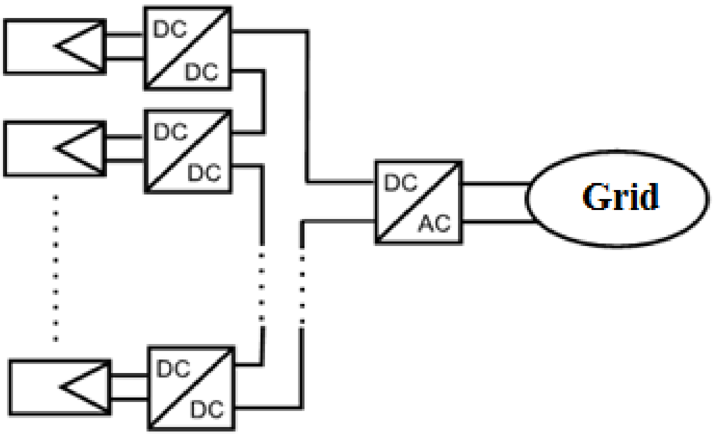

Fig. 3.9 Series modular chopper topology

This topology retains all the advantages of the previous topology while decreasing the elevation ratio of the choppers and thus increases the yield. On the other hand, the serialization of the choppers implies a dependence of the operating points on each other and complicates the control laws and the dimensioning of the structure **[63]**.

3.5 Conclusion

In this chapter, we have presented in detail the mathematical model of the PV cell, the PV module and the PV generator and the calculation of some parameters. We have identified the main functions that manage a PV generator connected to the power grid and the different diagrams that show the connection of the PV generator to the power grid.

CHAPTER 4: PERFORMANCE INVESTIGATION OF A GRID-CONNECTED PV SYSTEM FOR FAMILY FARMS

4.1 Introduction

Farms have roofs of large areas, therefore they are well suited to accommodate a photovoltaic electricity production system. As far as the farmers are concerned, the construction of solar power plants on their land can indeed prove a lucrative solution that guarantees annual revenues. To make a performance investigation of a grid-connected PV system for farms, a detailed study on their electrical energy consumption is necessary to install an economical and reliable photovoltaic generator.

4.2 Presentation of family farms

Economic diversification and the reduction of dependence on the hydrocarbons sector are two essential conditions for achieving strong and balanced economic growth, and also acquire a much desired independence of food. Agriculture is an important factor in the economy of Algeria. Over the period 2010-2014, it generated almost 10% of the gross domestic product, including the agro-food industries. This sector employed 11% of the working population **[64]**. In both developed and developing countries, more than 500 million, or nine out of ten, farms are managed by families, making family farms the predominant form of agriculture. They not only produce about 80% of the world's food but also serve as custodians of about 70 – 80% of farm land. The United Nations launched the 2014 International Year of Family Farming to stress the vast potential family farmers have to eradicate hunger and preserve natural resources **[65]**.

In Algeria, the Ministry of Agriculture and Rural Development (MARD) has designed and developed agriculture general census in 2001 with the help of the National Office of Statistics (ONS) and the United Nations Organization of Food and Agriculture (FAO). This census has affected all farms in Algeria (Fig. 4.1), the agriculture sector had more than 1 million of farms and the family farm predominated with 83.1% of the total number of the farms **[66]**. Since 2001, no census has been done. Depending on the region, family farms in Algeria have diversified agricultural productions (cattle, eggs, fruits, vegetables, cereals, wool, etc.). Today, these farms can make agriculture an even more important sector in the development of the country's economy by producing agricultural food products and electric power.

Fig. 4.1 Geographical location of the Chlef district

4.3 Family farms electricity consumption

The family farms supply the local and regional food market, contributing significantly to food security at the local, national and regional level. The electrical energy in the family farm is required for different usages, lighting, mechanical ventilation, water pumping, milking, milk cooling and refrigeration for agricultural products storage, as shown in Fig. 4.2.

Fig. 4.2 Electrical energy usages of the studied farm

4.3.1 Lighting load

Natural lighting is not enough in a livestock building, it must be supplemented by artificial lighting to improve comfort, production or even fertility and health of animals. The artificial lighting stimulates the ingestion of animals and thus increases the milk production and the weight gain. A regime of 16 h of light at a level of 150–200 lux followed by 8 h of darkness in dairy cows produces significantly more milk and milk fat **[67,68]**. Although, this regime vary from period to another period. The energy consumption of lighting can be calculated by Eq. (4.1):

$$E_L = P_L N_L t_L \tag{4.1}$$

Where: E_L is the daily electrical energy consumption of lighting (Wh/d),P_L is the power of the lamp (W), N_L is the lamps number and t_L is the lighting time.
The lamps number to be installed inside livestock building is equal to the total luminous flux L (lumen) required divided by the flux emitted by one lamp ℓ (lumen), as it is expressed by Eq. (4.2)

$$N_L = \frac{L}{\ell} \tag{4.2}$$

The total luminous flux to be installed is given by Eq. (4.3):

$$L = IN_AS \tag{4.3}$$

Where : I is the illumination required per animal (lux), N_A is the animals number, S is the surface required per animal (m^2).

4.3.2 Mechanical ventilation load

The aim of using mechanical ventilating system in livestock building is to provide sufficient airflow at a low pressure difference to maintain a good quality of the environment in livestock buildings where it fulfils several functions, controlling the temperature and the moisture within a building, removing generated gases animals, dust, odors and pathogens. Table 4.1 recommended three seasonal ventilating rates for livestock building of dairy mature cows, which depend on the animal weight **[69,70]**.

Table 4.1: Mechanical ventilating rates in livestock building for dairy cows.

Period	**Ventilation rates (m^3/h/454 kg)**
Cold weather	61
Mild weather	204
Hot weather	569

The mechanical ventilation load E_V (Wh) is calculated by Eq.(4.4).

$$E_V = N_F P_F f_F \tag{4.4}$$

Where : P_F is the power of the fan (W), f_F is the fan operating frequency (8 h/d for dairy cows), N_F is the fans number. The fans number to be installed in a livestock building is given by Eq (4.5).

$$N_F = \frac{N_A AF_A}{AF_F} \tag{4.5}$$

Where : AF_A is the airflow required by animal (m^3/h) and AF_F is the fan air flow (m^3/h).

4.3.3 Pumping load

Among the main applications of using PV systems in the farms are pumping water for farmland irrigation and animals watering **[71–74]**. In the visited family farms, the amount of water required for animals watering varies from 50 l per animal per day in cold season to 100 l per animal per day in hot season. The amount of water to be pumped to irrigate the orange field of the studied farm depends on the season, it is very important in the summer season. The requirement amount of water in the studied farm is calculated by using the Eq (4.6).

$$Q = N_A\, q_A + Q_{irr} \tag{4.6}$$

Where : Q (l/d) is the total water requirement per day, q_A is the water required amount per animal per day (l/d) and Q_{irr} is the amount of water for irrigation per day (l/d). The time required to pumping this amount of water can be calculated by Eq.(4.7).

$$f_P = \frac{Q}{Q_V} \tag{4.7}$$

Where : Q_V is the pump flow rate (l/mn). The energy consumption required for water pumping can be estimated by Eq (4.8):

$$E_P = P_P f_P \tag{4.8}$$

Where : P_P (W) is the pump power.

4.3.4 Milk cooling and milking loads

In the studied farm, a cow is treated twice a day, in the morning and evening. The time spent on milking is about 2.7 h/d. The energy consumption due to cows milking is calculated by the following equation :

$$E_M = P_M N_A t_M \tag{4.9}$$

Where : E_M is the energy consumption due to milking (Wh), P_M is the milking machine power (W) and t_M is the milking time (h).

Milk cooling depends on the milk tank power which allows the cooling of the milk from 35 °C to 4 °C, while the storage time of it depends on the temperature of the outside. E_{MC} that is the energy consumption due to milk cooling (Wh), is calculated by Eq (4.10):

$$E_{MC} = P_T t_{MS} \tag{4.10}$$

Where : P_T is the tank power (W) and t_{MS} is the milk storage time (h).

4.3.5 Refrigeration load:

Cold rooms for agricultural products storage are crucial to minimize post-harvest losses, on the other side necessitate a great electrical energy with a reliable supply with it. Their electrical energy consumption depends on the storage time, the number and power of the cooling machine. The energy consumption of the cold rooms is calculated by Eq (4.11):

$$E_R = P_{RP} N_{CM} t_S \tag{4.11}$$

Where : E_R is the energy consumption of the cold rooms (Wh), P_{RP} is the cooling machine power (W), N_{CM} is the cooling machine number and t_{RS} is the agricultural products storage time (h).

4.4 Case study

4.4.1 Presentation of Chlef district

4.4.1.1 Location

A case study is developed in the Chlef district located in the Northwestern of Algeria (36°16 N and 1°33 E, 200 km from the capital Algiers) as shown in Fig. 4.1. The area of the district Chlef is 4 791 km^2 and divided into 23 municipalities. The geographical relief in it is mainly characterized by two mountains ranges (Dahra and Ouarsenis), a central plain and a seacoast. It is also mostly characterized by the agricultural vocation and the existence of significant water resources **[75]**. The agricultural activity in this area is based on breeding of cows and sheep, agriculture and agricultural products storage.

4.4.1.2 Electrical energy situation

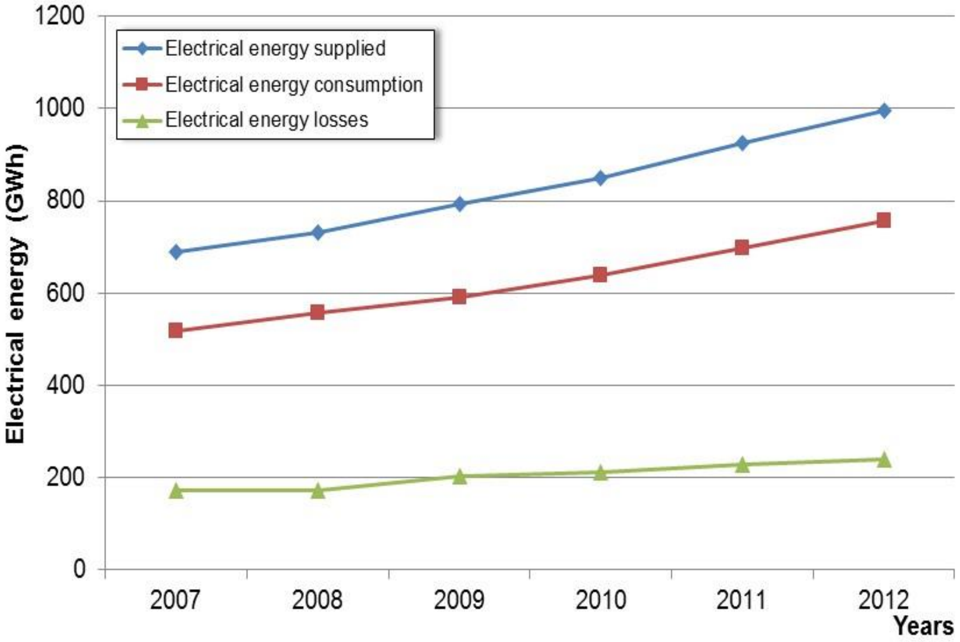

Fig. 4.3 Electrical energy evolution in Chlef district.

The electrical energy distribution in the district of Chlef has frequent power cuts especially in summer period where there is a sharp increase in the use of electrical energy and a high number of maintenance work.

Fig. 4.3 shows the evolution of the electrical energy during the period 2007–2012 **[32]**. As shown, the electrical energy supplied to the Chlef district increased from 689 GWh in 2007 to 997 GWh in 2012 and the electrical energy consumption increased from 517 GWh in 2007 to 757 GWh in 2012. The electrical energy losses increases from 171 GWh in 2007 to 240 GWh in 2012. Thus, the rate of the electrical energy losses varied between 24% and 25% during 2007–2012.

4.4.1.3 Weather conditions

The Chlef district is characterized by a Mediterranean climate, cold in winter, hot in summer and mild in autumn and spring. The monthly averaged daily global solar radiation and the average monthly temperature data for the Chlef district are shown in Figs. 4.4 and 4.5 **[76]**. The maximum values are found in summer (7.97 kWh/m^2/d and 34 °C) and the minimum values in winter (2.77 kWh/m^2/d and 12.3 °C).

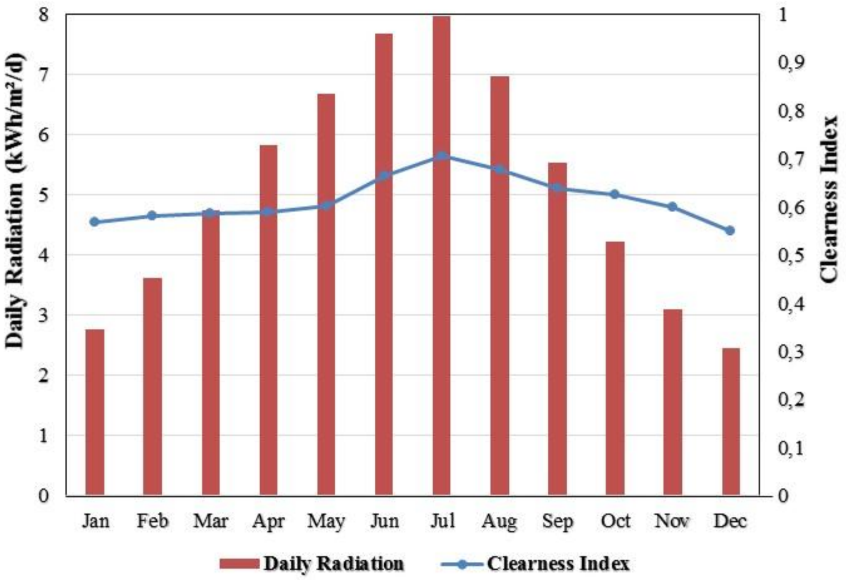

Fig. 4.4 Monthly global solar radiation and clearness index for Chlef district

The average global solar radiation and the average daytime ambient temperature over the year are 5.24 kWh/m^2/d and 22 °C. The monthly clearness index (Fig. 4.4) indicates the fraction of the solar radiation striking the top of the atmosphere that makes it through the atmosphere to strike the Earth's surface, it varies between 0.55 in the month of December (rainy season) and 0.706 in the month of July (dry season).

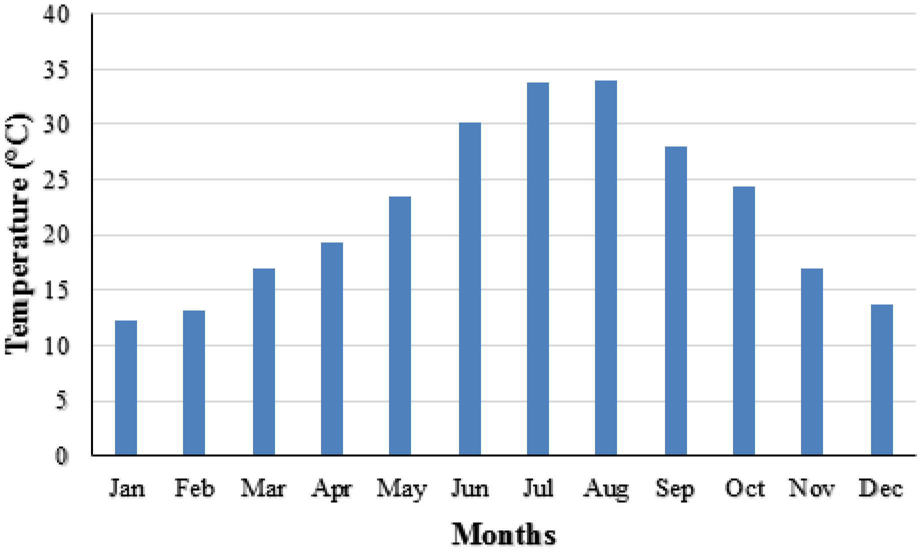

Fig. 4.5 Average monthly temperature in Chlef district

4.4.2 Family farms loads in Chlef district

The survey carried out in Chlef district showed that there were 97 family farms spread over twelve municipalities marked by blue on the map of the Chlef district (Fig. 4.6). According to the subsidiary of Sonelgaz in Chlef district, the electrical energy consumption of these farms varied from 3.9 to 457.2 MWh/yr and the total has reached 8.3 GWh in 2011. As shown in Fig. 4.7, the electrical energy consumptions of 67 farms are below 95 MWh/yr. Therefore, in the present study, a farm of the annual electrical energy consumption (91.53 MWh/yr) was chosen as a reference farm to study the feasibility of utilizing a grid-connected PV system.

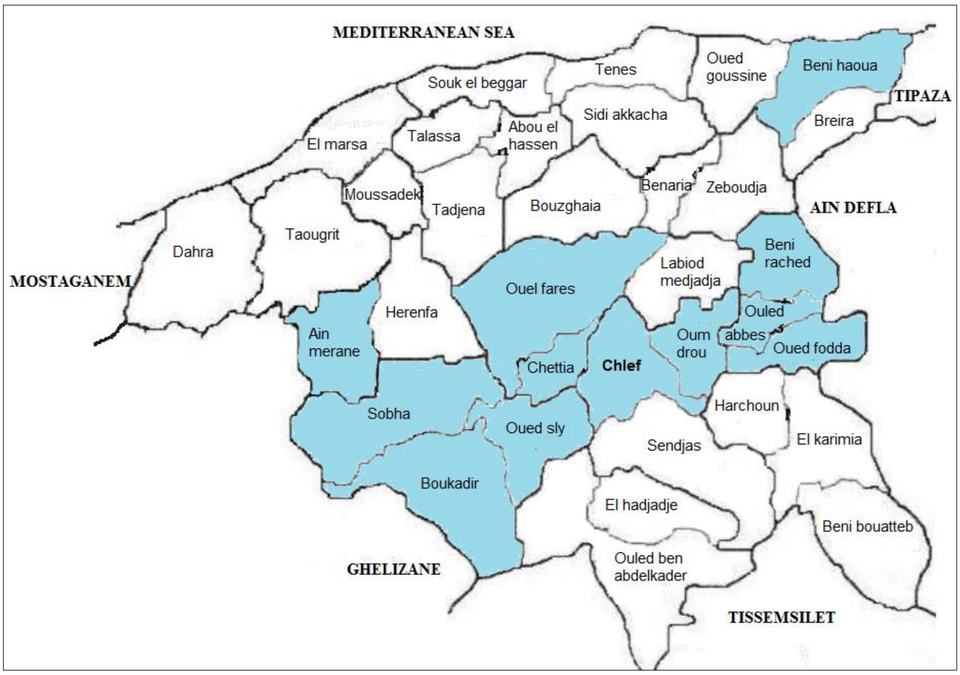

Fig. 4.6 Family farms distribution in the municipalities (blue) of the Chlef district.

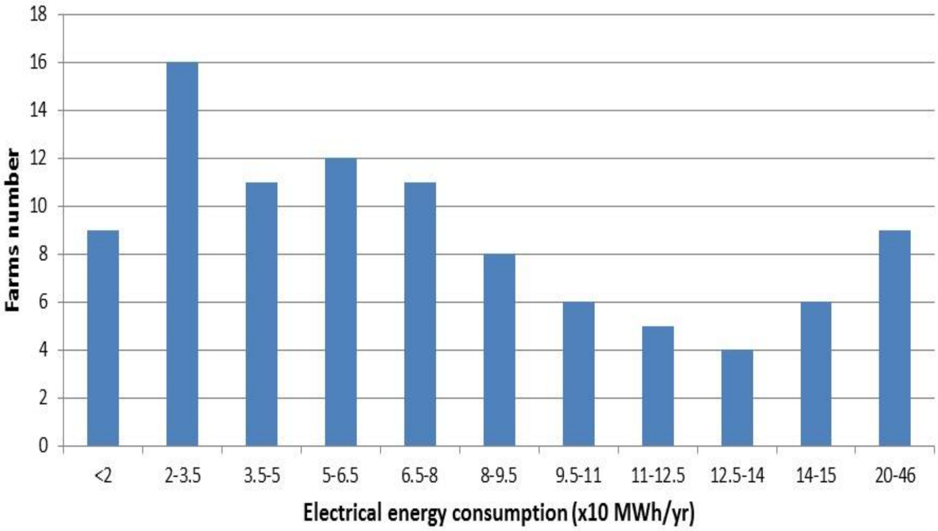

Fig. 4.7 Farms number according to the electrical energy consumption

4.4.3 Load profile of a reference family farm

The studied family farm located in Chettia municipality consists of a breeding building with fifteen cows and six calves, a storage building for fodder, seven cold rooms to store agricultural products, an irrigation well, a water basin and an orange grove of twenty acres (Fig. 4.8).

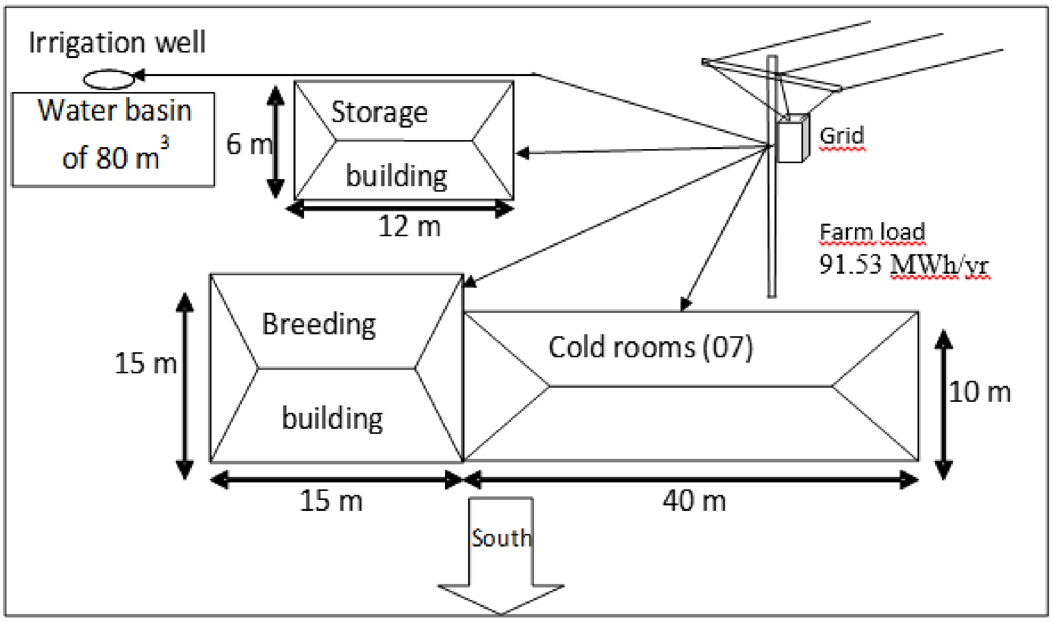

Fig. 4.8 Schematic diagram of the farm.

Fig. 4.9 Aerial view of the studied farm located in Chlef district of Algeria.

The aerial view of the studied farm is shown in Fig. 4.9. Fig. 4.10 shows an interior view of this farm. Based on the electricity bill of the studied family farm, Fig. 4.11 shows the monthly electrical energy consumption during 2011. It includes the following loads, lighting, ventilation, pumping water for irrigation and animals watering, milking, milk cooling and refrigeration of agricultural product storage. According to Fig. 4.11, the electrical energy consumption can be divided into three periods, it is low in the months of January, February, March, October, November and December (first period), while it is average in the months of April, May and September (second period) and very high in the months of June, July and August (third period). The electrical energy consumption in the first period has reached 9.38 MWh, in the second period 21.9 MWh and in the third period 60.7 MWh. Fig. 4.12 shows the electrical energy consumption per hour during the three periods, which is higher during the day than in the night particularly in the second and in the third period.

Fig. 4.10 Interior view of the studied family farm, (a) inside the breeding building, (b) outside and (c) orange grove

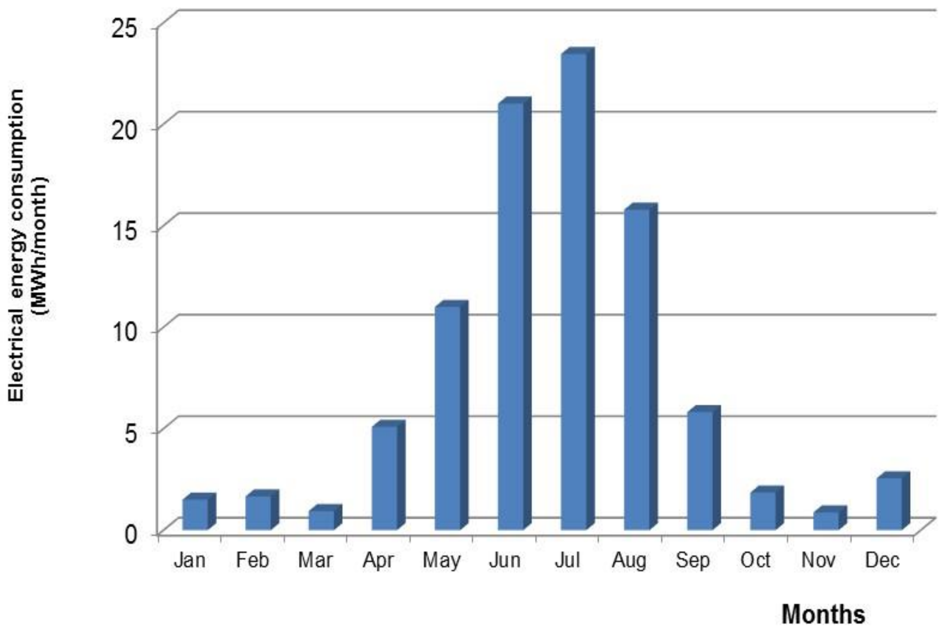

Fig. 4.11 Monthly electrical energy consumption.

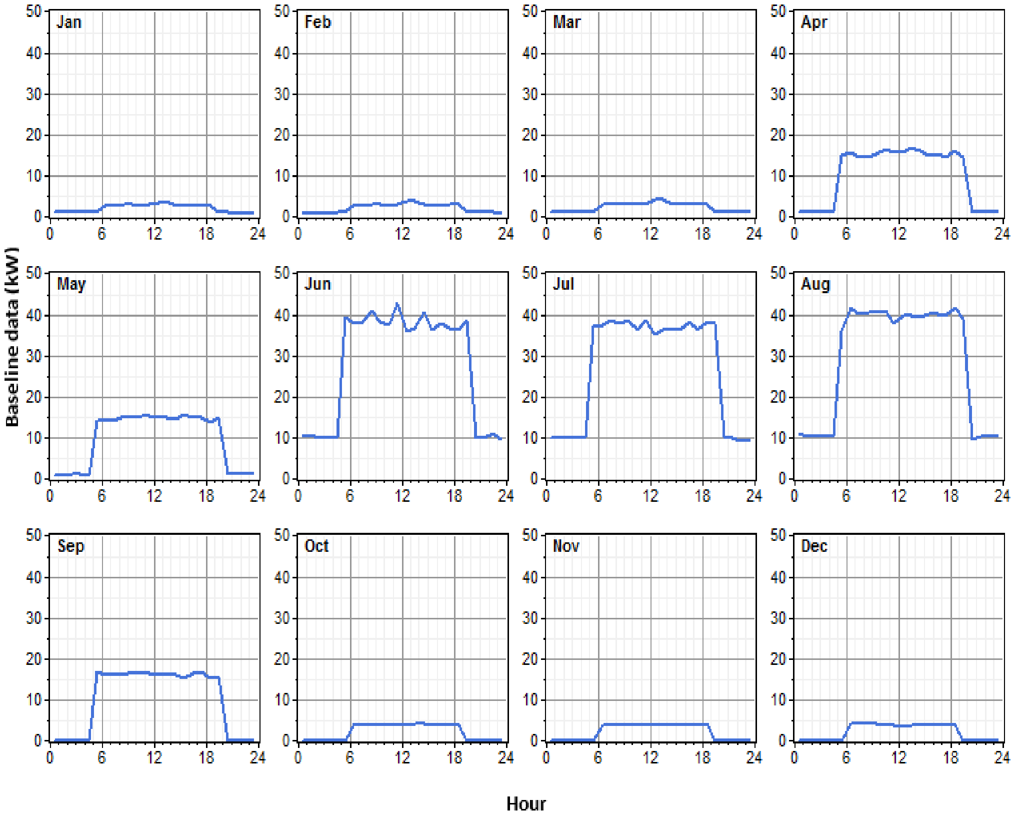

Fig. 4.12 Electrical energy consumption profile of the studied farm.

4.5 Power calculation of the grid-connected PV system

The grid-connected PV system considered for simulation can be seen in Fig. 4.13. It consists of a PV array, a grid, an AC bus, a DC bus, an inverter and a farm load. The peak power of the PV system is calculated by using Eq (4.12):

$$P = \frac{E_{AC}\ G_{T,STC}}{G_g\ f_{PV}\ \eta_{inv}} \tag{4.12}$$

Where : P is the peak power of the PV system (kW_p), $G_{T,STC}$ is the solar radiation at STC (1 kW/m^2), G_g is the global solar radiation (kWh/m^2/d), f_{PV} is the PV derating factor (0.8), E_{AC} is the daily power consumption (253 kWh/d) and η_{inv} is the inverter yield (0.95). Since we have two power sources (PV system and grid), the computation of the peak power value of the PV system is based on the irradiation of the most favourable month. 7.97 kWh/m^2/d is the maximum value, which is observed in the month of July. Using the Eq (4.12), the peak power of the PV system is 40 kW_p.

Given that the power of the PV module is given under standard conditions (STC: 1000 W/m^2, 25 °C, Solar Spectrum AM=1.5), which rarely correspond to real conditions, the power of the inverter must be less than about 5–10% compared to the maximum power of the PV array. It's expressed by Eq (4.13).

$$0.90\ P \leq P_{inv} \leq\ P \tag{4.13}$$

Where : P_{inv} is the power of the inverter (kW).

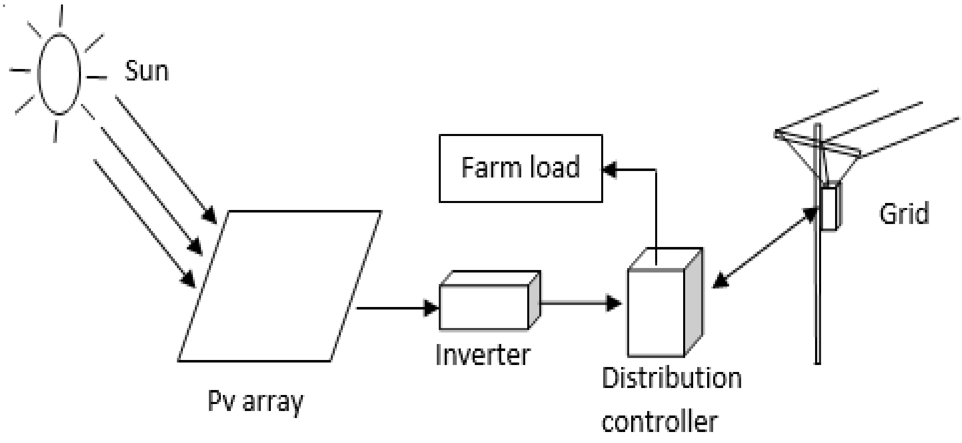

Fig. 4.13 Schematic of the grid-connected PV system.

4.6 HOMER model

Researchers have been using different optimization softwares such as HOMER and several other optimization algorithms such as particle swarm optimization (PSO) to assess the performance and reliability of hybrid power generation systems **[77–83]**. HOMER software developed by NREL (National Renewable Energy Laboratory (USA) **[84]** is one of such energy modelling tools, which is being used by the researchers for the optimization and modelling power generating systems such as wind turbines, fuel cells, hydropower, biomass, converters, batteries, conventional generators, and PV systems **[85–89]**. HOMER is a powerful tool for the optimal designing, sizing and planning of hybrid renewable energy systems by carrying out techno-economic analysis for off-grid and grid connected power systems. It takes inputs such as electric loads to perform simulations based on different system's configurations or the hybrid combinations of components and generates the optimized system configurations sorted in term of NPC. HOMER models the operation of a system by generating energy balance calculations for each of the 8760 h in a year. For every hour, HOMER compares the electric demand in one hour to the energy that the system can supply in that hour, calculates the energy flows to and from each component of the system. This subsection highlights the mathematical models used in the HOMER simulation to achieve a balance between energy demand and the energy that can be supplied by the power generating system.

Eq (4.14) is used to calculate the PV energy output from the PV system for each of the 8 760 h in a year by using HOMER software.

$$E_{PV} = Y_{PV} f_{PV} (\frac{G_T}{G_{T,STC}}) \left[1 + \alpha_P (T_C - T_{C,STC})\right] \tag{4.14}$$

Where : Y_{PV} is the rated capacity of the PV array, meaning its power output under standard test conditions (kW), G_T is the solar radiation incident on the PV array in the current time step (kW/m^2), $G_{T,STC}$ is the incident radiation at standard test conditions (1 kW/m^2), α_P is the temperature coefficient of power

(%/°C),T_c is the PV cell temperature in the current time step (°C), $T_{c,STC}$ is the PV cell temperature under standard test conditions (25 °C). The hourly PV energy purchased and injected from/to the grid are calculated by Eqs (4.15) and (4.16). the hourly energy purchased from the grid is done when the energy demand is higher the the PV energy, and the PV energy injected into the grid is done when the energy demand is lower than the PV energy.

$$E_{grid,h} = E_{Load,h} - E_{PV,h} \text{ if } E_{Load,h} > E_{PV,h} \tag{4.15}$$

$$E_{sold,h} = E_{Load,h} - E_{PV,h} \quad \text{if} \quad E_{Load,h} < E_{PV,h} \tag{4.16}$$

Eqs (4.17) and (4.18) calculate the annual energy produced (E_{an}) during the year (8 760 h) and the renewable fraction (RF) which represents the PV energy contribution.

$$E_{an} = E_{PV} + E_{grid} \tag{4.17}$$

$$RF = \frac{E_{PV}}{E_{an}} \tag{4.18}$$

Where : E_{grid} is the grid energy (kWh/yr), E_{PV} is PV energy (kWh/yr) and E_{an} is the annual energy production (kWh/yr).

The steps for calculating the PV power output, the grid energy purchased, the PV energy sold, the annual energy production and the renewable fraction are treated in the algorithm in the Fig 4.14.

The first step consists of introduction into Homer software the following data, meteorological and geographic coordinates data of Chlef district, equipment characteristics of the grid-connected PV system sized and load profile of the studied farm.

The second step consists of calculation the peak power of the PV system and the inverter power.

The third step consists of calculation for each hour the PV energy output, the grid energy purchased and the PV energy sold.

The fourth step consists of calculation of the annual energy supplied by the grid-connected PV system sized and the renewable fraction.

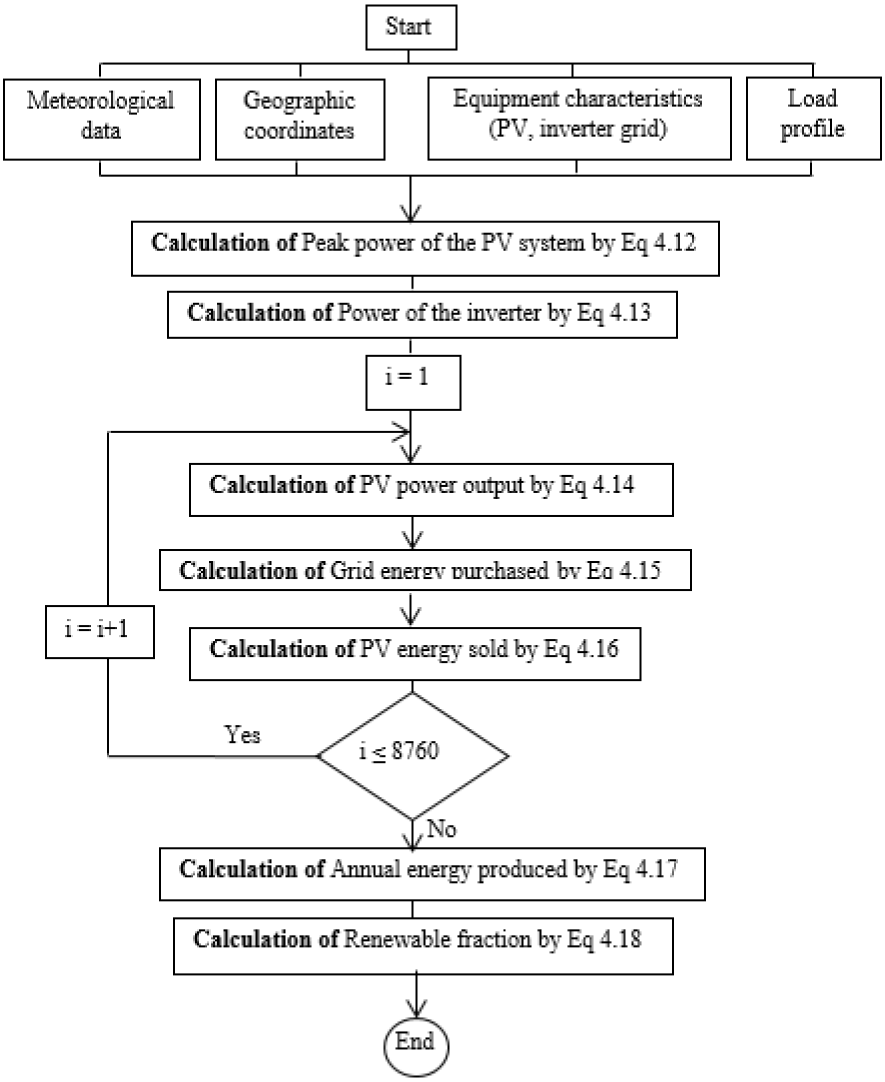

Fig. 4.14 Algorithm for calculating the annual energy production and the renewable fraction

4.7 Simulation results

The following data were used in the simulation, an hourly electrical energy consumption profile of each month, the power of the PV system 40 kW_p, different tilt angles of the PV array (15°, 20°, 25°, 30°, 35° and 40°), the daily radiation and the monthly average temperature.

Table 4.2 shows for different tilt angles during one year the PV energy production (E_{PV}), the grid energy used (E_{grid}), the annual energy (E_{an}) and the renewable fraction (RF). The tilt angle 35° gives the best PV energy production compared with the following angles 15°, 20°, 25°, 30° and 40°. The renewable fraction of the PV array with 35° represents 54% and the grid energy consumed (56.91 MWh/yr) by the farm represents 46% of the annual energy.

Table 4.2 : PV Energy produced at different tilt angles

Tilt angle (°)	PV energy (MWh/yr)	Grid energy (MWh/yr)	Annual energy (MWh/yr)	Renewable fraction (RF) (%)
15	63,72	55,30	119,03	54
20	64,84	55,55	120,39	54
25	65,61	55,89	121,50	54
30	66,03	56,34	122,37	54
35	66,07	56,91	122,98	54
40	65,73	57,59	123,33	53

Based on the optimal tilt angle found, we will simulate the PV system operation using different PV system powers (30, 35 and 40 kW_p) in order to determine the minimum peak power of the PV system that could give an annual PV energy production equals the annual energy purchased from the grid. Table 4.3 gives for three PV system powers 30, 35 and 40 kW_p the PV energy production (E_{PV}), the grid energy used (E_{grid}), the annual energy (E_{an}) and the renewable fraction (RF). During one year, the PV system of 35 kW_p produces PV energy that nearly equals the energy purchased from the grid, this production represents 49% of the total energy supplied by the grid and the PV system, which is equal to 117.6 MWh/yr. The energy purchased from the grid represents 51% of the annual energy.

Table 4.3 : Energy production by different PV systems

PV system power (kW_p)	PV energy (kWh/yr)	Grid energy (kWh/yr)	Annual energy (kWh/yr)	Renewable fraction (RF) (%)
30	49,55	62,89	112,44	44
35	57,81	59,75	117,57	49
40	66,07	56,91	122,98	54

Fig. 4.15 shows the monthly average electrical energy produced by the PV system of 35 kW$_p$ and the electrical energy purchased from the grid. The PV system of 35 kW$_p$ covers almost the farm load throughout the year except for the followings months June, July and August where there is high electrical energy consumption. The installation of the PV system of 35 kW$_p$ will be less costly and take less space than the installation of the PV system of 40 kW$_p$.

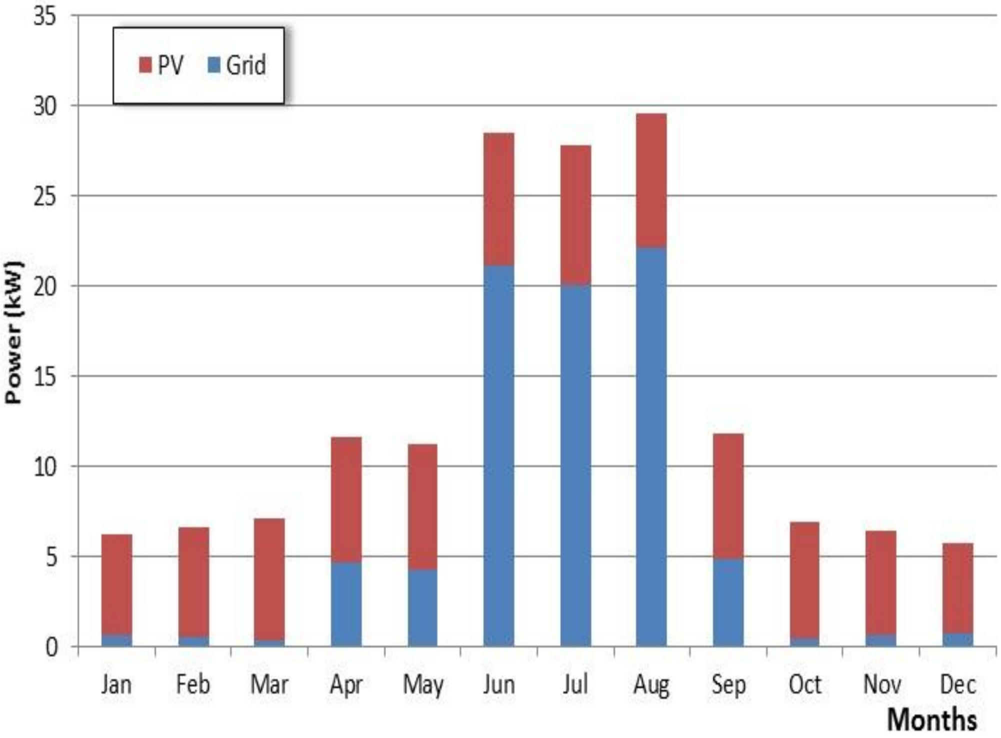

Fig. 4.15 Monthly average electric production.

Hourly energy balance of the 15th February day between the farm load and the power supplied by the grid-connected PV system is shown in Fig. 4.16. From 00.00 a.m. to 09.00 a.m. and 19.00 p.m. to 00.00 a.m., the farm load is supplied by the grid. From 09:00 a.m. to 19:00 p.m., the PV power is greater than the farm load, the PV power not consumed will be sold to the grid. This figure shows also that the PV power depends on the incident solar. Daily energy balance shows that the PV energy is greater than the farm load.

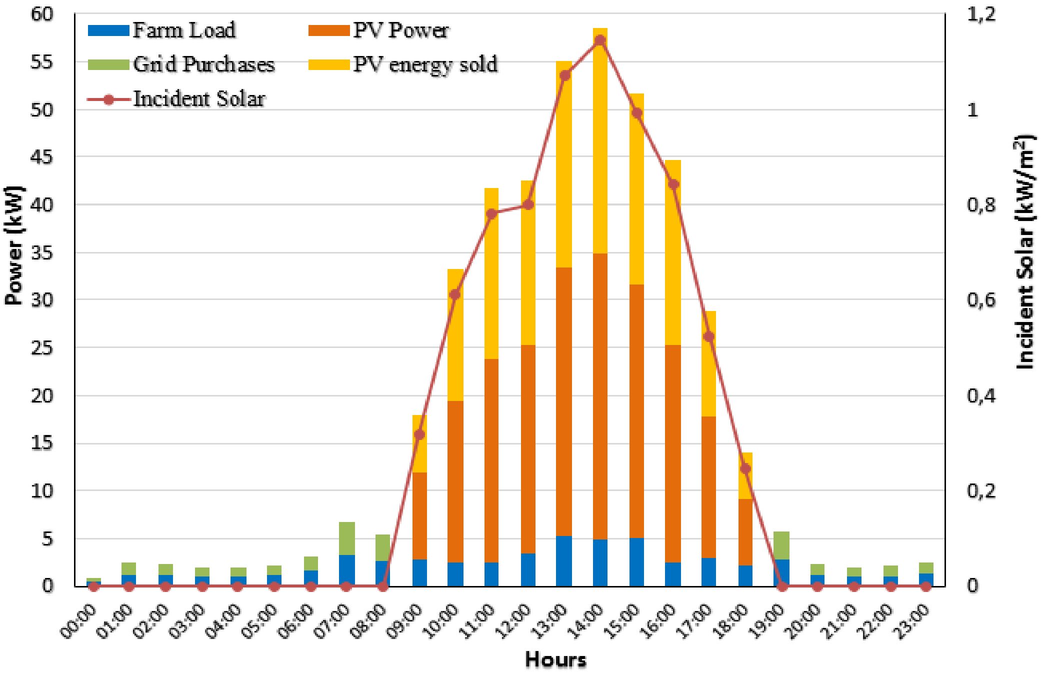

Fig. 4.16 Hourly energy balance calculated of the 15 February.

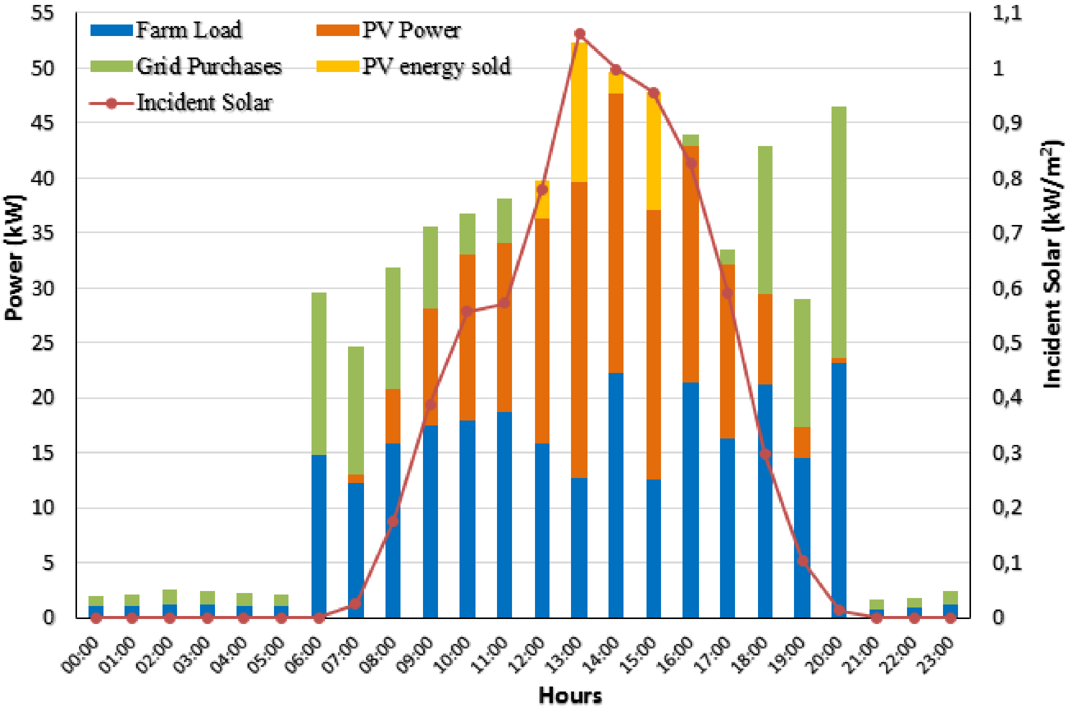

Fig. 4.17 Hourly energy balance calculated of the 15 May.

Hourly energy balance of the 15th May day between the farm load and the power supplied by the grid-connected PV system is shown in Fig. 4.17. From 00.00 a.m. to 07.00 a.m. and 21.00 p.m. to 00.00 a.m., the farm load is supplied by the grid. From 7:00 a.m. to 12:00 p.m. and 16.00 p.m.to 21.00 p.m., the PV power is less than the farm load, the power lack will be purchased from the grid. From 12:00 p.m.to 16:00 p.m., the PV power is greater than the farm load, the excess of PV power will be sold to the grid. This figure shows also that the PV power depends on the incident solar. Daily energy balance shows that the PV energy is less than the farm load.

Hourly energy balance of the 15th July day between the farm load and the power supplied by the grid-connected PV system is shown in Fig. 4.18. From 00.00 a.m. to 07.00 a.m. and from 20.00 p.m. to 00.00 a.m., the farm load is supplied by the grid. From 07:00 a.m. to 20:00 p.m., the PV power is less than the farm load, the power lack will be purchased from the grid. This figure shows also that the PV power depends on the incident solar. Daily energy balance shows that the PV energy is less than the farm load.

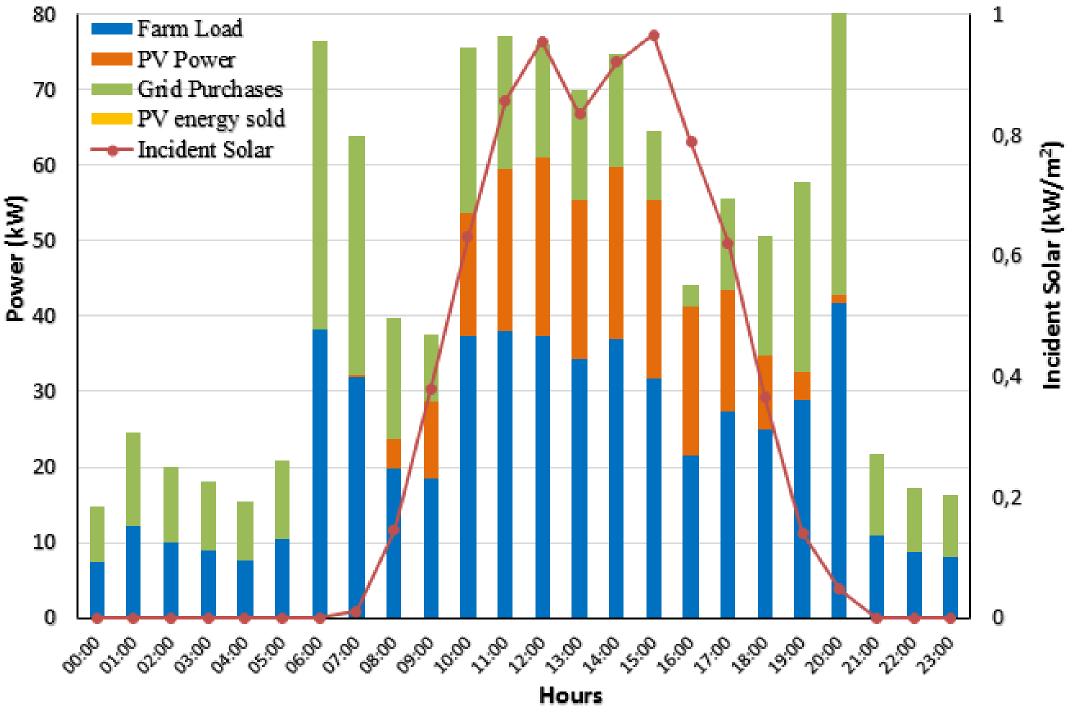

Fig. 4.18 Hourly energy balance calculated of the 15 July.

Fig. 4.19 shows the monthly load of the studied family farm, the monthly PV energy production and the monthly grid energy purchased to satisfy the load demand of the farm in times when the PV energy production is insufficient and to supply it in the night when there is no PV energy production. It is shown also, the monthly PV energy consumed by the farm and the monthly PV energy excess sold to the grid in times when the PV energy production is greater than the farm load demand. We note that the PV energy consumed by the farm is greater than the grid energy purchased except in the following months, Jun, Jul and Aug. The difference between the PV energy sold to the grid and the grid energy purchased in the months (Jan, Feb, Oct, Nov and Dec) represents additional income for the farmer.

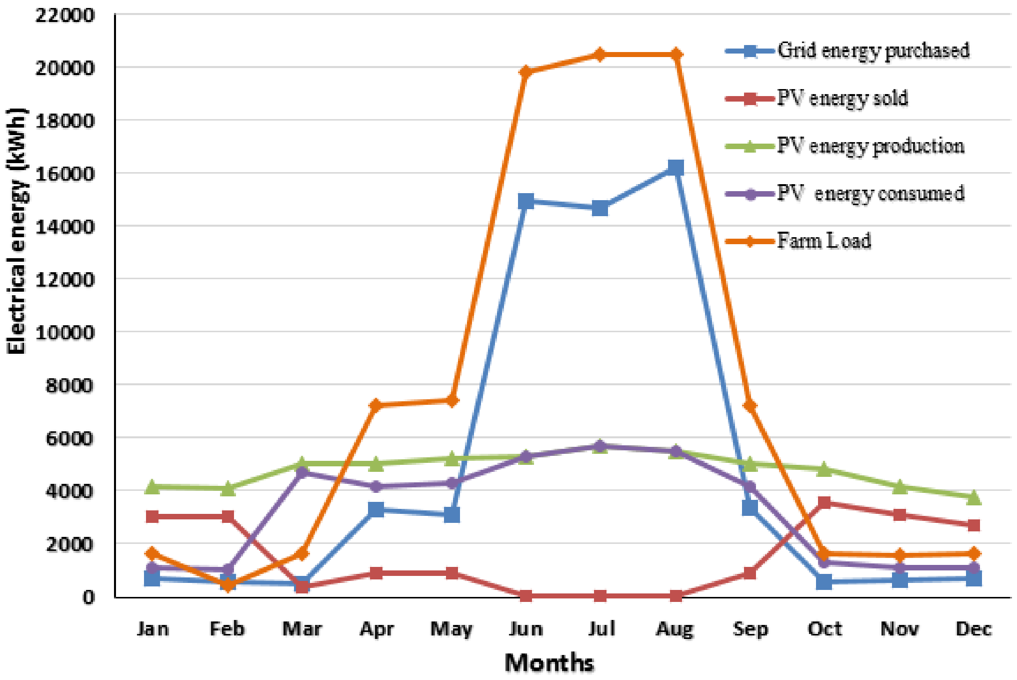

Fig. 4.19 Monthly electrical energies balance of the grid, PV array and farm load.

The yearly electrical energy balance of the studied grid-connected PV system is presented in the Table 4.4. The electrical energy supplied by the grid-connected PV system is 117.06 MWh/yr, 57.81 MWh/yr have produced by the PV array and 59.25 MWh/yr purchased from the grid. The PV energy injected into the grid has reached 21.83 MWh/yr and the PV energy remaining (35.98 MWh/yr) has consumed by the farm. The renewable fraction (RF) which represents the PV energy contribution has reached 49%.

Table 4.4: Yearly electrical energy balance.

	Production			Consumption	
	MWh/yr	%		MWh/yr	%
PV array	57.81	49	Farm load	91.53	81
Grid purchases	59.25	51	Grid sales	21.83	19
Total	117.06	100	Total	113.16	100

4.8 Conclusion

The aim of the present paper was to give a conscious analysis of the performance of a grid-connected PV system for family farms in North-West of Algeria. A reference family farm with an electrical energy consumption of 91.53 MWh/yr was chosen through a survey performed in the Chlef district. To conduct this investigation, a grid-connected PV system was sized to supply this farm and improve consequently its energy balance. The yearly electrical energy balance showed that the 35 kWp grid-connected PV system could produce 117.06 MWh/yr, the renewable fraction (RF) which represents the PV energy contribution reached 49%, and the PV energy consumed by the farm covered almost 60% of its load.

CHAPTER 5: IMPACT OF GRID-PHOTOVOLTAIC USE ON FARMS AND ON SOLAR DEVELOPMENT

5.1 Introduction

The challenges faced by farmers in expanding their cultivated areas and developing their livestock are the supply by electricity and the continuous increase of the purchase price of it. Fortunately, solar photovoltaic electricity generation can supply and supplement many farm energy requirements. Although the electricity generated by photovoltaic modules can help to reduce electricity consumption from the grid and to sell PV energy to the grid when the farm demand is lower than the PV energy production. The price of the PV energy sold to the grid encourages expanding the PV installation in farms if it is higher than the price of the grid energy purchased from the grid. Solar photovoltaic power can be installed on a wide range of power to power agricultural farms with electrical energy according to their power consumption. This is now a proven technology with the ability to reduce energy bills and reduce carbon emissions. It is a particular advantage where the majority of the electricity can be used in the farms. Agricultural farms in Chlef are connected to the grid by low voltage and we have seen in Chapter 2 that more than 50% of the electrical energy produced in Algeria is intended for consumers who uses low voltage. In this case, Photovoltaic energy should be of great importance by the government in its policy by encouraging farmers to install a photovoltaic generator on their farms.

5.2 Impact of the grid-connected PV system on the overall farms load

In order to analyze the impact of the grid-connected PV system on the overall farms load, the yearly PV energy production of each grid-connected PV system is calculated by HOMER software **[84]** and PVGIS software **[76]**. The following data were used, optimal tilt (35°), η_{inv} is the inverter yield (0.95), the irradiation of the most favorable month (7.97 kWh/m^2/d), the PV derating factor (0.8), the daily electrical energy consumption of each farm and the peak power of PV array for each farm which was calculated by Eq (4.12). Fig. 5.1 shows that the load of 97 farms ranges from 3.9 to 457.2 MWh/yr while the peak power of the PV array ranges from 1 to 207 kW$_p$. Fig. 5.2 shows that the results of these two software are appropriately close. This study has concluded that the yearly PV energy produced in the overall farms located in Chlef district has reached 6.2 GWh and represented 74% of the total load of these farms.

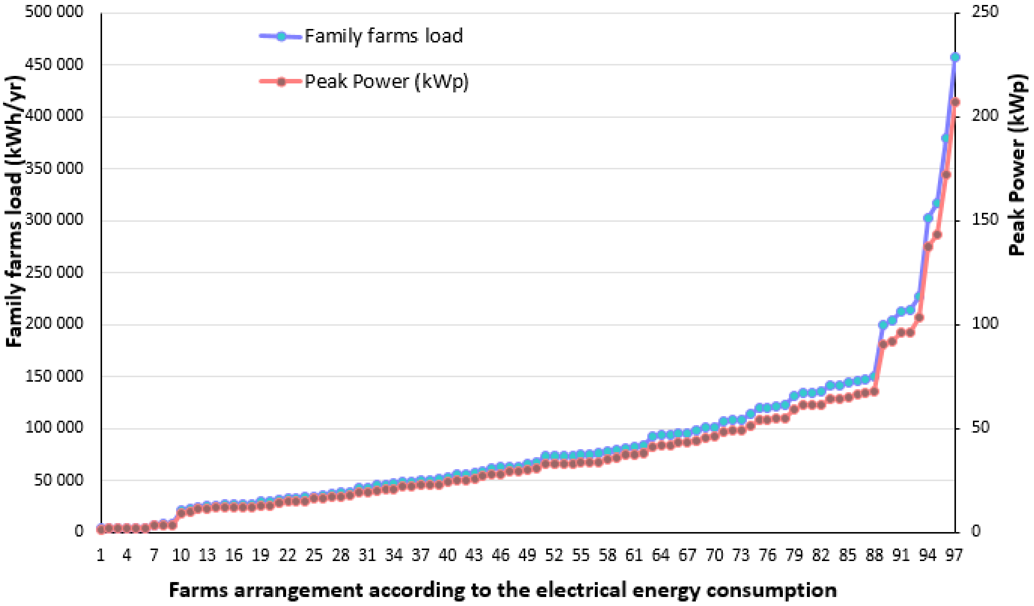

Fig. 5.1 Different peak power of the PV system for family farms load.

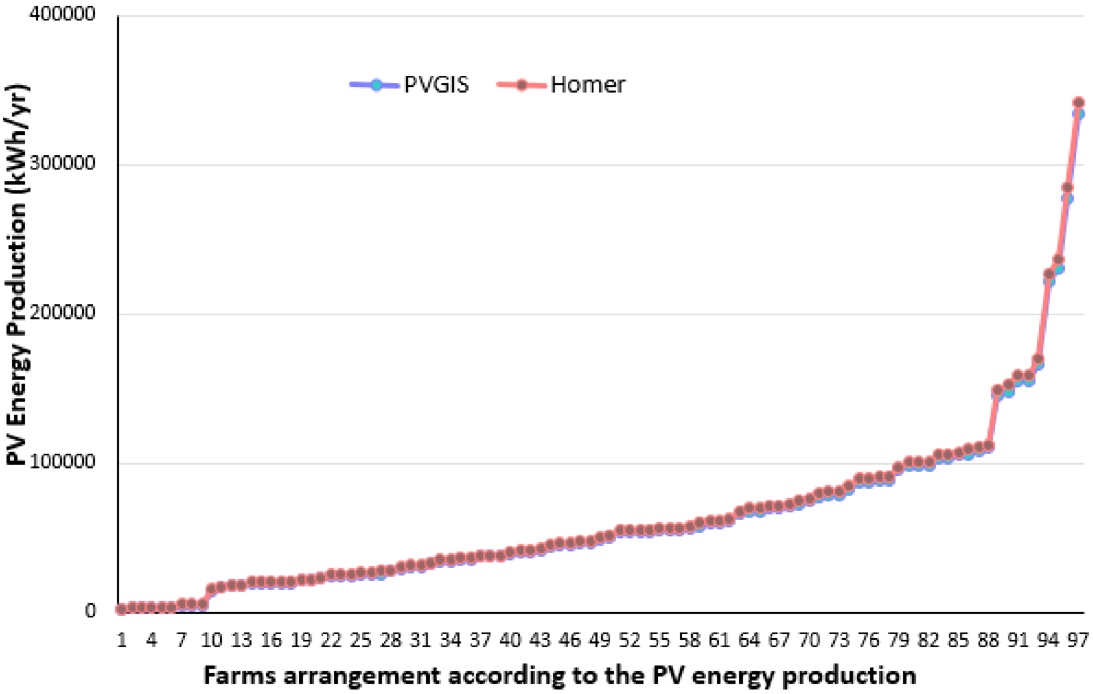

Fig. 5.2 Yearly PV energy production calculated by Homer and PVGIS software.

5.3 Economic analysis of the grid-connected PV system in 2012 and 2017

In this sudy, we will evaluate the Total net present cost (NPC) of the grid-connected PV system which is the present value of all the costs that it incurs over its lifetime minus the present value of all the revenue that it earns over its lifetime. In this case, different costs are used, the annualized capital cost C_{acap} ($), the annualized replacement cost (C_{arep}), the annual operation & maintenance cost $C_{aO\&M}$ ($), the salvage cost C_{sal} ($), and the total annualized cost of the system $C_{ann,tot}$ ($) as it is expressed by Eq (5.1).

$$C_{ann,tot} = C_{acap} + C_{arep} + C_{aO\&M} - C_{sal} \tag{5.1}$$

The annualized capital cost of each component is given by Eq (5.2):

$$C_{acap} = C_{cap} CRF(i, R_{proj}) \tag{5.2}$$

Where : C_{cap} is the initial capital cost of the component ($), i is the interest rate (6%) and R_{proj} is the project lifetime (25 years). CRF is the capital recovery factor, which can be calculated by Eq (5.3) :

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{5.3}$$

Where : N is the number of years.

Eq (5.4) calculates each component's annualized replacement cost :

$$C_{arep} = C_{rep}\, f_{rep}\, SFF\left(i, R_{comp}\right) - C_{sal}\, SFF(i, R_{proj}) \tag{5.4}$$

C_{rep} : Replacement cost of the component ($)

SFF() : Sinking fund factor

R_{comp} : Lifetime of the component (yr)

f_{rep} : A factor arising because the component lifetime can be different from the project lifetime, is given by Eq (5.5):

$$f_{rep} = \begin{cases} \frac{CRF\left(i, R_{proj}\right)}{CRF\left(i, R_{rep}\right)} & R_{rep} > 0 \\ 0 & R_{rep} = 0 \end{cases} \tag{5.5}$$

R_{rep} : Replacement cost duration (yr), is given by Eq (5.6):

$$R_{rep} = R_{comp}\, INT(\frac{R_{proj}}{R_{comp}}) \tag{5.6}$$

Where : INT() is the integer function, returning the integer portion of a real value. The sinking fund factor is a ratio used to calculate the future value of a series of equal annual cash flows. Eq (5.7) for the sinking fund factor is:

$$SFF(i, N) = \frac{i}{(1+i)^N - 1} \tag{5.7}$$

The annual O&M cost $C_{aO\&M}$ of each component is expressed by Eq (5.8):

$$C_{aO\&M} = C_{O\&M}\, R_{proj} \tag{5.8}$$

$C_{O\&M}$: Operation & maintenance cost (O&M cost) ($).

The salvage cost of each component is the present value earned at the end of the project lifetime. Salvage cost C_{sal} is expressed mathematically by Eq (5.9):

$$C_{sal} = C_{rep}\, \frac{R_{rem}}{R_{comp}} \tag{5.9}$$

R_{rem}, the remaining life of the component at the end of the project lifetime, it is given by Eq (5.10):

$$R_{rem} = R_{comp} - (R_{proj} - R_{rep}) \tag{5.10}$$

The total Net Present Cost (NPC) of the gird-connected PV system is used to investigate the viability of the studied grid-connected PV system. It can be obtained by Eq (5.11) :

$$Total\ NPC = \sum_{i=PV,inverter,grid} \left(\frac{C_{ann,tot}(i)}{CRF(i, R_{proj})}\right) \tag{5.11}$$

The algorithm in the Fig. 5.3 treats the economic aspect of the grid-connected PV system and calculates the Total NPC of the grid connected PV system for several values of project lifetime and sellback price of PV energy. In this algorithm, the first step consists of using initial costs of the equipment of the grid-connected PV system sized and the results of the for algorithm of Fig. 4.14

In second step, for each project lifetime value, we use several sellback prices of PV energy to calculate the Total NPC.

The initial capital and the replacement costs of the grid are maintained at zero in HOMER software. The grid O&M cost is equal to the annual cost of buying electricity from the grid minus any income from the PV electricity sold to the grid. The change in sellback price of PV energy affects only the grid O & M cost which also includes the standby charge. The difference between price of grid energy purchased and that of PV energy sold is a substantial factor in determining the project lifetime during which the farmer can recover the money he spent to install the PV system connected to the grid.

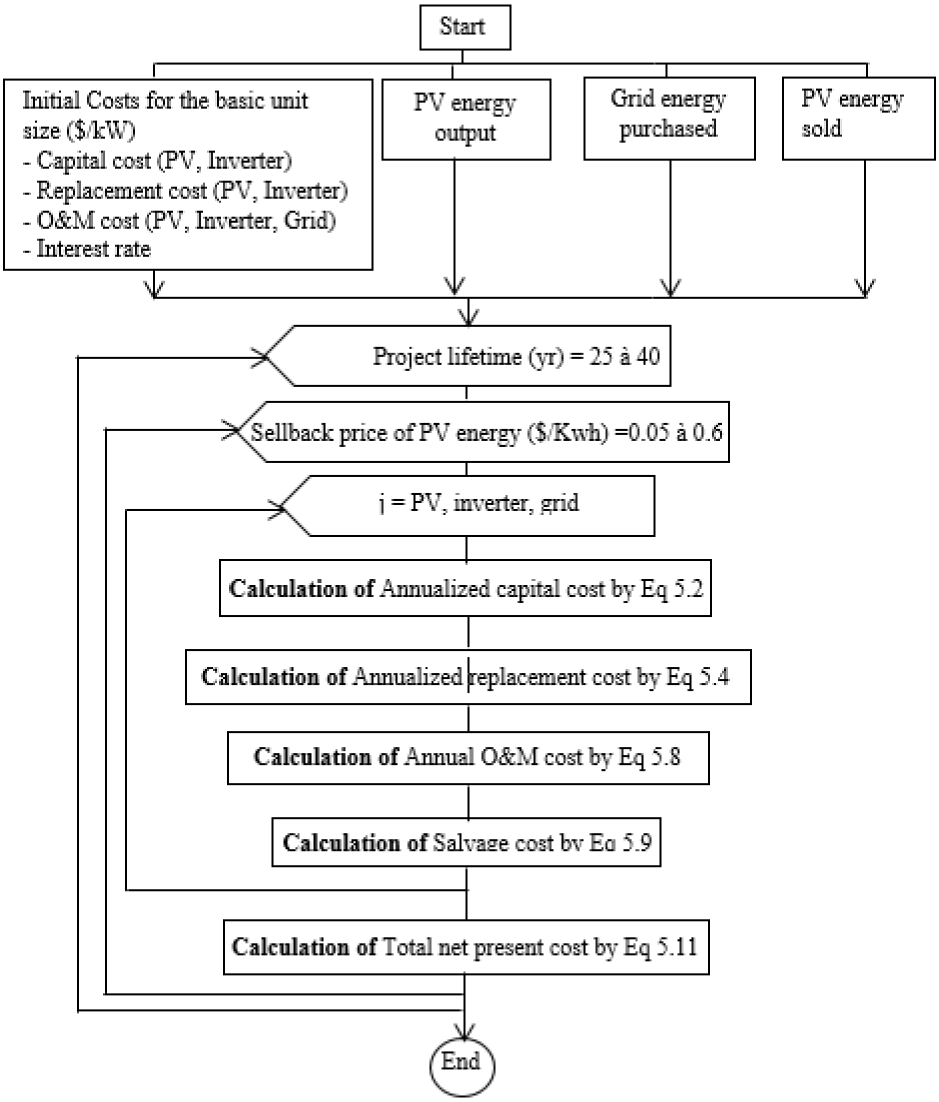

Fig. 5.3 Algorithm for calculating the Total NPC of the grid-connected PV system.

Table 5.1 presents for the years 2012 and 2017, the PV module price of 100 W, the inverter price of 1.2 kW, the electricity price of the grid and the exchange rate that we have used in the economic study.

Table 5.1 : PV module and inverter prices ($)

Year	PV module price of 100 W [90]		Converter price of 1.2 kW		Electricity Price		Exchange rate [91]
	(DA)	($)	(DA)	($)	(DA/kWh)	($/kWh)	($/DA)
2012	22 000	270.60	48 000	604.68	4.472	0.05	79.38
2017	11 115	101.53	48 465	442.72	4.472	0.04	109.47

In calculation we have to use kW/$ as shown in Table 5.2

Table 5.2 : PV module and inverter prices (kW/$)

Year	PV system price (kW/$)	Converter price (kW/$)
2012	2700	500
2017	1015	369

Based on the project lifetime 25 years and the sellback price of PV energy (0.05 $/kWh), Fig. 5.4 shows the NPC of each component of the grid connected PV system sized in the year 2012 and in the year 2017.

The Total NPC in the year 2012 has reached 154 692 $ and in the year 2017, it has reached 82 011 $. We can say that the Total NPC decrease is due to the price decrease of the PV module.

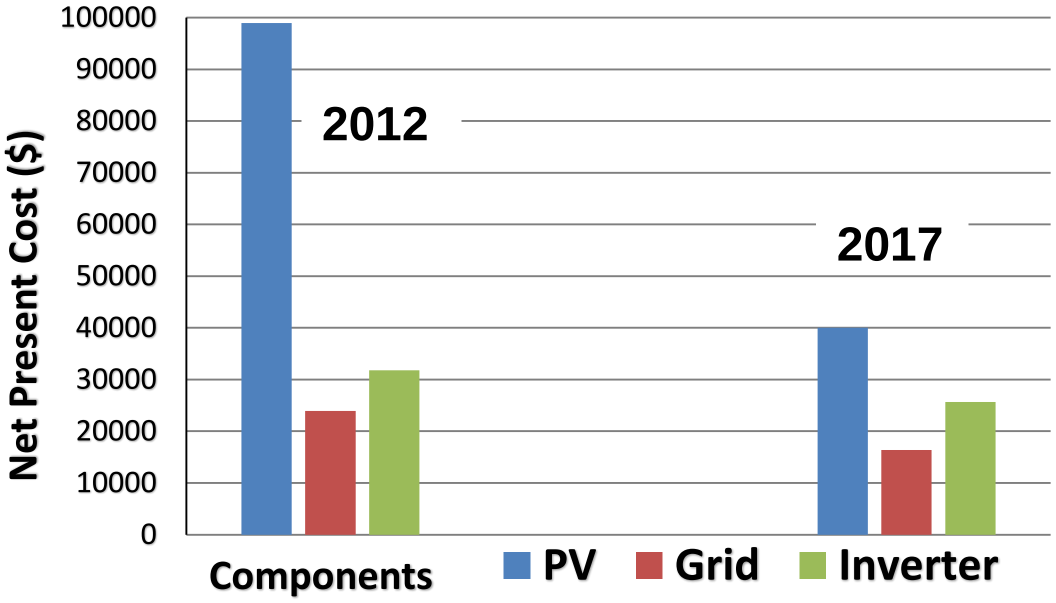

Fig. 5.4 NPC cost for each component of the grid-connected PV system in 2012 and 2017

Based also on the project lifetime 25 years and the sellback price of PV energy (0.05 $/kWh), the different annualized costs for the grid-connected PV system sized in the year 2012 and in the year 2017 are shown in Fig 5.5.

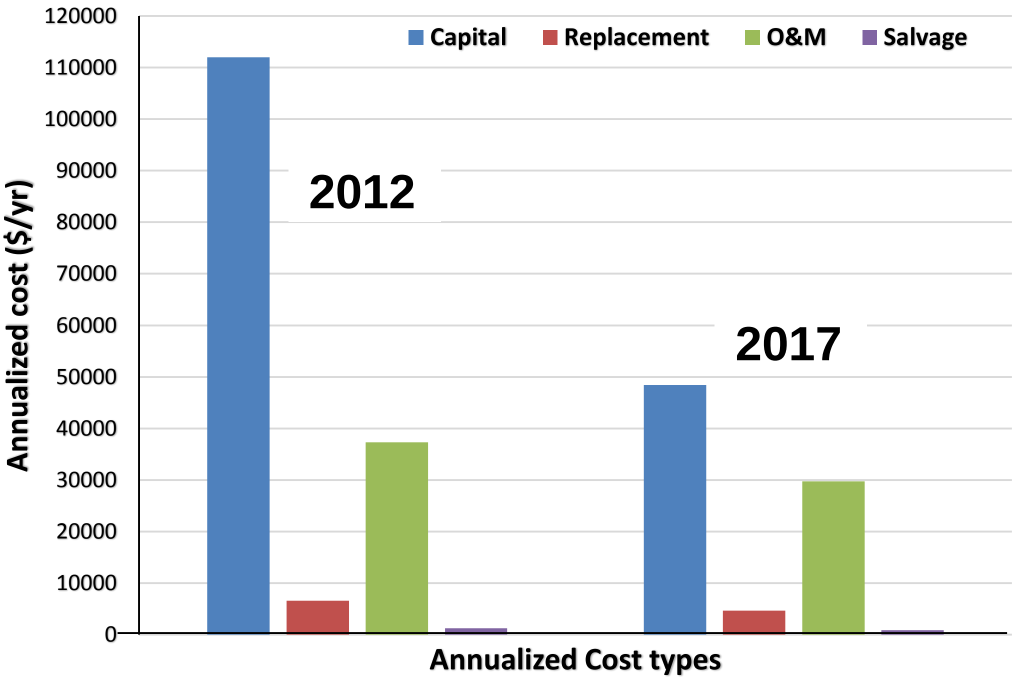

Fig. 5.5 Annualized costs of the grid-connected PV system in 2012 and 2017

The annualized capital cost C_{acap} which is the sum of the annualized capital costs of the PV array and the inverter is the highest cost than the other annualized costs. In addition, it is lower in the year 2017 than in the year 2012.

The relationship between the Total NPC, the sellback price of PV energy and the project lifetime helps to make a decision to install a grid-connected PV system in the studied farm. For different project lifetime values, we have varied the sellback price of PV energy to see the Total NPC evolution in the year 2012, we have obtain these curves (Fig 5.6).

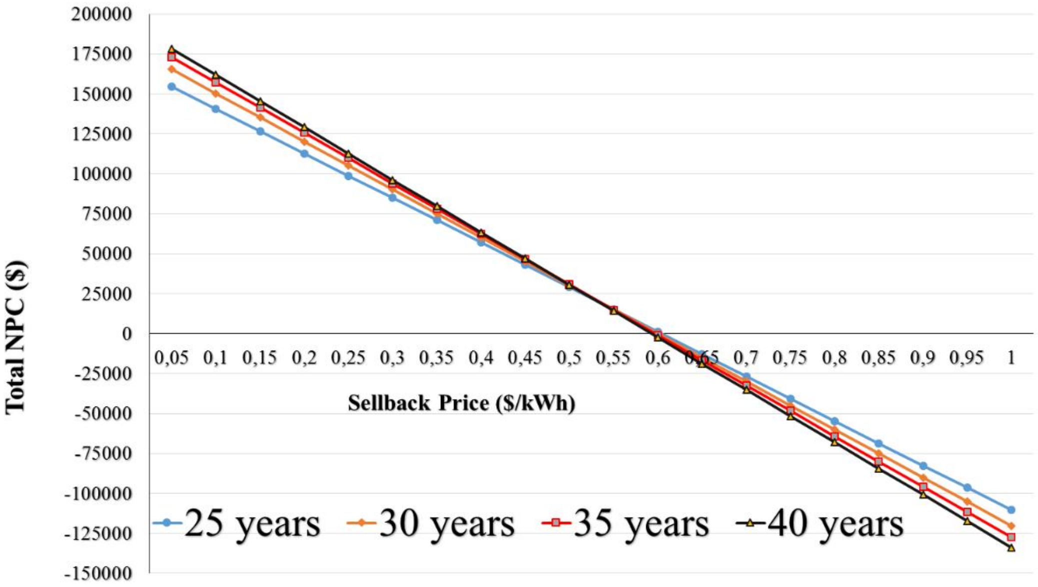

Fig 5.6 : Total NPC and Project lifetime vs. Sellback price of PV energy in 2012

From Fig 5.6, we can deduce four notes:

- First note, Total NPC decreases dramatically as the sellback price increases from 0.05 to 1 $/kWh for all project lifetimes (25–40 years).
- Second note, Total NPC decreases as the project lifetime decreases when the sellback price ranges from 0.05 to 0.6 $/kWh.
- Third note, Total NPC becomes zero when the sellback price equals to 0.6 $/kWh regardless of the project lifetime value

- Fourth note, Total NPC becomes negative and represents a financial gain for the farmer when the sellback price is higher than 0.6 $/kWh. This financial gain increases when the project lifetime increases.

The economic study in the year 2017 (Fig 5.7) showed the following notes :

- The Total NPC has the same evolution as that in 2012.
- The economic study in the year 2017 showed that the Total NPC is lower than the Total NPC in the year 2012 for all project lifetimes.
- The economic study in the year 2017 showed that when the sellback price of PV energy is equal to 0.35 $, Total NPC becomes zero regardless of the project lifetime value.
- This represents a strong incentive to invest in photovoltaic installation in farms.

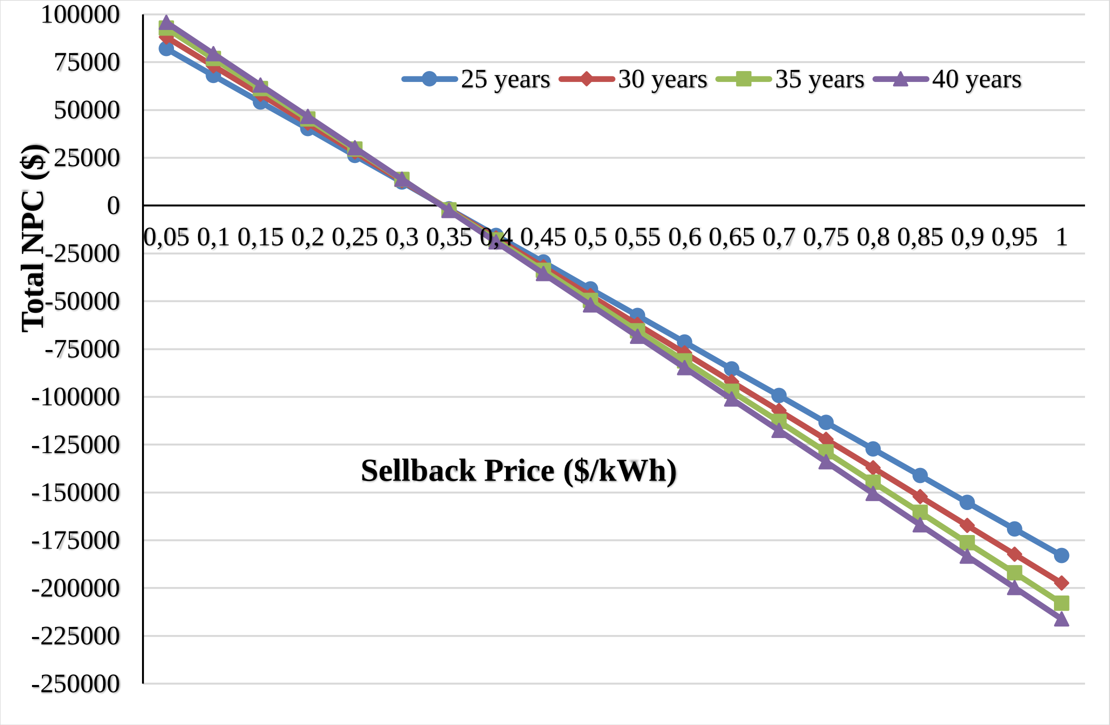

Fig 5.7 : Total NPC and Project lifetime vs. Sellback price of PV energy in 2017

5.4 Environmental impact

Table 5.1 shows pollutants emissions due the electrical energy consumption from the grid with and without PV system. It can be noticed that the PV system contributes strongly to reduce the amount of pollutants emissions, more than half of pollutants emissions amount may be avoided. Indeed, 56.34% of Carbon dioxide, 56.52% of sulfur dioxide and 56.45% of nitrogen oxides have been reduced.

Table 5.3 : Pollutant emissions reduction due to grid-connected PV system installation.

Pollutants	Emissions (kg/yr)		Reduction (%)
	Grid	Grid-connected PV system	
Carbon dioxide	58 362	25 478	56.34
Sulfur dioxide	253	110	56.52
Nitrogen oxides	124	54	56.45

5.5 Conclusion

This study has concluded that the yearly PV energy produced in 97 family farms located in Chlef district reached 6.2 GWh and represented 74% of the total load of these farms. The economic analysis of the studied farm shows that the Total NPC of the studied grid-connected PV system is very high, 154 690 $ for a project lifetime of 25 years, due to the high cost of the PV module in Algeria and no policy that encourages the sale of PV energy to the grid. To encourage the PV installation connected to the grid, the economic study showed also that when the sellback price of PV energy is higher than 0.6 $/kWh, the Total NPC becomes negative and represents a financial gain for the farmer. On another side, when the project lifetime increased, the financial gain obtained increased and encourages to expand the PV systems installation in all the farms close to the grid in Algeria. Consequently, policy that encourages the sale of PV energy to the grid can play an important role in Algeria electrical energy generation. Furthermore, the environmental analysis showed that the grid-connected PV system contributed strongly to reduce pollutants emissions, 56.34% of Carbon dioxide, 56.52% of sulfur dioxide and 56.45% of nitrogen oxides have been reduced. This paper gives worthwhile information about the electrical energy consumption of the farms and helps to develop them by self-production of clean energy by PV system installation connected to the grid in Algeria and nearby country.

GENERAL CONCLUSION AND RECOMMENDATIONS

Sustainable development is strongly linked to the development of renewable energies in all economic sectors that depend on the consumption of electricity from the grid or the direct consumption of fossil products such as industry, agriculture, housing, road transport, maritime transport, air transport....

In this study, we chose to study the agricultural sector because we saw in chapter 2 that its electricity consumption is very small compared to that of the housing sector, whereas the agricultural sector has many assets such as Space and absence of shading to install mini photovoltaic power plants connected to the grid to contribute to the development of agricultural farms and the improvement of the electricity grid. We began by giving a classification of the PV systems connected to the grid and the academic works that studied this kind of system on farms according to what exists in the literature. Then we gave a general overview on the evolution of fossil fuels consumption and carbon dioxide emissions, the different power plants, the electrical energy production and consumption vs customers number and the sale of electricity types in Algeria. After then, we gave another general overview on the renewable energy potential which is dominated by solar energy, renewable energy program, solar energy realizations and legislative framework.

A detailed study on the electrical energy consumption of farms was carried out and a case study was developed in the Chlef district located in the Northwestern of Algeria in order to design a PV system that could satisfy the farm load and reduce electricity demand from the power grid. The present work was divided into four steps. First, a survey was conducted to determine the farm’s number in Chlef district and their annual electrical energy consumption. Then, the choice of an experimental farm was performed based on the energy demand and farmer acceptation of renewable energy. In the third step, monthly load profiles were established for the sizing and energy balance optimization of the grid-connected PV system. Finally, we evaluated the impact of economic parameters such as project lifetime and electricity sellback price on the Total NPC of the system was assessed, and the impact of using the grid-connected PV system on the environment.

Simulation results showed that the yearly electrical energy balance showed that the 35 kWp grid-connected PV system could produce 117.06 MWh/yr, the renewable fraction (RF) which represents the PV energy contribution reached 49%, and the PV energy consumed by the farm covered almost 60% of its load. The expanding of the grid-connected PV systems in the other farms shoed that the yearly PV energy produced in 97 family farms located in Chlef district reached 6.2 GWh and represented 74% of the total load of these farms. The economic analysis of the studied farm showed that the Total NPC of the studied grid-connected PV system is very high, 154 690 $ for a project lifetime of 25 years. The economic study showed also that when the sellback price of PV energy is higher than 0.6 $/kWh, the Total NPC becomes negative and represents a financial gain for the farmer. On another side, when the project lifetime increased, the financial gain obtained increased and encourages to expand the PV systems installation in all the farms close to the grid in Algeria. The environmental analysis showed that the grid-connected PV system contributed strongly to reduce pollutants emissions, 56.34% of Carbon dioxide, 56.52% of sulfur dioxide and 56.45% of nitrogen oxides have been reduced. Renewable energies and farming are a winning combination for sustainable agriculture to assure food and energy security. Solar energy is one of them, which can be harvested forever, providing farmers with a long-term source of income. They can be used by the farmers to supply electrical equipment, to replace other fuels or sold as a cash crop. The farmers should be encouraged by subsidies to use renewable energy technology to play a significant role in determining the level of economic activity. This work could be even more valuable if it will be applied on the ground with financial aids and a PV electricity sales price appreciable. Because it helps a lot to build improved PV systems, more economical and that pays back in a few years. Another recommendation to develop this work is the study of the introduction of others sources of renewable energy. After doing this work, there are three parameters that can make this work applicable in the field :

- First parameter depends on the farmer decision, it’s the project lifetime.
- Second parameter depends on the government policy, it’s the sellback price of PV energy.
- Third parameter depends on the market, it is the PV module price.

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