

# THESIS

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**Dounia DAHLIOUI**

Engineer in Electrical Engineering and Renewable Energies

## Thesis Title

**Improvement of photovoltaic systems efficiency using innovative, ecological and low cost cleaning techniques**

## Thesis Examination Committee

Mohammed GAROUM	PES, Mohammed V University, Ecole Normale Supérieure- Rabat	Chairman
Abdelaziz EL GHZIZAL	PES, Sidi Mohammed Ben Abdellah University, Ecole Supérieure de Technologie- Fes	Rapporteur/ Examiner
Abdellah BAH	PES, Mohammed V University, Ecole Nationale Supérieure d'Arts et Métiers- Rabat	Rapporteur/ Examiner
Ahmed ABOU	PES, Mohammed V University, Ecole Mohammadia d'Ingénieurs- Rabat	Rapporteur/ Examiner
Bouchaib HARTITI	PES, Hassan II University, Faculté des Sciences et Techniques- Casablanca	Rapporteur
Asmae ARBAOUI	PES, Mohammed V University, Faculté des Sciences- Rabat	Examiner
Abdelouahed DAHROUCH	PA, Royal Gendarmerie Forensic Science Institute- Rabat	Guest
Abdelfettah BARHDADI	PES, Mohammed V University, Ecole Normale Supérieure- Rabat	Supervisor

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*Heartily and proudly dedicated to my mother ....*

## Dedication

*To my parents Atikā and Abdessalam*

*To my siblings Kawtar, Nassira, Fatimazahra and Badr*

*To all members of family Dahlioui and Boudra*

*To my professor Najia Medaghri and Chaouki Iftissen family*

*To my colleagues and friends Bouchra, Zineb, Sarah, Soukaina*

*It is thanks to your presence, your daily support and encouragement that I have  
come to where I am today.*

*Dounia Dahlioui*

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## Résumé

L'objectif de ce travail de thèse est l'optimisation des performances des panneaux photovoltaïques (PV) grâce à un nettoyage écologique et à faible coût. Dans ce travail, l'effet de la formation de rosée sur la surface des modules PV a été étudié vu son grand effet sur l'encrassement. L'analyse menée a montré que l'eau de rosée a un effet négatif se manifestant par la cimentation des salissures et un effet positif dû à l'auto-nettoyage naturel résultant du ruissellement de l'eau de rosée. C'est ce deuxième effet qui a été particulièrement étudié dans cette thèse et les résultats obtenus sont prometteurs. L'encrassement des salissures peut être réduit au tiers si une permutation de l'angle d'inclinaison des modules PV entre  $0^\circ$  (au coucher du soleil) et  $30^\circ$  (au lever du soleil) est effectuée d'une manière systématique. Des résultats similaires sont trouvés pour les modules PV dynamiques montés sur un suiveur solaire biaxe. L'impact des salissures sur les modules PV conduit à un taux d'encrassement annuel moyen d'environ 4% et une perte moyenne de productible journalier d'environ 2 Wh/Wc. En plus de l'approche de nettoyage écologique des modules PV par la rosée, ce travail propose aussi une nouvelle technique de nettoyage, utilisant un bras télescopique facilement intégrable sur le tracker biaxe. Toutefois, l'analyse économique effectuée montre que l'opération de nettoyage n'est vraiment rentable que lorsque les pertes d'énergie dues aux salissures dépassent 7%. C'est particulièrement le cas des zones désertiques où les taux de salissures sont souvent élevés.

**Mots clés :** Energie solaire; Encrassement; Panneaux photovoltaïques; Tracker solaire; Nettoyage automatique; Eau de rosée.

## Abstract

In this thesis, soiling of photovoltaic (PV) modules has been studied in details starting from the soiling particles generation to their adhesion on PV as well as the effect of dew formation on soiling of PV. Soiling was investigated in outdoor conditions leading to annual average soiling rate of 4%. Based on this approach, losses of energy production were calculated per one PV module which is 2 Wh/Wp per day. The soiling effect was also studied for PV on the dual-axis tracker in Rabat. During a year of study, soiling losses for the tracker were between 2 and 7% while those on fixed structures tilted 30° were ranging from 7 to 21%. This thesis work has also studied an approach for testing the soils cleaning by dew which has led to promising results. The soiling can be reduced to three times if an inclination angle tilting between 0° at sunset and 30° at sunrise is performed. Similar results were found for the tracking system. An investigation of the adaptability of the cleaning systems to dual-axis tracker has revealed that few among the studied cleaning systems that showed adaptability to the tracker. Therefore, a cleaning technique based on telescopic arm has been developed, realized and tested to deal with soiling of PV on dual-axis tracker. Through the performed economic analysis, it was found that the cleaning system is profitable only when the soiling losses exceed 7% as the case of arid areas where high soiling levels are frequently reached.

**Keywords:** Solar energy; Soiling; Photovoltaic panels; Solar tracker; Automatic cleaning technique; Dew water.

## Résumé développé

L'encrassement constitue un sérieux défi pour les panneaux solaires. C'est un phénomène fréquent qui se développe à la surface des panneaux et se traduit par des pertes importantes de productible, notamment dans les régions à fort potentiel de déploiement des installations solaires. Sa gestion entraîne une augmentation des coûts d'exploitation et de maintenance de ces installations. La principale motivation de ce travail de thèse est d'étudier ce phénomène et proposer des solutions écologiques, économiques et attractives pour réduire son impact sur les performances des panneaux solaires photovoltaïques (PV).

Dans ce rapport, le processus de l'encrassement du PV a été étudié en détail à partir de la génération de particules de salissure jusqu'à leur adhésion à la surface des panneaux PV. Les différentes études expérimentales menées à Rabat ont bien contribué à l'explication des mécanismes de l'encrassement et l'effet des conditions météorologiques sur son développement. Une partie importante de ce travail a été dédiée à l'étude de l'effet de la rosée, formée à la surface des modules PV, sur l'évolution de l'encrassement. D'après la revue bibliographique réalisée, la rosée présente un effet négatif provoquée par la cimentation des salissures à la surface des modules, et un effet positif dû à l'auto-nettoyage naturel des modules par écoulement. Environ les 2/3 des travaux publiés recommandent la provocation de la formation de rosée basée sur des solutions passives comme les revêtements.

L'encrassement des modules PV a été étudié dans des conditions extérieures par la mesure de l'irradiance solaire. Le taux d'encrassement annuel moyen trouvé est de 4%. Sur la base de cette approche, les pertes de production d'énergie ont été calculées. Elles sont autour de 2 Wh/Wc par jour. L'effet d'encrassement sur les modules PV montés sur un suiveur solaire (tracker) biaxe installé à Rabat a également été étudié. On trouve que les pertes par salissures relatives à ces modules sont comprises entre 2 et 7 %, alors que celles sur les modules fixes inclinés à 30° varient de 7 à 21 %.

Ce travail de thèse a également étudié la possibilité de nettoyage des salissures par la rosée formée sur la surface des modules PV. Les expériences effectuées ont conduit à des résultats prometteurs. En effet, l'encrassement peut être considérablement réduit si un basculement de l'angle d'inclinaison entre 0° (au coucher du soleil) et 30° (au lever du soleil) est effectué quotidiennement. Des résultats similaires ont été trouvés pour les modules PV dynamiques sur tracker en raison de la réduction des salissures par rapport aux modules statiques sur supports fixes. Cette étude montre qu'il est effectivement possible de convertir l'effet négatif de la rosée qui se manifeste par la cimentation des salissures en un effet positif résultant de la formation et

l'accumulation de rosée pendant la nuit et son écoulement sur la surface des modules PV au début de la matinée.

Une revue critique sur les techniques de nettoyage des modules PV a été également effectuée. Elle a révélé que celles présentant une certaine adaptabilité au nettoyage des modules montés sur un tracker biaxe sont assez rares. Dans ce travail, une nouvelle technique de nettoyage utilisant un bras télescopique a été développée, réalisée et testée pour nettoyer les modules dynamiques sur un tracker biaxe. À travers l'analyse économique réalisée dans ce travail, il a été constaté que le système de nettoyage n'est rentable que lorsque les pertes de salissures dépassent 7%. C'est le cas des zones désertiques où des taux de salissures élevés sont fréquemment atteints.

**Mots clés :** Energie solaire; Encrassement; Panneaux photovoltaïques; Tracker solaire; Nettoyage automatique; Eau de rosée.

## ملخص

يعتبر تلوث الألواح الشمسية تحدياً كبيراً لأنظمة الطاقة الشمسية، والذي يتجلى في خسائر مهمة في إنتاج الطاقة في المناطق ذات الإمكانيات العالية للطاقة الشمسية. إذ تؤدي هذه الظاهرة إلى زيادة التكاليف المرتبطة بالتشغيل والصيانة للوحدة الشمسية. من المعروف أن المغرب هو مثال لبلد يتمتع بإمكانيات كبيرة لإنتاج الطاقة الشمسية بسبب مستوى إشعاعه الشمسي. لخدمة الطاقة الشمسية، فإن الدافع الرئيسي لهذه الأطروحة هو تحسين أداء الألواح الكهروضوئية من خلال التنظيف منخفض التكلفة والصدى للبيئة.

اعتماداً على دراسة الأبحاث المتعلقة بتلوث الألواح الكهروضوئية، تمت دراسة هذا الأخير بالتفصيل من توليد جزيئات الملوثات إلى التصاقها بسطح الألواح الكهروضوئية. وقد ساهمت الدراسات التجريبية المختلفة التي أجريت في الرباط في شرح آليات التلوث وتفاعله مع الظروف المناخية. في هذا العمل تمت دراسة تأثير تشكل الندى على سطح الوحدة الكهروضوئية نظراً لتأثيره الكبير على التلوث. أظهر التحليل الذي تم إجراؤه أن الندى له تأثير سلبي على تلوث الألواح يتجلى من خلال تثبيت جزيئات الغبار بالإضافة إلى تأثيره الإيجابي على التنظيف الذاتي الناتج عن الندى. وفقاً للمراجعة الدقيقة التي تم إجراؤها، أوصت 61% من المقالات بتحفيز تكوين ماء الندى مع الأخذ في الاعتبار المزايا العديدة مثل الحلول الغير نشيطة القائمة على الطلاءات المبتكرة أو الأغشية التي لا تتطلب تزويدها بالطاقة الكهربائية.

تمت دراسة تأثير تلوث الزجاج الأمامي للألواح الكهروضوئية في الظروف الخارجية عن طريق قياس الإشعاع الشمسي، مما أدى إلى متوسط معدل تلوث سنوي يبلغ حوالي 4%. بناءً على النهج الدقيق المقدم في هذا العمل، تم حساب خسائر إنتاج الطاقة للوحدة الكهروضوئية، أي ما يقرب من 2 واط ساعة/ واط ذروة في اليوم. تمت دراسة تأثير الملوثات أيضاً على الخلايا الكهروضوئية المركبة على متنوع مسار الشمس ثنائي المحور الموجود في منصة البحث بالرباط. في الواقع، كانت الخسائر عن طريق تلوين الخلايا الكهروضوئية على متنوع المسار الشمسي المزدوج تتراوح بين 2 و 7 %، بينما تفاوتت الخسائر على الألواح الكهروضوئية الثابتة عند 30 درجة من 7 إلى 21 %. درس هذا البحث أيضاً إمكانية تنظيف الغبار بالندى المتكون على سطح الألواح الكهروضوئية مما أدى إلى نتائج واعدة. إذ يمكن تقليل التلوث ثلاث مرات إذا تم تغيير زاوية الإمالة من 0 درجة (بعد غروب الشمس) إلى 30 درجة (عند شروقها). تم الحصول على نتائج مماثلة بالنسبة بالألواح المتحركة مقارنة بالوحدات الثابتة. من خلال هذه الدراسة، يوصى بشدة تحويل التأثير السلبي للندى الذي يتجلى من خلال تثبيت الغبار إلى تأثير إيجابي يعتمد على تكوين وتراكم الندى أثناء الليل وتدفعه على سطح الألواح الكهروضوئية في الصباح الباكر.

في هذا العمل تمت مراجعة نقدية لإمكانية تكيف أنظمة تنظيف الألواح الكهروضوئية لمتنوع المسار الشمسي ثنائية المحور. أظهرت هاته المراجعة أن عددًا قليلاً من أنظمة التنظيف قابلة لتنظيف الألواح المتحركة فوق متنوع المسار الشمسي. لذلك قمنا بدراسة تطبيقية لتقنية تنظيف مبتكرة، تعتمد على ذراع تلسكوبي أوتوماتيكي، وشرعنا في اختبارها على متنوع المسار الشمسي ثنائي المحور. ومن خلال دراسة الجدوى والمنفعة الاقتصادية، تبين أن نظام التنظيف لا يكون مربحاً إلا عندما تتجاوز نسبة الخسارة الناتجة عن تلوث الألواح 7% كما هو الحال في أغلب المناطق الصحراوية.

**الكلمات الدالة:** طاقة شمسية - الألواح الكهروضوئية - تلوث - تقنية تنظيف - أوتوماتيكي - متنوع المسار الشمسي - الندى.

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## Nomenclature

### List of acronyms

Acronym	Description
PV	Photovoltaic
CSP	Concentrated Solar Power
IRESEN	Institut de Recherche en Energie Solaire et Energies Nouvelles
MENA	Middle East and North Africa
AM	Air Mass
UV	Ultraviolet
VIS	Visible
IV curve	Current-Voltage curve
CPV	Concentrated Photovoltaic
R&D	Research & Development
SAT	Single-Axis Tracker
DAT	Dual-axis Tracker
FTIR	Fourier Transform Infrared spectroscopy
EDS	Electrodynamic Screens
NE	North-East
PM	Particulate Matter
PVC	Polyvinyl Chloride
NASA	National Aeronautics and Space Administration
CA	Contact Angle
PCM	Phase Change Material
DNI	Direct Normal Irradiation
GHI	Global Horizontal Irradiation
SPM	Solar Power Meter
BTS	Brevet de Technicien Supérieur
XF	X-ray Fluorescence Analysis
V	Verified
NV	Not Verified
A	Adaptive
VA	Very Adaptive
CAPEX	Capital expenditures
OPEX	Operating expenses
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
TiO <sub>2</sub>	Titanium dioxide
NaCl	Sodium chloride
AC	Alternating Current
DC	Direct Current
MAD	Moroccan Dirham code

## List of symbols

Symbol	Unit	Description
$\theta$	$^{\circ}$	Angle from the vertical (zenith angle)
$E_{\lambda}$	J	Energy of the photons
$\lambda$	m	Wavelength
$h$	$\text{m}^2.\text{kg}.\text{s}^{-1}$	Planck constant
$C$	m/s	Speed of light
$I$	A	Output current
$I_{ph}$	A	Photocurrent produced by the cell
$I_{SH}$	A	Shunt current
$R_{SH}$	$\Omega$	Shunt resistance
$I_S$	A	Reverse saturation current
$R_S$	$\Omega$	Series resistance
$V$	V	Output voltage
$k$	$\text{J.K}^{-1}$	Boltzmann constant
$T$	K	Effective temperature of the cell
$I_D$	A	Diode dark current
$n$	-	Diode ideality factor
$V_{oc}$	V	Open circuit voltage
$I_{sc}$	A	Short-circuit current
$P_{mp}$	W	Maximum power of a photovoltaic cell
$I_{mp}$	A	Current at maximum power point
$V_{mp}$	V	Voltage at maximum power point
$SRatio$	-	Soiling Ratio
$G$	$\text{W}/\text{m}^2$	Solar irradiance
$SL$	%	Soiling losses
$G_{av}$	$\text{W}/\text{m}^2$	Average of irradiance
$E_p$	Wh	Energy produced by the PV module
$\Delta t$	h	Sunshine duration
$P$	W	Produced power
$S$	$\text{m}^2$	Effective surface of the considered PV module
$\eta$	-	Instantaneous efficiency in real operating conditions
$\eta_r$	-	PV module nominal efficiency at STC conditions ( $T = 25^{\circ}\text{C}$ , $G = 1 \text{ kW}/\text{m}^2$ and $AM = 1.5$ )
$T_c$	$^{\circ}\text{C}$	Module temperature
$T_a$	$^{\circ}\text{C}$	Reference module Temperature
$\omega$	$^{\circ}$	Hour angle
$\delta$	$^{\circ}$	Solar declination
$\Phi$	$^{\circ}$	Latitude of the place
$n$	-	Year day since January
$SRate$	$\text{\%/day}$ $\text{\%/month}$	Soiling Rate
$Kt$	-	Clearness index
$RH$	%	Relative humidity
$a$	mm	Length of the lozenge arm
$d_1, d_2$	mm	Diagonals of the lozenge
$D$	mm	Diagonal of four PV modules mounted on tracker
$N$	-	Number of bars of length ( $a$ )

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$T_s$	s	Time delay of the rotating brush
$C_{CS}$	MAD	Cost the proposed cleaning system
$C_{initial}$	MAD	Initial cost
$C_{maintenance}$	MAD	Maintenance cost
$C_w$	MAD	Cost of energy consumption of the cleaning solution
$E_{loss}$	kWh	Energy losses due to soiling
$C_{El}$	MAD	Cost of electricity losses
$C_{oE}$	MAD	Cost of electricity per kWh
$E_{gc}$	kWh	Energy generated at clean state of the PV modules on tracker
$E_{gs}$	kWh	Energy generated at soiled state of the PV modules on tracker

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## **Chapter I: General Introduction**

### **1. Global energy context**

A reliable energy supply is paramount to meet the growing demand for electricity which is increasing intensely in developed and developing countries. Some insights about the energy demand corresponding to 2030 are given in the work of [1]. Indeed, an increase of 40% in energy consumption is expected in Europe while 50% in the USA by 2030. This latter will be doubled in India and it is expected to triple in China [1]. This demand is mainly satisfied by the means of fossil resources which are in the process of reduction and are considered as the main source of pollution [2]. Indeed, the trend of carbon emissions is worrying in recent years. The slowdown in the growth of carbon emissions to 0.5% in 2019 may suggest reasons for positivity. The average annual growth in carbon emissions over 2018 and 2019 was above its 10-year average [3]. But to get to net zero by 2050, the world requires, for the next 25 years, a radical change in all our activities by using resources and energy more efficiently. This goal can be achieved as well by implementing the full range of zero and low carbon energies and technologies at our disposal including renewable energies, electrification, hydrogen, and many more. These technologies exist today but the challenge is to adapt them appropriately at scale [3].

Renewable energy resources are considered the most efficient and effective solutions to the main environmental challenge related to greenhouse effect [4]. Since decades, a great growth has been made on the solar energy technologies given the progress made in increasing their electrical productivity, reducing their price as well as their sustainability [5]. Solar energy can be exploited by different technologies namely solar thermal, solar photovoltaic (PV) and solar thermodynamics (CSP). PV allows the direct conversion of solar radiation into electrical energy by photovoltaic cells which are made with semiconductor materials. As for CSP, it has the advantage of being able to provide energy production in the form of thermal heat or in the form of electrical energy depending on the use.

The promotion of these solar technologies cannot be encouraged without considering the consumption of water required for the solar panels cleaning [6]. In fact, solar power plants are facing a real challenge of soiling which manifests by the accumulation of dust, dirt and birds dropping on their surfaces. Depending on the location and the type of dust deposited [7,8], the cleaning is of utmost importance to recover the performance of the solar panels.

## 2. Morocco: Kingdom of the sun

Morocco is among countries situated in one of the world's most favorable areas for the generation of electricity from solar energy. It is characterized by a considerable solar potential with 3000 hours/year of sunshine and an average irradiation of 5.3 kWh/m<sup>2</sup> per day [9]. Fig I.1 shows the solar irradiation map of Morocco [10]. Regarding this great resource, Morocco has launched the Moroccan solar plan aiming at installing 2 GW of solar power plant in the framework of his energy strategy. This latter comes with a goal of satisfying 52% of Morocco energy production capacity mix based on renewable sources by the end of 2030 [11]. The country has translated this strategy by the development of several projects base on different solar technologies. Noor IV à Ouarzazate, Noor Laayoune and Noor Boujdour are the PV solar power plants that have been installed recently. While for CSP, we note Noor I, II and III in Ouarzazate as well as hybrid CSP/PV that has been also targeted for Noor Midelt [11].

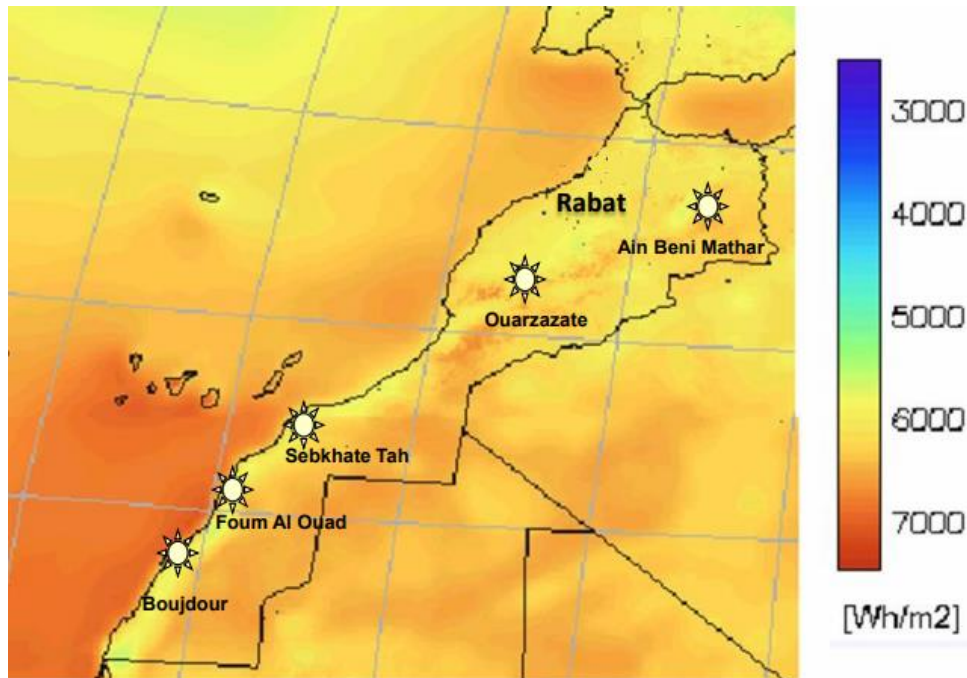


Fig I. 1. Solar irradiation map of the Kingdom of Morocco [10].

## 3. Water-energy nexus for sustainable development

Water management is a national responsibility. It plays an essential role in the sustainable development program of a country. As an arid ecosystem, Morocco is exposed to water scarcity. For this reason, several initiatives related to water management were launched since 2009 [12] mainly the Green Morocco Plan. This latter has been launched to meet the country's water need as well as managing the conventional and non-conventional water resources. In the same context, several other plans have been launched to encourage the reuse and water treatment. As

previously mentioned, the use of water in the renewable energy sector including solar energy is highly required. Indeed, the sustainability of the solar technologies has to consider without an important factor which is the consumption of water required for the solar panels cleaning and cooling. Since we are interested in this thesis in soiling of solar panels, water consumption in cooling and cleaning processes for CSP is out of scope. However, it has been reported that soiling is more than 10 times pronounced for CSP compared to PV technology [13]. This implies then an increase in water consumption required for cleaning operations (Fig I.2).

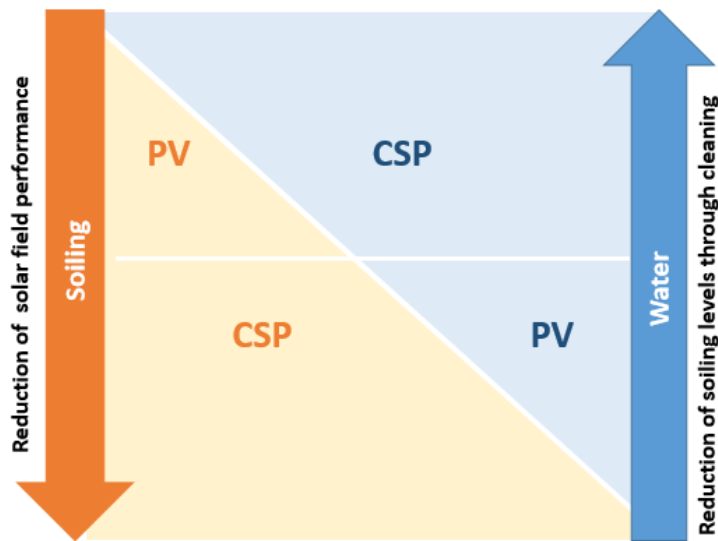


Fig I. 2. Comparison of the level of water consumption for CSP and PV technologies according to their soiling level.

Since wet cleaning is the most common soiling reduction strategy [14]. Indeed, many works have been published regarding the cleaning schedules and strategies in order to reduce the use of water in cleaning of the solar field [13]. Most of these strategies emanate from an economic decision as performing the cleaning in case the soiling revenue loss is higher than the cleaning costs [15]. As a non-conventional source of water, dew is considered as a very promising source of water all over the world and its yield depends on the climatic conditions and the properties of the substrate that is in contact with the atmosphere. Actually, high daily occurrence of dew is reported in all continental areas [16] as shown in Fig I.3. For example, in Morocco dew could present up to 40% of the yearly rain contribution as predicted by Lekouch et al. [17]. Thus, it would be more recommended investigating this latter as a cleaning factor for solar power plants [18].

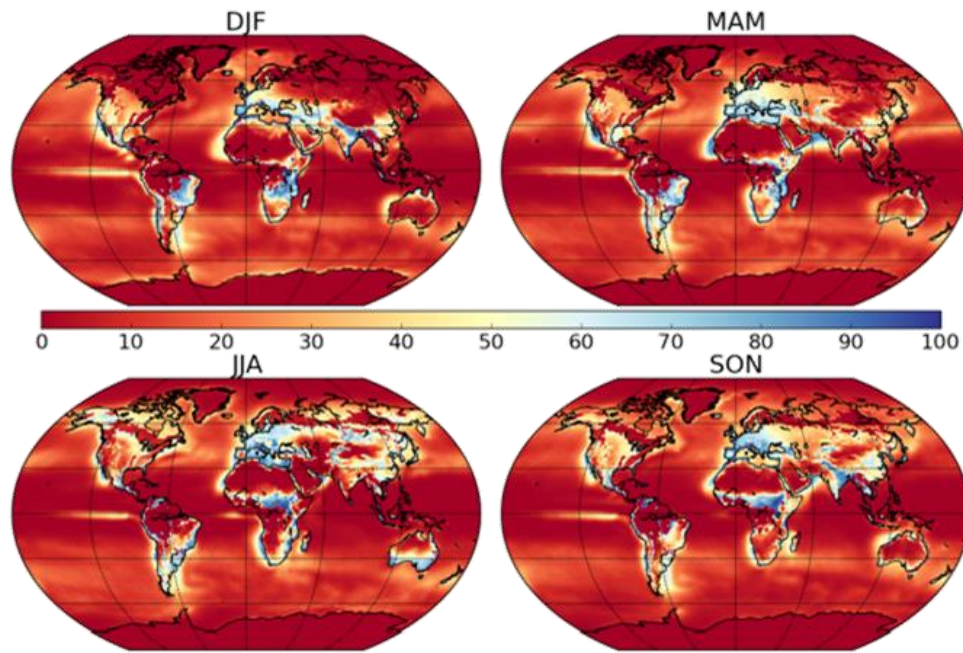


Fig I. 3. Formation of dew by seasons as a section of days with a threshold of 0.1 mm/day; DJF, MAM, JJA, SON corresponds to the initial letters of months from December to November [16].

#### 4. Outline of thesis

Further on what has been previously mentioned regarding the great challenge of soiling that still face the research community and solar installations developers, this work thesis has been performed to investigate this phenomenon. This work presents as well ecological and low cost techniques to tackle the challenge of soiling. These objectives are a part of Soleil InnoPV Research Project co-funded by IRESEN (Institut de Recherche en Energie Solaire et Energies Nouvelles) and entitled: New solutions to optimize the efficiency of photovoltaic systems by a low cost, ecological and strongly integrated locally cleaning.

The dual-axis solar tracker optimizes energy production. But, only few researches have been done on soiling of modules mounted on trackers and how these later can reduce the soiling losses. Moreover, rare are also the works that have proposed ecological and low cost cleaning systems that can be integrated into the tracker structure so that the energy production would be well optimized. Thus, the overall objective of this work is to optimize photovoltaic productivity by developing corrective solutions for PV panels on dual-axis tracker.

In the first chapter of this thesis, we present the global context of the study and the crucial importance of presenting appropriate solutions to soiling of solar installations. The second chapter is an overview of fundamentals on solar energy and literature survey aiming to

understand the soiling process and the mechanisms involved in the dust deposition on PV modules. This chapter details the factors influencing the soiling phenomenon and presents an updated review of the cleaning and soiling mitigation techniques.

Based on the literature presented in the previous chapter, it has been underlined that the effect of dew on soiling of solar panels is not well addressed. Therefore, first of its kind, this work thesis presents as well a detailed review as a third chapter on the effect of dew water on soiling of PV panels.

The fourth chapter presents different experimental studies targeting the investigation of soiling losses of fixed PV modules as well as on the dual-axis tracker installed in the site of Rabat. In this chapter, an alternative solution is studied to mitigate soiling. It consists in exploitation of dew water that condenses on the cover glass of PV panels in cleaning operations.

The development of an integrated and innovative cleaning technique is the subject of the fifth chapter of this thesis. A prototype has been realized and tested to give the first insights of the cleaning functioning and efficiency. While in the sixth and last chapter, a summary of the thesis findings is presented as well as future directions and research perspectives to be targeted.

## **Chapter II: Background and literature survey on soiling of PV**

### **1. Introduction**

High efficiency gains PV systems are a challenge of the most countries with great potential of utilizing PV. Indeed, photovoltaic panels soiling which is a major factor that prevents solar irradiation from reaching the cells, reduce significantly the electrical performance of photovoltaic systems. The optical loss causes by the accumulation of dirt and other contaminants on solar panels is the third most important meteorological factor, after insolation and air temperature that determines energy yield of solar power plant [19]. For this reason, research on this factor is increasing over the years as well as 85% of publications have focused on the PV technology [20]. It has been found that daily power losses and monthly reduction due to soiling in some areas is respectively more than 1% and 80% [21]. Depending on several factors related to the site location, climatic conditions and on the different properties of dust deposited [6,7], the cleaning is of utmost importance to recover the performance of the solar panels. To tackle the challenge of soiling several cleaning methods can be adopted especially the automated systems which are characterized by a large dust removal force, fast operation, control performance and good environmental adaptability while preserving water [22]. This makes maintaining or enhancing the performance of the solar power plants through low cost and ecological soiling mitigation techniques the trend today [23,24].

In this chapter, the basic concepts and definitions related to solar energy will be presented. A focus will be given to solar photovoltaic (PV) since this work thesis is dedicated to PV. An overview on solar trackers technologies will also be highlighted. The second part of the chapter is a detailed literature survey regarding several aspects related to soiling starting from the soiling process until the investigation of the cleaning approaches. As previously mentioned, the different parameters influencing the soiling of PV are also analyzed. This chapter presents as well an overview of the cleaning and soiling mitigation approaches that can recover the performance of solar power plants with a special focus on the automated cleaning systems.

### **2. General aspects of solar Photovoltaic**

#### **2.1. Solar radiation**

The sun is one of the renewable energy sources which is the most abundant kind although distant about 150 million km from earth. The solar radiation that reaches the earth surface is about  $1.2 \cdot 10^5 \text{ TW}$  [25]. The calculated solar irradiance at the earth's atmosphere is about  $1.36 \text{ kW/m}^2$  which is relatively constant. For the radiation at the earth's surface, it knows

several variations due to atmospheric effects (absorption and scattering) and local variations in the atmosphere such as water vapor, clouds and air pollution. These variations are caused as well by the latitude of a location and time of the year.

The path length which the solar radiation takes over the atmosphere is known by the Air Mass (AM) which is defined by Eq. 1. This parameter is used to compare and unify the performance of photovoltaic cells developed in different laboratories around the world.

$$AM = \frac{1}{\cos \theta} \quad \text{Eq.1}$$

where  $\theta$  is the angle from the vertical (zenith angle). When the sun is directly overhead, the AM is 1.

The surface of the sun behaves like a black body at a temperature of about 5800 K. As shown in Fig. II.1, AM0 corresponds to the extraterrestrial solar radiation while AM1.5 corresponds to the global solar irradiance after it has passed through a thickness of cloudless air of 1.5 times the thickness of the atmosphere. This situation arises in practice when the sky is very clear and the sun is at a height of 41.8°. The sun spectrum includes different wavelengths ranges from the short infrared to the long ultraviolet (UV). The maximum of solar radiation is located in the visible (VIS).

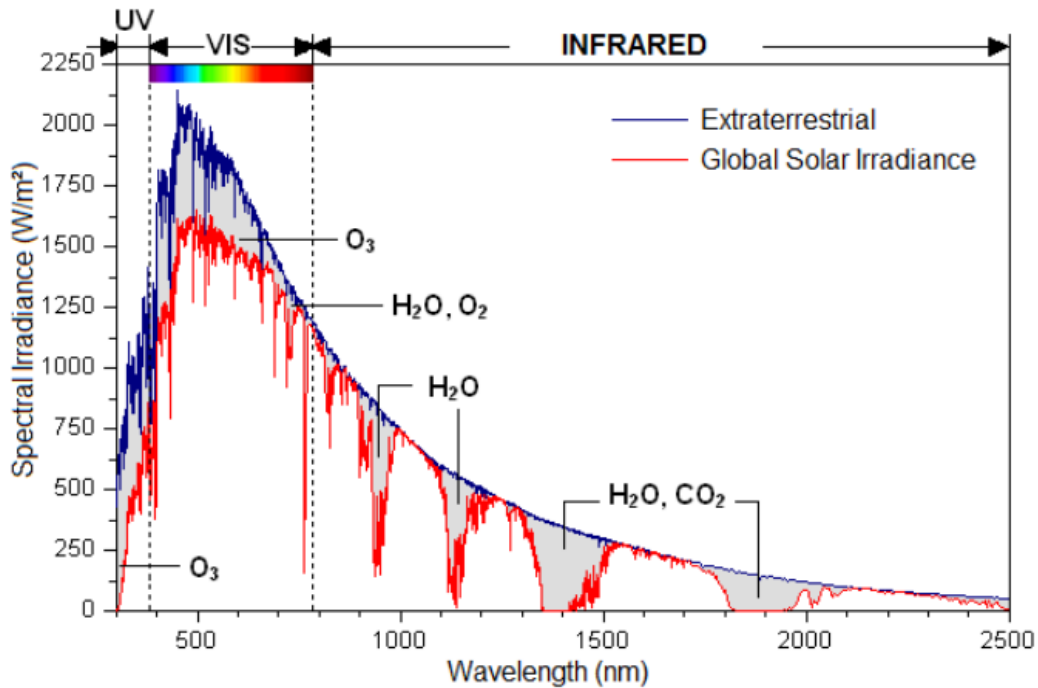


Fig II. 1. Standard Solar Spectrum [26].

## 2.2. Solar Photovoltaic (PV)

### 2.2.1. Photovoltaic effect

The photovoltaic cells (PV) use the photovoltaic effect to convert energy received from the solar radiation directly into electrical energy. The union of two different conductive regions of a semiconductor material (Silicon for example) presents the architecture of PV cells shown in Fig. II.2, these semiconductors can be of p-type (materials with an excess of holes, called positive charges, usually doped by Boron) or n-type (materials with excess of electrons as phosphorous, called negative charges). When these two different kinds of semiconductors are in a union, they form a junction called PN junction. Electrons and holes concentration is formed near the surface cause holes to diffuse from p-type to n-type and electrons to diffuse from n-type to p-type [27]. Indeed, it is known that the sunlight is basically a bombardment of photons similar to any other electromagnetic wave. The energy of the photon ( $E_\lambda$ ) determines the wavelength ( $\lambda$ ) and spectral properties of electromagnetic waves and can be mathematically defined by Eq. 2:

$$E_\lambda = \frac{hC}{\lambda} \quad \text{Eq. 2}$$

where  $h$  is Planck's constant and  $C$  is the light velocity. In the PV process, to make the energy conversion possible  $E_\lambda$  should be more than the band-gap energy of the receiving material, which is about 1.12 eV for silicon. This implies that photons' energy level must be high enough to break some of the covalent bonds of the semiconductor material and push electrons from the valance band to the conduction band and thereby create free charge carriers, i.e., electrons and holes.

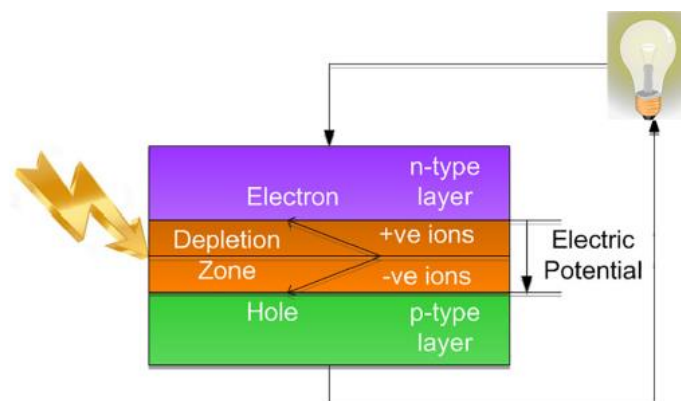


Fig II. 2. PV cell representation presenting both layers (p-type and n-type) [27].

In the absence of radiation in semiconductor materials, some of the covalent bonds break, and charge carriers, which means free electrons and holes, are created at a temperature above absolute zero. Though, in that case, the free charge carriers recombine continuously at the same

rate, and as a result, the material remains in a stable state. When photons of more energy than the band-gap energy of materials (e.g., solar irradiance) irradiate the semiconductor materials, the generation rate of free charge carrier increases more than the recombination rate. Consequently, a potential difference is created through the junction (Fig. II.2). Free charge carriers start flowing through the external load when connected. The performance characteristics of the semiconductor p-n are non-linear in nature. The current produced by the p-n junctions is a function of the potential difference across the p-n junction, which may be represented by the equivalent circuit model shown in Fig. II.3. From the equivalent circuit, the output current ( $I$ ) can be mathematically defined by Eq. 3:

$$I = I_{ph} - I_S \left( e^{\frac{V+IR_S}{nkT}} - 1 \right) - \frac{V-IR_S}{R_{SH}} \quad \text{Eq.3}$$

where  $I_{ph}$  is the photocurrent produced by the cell and  $I_{SH}$  is the shunt current through the shunt resistance ( $R_{SH}$ ).  $I_D$  is the diode dark current while  $I_S$  is defined as the reverse saturation current of the diode.  $R_S$  is the series resistance and  $n$  is the diode ideality factor. The output electrical characteristics are changing with environmental conditions because  $I_{ph}$  and  $V$  are functions of irradiance and cell temperature.  $k$  is the Boltzmann constant and  $T$  is the effective temperature of the cell in K.

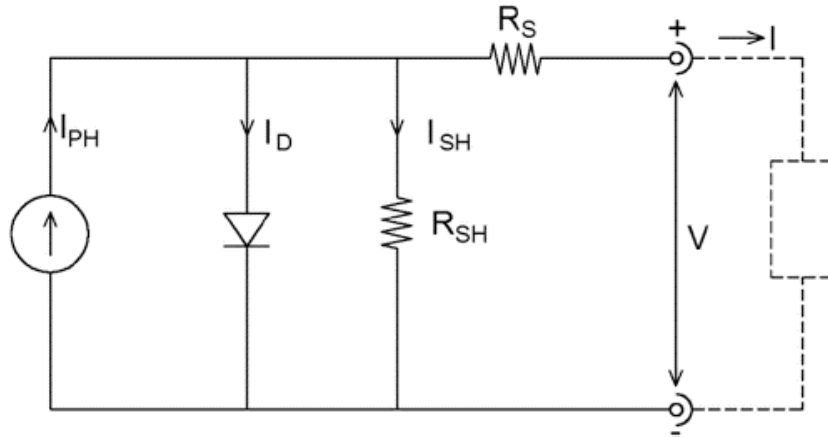


Fig II. 3. PV cell equivalent circuit model [27].

### 2.2.2. Properties of solar PV cell

#### a. Open circuit voltage ( $V_{oc}$ )

The open circuit voltage ( $V_{oc}$ ) is the voltage measured at the terminals of the cell when the current supplied by the cell is zero. Most commonly, the  $V_{oc}$  of solar PV cells has been noticed between 0.5 and 0.6 V.

#### b. Short-circuit current ( $I_{sc}$ )

Short-circuit current ( $I_{sc}$ ) is the current through the solar cell when the voltage across the solar cell is zero. For most PV modules (whose  $R_S$  is low), and under normal irradiance, the term  $I_S \left( e^{\frac{I_{sc} R_S}{nkT}} - 1 \right)$  can be neglected in front of  $I_{ph}$ . So the approximate expression of  $I_{sc}$  is:

$$I_{sc} = I_{ph} - \frac{I_{sc} R_S}{R_{SH}} \quad \text{Eq.4}$$

In the ideal case ( $R_S$  zero and  $R_{SH}$  infinite), the short-circuit current  $I_{sc}$  is very close to the photocurrent  $I_{ph}$ .

### c. Maximum power

The maximum power of a photovoltaic cell ( $P_{mp}$ ) corresponds to the power generated at the maximum power point and it is given by the following equation:

$$P_{mp} = I_{mp} \cdot V_{mp} \quad \text{Eq.5}$$

$P_{mp}$  is also indicated as  $P_{max}$  (maximum power point, MPP) corresponding to  $V_{mp}$  voltage and  $I_{mp}$  current as illustrated in Fig II.4 [28].

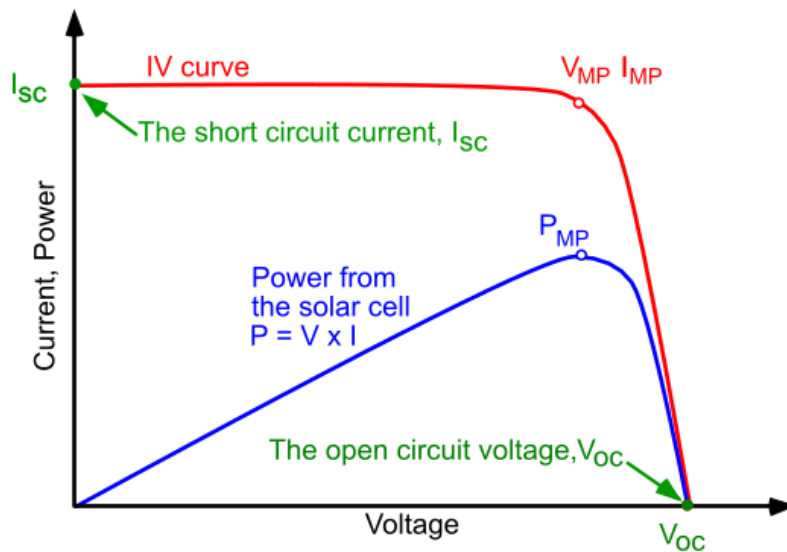


Fig II. 4. Current and Power versus Voltage curves of a solar cell [28].

## 2.3. Solar PV technologies

Commercial production of PV energy has been focused on crystalline silicon and thin-film technologies (e.g., Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS)). However, more recently, a large number of emerging PV technologies are being developed by researchers and industries for creating better options in terms of efficiency, recyclability,

consumption of energy and resources during production, and sustainability, such as dyesensitizers, carbon nanotubes, organic polymers, inorganic materials, and inorganic–organic hybrid materials (e.g., perovskites) [29]. National Renewable Energy Laboratory (NREL) has reported the increase in efficiency in recent decades and underlines the progress made by research and development efforts. It maintains a chart of the highest confirmed conversion efficiencies for research cells for a range of photovoltaic technologies, plotted from 1976 to the present [30].

In order to maximize the conversion efficiency of PV cells, the concept of multi-junction devices was introduced by matching the wavelength of photons with the band-gap of the material. This concept is added to tracking in concentrated PV to enrich high efficiency.

#### **2.4. Concentrated PV (CPV)**

An ever-increasing attention has been given to CPV technology, as an energy saving method which can directly generate electricity from the sun, especially with the deepening worldwide energy crisis. Low cost, high efficiency, and climate-friendly are the main advantages of CPV [31]. In CPV systems, increasing concentration ratio monotonically yields higher cell temperature, apart from space heating and residential water, the waste heat at the back of CPV cells can be recovered and injected into various industrial applications. Note that CPV temperature frequently rises above 200°C as CPVs are mostly installed and operated under immense and stable solar radiation intensity [32]. As the sunlight concentration increased, excess cell temperature causes electrical conversion efficiency loss and cell lifespan decrease. Thus cooling mechanism became crucial in the CPV. Different strategies to implement cooling mechanisms (passive or active), innovative technologies, and materials are being investigated [33].

PV cell's material determines the spectral response. For example, silicon solar cells absorb sunlight with the wavelength of 400–1200 nm, whereas gallium arsenide solar cells can absorb between 400 and 900 nm. An example of this technology is presented in Fig II.5. The absorbable wavelength takes up only a small part of the entire sunlight spectrum, and the other sun radiation which is out of PV cells' response wave band, would turn into thermal energy that causes continuous rise of the cell temperature and seriously affects the photoelectric conversion efficiency.

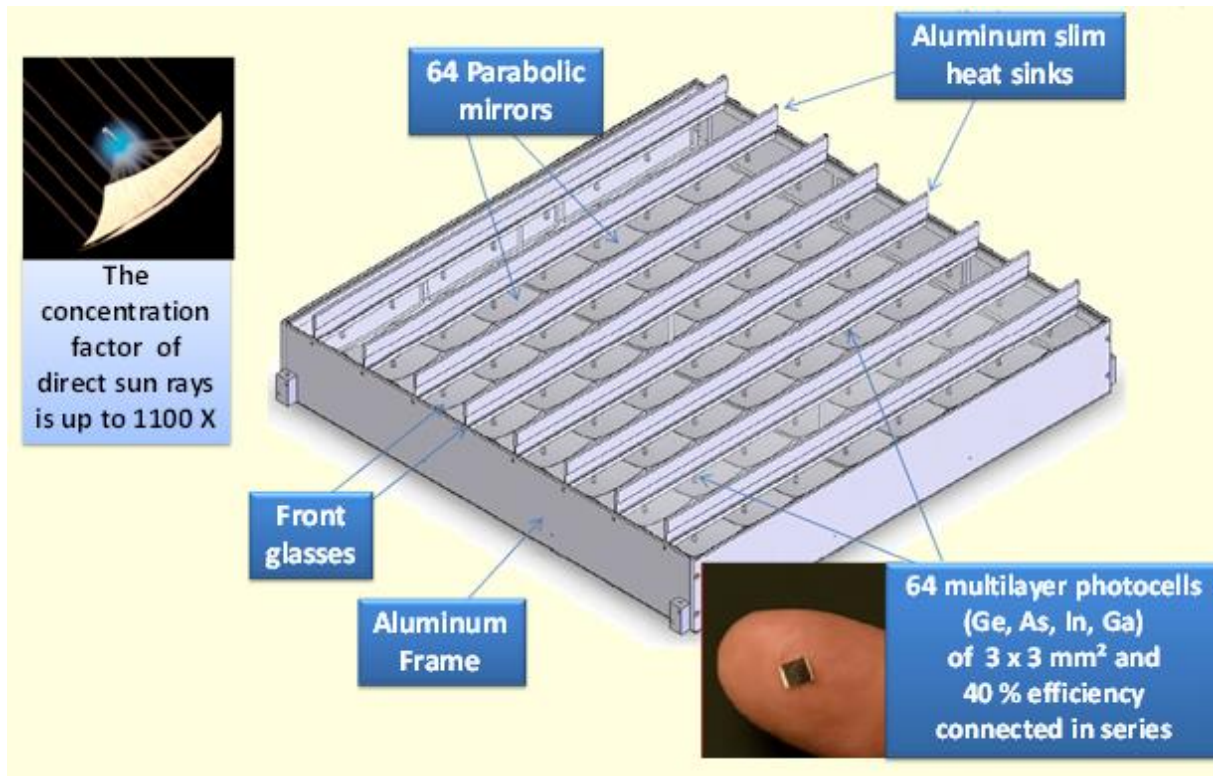


Fig II. 5. High Concentrated PV module from the power generator installed in the R&D Solar Energy Platform of PSES in Rabat.

For the efficiency, 44.4% for 3-junction, 46.0% for 4-junction, and 47.1% for 6-junction solar cells have been reported in literature. While CPV modules can reach efficiency records of 40% at the prototype level and 30% for commercial designs [33].

## 2.5. Solar trackers

Since many years, fixed or static solar systems were in use but now with the progress of technologies, the efficiency of solar systems is being increased by using single axis and dual axis solar tracking systems. These systems can track the sun position according to the season and time of the day [34]. Solar trackers are being used widely as they have improved the efficiency of energy extraction. Dual-axis tracking system can give maximum amount of output energy where single axis tracking system's energy output falls by 5% - 10% and fixed system's fall by 50% [35]. Solar tracking systems can be classified on the basis of the control system used, drivers used, tracking strategy used or on the basis of degree of freedom of movement exhibited by the system. Table II.1 gives an overview of the existing solar trackers.

Table II. 1. Overview on the existing solar trackers.

<b>Solar trackers</b>	
<b>Trackers based on control strategy</b>	<p><u>Closed loop tracking system</u>: These trackers use algorithm on the basis of mathematical calculations based on the sun's trajectory and sensors to detect the position of the sun which is then feed-backed to the system so that the microprocessor can detect the error and give the required actuating signal to the motors. The error then is corrected.</p> <p><u>Open loop tracking system</u>: These trackers use a controller which gives the driving signal to the motor purely on the basis of current data inputs and operating algorithm of the system alone. They are less expensive and simpler to implement in comparison with the closed loop trackers but it involves no adaptation process and thus the algorithm alone has to ensure that it achieves the desired goal.</p>
<b>Trackers based on drives</b>	They use electrical drives and mechanical gear to orient the panels normal to the sun's radiations. It uses sensors, motors and microprocessors for the tracking.
<b>Trackers based on degree of freedom</b>	<p>Degree of freedom represents the number of directions in which independent movement can occur. Based on this, tracking systems have been classified into single axis (SAT) and dual-axis solar tracking systems (DAT).</p> <p>SATs are cheaper and less complex but less efficient in comparison with DATs. SAT involves a single axis about which the rotation is possible in order to align the panel perpendicular to the sun's radiation. These systems are cheaper and less complex but less efficient in comparison with DATs. DAT involves two axes of rotation which are usually perpendicular to each other. It requires a more complex control system.</p>
<b>Based on tracking strategies</b>	<p>This category uses predefined algorithms based on mathematical calculations about sun's trajectory to determine the sun's position at a given time. The orientation is based on the calculation of the azimuth and altitude angles. The second subcategory involves sensors to detect the sun's position and the signal is transmitted to the microprocessor that drives motors. Another strategy is adopted for trackers, which is the combination of sensors, date and time. It is based on the predefined algorithm but sensors are also used to check the sun's position.</p>

### 3. Soiling of Solar photovoltaic panels

#### 3.1. Process of soiling

Soiling of photovoltaic panels is a major factor that prevents solar irradiation from reaching the cells. This phenomenon, which is linked to dust, soot, pollen, sand, tree leaves, moss, mushrooms, salts in marine environments, limestone, residues of cleaning products, etc., can reduce the electrical performance of photovoltaic systems. Indeed, the optical loss causes by

the accumulation of dirt and other pollutants on solar collectors is the third most important meteorological input, after insolation and air temperature that determines energy yield in photovoltaic power plant [36]. As shown in Fig II.6, many steps are involved in the soiling process starting from the transportation of dust until its alteration on the surface [37].

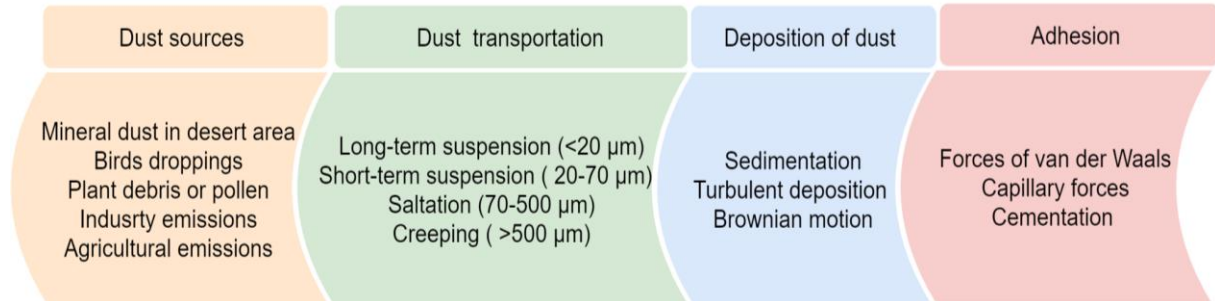


Fig II. 6. Soiling process.

### a. Dust transportation

Based on the work presented in [37], soiling particles previously defined can be transported via several mechanisms depending on wind speed and particles size; creeping, saltation, short-term suspension and long-term suspension. Indeed, creeping mechanism concerns soiling particles with a diameter greater than 500  $\mu\text{m}$ . These particles can roll on the ground, or after a short jump of less than a centimeter can settle on the ground. The second transportation mechanism is saltation which occurs for particles with a diameter between 70 and 500  $\mu\text{m}$ . These particles move by lifting and jumping along the ground towards a given surface. The last two mechanisms regarding the transportation of soiling particles are short-term (20 - 70  $\mu\text{m}$ ) and long-term suspension (< 20  $\mu\text{m}$ ) [38]. Actually, particles transported by long-term suspension can remain in the air for long time (many weeks) along kilometers from the source.

### b. Deposition

The deposition of dust on solar panels surface can be done through different processes [39]. The most common deposition mechanisms are cited in Fig II.6. Indeed, particles with diameter equals or greater than 100  $\mu\text{m}$  and larger can be deposited via the gravitational settlement [40]. The deposition rates depend on many properties such as particles diameter, shape and size. Particles having a reduced diameter less than or equal to 1  $\mu\text{m}$  are subjected to Brownian motion; they diffuse in an arbitrary manner in the atmosphere and have recourse to remain entrained in the flows [41]. As for the particles with medium size (order of 10  $\mu\text{m}$ ) are exposed to turbulent depositions which means they remain in suspension in the air during long period. These particles end up by the deposition once in contact with an object or only by sedimentation in windy conditions.

### **c. Adhesion**

The initial adhesion mechanism depends on the morphology of the surface (smoothness and roughness), its composition, chemistry, conductivity, charge, orientation, optical properties, temperature and others [42]. The adhesion mechanism between deposited soiling particles and the surface tends to change with time due to the influence of the environment. The main particle-adhesion forces mostly considered are van der Waals force, capillary adhesion (liquid bridge) and electrostatic forces. Indeed, at lower relative humidity values, van der Waals forces are dominating, and at higher relative humidity, capillary forces can dominate if the water layer is thick enough to overcome the surface asperity [43]. In presence of dew and soluble dust content, the cementation is highly relevant wherein soluble dust dissolves in condensation and re-solidifies upon drying, forming a solid bridge between the particle and surface.

### **3.2. Factors affecting soiling**

Soiling is a great challenge in regions with high aerosol concentrations and little rain such as arid and semi-arid climates. Because of several influencing factors, which are often site-dependent, the soiling process is not fully understood [44]. Many works have been published aiming to analyze the various influencing factors that are interacting with each other [7]. In what follows, the determination and analysis of each of the factors that affect the soiling process will be established.

#### **3.2.1. Climatic conditions**

##### **a. Rainfall, wind speed and direction**

PV soiling is a complex phenomenon influenced by diverse site-specific environmental and weather variables such as rainfall, wind speed and its direction. Actually, rainfall is considered the main natural cleaning factor which implies soiling recovery. This recovery is a site-dependent. Indeed, a study in Spain has shown that around 2.2 mm of rainfall has 50% chance to reduce the soiling ratio [45]. It has been also reported in Qatar that 3 mm of rainfall can ensure an efficient cleaning and restore the initial state of solar panels [46,47]. Less than this amount can lead to a partial cleaning. The effect of rainfall can be affected positively or negatively by wind velocity [48]. Indeed, high wind speeds with the presence of rain enhance the cleaning of the solar panels by blowing rain to remove the dust out of the panel. The effect can be reversed in the absence of rain and depending on wind direction. The dust can be blown on the surface and lead to dust accumulation as shown in Fig II. 7.



Fig II. 7. Schematic showing a proposed theory of how wind and rain can possibly interact reduce dust accumulation [48].

In the work of [49], the cleaning of PV panels by wind has been analyzed and it has been found that large particles with diameter larger than  $1\ \mu\text{m}$  were effectively removed by wind due to the low required resuspension velocity compared with small particles. In the same work, the wind velocity that can lead to a natural is ranged between 0.82 to 2219.8 m/s as estimated by the developed model.

### b. Air humidity

In open natural environments, water, in the form of humidity in the air, condenses on surfaces. Humidity promotes particle adhesion to the surface and increases the hydrodynamic force of wind needed to induce resuspension of particles [50]. Depending on the values of relative humidity, different adhesion forces of soiling particles to the glass surface occur. At lower relative humidity values, van der Waals forces dominate, while at higher values capillary forces can dominate [43]. The effect of this parameter is well investigated in the following chapter where the interaction between air humidity and dew water is presented.

### 3.2.2. Dust properties

The properties of airborne dust, including size distribution, shape and chemical/mineralogy composition can vary greatly by location and affect the soiling losses strongly. EL-Shobokshy and Hussein [51] were pioneers on a comprehensive study into the impact of dust on the performance of PV cell, including the physical properties of the dust accumulation and deposition density on their impact on parameters degrading PV efficiency. The experiment was entirely simulated with artificial dust (including limestone, cement and carbon particulates) and halogen lamps. While keeping the solar (light) intensity constant and varying different densities of dust the test was repeated several times. The study revealed the impact of cement particles to be the most significant, with a  $73\ \text{g/m}^2$  deposition of cement dust resulting in a 80% drop in PV short-circuit voltage; atmospheric dust with mean diameter  $80\ \mu\text{m}$  at  $250\ \text{g/m}^2$  was found

to reduce the short-circuit current by 82%. Regarding the size effect, fine carbon particulates (5  $\mu\text{m}$ ) were found to have the most deteriorating effect on the PV efficiency.

Various analytical tools including optical, scanning electron, X-ray diffraction, atomic force microscopy, Raman, FTIR and UV-Vis spectroscopy are used to analyze dust particles. The results of the analyses of dust collected from PV panels in Doha city that has been analyzed, showed that dust particles have mainly an average size of about 2  $\mu\text{m}$ , in addition to the presence of larger non-uniform particles of few tens of micron size [52]. EDS and X-ray diffraction analysis have shown that the particles are mostly composed of calcite mineral structure with about 58% atomic content as verified as well by Raman and FTIR spectra. In Rabat city of Morocco [53], the collected dust that has been analyzed showed a large variety of chemical element and other constituents composing the dust powder. The results indicate that the most abundant elements are essentially silica (35.5 %), alumina, iron oxide, calcium oxide, magnesium oxide and potassium oxide. There are also several minerals as Muscovite and Kaolinite which can be opaque to sunlight.

In arid and semi-arid climates, the main proportion of soiling is attributed to dust particles with a diameter ranging between 2 and 63  $\mu\text{m}$ , since larger sand particles (diameter > 63  $\mu\text{m}$ ) are too heavy to be lifted high enough to settle on PV modules except in very strong wind events like desert storms. Lawrence et al. [54] have reviewed and summarized different size distributions for dust deposits from local, regional and global soiling sources. They found the main fraction of particles to be in the silt size range (50%, 60% and 70%, respectively) and minor fractions of clay (< 2  $\mu\text{m}$ ) and sand. It can be assumed that there is a correlation between airborne size distribution and particle size distribution of dust deposited on PV modules. For example, Javed et al. [55] reported mean and median size ranges on PV modules in Qatar to be between 9 and 25  $\mu\text{m}$  including monthly changes as well as lower size ranges for longer durations of exposure of the surfaces. A literature overview performed by Figgis et al. [56] of particles accumulating on outdoor surfaces has shown dominant particle sizes of 10 - 32  $\mu\text{m}$ .

### **3.2.3. Tilt angle, orientation and height**

PV tilt angle has a direct effect on the accumulation of dust on the surface. The smaller the tilt angle, the greater the amount of dust that accumulates on the surface [57,58]. This effect has been confirmed in Rabat (Morocco) on the glass coupons through the transmittance measurements [59]. Soiling is highly affected by a surface's tilt angle. Indeed soiling rates significantly decrease at steep tilt angles [42,59]. In Portugal, a model based on irradiance and

soiling data has been developed to set tilt angle configurations to maximize the energy production [60]. For large solar field, the different tilt angle configurations could be concretized by movable tilt angle frames which present better costs optimization rather than single or dual-axis trackers.

In areas north of the equator, solar power plants are facing south and at a tilt angle equal to the latitude of this region, and usually depending on the solar irradiance of the region. Despite the tilt angle, it has been found by [46] that the reduction in glass normal transmittance depends on the orientation of the surface with respect to the dominant wind direction. It has been found in this study that glass samples oriented North-East (NE) accumulated more dust than any other orientation because of the influence of the prevalent NE winds.

The height was not well investigated in literature and its effect has been attributed to the dust concentration in the atmosphere. Indeed, particulate matter less than 10  $\mu\text{m}$  (PM10) or less than 2.5  $\mu\text{m}$  (PM2.5) in diameter are the most commonly measured parameter to estimate the airborne dust. The study conducted in western Queensland, Australia [61] has shown that dust concentration decrease rapidly with increasing height. Hence the accumulation of dust on PV modules would decrease with increasing height as well.

#### **3.2.4. Front glass characteristics**

The transmissivity of the front glass of PV panels is affected negatively by dust deposition. However, the nature of the glass surface is one of the influencing parameters that need to be considered. Actually, Polyvinyl Chloride (PVC) and acrylic surfaces generally show a greater loss of transmittance to that of a glass. This latter is the most commonly used material for manufacturing PV modules. Nowadays, surface engineering can help increase the amount of light transmitted through the glass layer in the cell and, as a result, the overall performance of the modules improves [62]. It has been reported in literature that an anti-reflective coating and micro-texturing of the surface can reduce the soiling effect by 3 to 4% [63]. Another study has shown that a super-hydrophobic silica surface presents some self-cleaning properties, thus reducing the soiling rates [64]. It has been found that in the first thirty days, the rate of accumulation of dust on a surface is maximum and after this period the surface attraction forces tend to decrease [65]. So in order to increase the resistance to soiling, the surface has to gather many properties; smoothness to limit the accumulation of dirt in pits, low surface energy to reduce the adhesion forces that can occur between the surface and the soiling particles, hydrophobic (less attractive to ionic species, adsorption of solids, and retention of water) [66].

### 3.3. Soiling quantification

Soiling is the third-most significant environmental factor impacting PV power plant performance, after irradiance and temperature, it should be quantified with the same care taken to monitor the performance factors [67].

Investigations related to soiling impact are divided into those who have been based on solar glass [10], [68,69] and those who have mitigated the soiling impact directly on photovoltaic modules [67], [70,71]. PV soiling losses have been studied at various locations around the world, the results are typically site specific (Table II.2) and related to mounting angles and other parameters as explained in the previous section. We found in the literature countries who have investigated the soiling impact based on the output power, the optical transmission, current produced by the panels and the energy losses. All this different refer to the soiling ratio ( $SR$ ) which can be calculated by the Eq.6 [72].

$$SR = \frac{G_2}{G_1} \quad \text{Eq.6}$$

where  $G_1$  refers to irradiance of the clean PV module and  $G_2$  refers to the soiled PV module.

Based on the soiling ratio  $SR$ , the common parameter called soiling losses ( $SL$ ) is calculated using Eq.7 [37]:

$$SL [\%] = 100. \left( 1 - \frac{X_{soiled}}{X_{clean}} \right) \quad \text{Eq.7}$$

where X can refer to short current ( $I_{sc}$ ), power output ( $P_{max}$ ) or daily produced energy.

Table II. 2. Soiling losses of PV modules in all over the world.

Ref.	Location	Period of study	Soiling losses
[73]	Arizona, USA	16 months to 5 years	Soiling effect on PV module increases as the angle on incident increases. Losses increased from 2.3 % at normal incident to 4.7% at 24°
[74]	Atacama, USA	12 months	Daily energy yield of PV modules deployed in five cities across a north-south transept of approximately 1300 km in the Atacama Desert has been assessed. 39% was found for energy loss while 7% was found in Santiago.
[75]	United Arab Emirates (UAE)	1 year	Coated PV modules showed average daily soiling losses of 2.5%, while uncoated modules a daily average of 3.3%.
[76]	Navarre, Spain	1 year	Daily optical energy losses vary, along the year, from 1 to 8% in the case of tracking surfaces, and from 8 to 22% in the case of horizontal surfaces

[47]	Doha, Qatar	6 years	Severe soiling losses of the PV panels were found in summer months due to dust storms. 8% attenuation of solar radiation reaching the PV panels because of the dust storms.
[15]	South of Spain	1 year	Yearly soiling losses were 3% for 1 MW PV installation.
[77]	Bangkok, Thailand	30 days	Experimental observations of natural dust accumulation on an angle 15° tilted glass at a tropical climatic condition during a 30 days period indicates a dust accumulation of 3.72 g/m <sup>2</sup> and is found to reduce the global transmittance of the glazing from about 87.9% to 75.8%.
[78]	Indoor	Indoor	The dust load ranged from 1.30 to 1.63 g/m <sup>2</sup> promoting electrical losses from 4.73 to 6.90% depending not only on the dust load but also on the conditions in which it was deposited.
[79]	Sharjah, UAE	5 months	An increase of 12.7% in soiling loss and 5.44 g/m <sup>2</sup> of increase in dust density during the period of exposure. Indoor and outdoor studies can be useful to predict the soiling loss of PV.
[80]	Benguerir, Morocco	4 months	Soiling loss for glass samples has reached 12% in only one week in Benguerir, Morocco.

#### 4. Cleaning techniques and soiling mitigation approaches

##### 4.1. Introduction

The trend today is to maintain or enhance the performance of the PV modules and this through a low cost and ecological cleaning as well as the use of tracking systems. Several systems of cleaning have been conceived seeking to avoid significant lost in power generated by solar panels due to soiling, this is, on the one hand. On the other hand, tracking systems have been proven to have smaller losses due to soiling in comparison to fixed modules, but these losses come more and more important if the tracker is implanted in a desert area.

Mitigation techniques and cleaning is one of the topics that are receiving interesting attention in last few years [23]. As detailed by [81], different cleaning techniques were the result of the awareness to keep the solar panels constantly clean, then improve the performance of the solar power plants. Fig II.8 presents a classification of the cleaning techniques that can be divided into three categories.

As the natural cleaning is dependent on the availability of rainfall, the manual cleaning, which is related to labor, is used in the dustiest areas. Given the costs that can occur by labor, another other corrective and preventive categories of cleaning were developed. The corrective

cleaning includes manual cleaning, mechanical techniques that can be fully automated or semi-automated as well as the electrodynamic screen, while the preventive cleaning can be ensured by treating the surface of the solar panels. Regarding the analysis of different cleaning methods carried out by Jamil et al. [81], mechanical cleaning techniques did not show any limitations.

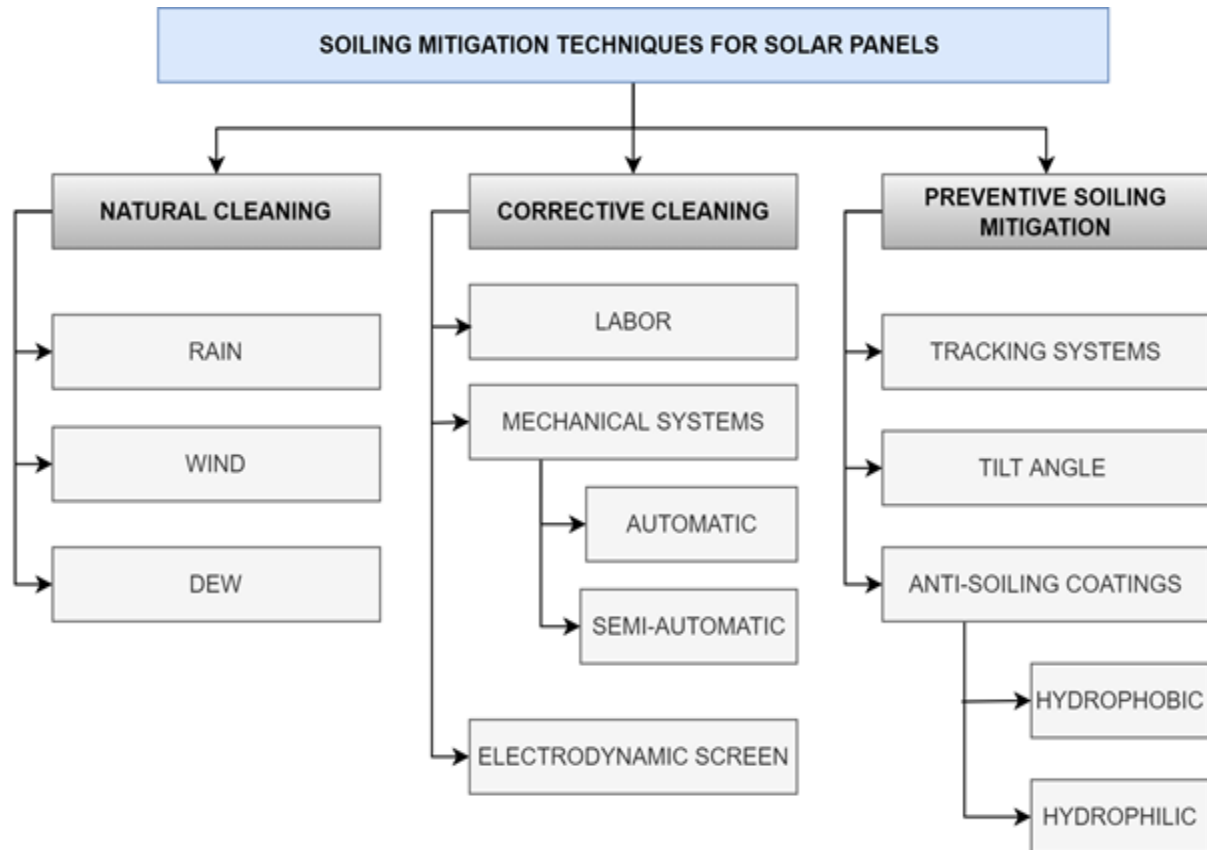


Fig II. 8. Overview of the different sub-categories of cleaning techniques for solar panels.

#### 4.2. Natural cleaning

The first category concerns the natural cleaning which can be done by rainfall, wind and dew depending on the climate conditions. No cost is required by natural cleaning but it has been reported as being not effective for small dust particles [82]. The efficiency of cleaning by natural events depends on the amount of rainfall (rain or dew) and the wind direction as previously mentioned. Indeed, high wind speeds with presence of rain enhance the cleaning of the solar panels by blowing rain to remove the dust out of the panel. The cleaning through rainfall and wind has been well discussed earlier (section 3.2.1. Climatic conditions).

Regarding the cleaning by dew, an important amount of dew water is observed on the solar panels which leads to their self-cleaning especially in early mornings [8]. The effect of dew as a cleaning factor will be addressed in detail in a separate chapter that was a subject of a published review.

### **4.3. Corrective cleaning**

#### **4.3.1. Manual cleaning**

Manual cleaning requires human resources (labor), material such as soft brushes for dry cleaning as well as water in the case of wet cleaning. Karcher [83], which is a company specialized in the cleaning products, has developed cleaning brushes made by natural and nylon bristles that avoid micro-scratches to be created on the solar glass surface. These brushes can be fitted with air pressure cleaners.







As benefits, the manual cleaning is considered the most efficient method to recover PV performance and it can be performed whenever required [82]. However, it requires high cost and it is limited water in arid area as well as scratches may be produced. According to the study of [84], the use of demineralized water and a brush was the most effective compared with a jet of air or water with high pressure. The use of detergent is not required since it does not increase the effectiveness of cleaning.







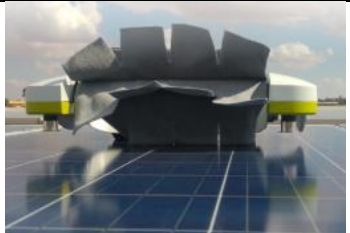
#### **4.3.2. Mechanical systems**

The corrective cleaning category includes as well mechanical techniques that can be fully automatic or semi-automatic. Mechanical cleaning systems denote any cleaning technique with motorization able to replace the physical effort provided by the operator. They are characterized by a large dust removal force, fast operation, good environmental adaptability and control performance [22]. According to the system dimensions (motorization axes), the mechanical solutions are divided into three categories: single dimension, two dimensions and autonomous robots. Table II.3 presents an overview on these cleaning systems. We can see that many of the systems have been developed to tackle the challenge of soiling, and most of them are dedicated to fixed panels except Ecoppia that proposes an autonomous system for single axe trackers.

Table II. 3. Some of commercial mechanical cleaning systems of solar panels.

	<b>Technique</b>	<b>Specifications</b>	<b>Technique view</b>
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Travelling Brush – 1 Dimension	NOMADD	<p>Dry cleaning</p> <p>Travels on twin mounted rails</p> <p>Row width <math>\leq 4\text{m}</math>, length <math>\leq 200\text{m}</math></p> <p>Relatively heavy (<math>\sim 50\text{ kg}</math>)</p> <p>One device for each row</p> <p>Early commercial</p> <p>Internal use/demonstration</p>	
	Greenbotics/ SunPower	<p>Wet cleaning (using water)</p> <p>Caterpillar tracks on module surface without rails</p> <p><math>\sim 100\text{ ml}</math> water per panel</p> <p>Only provided for SunPower Oasis PV systems.</p> <p>Stage: Commercial</p>	
	Washpanel	<p>Wet and dry cleaning</p> <p>Self-tracking without rails (patented)</p> <p>No guide rails required</p> <p>Very wide rows for dry cleaning.</p> <p>Stage: Commercial</p>	
	SunBrush (Germany)	<p>Wet cleaning with brush</p> <p>Mounted rails</p> <p>The system can be started by rain</p> <p>Stage: Early commercial</p>	
	Geva-Bot	<p>Wet and dry cleaning</p> <p>1 l per 1 panel for the wet cleaning.</p> <p>Dimensions vary from 1 m to 6 m long.</p> <p>Stage: Commercial</p>	
	Ecotaqa	<p>Dry cleaning</p> <p>Fully automatic</p> <p>Stage: Research</p>	
Travelling Brush – 2 Dimensions	Ecoppia E4	<p>Dry spinning microfiber strips</p> <p>Guided by rails</p> <p>Fully automatic</p> <p>Dedicated for desert</p> <p>Stage: Commercial</p>	

	Solmaks	<p>Wet cleaning</p> <p>System can be adapted to dry cleaning.</p> <p>Guided by rails</p> <p>One device for each row</p> <p>Stage: Commercial</p>	
	Mirai	<p>Clean PV modules at a speeds of up to 2.16 m<sup>2</sup>/hour</p> <p>Autonomous control system</p> <p>The system can easily cross gaps between PV modules rows</p> <p>Stage: Commercial</p>	
Autonomous And Operated	HyCleaner	<p>Wet cleaning</p> <p>Controlled by radio control with a range of 100 m.</p> <p>Use on different tilt angles</p> <p>Stage: Commercial</p>	
	SolarCleano	<p>Dry and wet cleaning</p> <p>Operated (the system needs an operator for remote)</p> <p>Cleaning of large area</p> <p>Stage: Commercial</p>	
	Mirai	<p>Dry cleaning by linear brushes</p> <p>Designed for desert climate</p> <p>Portable by hand</p> <p>Relatively fast and Autonomous</p> <p>Single button operation</p> <p>Stage: Commercial</p>	
	Serbot Gekko	<p>Wet cleaning</p> <p>Operated</p> <p>Installation angle of max. 15° and max. 30° with additional safety device</p> <p>Max. 1440 m<sup>2</sup> per hour</p> <p>Water consumption: 150 l/h</p>	
	Ecoppia E4	<p>Dry cleaning</p> <p>Designed for trackers single axis</p> <p>Autonomous</p> <p>Operational only in flat surfaces (stow position)</p> <p>Stage: Commercial</p>	

#### 4.3.3. Electrodynamic screen (EDS)

As a corrective cleaning method, the electrodynamic screen has been proposed and tested in different environments and adopted as the main dust removal by the National Aeronautics and

Space Administration (NASA) on Mars and Moon missions [85]. The EDS uses a traveling-wave effect to deter dust out from the panel surface. The principle of EDS is based on the manufacture of electrodes on a substrate (Fig. II.9). The electrodes are either transparent or very thin in order to minimize the shading effects. In order to insulate the electrodes from the air, a transparent dielectric cover is placed over the electrodes. This dielectric layer becomes the outermost layer thus requiring protection from dirt or even its mitigation. During field operations, dust deposition occurs on the air side of the dielectric cover, so that the activation of the EDS can repel the deposited dust, taking advantage of the electrostatic charges carried by the dust particles [86]. The dielectric blanket is a thin sheet which is bonded to the electrodes/substrate through an adhesive, or applied as a coating [87]. The activation of the EDS consists in applying a high alternative voltage to the electrodes, which leads to an alternative electric field. The electrically charged dust that has settled on the air side of the dielectric cover can then be pushed out of the EDS. This latter can be either a self-contained thin structure that covers the front surface of a solar panel or a component integrated into the solar module [88].

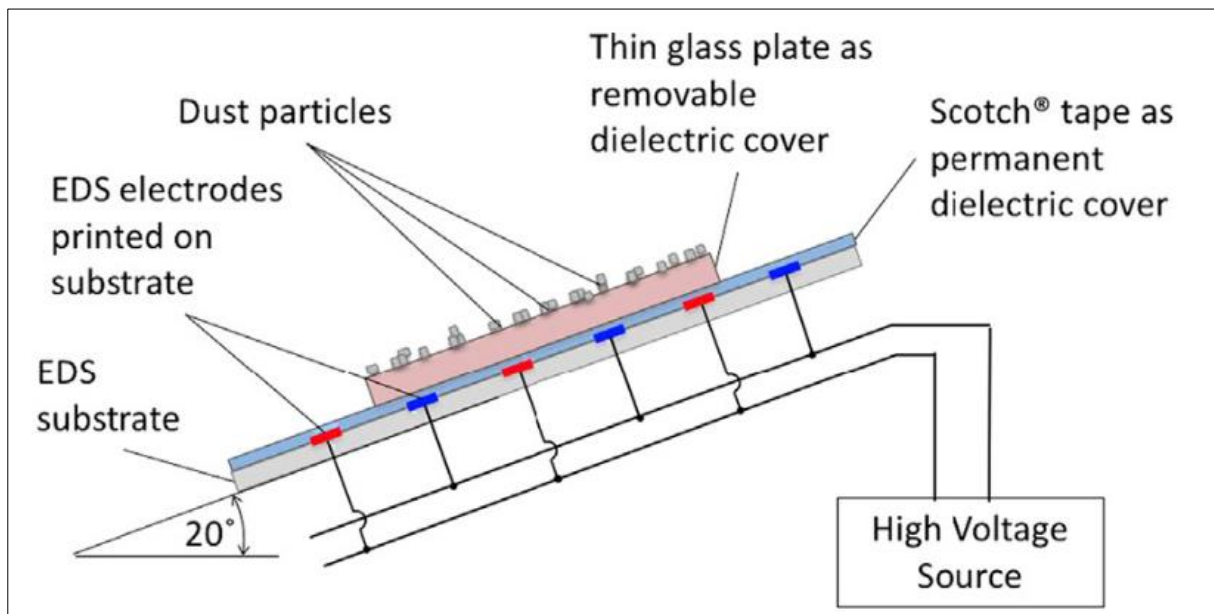


Fig II. 9. Schematic view of an Electrodynamic Screen [88].

The EDS is considered faster compared to other methods. However, there is a risk of screen degradation due to ultraviolet (UV) rays [89]. Also, the system involves high voltage supply to generate electric field, thus reducing the generation efficiency by 15%. It has been also reported that the EDS is not effective for wet or cemented dust particulates (in presence of dew), and so it is less efficient for small sized particles [88].

#### **4.4. Preventive soiling mitigation**

##### **4.4.1. Anti-soiling coatings**

The preventive methods include different approaches aiming to repel the dust out from the panels surface based on the treatment of the surface properties [90]. This category of soiling mitigation focuses on special coatings that can be super-hydrophilic [91] or super-hydrophobic [92].

##### **a. Super-hydrophilic coating**

The common super-hydrophilic coating is based on Titanium dioxide  $\text{TiO}_2$ , which has hydrophilicity and photocatalytic activity [90]. This preventive approach has two phases. The first one is a photocatalytic process which  $\text{TiO}_2$  film reacts under the UV radiation leading to splitting the dust particles. Then, because of the hydrophilicity, the rainfall will diffuse to the whole surface instead of getting together and rinse the dust. Several works have been developed related to the preparation, doping and amendment of this material. This self-cleaning method cannot be used in solar cell array because they worked mostly in the desert region where the occurrence of rain is very limited.

##### **b. Super-hydrophobic coating**

Inspired by the Lotus leaf [93] with a hydrophobic effect and less wettability, has raised a great interest among the research community because of its capability to be reproduced as coatings for self-cleaning by developing nano-structures and micro-structures [94]. The hydrophobic coating consists in forming a layer which is considered as a barrier so that water accumulates on the substrate in a spherical shape without being adhered to the surface. These spherical water droplets could roll off easily on the treated tilted surface thus leading to its self-cleaning. Indeed, it has been reported in literature that the contact angle (CA) can be enhanced by reaching more than  $150^\circ$  [95,96]. Fig II.10 shows an illustration of water droplet on a normal hydrophobic surface as well as on a super-hydrophobic surface. Many works are ongoing with a great focus to improve the non-wettability property for the hydrophobic coating as well as the lifetime and durability concerns especially for real environmental conditions [42]. Indeed, exposed candidate coatings in Denmark started to degrade after only two weeks outdoors. This degradation was manifested by CA decrease [97].

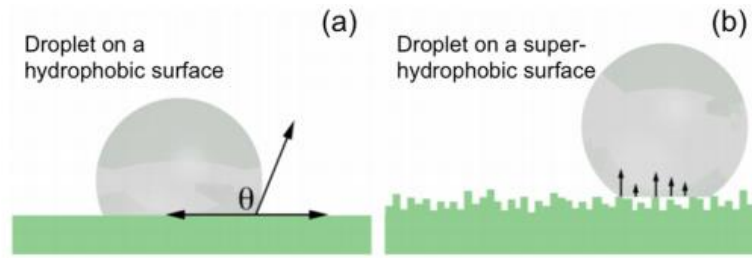


Fig II. 10. Schematic of (a) water droplet on normal hydrophobic surface with contact angle greater than  $90^\circ$  and (b) water droplet on a super-hydrophobic surface with a contact angle  $\geq 150^\circ$ . A super-hydrophobic surface is defined as a surface that has a water CA angle  $\geq 150^\circ$ . Micro- and nano-structuring a surface amplifies the natural tendency of the surface to achieve super-hydrophobicity [96].

#### 4.4.2. Tilt angle and tracking effect

Soiling is highly affected by a surface's tilt angle. Indeed soiling rates significantly decrease at steep tilt angles [42,59]. In Portugal, a model based on irradiance and soiling data has been developed to set tilt angle configurations to maximize the energy production [60]. For large solar field, the different tilt angle configurations could be concretized by movable tilt angle frames which present better costs optimization rather than single or dual-axis trackers. Since soiling can reach higher rates during the night [18], stowing the PV modules equipped with solar tracker vertically or upside at night can significantly reduce soiling [98] as well. In case of trackers, many stowage positions have been proposed to mitigate soiling [14]. It has been found that facedown position illustrated in Fig. II.11 is obviously more opportune [75]. Another stowage positions have been recently investigated [99]. They consist in stowing the PV trackers at a maximum tilt toward the wind, to minimize soiling at night. However, only few studies have been performed on the negative effect of the upward stowage position of trackers which maximize dust deposition [66,100].

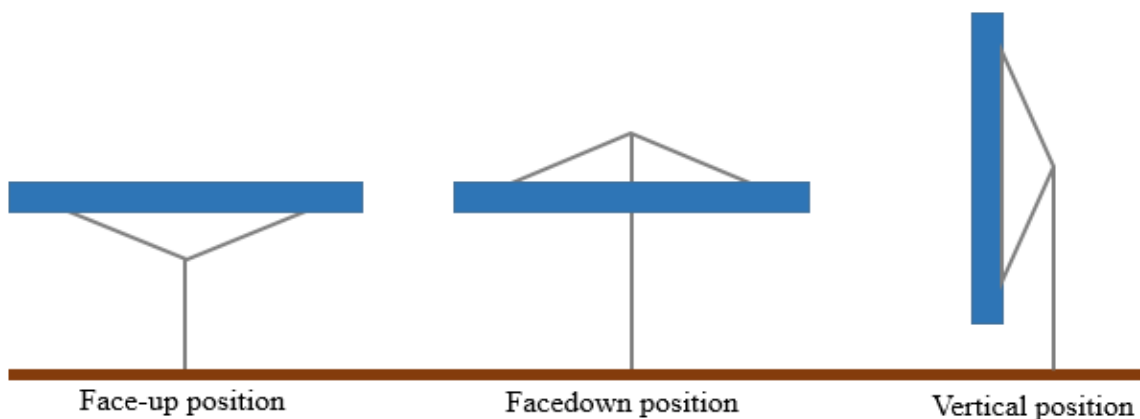


Fig II. 11. Main stowage positions at night for solar trackers [14].

## 5. Synthesis and conclusion

Soiling has received a lot of attention in the research community regarding its effect on solar power performance that could be recovered through cleaning operations. This subject is becoming more and more challenging in regions with high solar irradiance but suffering from water scarcity. Furthermore, this phenomenon is quite complex since it is influenced by diverse site-specific environmental and weather variables as investigated in this chapter.

In order to restore the losses in optical performance due to soiling phenomenon, several cleaning techniques can be adopted in solar power plants as summarized in Table II.4.

Table II. 4. Summary of the cleaning and soiling mitigation techniques with their advantages and disadvantages.

Soiling mitigation techniques		Advantages	Disadvantages
<b>Natural</b>	Rain	Free of charge	Availability
	Wind		Climate site dependent
	Dew		Less efficient for birds dropping and cemented dust.
<b>Manual</b>	Labour	Efficient	- High costs - Micro-scratches
<b>Corrective</b>	Electrodynamic Screen (EDS)	Faster compared to other methods	- Screen degradation due to UV
	Mechanical systems	- Fast operation, good environmental adaptability and control performance	- Less adaptability to solar trackers - Maintenance costs - Less efficient for fine dust particles
<b>Preventive</b>	Trackers/Tilt angle	Efficient in soiling mitigation compared to fixed structures	Economic applicability for large solar field
	Anti-soiling coatings	Passive (no energy requirements) - Efficient	Durability concerns

The cleaning and mitigation approaches studied have advantages and disadvantages related to some aspects of efficiency, costs and durability. Regarding manual cleaning, despite its high efficiency but the costs are still challenging especially in areas characterized by water scarcity. The corrective cleaning methods such as automated systems; present the advantage of being fast and ecological since they are either waterless or the use of water is quite optimized. However, they may present high maintenance costs. On another hand, according to the intensive research carried out, only few cleaning systems that showed their adaptability to solar trackers. However, this adaptability is relative since it will be necessary to invest more to make these cleaning systems completely appropriate especially to the dual-axis trackers. Therefore, it is of utmost importance to present an innovative cleaning solution to tackle the challenge of soiling especially for countries with great potential in solar energy. For the preventive soiling mitigation approaches, it can be concluded that despite their efficiency, their durability and economic applicability for large solar field, has to be more developed.

## **Chapter III: Use of dew in cleaning of solar power plants**

### **1. Introduction**

From another perspective, soiling depends strongly on dew formation that occurs on the front surface of solar panels. Dew water could have a negative effect manifested by the cementation of dust particles on the glass surface. Indeed, dew is responsible for particles caking which prevents natural cleaning by the wind. It is so assumed to increase the rates of soiling especially for desert regions that experience humidity conditions [10]. This leads us to a positive perspective that dew can be considered as a source of water that may be used for cleaning. Indeed, the positive effect of dew is less discussed in literature but it is reported in many works especially when dew contributes in self-cleaning of the solar panels.

First of its kind [62], the main purpose of this chapter is to provide a comprehensive review of previous publications related to the effect of dew on soiling of the solar panels. This through the summary of papers published so far by highlighting the main findings. The second section concerns the meta-analysis and discussion by investigating the negative and positive effect of dew and the solutions for its enhancement or mitigation. The last section presents the main conclusions and perspectives derived from the present work.

### **2. Literature Survey**

In this section, the published papers on the subject of dew are gathered and summarized (Table III.1). For each paper, the main findings regarding dew are presented. The effect of dew, positive or negative, is discussed as well. Through this survey, the classification of papers has also considered if dew was the main topic of the paper or it is just mentioned as influencing factor on soiling. For some studies, it was not possible to judge the effect either it is expected or found especially for studies of modeling and reviews which are other works results based.

Table III. 1. Summary of the published papers on dew effect on soiling of solar installations.

Ref.	Study device	Dew studied as	Main findings	Effect of dew	Proposed solution
[101]	Glass samples	Main Topic	In this study the authors have investigated the effect of heating on glass samples in order to break the capillary forces formed between the dust and the glass surface due to dew. Different powers have been applied to heat the samples that are compared to unheated ones. These samples were subject to outdoor microscopy studies as well. It has been concluded that after only one dew cycle, particles are intensely bounded on the glass surface and sample heating could be a promising approach to tackle soiling.	Found Negative	Approach to avoid dew formation
[66]	PV Panels	Factor	In this review, studies regarding the effect of dew on soiling have been summarized. Most of these studies cited the effect of dew as negative because dust particles can be cemented on the PV (photovoltaic) panel surface with occurrence of dew after being exposed to sunlight. However, the amount of dew water accumulated on the PV surface especially in early mornings can be used for cleaning which make its effect positive. It has been concluded that in order to enhance this positive effect, super-hydrophobic coatings may need to be included to guide off the moisture.	Expected Positive/Negative	Hydrophobic coating to be added
[102]	PV Modules	Factor	The effect of utilization of PCM (Phase Change Materials) for passive cooling of PV modules during the day has been explored in this study. It has been concluded that formation of dew water on the PV module at night can be mitigated by keeping the temperature of PV surface above the dew point during the night.	Found Negative	Heating using PCM
[100]	Glass coupon	Factor	In Doha City, an outdoor soiling microscope was used to measure the deposition of dust on a horizontal glass coupon. The study has shown that the high relative humidity has suppressed dust resuspension that increased the soiling rate. The authors have recommended steep tilting of the PV panels as well as coatings that inhibit condensation and particle cementation especially in humid climates.	Negative	Steep tilting of the PV panels as well as coatings

[103]	PV modules	Main Topic	In this study, the authors have proposed an approach to clean the PV modules based on absorption of ambient humidity and making the module surface super-hydrophilic by TiO <sub>2</sub> coating.	Found Positive	Hydrophilic coating and absorption of ambient moisture
[104]	Solar glass	Factor	The authors provided a detailed summary of macroscopic and microscopic factors that affect soiling phenomenon including dew. Dew has been found to be responsible for particles caking and is expected to raise the rates of soiling by preventing natural cleaning by the wind. As mitigation approach, inhibiting dew formation by sample heating has been cited to inhibit cementation and considerably reduce dust accumulation. It has been mentioned as well that the effect of dew can be positive and used to clean the surface of the PV modules if its formation is promoted at night.	Found Negative Expected Positive	Heating to inhibit condensation Promoting dew formation at night to help roll-in off the dew droplets.
[44]	Glass samples	Factor	In this work, an investigation of soiling layers was carried out at a PV test site in Doha, Qatar where the dew formation and evaporation have been found as an important mechanism supporting caking processes. Heating was proposed as a mitigation procedure to reduce soiling.	Negative	Heating
[105]	Glass coupons	Factor	In this study, the behavior of 4 coated glass has been investigated regarding soiling in the Atacama Desert. The authors outlined the effect of dew as an influencing factor for the performance of the coating. Indeed, it is a tough objective to inhibit condensation, for the reason that it may occur as microscopic droplets even on hydrophobic surfaces with a temperature greater than the dew point. It has been proposed that hydrophilic coating could enhance dew formation for more water run-off and self-cleaning.	Found Negative	Hydrophilic coating
[106]	PV modules	Factor	In this study, the effect of four parameters involved in condensation that occurs on soiled surfaces was investigated including surface-dew point temperature difference. It has been indicated in this work that water droplets growth is highly affected by the difference in surface-dew point temperature whereas the relative humidity alone did not explain the droplet growth.	Found Negative Expected Positive	Hydrophilic coating to enhance water condensation and then switching the effect into positive

[107]	CPV Module	Factor	The authors studied in this work the performance of a single CPV (concentrated photovoltaic) module based on the produced energy. It turned out in this study that dew on the modules reduces the generated power especially in the first hours of the day.	Found Negative	-
[108]	PV modules	Factor	This review has presented an overview of the past studies of the impact of dust especially in MENA regions. It has presented as well soiling mitigation approaches with a focus on chemical analysis of dust from MENA regions and India. It has been shown that sand particles (1 $\mu\text{m}$ to 500 $\mu\text{m}$ ) are a great challenge and this becomes more serious in presence of dew or other moisture creating cementitious layers that is considered difficult to eliminate.	Found Negative	-
[74]	PV modules	Factor	In this study, measurements of soiling impact on the energy efficiency of PV modules have been evaluated in Atacama Desert. It has been shown that self-cleaning is ensured from formed dew that implied noticeable variations in the SR (soiling rate) evolution.	Found Positive	-
[70]	PV modules	Factor	The effect of soiling on monocrystalline on-grid PV plant has been studied in Benguerir-Morocco after six months of exposure without cleaning. It has been shown that with high relative humidity greater than 80% and low wind speed less than 2 m/s, the soiling ratio was almost 0.8, which might be interpreted by dew formation on the PV surface during early morning and night that led to partial cleaning.	Expected Positive	-
[109]	PV system	Factor	In this study, data gathering related to climatic conditions and the output of PV systems in Sultanate of Oman have been done. The study of the data regarding soiling including several cleaning method has been carried out. Dew was a significant factor for building salts layer on the PV surface.	Found Negative	-
[78]	Solar cell glasses	Factor	This paper has presented a procedure to simulate the soiling process and analyzing its effect through optical and electrical methods. The simulation of climatic parameters has been done including the formation of dew and its impact on soiling. It has been found that dew generated clean channels on the glass	Expected Negative	-

			that could not be correlated with the non-uniformities in the $I_{sc}$ (short-circuit current) drop.		
[110]	PV modules	Factor	The review is focused on elaborating and summarizing the effect of dust deposition on the electrical properties of PV panels with an overview of the factors affecting this deposition. Dew formation was investigated as a significant factor leading to dust settlements on flat surfaces as well as its adhesion reinforced by evaporation.	Negative	-
[111]	PV modules	Factor	The study presents a comparison between man-made and naturally cleaned PV panels installed in Bahrain. It has been shown that rain or dew contributes in cleaning and the naturally cleaned PV produces less solar yield than the clean by 9 %.	Expected Positive	-
[112]	PV modules	Factor	This review highlights the state of art of the impact of desert conditions on the performance of PV systems in Chile as well as in some regions of MENA. Based on this review, dew appears to contribute in self-cleaning in some areas.	Found Positive	-
[113]	PV modules	Factor	The authors have evaluated the effect of soiling on the cooling capacity of wind that has been blown over a PV module through a wind tunnel. In this study, dew formation has been reported as a strong factor responsible for dust accumulation on PV, particularly after the module has dried. It has been found that dew and humidity can intensely minimize the wind erosion that can affect the adhered dust to the surface.	Found Negative	-
[114]	PV modules	Factor	In this paper, different methods to prevent the dew water from affecting the PV modules were evaluated: 1. Daily cleaning of the PV at the evening, 2. The use of plastic cover of the PV modules from evening until early morning, 3. The PV ground facing in the evening. The first method has shown limitations regarding effectiveness, while the second and third methods were effective in decreasing dust accumulation and its interaction with dew.	Found Negative	Covering the PV module. Facedown as a night position.
[115]	Glass samples	Main Topic	Cleaning based on dew formed during the night was exploited to ensure cleaning in the	Found Positive	Ground facing of the

			morning relying on the change of the tilt angle from horizontal position to tilted one. The effectiveness of the cleaning needs to be evaluated.		PV panels at night.
[14]	PV and CSP	Factor	This techno-economic study has considered the yield relative to the soiling losses and the state of the art of cleaning techniques of PV and CSP (concentrated solar power). It has highlighted the mitigation approaches of soiling and their efficiency to tackle this challenge. It has been reported that relative humidity and dew increase significantly dust adhesion to surfaces through capillary forces, cementation and particles caking. It has been concluded as well that dew mitigation needs additional research and development to be economically applied for large-scale application.	Found Negative	Ground facing of the PV panels at night.
[116]	Glass Samples	Main Topic	In this work, a hydrophilic coating was fabricated and applied on hydrophobic coated cover glass in order to improve dew formation. Dew can be used in self-cleaning glass surface. This self-cleaning has occurred based on dew formed which has contributed in reducing the soiling rate.	Found Positive	Hybrid hydrophilic-hydrophobic coating
[117]	Solar panels	Factor	The main scope of this study is the analysis of several machine learning techniques to predict the power generated for horizontal solar panels. Indeed, many factors that affect the output power have been taken into consideration such the effect of dew which increases coagulation of dust. However in comparison to humid air, dew formation on PV modules surface may increase their performance.	Positive and Negative	-
[118]	Solar cells	Main Topic	The effect of dew formation on the performance of mc-Si (mono-crystalline silicon) and pc-Si (polycrystalline silicon) solar cells was studied indoor at ambient temperature of 25 °C and different relative humidity levels. The results of this study revealed that dew formation that occurs on the PV modules surface has improved their performance compared to humid air.	Found Positive	-
[45]	PV modules	Factor	A full year measurements of short-circuit current of 2 PV modules have been carried	Expected Positive	-

			out in this study to investigate the seasonal behavior of soiling. It has been found that dew, which forms frequently during June and July in the region of Evora in Portugal, is expected to be responsible for some of the soiling ratio recoveries.		
[64]	Solar cells	Factor	This study presents a super-hydrophobic silica surface characterized by some self-cleaning properties. It has been found that even in arid areas, dust deposited on the surface is detached independently through the run-off of dew droplets which enhances the self-cleaning efficiency of the modules.	Found Positive	-
[119]	Glass samples	Factor	The authors of this paper have modeled the soiling phenomenon of PV glass using ANN methodology and dew has been among the factors that promote cementing and adhesion of particles.	Negative	-
[120]	PV modules	Factor	The authors have investigated the dust effect on PV modules taking into account the meteorological conditions of Kathmandu-Nepal. Natural cleaning by dew has occurred which has slightly improved efficiency.	Found Positive	-
[121]	PV modules	Factor	In this study, an improved model has been developed to predict daily and accumulative PV soiling based on the environmental conditions. It has been concluded that there are further aspects that impact the soiling and PV performance such as dew formation but additional studies on dew effect are still needed.	Negative /Positive	-
[36]	PV modules	Factor	The authors have proposed an automated technique to measure the soiling rate of PV modules, which has been tested in California. In this region, a soiling rate was up to 11.5% /month is found. Dew accumulated on the front side of the modules has contributed to a partial cleaning.	Found Positive	-
[122]	PV modules	Factor	The authors aim to study the effect of soiling of PV modules under the same climatic conditions. It has been found that condensed water formed on the surface forms capillary bridge between the particles and the surface. However, further studies might be needed in this regard.	Expected Negative	-
[82]	PV modules	Factor	In this review, the causes of dust deposition on PV modules were presented as well as the	Found Positive	Hydrophilic coating

			effect of soiling on the electrical PV output. It has been reported that the dew effect depends on the surface coating. Indeed, the dew water spread on a super hydrophilic surface leading to run off the particles. For the super hydrophobic surface, dew is formed as droplets (circle) and do not spread on the whole surface.		
[79]	PV modules	Factor	This paper studied the nature of dust in the UAE as well as its effect on PV performance. The results have shown that dew can easily form on the surfaces of PV and attract fine particles suspended in the air. When the temperature increases during the day, the dew leaves a dust layer after its evaporation. In this study, it has been reported that the combination of humidity, wind and dust affects more the PV performance more than humidity by itself.	Found Negative	-
[123]	PV modules And glass plate	Factor	The authors developed and tested an electrostatic cleaning in Doha, Qatar. The results of the test of this equipment showed its inability to clean cemented dust. This is due to the adhesion force of the cemented particles that was extremely higher than the electrostatic force.	Found Negative	-
[124]	PV modules	Factor	A removable cleaning system based on electrostatics force was improved to eliminate hardly cemented dust particles. The moisture absorption can be prevented by an operational scheme that can affect negatively the electrostatics cleaning. As a perspective of this study, the equipment will be tested within one day after the ambient temperature became less than the dew point so that the cementation of dust would be prevented.	Expected Negative	-
[43]	Solar glass	Factor	The author of this paper has used an atomic force microscope (AFM) to study the adhesion of the first phases of the soiling process for solar panels. It has been reported that many factors are involved in the yield of dew formation namely the relative humidity, wettability, dew point, and PV module temperature. This layer formed by dew water is expected to increase the capillary force.	Expected Negative	-

[8]	PV modules and glass plate	Factor	This study investigates the effect of soiling on solar front glass transmittance and presents an appropriate approach to calculate the energy production loss due to soiling. It has been found that an important amount of dew is formed on the PV modules installed in Rabat and used for cleaning.	Found Positive	-
[88]	Glass plate	Factor	In this study, the electrodynamic dust shield has been presented as a removal dust particle. It has been found that dew can affect negatively the efficiency of the proposed cleaning solution. Indeed, dust remaining on a PV module surface for more than 24 h is expected to experience dew formation and caking. Nevertheless, it was decided not to include dew effect at this stage of research.	Expected Negative	-
[125]	Glass plate	Factor	In this work, the authors have studied the durability of surface coatings for PV modules. To evaluate the degradation of the coating, one of the PV modules was never cleaned except by rain or dew that considered as natural cleaning factor.	Expected Positive	-
[126]	PV modules	Factor	In this study, four crucial adhesion forces were assessed: capillary, Van der Waal, electrostatic and gravitational forces. Data regarding soiling has been gathered for long periods over solar panels in Qatar that has been studied. Indeed, it has been found that the adhesion of dust particles is dominated by capillary force (enhanced by dew) formed under high relative humidity, while Van der Waal force is dominating under dry conditions.	Found Negative	-
[127]	Solar glass	factor	This study describes the anti-soiling characteristics of a nano-textured fluoropolymer coating of solar glass with and without the presence of dew. It has been found that soiling rate increases in presence of dew. This latter should be considered when evaluating anti-soiling effects.	Found Negative	-
[128]	CSP Heliostat	Main Topic	In this paper, dew has been proposed to contribute in heliostats cleaning combined to a mechanical cleaning system. This solution is based on installing a movable lip by gravity and guided at the edges of a heliostat's mirror panel. The test of cleaning using dew was planned to be done.	Expected Positive	Dew-based technology (lip)

[6]	CSP	Factor	This review deals with the conventional techniques of cleaning reflectors. It has cited many innovative techniques that use dew water to perform a cleaning. However, the quantity of dew water may not be sufficient to ensure an efficient cleaning, so extra water is highly recommended.	Expected Positive	-
[129]	CSP	Main Topic	The authors propose a new cleaning mechanism using dew which has been tested indoor with different types of wipers, different cleaning angles and with different surface wetting time. The cleaning efficiency with this mechanism was very high, reaching 99.3% for normal single wiper, 98.9% for industrial wiper and 98.3% for normal car wiper. This mechanism can save big quantities of water consequently lead to reduction in operation and maintenance cost. Nevertheless, it must be considered that the system depends on dew potential of the CSP plant area, which is exemplarily investigated for one solar site.	Found Positive	-
[130]	PV cells	Main Topic	In this paper, the effect of dew and rain droplets on the performance of solar photovoltaic glass was investigated. For the angle of incidence greater than 30°, the droplet significantly reduced the performance of the solar cell, especially for large droplet contact angles and/or surface coverage. This degradation was explained by the backscattering of the incident light through the droplets instead of being transmitted to the solar cell.	Found Negative	-
[131]	CSP Flat mirror	Factor	The authors of this paper have exploited several measurements of soiling effect on the mirror reflectance using a TraCS (Tracking Cleanliness Sensor). The aim was to present a prediction and evaluate the interaction between environmental variables. Dew was observed and led to natural cleaning, however, if the amount of dew water is not high, the particles will trap more through capillary forces.	Found Positive Expected Negative	-
[132]	PV panels	Factor	This review deals with the different mechanisms and mitigation approaches to tackle the challenge of soiling. It has been	Expected Positive	-

			reported that some dew cycles or events of high relative humidity that occur between heavy rain periods can reduce the soiling rate especially when dew is combined with hydrophilic coating.		
[133]	PV panels	Factor	In this study the effect of the azimuth angle on the optimization of the cleaning frequency of a PV plant was evaluated. It has been found that light event of rain of less than 6 mm did not contribute in cleaning improvement. In contrary, the soiling gets worse due to the cementation effect caused by light rainfall. This latter has a similar impact as high humidity and dew.	Expected Negative	-
[134]	PV panels	Factor	In this study, three metrics have been analyzed to investigate the performance of a PV plant in Central Greece namely performance ratio, prediction mathematical model and normalized efficiency. The effect of dust accumulation has been taken into consideration in the study. It has been found that morning humidity may contribute to self-cleaning of the panels and enhance the PV panel's performance.	Expected Positive	-
[135]	PV panels	Factor	In this work, a mitigation approach of soiling was proposed based on inverting the PV panel to face the ground instead of the sky, during the non-sunshine hours. The results have shown that dew drops acts as a cleaning mechanism in this inversion, whereas in the fixed module these dewdrops act as an adhering property, which helps the dust to stick to the surface of the module. It is an easy way to reduce the rate of soiling and hence help in increasing the daily energy yield of the PV modules.	Found Positive	Inverting the PV panels to face the ground
[136]	Glass coupons	Factor	This study presents the analysis of 1-year data gathered from a soiling station located in Colorado. The authors thought that it is possible that soiling could be enhanced by dew occurrence during the outdoor coupon exposure. For this reason, depending on dew formation, soiling intervals were defined. Indeed, it has been also mentioned in the study that dew is not the only initiating factor of soiling but does contribute significantly in the soiling process.	Expected Negative	-

[137]	CPV module	Main Topic	A cleaning method was proposed in this patent, which uses dew condensation and gravity. It is based on inverting the CPV panels after accumulating dew water during night. During night-time, the CPV panel is horizontal upward then the dew formation occurs which softens the dust. In the morning the tracking causes the trolling off of dew with dust. The method is more efficient if a hydrophilic coating is added.	Found Positive	Inverting the CPV from upward to face-down
[138]	PV panels	Main Topic	This patent presents a self-cleaning method for PV modules which is based on the assembly of rectangular square PV modules including slots for collecting the dew water. It is then poured onto the surface of the modules leading to a self-cleaning.	Found Positive	-
[139]	PV panels	Main Topic	A method for operating a photovoltaic module array includes identifying when an atmospheric temperature drops below a dew point. A photovoltaic module is then positioned such that the module face is oriented at first position parallel to a ground surface permitting dew to form on the module face and then the dew mix with dust present on the module face. An angular orientation of the photovoltaic module is applied after dew formation so the module face is oriented at a second position angled away from the first position facilitating the removal of the dew entrained with the dust, thereby cleaning the module face.	Found Positive	An angular orientation of the photovoltaic module is applied after dew formation when the panel was oriented parallel to the ground

### 3. Meta-analysis and discussion

#### 3.1. Dew papers by technology

The condensation of dew water on the surface of the modules has been reported since decades as a challenge in front of the performance of solar panels [140]. Fig III.1 presents a histogram which shows the evolution of soiling studies that have considered the effect of dew as a phenomenon affecting the performance of PV and CSP. As shown in the same figure, the research on the topic was increasing in recent years with a great focus on PV technology with 91% of publications dealing with the effect of dew on solar front glass, solar cells, concentrated PV or PV modules performance. In the study conducted by [141], aluminum material has experienced high quantities of dew in comparison to glass and polyethylene respectively. This means that CSP plants with aluminum front-surface [142] would experience dew formation

more than PV plants, which will be good if the aim is to enhance dew formation and bad if the aim is the suppression of dew. Nevertheless, in Fig III.1, the studies on the effect of dew on CSP plants were very limited which can be explained by the fact that PV plants exist in high number in comparison to CSP plants due to the significant decrease in PV pricing [23]. In Fig III.1, we noticed as well a decrease in the studies carried out during the last year (2020) which has coincided with the global health crisis caused by covid-19 which has significantly affected the progress of studies on this subject, in particular those requiring the mobility of people on the solar installation site.

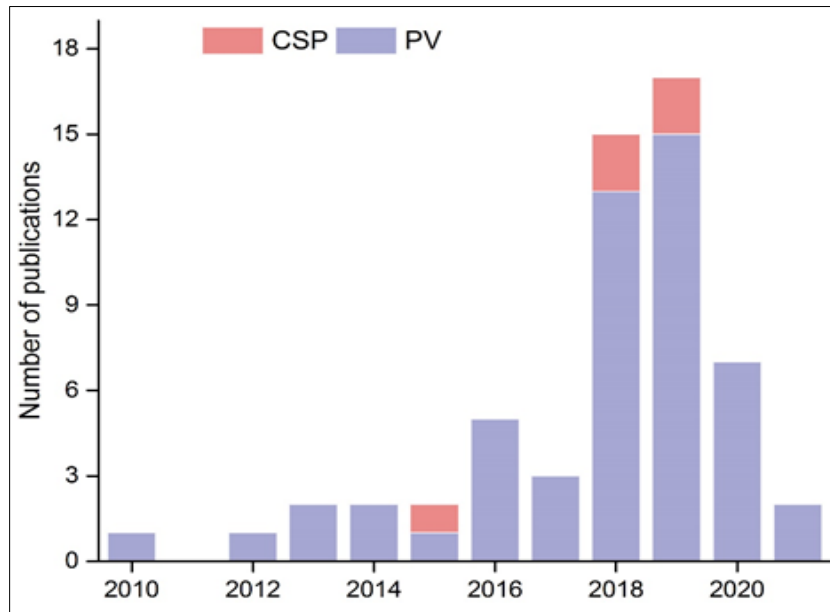


Fig III. 1. Histogram of publications evolution on dew effect on PV and CSP so far.

### 3.2. Positive and negative dew effect

A self-cleaning or adhesion of soils on the surface of solar panels are two opposite results that can be obtained due to the condensation of dew water on their surface (Fig III.2). According to the gathered papers and data, soiling is very dependent on dew formation that happens on the surface of PV modules. Dew is known with his negative effect on soiling because dust particles adhere to the glass surface after a single dew cycle [101]. This negative effect has been reported as well for the efficiency of certain soiling mitigation techniques such as the electrodynamic dust shield [88]. Indeed, it has been reported in [118] that cementation phenomenon becomes more challenging for particles between 1  $\mu\text{m}$  and 500  $\mu\text{m}$  that combined directly with dew and get dried after receiving sunlight. In climatic conditions that promote the formation of dew as high relative humidity greater than 60% [101], the resuspension of dust particles by wind is strongly inhibited due to capillary forces between dust and the glass surface leading to particles caking [108]. Furthermore, in regions having view on ocean, the air humidity is full of salts

such as sodium chloride (NaCl) as reported in Sultanate Oman [57]. Indeed, in presence of dew, the dust accumulated containing this chemical material form a salt layer on PV surface. On the other hand, 48% of papers have reported the positive effect of dew on solar panels performance manifesting by a self-cleaning of the surface as shown in Fig III.3. The amount of dew formed especially during early mornings contributes to self-cleaning of the solar panels [36,45,66,70,74,111,112,115,120,134]. The percentages of both effects are 52% for negative effect in comparison to 48% of positive effect.

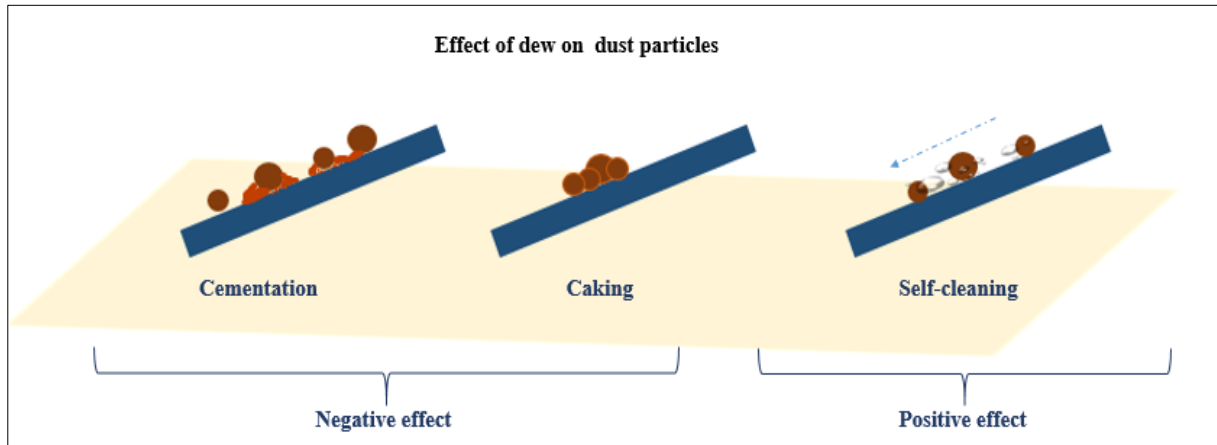


Fig III. 2. Different effects of dew on dust particles.

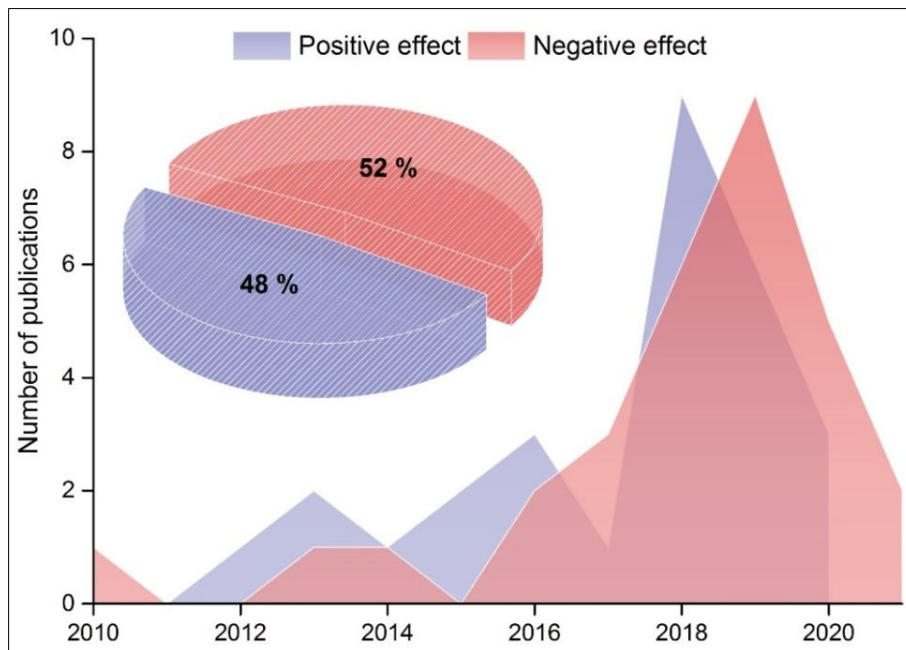


Fig III. 3. Distribution of the scientific papers on dew effect on soiling of solar panels.

### 3.3. Dew studied as factor or main topic

Through the papers gathered shown in Fig III.4, we found that studies on dew are divided into two parts. The first and the most important part of the studies (around 80%) has studied

dew as a factor that affects the performance of solar panels while only 20% of the studies assess the effect of dew as a main topic. If we go a little more into this distribution, we can clearly see that the negative effect is mostly attributed to works which have studied dew as a factor maximizing soiling. Unlike the second part which studied dew as a main topic, the positive effect has been attributed to the majority of works. Furthermore, this has been confirmed more in the in-depth distribution shown in Fig III.5, which identify whether the dew effect studied was experimentally found or just expected. Indeed, this distribution shows that in every category, the conclusion is obtained based on the results that were effectively found in soiling experiments. This is due to the fact that the study of soiling, in particular in geographical areas which favors the formation of dew water with quantities not allowing self-cleaning, cites this factor as a promoter for the adhesion of particles to the surface of the glass. Indeed, apart from the work of Chetika et al. [133] that mentioned an amount less than 6 mm of water, the amount of dew which maximizes soiling has not been studied before. Still in the same distribution, around 10 studies have shown that dew contributes in recovering the soiling ratio thus maximizing the solar panel performance [36,45,66,70,74,111,112,115,120,134].

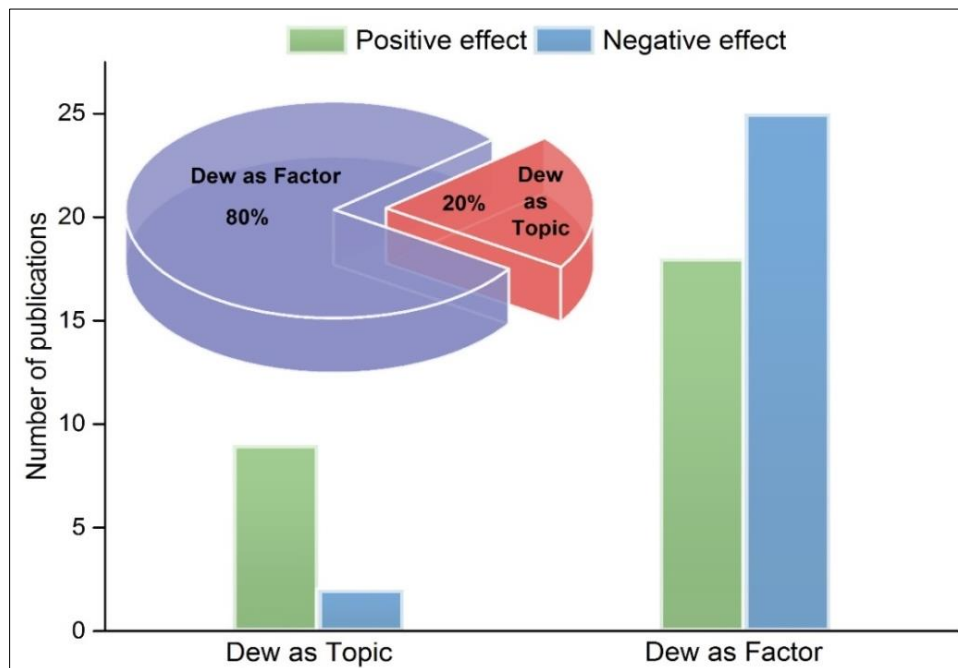


Fig III. 4. Distribution of publications on the effect of dew on the soiling of solar panels according to the type of study.

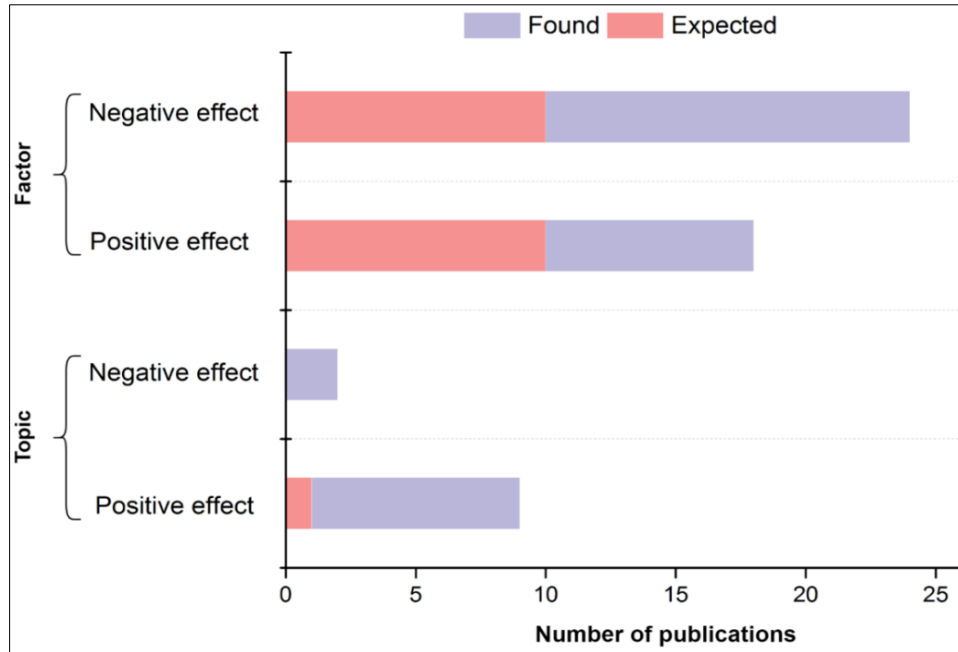


Fig III. 5. Distribution of publications relative to the effect of dew on soiling of solar panels according to the certainty of the obtained result (found or expected).

### 3.4. Soiling based on the enhancement and the suppression of dew water

In this work, we are interested in studies that have dealt with dew as being a main topic, in particular those that have proposed dew based solutions for optimizing the PV yield. Indeed, as it has been reported in [14], these solutions are divided into two parts, those which propose the enhancement of dew water formation while the second category studied its suppression. Fig III.6 shows that 61% of studies opted for the enhancement of dew water for soiling mitigation.

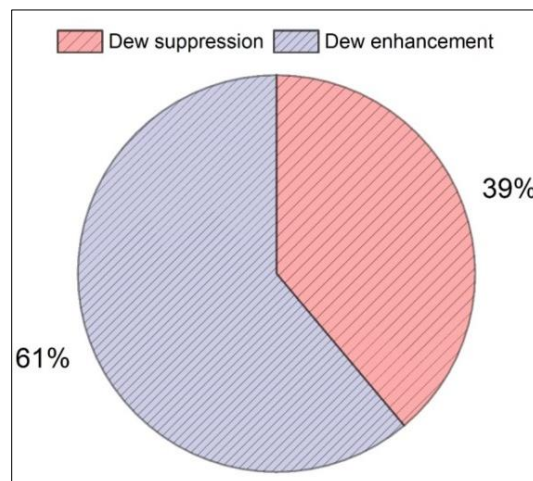


Fig III. 6. Distribution of mitigation solutions of soiling based on the enhancement and the suppression of dew water.

In the context of inhibiting water condensation on the glass surface, several approaches have been proposed such as heating [14, 20]. This approach consists of applying heating during night

on the back side of the glass samples by means of electric heater pad supplied with different powers. It has been demonstrated that heating led to less dew water formation and a decrease of dust accumulation of 14%. In the same context, by integrating PCM, latent heat can be used to maintain the temperature of the PV panel above the dew point, so that the formation of dew is avoided [102]. However, according to authors, this mitigation approach requires more evaluation of its applicability and economic feasibility. Among the solutions based on dew suppression, covering the PV surface with plastic film from the evening until the morning was very effective in preventing dust accumulation as well as its interaction with dew on the PV surface [114]. However, this method is not very practice since it requires human resources to apply the plastic film especially during non-working hours. Another approach has been adopted to mitigate soiling which consists of inverting the PV panels at night to face the ground. However this solution is dedicated to PV on tracking to exploit the motorization hence its limitation [133]. Despite the efficiency of the previous cited solutions, the suppression of water condensation is a real challenge because it can occur at microscopic level as demonstrated in Atacama desert [105]. Therefore, it has been highly recommended to enhance the dew formation to lead to water run-off and self-cleaning. In fact, about 61% of papers presented in this work dealt with solutions based on dew enhancement to ensure the cleaning of PV as shown in Fig III.6. This latter is improved on hydrophilic coating that is applied on the surface of PV panels. Moreover, the combination of both hydrophobic and hydrophilic coating has been found to be more efficient in dew water collection leading to an increase in the droplets diameter which is quite easy to be rolled off from the surface of the glass [116]. Despite the great progress achieved in the fabrication and development of the coating, the challenge of durability still exist and need to be resolved especially with the outdoor temperature variations [143]. Many studies and patents have been published regarding the use of the accumulation of dew water at night and exploit the gravity in the morning to clean the solar installations especially for CPV generators which are equipped with tracking [115,137,138] [134, 135] or by the means of cleaning wipers that can be added to the system [128]. However, the efficiency of cleaning relying on these approaches is not well investigated especially that the formation of dew can only occur when the favorable conditions are met. The table below summarizes the discussed solutions and presents the main limitations that need further development. From this table, it can be observed that the case of solutions based on dew suppression, the two main used solutions are heating and ground facing for trackers. While in the case of enhancement of dew, the main based solution is the coating. It can be concluded as well that the main limitations that still facing these solutions are: the applicability, the cost, the durability and the efficiency.

Table III. 2. Summary of the solutions based on dew. [+++]: High, [++]: Moderate, [+]: Low.

	Soiling mitigation based on dew	Frequency of publications	Limitations
<b>Solutions based on dew suppression</b>	Heating	+++	Economic feasibility and applicability
	Covering the PV surface	+	Applicability
	Ground facing of the PV	+++	Only for trackers or movable structures
<b>Solutions based on dew enhancement</b>	Surface coatings	+++	Coating durability
	Angular orientation from upward	++	Cleaning efficiency
	Cleaning by wiping of dew	+	Cleaning efficiency depending on dew amount

### 3.5. Parameters affecting dew formation

Based on Table III.1 and as previously discussed about the dual effect of dew, the factors that affect the formation of dew should be determined and analyzed. Based on this, a summary of these factors is presented and the effect of each factor is described according to the different studies conducted. In Fig III.7, the most influencing factors have been illustrated.

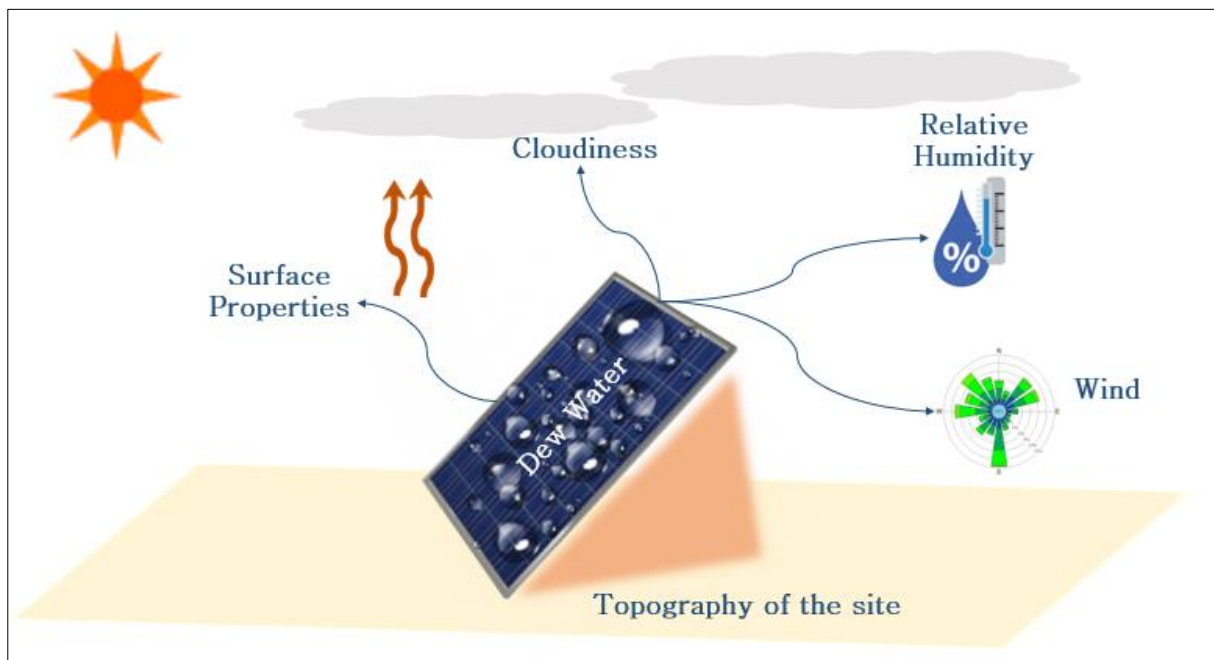


Fig III. 7. Illustration of the different factors involved in the dew formation on front glass of PV panels.

#### a. Relative humidity

In the study conducted by Lekouch et al. [17], the effect of relative humidity on dew has been discussed and reported as being the main parameter influencing the dew formation yield. The results of this study have shown that the occurrence of condensation is mostly in the relative humidity range 74% - 92%. The study also revealed that relative humidity (or air and dew temperature) along with wind speed and cloud cover strongly correlate with dew water yields. Almost similar result has been found in Qatar, that dew start forming already at relative humidity level of 70% [106] and even lower at 60% [101].

### **b. Wind**

The wind speed has been found to have an effect on dew formation. In some studies, authors tried to categorized wind speed into ranges that have high effect and those that have less effect. For instance, in the work of [144], they found that windy morning experienced the lowest dew formation and duration followed respectively by cloudy and clear mornings. In the study carried out by Clus et al. [145], dew yields found reduced for wind speeds higher than 3m/s, and were almost absent for wind speeds higher than 4 m/s. In another study, the limiting wind speed was found to be 4.7 m/s [146]. However, in the study conducted by Lekouch et al. the formation of dew required a low wind speed to move atmospheric water vapor close to the surface that ranges between 0.15 and 5.7 m/s [17].

It has been reported regarding wind that its direction does not affect dew formation that much. Indeed, in the study led by [17], the wind directions that experienced low dew or no dew formation, by coincidence, had low relative humidity, high wind speed and high cloud cover. Nevertheless, when wind is coming from Sahara then it is more likely to affect negatively the dew formation due to its dryness.

### **c. Cloudiness**

The surface emits radiation towards the sky at night, and thus it cools. Indeed, higher temperature difference between the surface and the atmosphere is required to obtain more dew quantities. Clear sky then favors the cooling of the surface, however, when it is cloudy, it reflects back the radiation toward the ground and thus reduce the cooling of the surface [118] [146]. This is confirmed by the study conducted by [144] where cloudy mornings experienced medium dew formation in comparison to windy (the lowest value) and clear mornings which had the highest value of dew. Similarly, during cloudy and moderate humidity, macroscopic condensation did not occur [101].

#### **d. Topography of the site**

The topography of the site has been considered as an influencing factor in dew formation. Indeed, in the study carried out by [144], hilltops and sun-shaded areas exhibit higher dew formation and duration in comparison to downhills. Furthermore, an installation with an open structure has shown to collect more dew in comparison with an enclosed sides installation [147]. This has been explained by the fact that, when the surface is close to the ground is more likely to experience more heating effect from the ground.

#### **e. Surface properties**

The surface properties such as the smoothness, the emissivity and hydrophilic characteristics impact as well the dew formation. In the study published by Kidron [148], we found that a smooth Plexiglas has collected more dew in comparison with a rough one. In addition, high emittance in infrared wavelengths range enhance the performance of the surface in condensing more dew [141]. This is because high emittance favors the cooling of the surface by increasing the thermal power loss. Furthermore, a hydrophilic surface is highly recommended increasing the dew yields [146].

### **4. Conclusion**

Dew research studies have always focused on using dew to provide an alternative source for drinking water. However, in the last years, this subject has been associated to soiling of the solar power plants. Indeed, dew has a great effect on soiling and it can be positive or negative depending on the characteristics of the installation environment. The work review presented in this chapter has shown that the negative effect of dew on soiling, which is manifested by the cementation of dust particles on the glass surface, has been reported by 52% in comparison with 48% of studies that have highlighted the self-cleaning caused by dew.

From the analysis conducted of the soiling mitigation based on dew, 61% of papers have recommended its enhancement while only 39% of works have proposed some approaches towards its suppression. Indeed, this second category presents the big challenge of economic feasibility and applicability, in particular that these solutions require being supplied in energy as the case of heating. On the other hand, the enhancement of dew water must attract much more attention since it presents many advantages in particular that they are passive solutions based, that use innovative coatings or films.

Regarding the negative effect, up to now, the amount of dew which increases soiling has not

been studied yet. In most cases, the amount of dew is addressed as a light rain. Nevertheless, some climatic parameters favoring the formation of dew have been set such as the case of the relative humidity. Indeed, dew formation and its yield depend on the combination of factors that interact with each other. In this case, the threshold should be investigated taking into account the behavior of each factor which can be achieved through a physical or neuronal modeling that have not been well addressed in literature.

Thinking about sustainable development, it is highly recommended digging into the solutions of the enhancement of dew water formation especially in the areas that suffer from water scarcity. This recommendation was supported particularly with the positive effect of dew reported by numerous studies that have dealt with dew as a main topic and not as a factor.

## **Chapter IV: Investigation of soiling losses of PV modules and the use of dew in cleaning**

### **1. Introduction**

Several investigations related to soiling impact give the rate of soiling for different sites during dissimilar periods starting with a few days as the case of [68] to a few months [149] until years of exposure [150,151]. Note that soiling rates have been as well calculated for different seasons of the year as found by [152]. The studies are divided into those that have been based on solar glass and those that have assessed the soiling impact directly on photovoltaic modules. For the studies carried out using solar front-glass to evaluate the reduction in transmission due to soiling, most of them [68, 150 - 155] are limited to determining the soiling rate without having covered the losses in kWh. Therefore, in the first section of this chapter, a rigorous procedure has been followed to identify the effect of soiling and its impact on the energy production of photovoltaic fixed systems installed in Rabat and Errachidia; cities located respectively in Northwest and Southeast of Morocco. Since the soiling is a site-specific phenomenon, each site is characterized by different climate.

Solar trackers are among the systems that have shown their contribution to mitigate soiling effect thanks to their movements during the day. Actually tracking systems have been proven to have smaller losses due to soiling in comparison to fixed structures [75]. Soiling losses for trackers can be more significant if the tracker is stowed at night in appropriate positions especially when dust storms events occur frequently. In this case, facedown position illustrated by Fig. II.11 in chapter II is obviously more opportune [153][75]. Since the stowage position of the dual-axis tracker used in the first section of this study is horizontal upward during night, it has been decided to go deeper in the topic and study how soiling affects the performance of PV modules in this kind of tracker. In the second section of the current chapter, an investigation of soiling for PV mounted on a dual-axis tracker installed in Rabat is presented.

Apart from its effectiveness, wet cleaning of PV panels is rarely the optimal way since, in many cases, water is not always available and its obtaining requires high costs depending on the location. An alternative solution that can be exploited and developed is the dew water that condenses on the front glass of PV panels.

Different meteorological variables are involved in the dew formation and affect its yield namely the relative humidity, ambient temperature, wind speed and cloud cover. Indeed, dew occurs mostly during nights with high relative humidity, low cloud cover and moderate or low winds [146]. In many cases, dust can be the subject of cementation on the glass surface in the

presence of dew when exposed to sunlight after only one dew cycle [18]. Consequently, it was recommended to clean the surface after each dew event using a wiper as reported by Pfahl et al. [128]. In this context, the approach that has been suggested is heating to break the capillary forces that are formed between soiling particles and glass surface when dew occurs [154]. However, it has been demonstrated that it would be difficult to eliminate condensation in presence of microscopic droplets [155]. Indeed, dew could have a positive effect thus clean the surface of PV panels if the dew droplets can slide and sweep-away absorbed dust, resulting in a cleaned surface [55,156]. As stated in literature, at high relative humidity around 75%, the cleanliness factor of PV modules has been positive in Doha [55], which corresponds to a natural cleaning of PV panels as a consequence of the frequent condensation. It has been reported as well that the presence of dew on the surface of solar panels has enhanced the PV performance parameters compared to humid air, for both mono-crystalline Silicon (mc-Si) and polycrystalline Silicon (pc-Si) solar cells [118].

Few publications have been published regarding the use of the accumulation of dew water at night and exploit the gravity in the morning to clean the solar installations. Most of them studied the dew approach for concentrated PV generators which are equipped with tracking [137–139] or by the means of cleaning wipers that can be added to the system [128]. However, the efficiency of cleaning relying on these approaches was not investigated. Detailed review of the effect of dew in soiling is presented in the previous chapter of this thesis. Through this work, it has been shown that 61% of published works have supported the use of dew as a cleaning factor. In the last section, an experimental approach is presented to test and evaluate the efficiency of cleaning based on the use of dew that is combined to the change in the tilt angle from the horizontal position to a tilted one.

## **2. Evaluation of soiling for fixed PV**

### **2.1. Exposure sites**

The first site where the study of the soiling effect on PV modules has been conducted was in Rabat (Fig. IV.1), the capital city of Morocco, at the RDI solar energy platform of PSES in Ecole Normale Supérieure belonging to Mohammed V University [157]. The coordinates of this site are: Rabat- 33°58'47.3"N; 6°49'36.3"W. This region is characterized by a semi-arid climate according to De Martonne aridity index. The average annual temperature is 18.8°C. The average annual precipitation is 523 mm [158]. The Direct Normal Irradiation (DNI) and Global Horizontal Irradiation (GHI) are about 1792 kWh/m<sup>2</sup>/year and 1849 kWh/m<sup>2</sup>/year

respectively [159]. The second site where the study has been performed was in Errachidia, city in southeast of Morocco (Fig. IV. 1) at its Technical High School (Lycée technique). According to the classification of De Martonne, Errachidia belongs to the hyperarid climate [160]. Its average annual temperature and rainfall are 17.7 °C and 156.9 mm respectively. It is also characterized by an interesting irradiation average of 2241 kWh/m<sup>2</sup>/year for the DNI and 2100 kWh/m<sup>2</sup>/year for the GHI [161].



Fig IV. 1. Sites location of the conducted studies.

## **2.2. Experimental setup and methodology**

### **2.2.1. Rabat site**

#### **a. Soiling Ratio**

The experimental study in Rabat site consists of developing experiments directly on real size solar front-glass used in the fabrication of PV modules performed locally. The front-glass is exposed to real outdoor environment and conditions exactly as one of the PV modules installed in the RDI solar energy platform. The front-glass is of 1650 mm x 980 mm size and it has a high optical transmittance, approximately equals to 96%. It has been smoothly installed between two strings of a multi-silicon photovoltaic generator on a rigid metal support performed locally shown in Fig IV.2. The glass was exposed over a period of two years in the real outdoor conditions to get more concrete conclusions about the soiling issue.



Fig IV. 1. View of the solar glass used in this study with a tilt angle of 30° exposed over 2 years. a) Corresponds to the 1st day of exposure and b) Corresponds to 2 years of exposure.

Numerous measurements of solar irradiance ( $G$ ), using a solar power meter, have been performed to evaluate the soiling rate which is defined as the derivative of the soiling ratio ( $SRatio$ ) of the solar front-glass. Indeed, the solar front-glass surface has been divided into 24 equal-sized rectangular units. The measurement of the irradiance is made manually at the center of the back side of each rectangular unit using a Solar Power Meter SPM 72 of the Multimetrix brand (Fig IV.3).



Fig IV. 2. Solar Power Meter SPM 72 of the Multimetrix brand used in the study performed in Rabat for fixed structure.

The whole measurement operation, between the first and the last unit, takes less than 2 minutes. Solar noon and clear sky have been chosen as necessary conditions for which the uncertainty of measurement is the lowest. As demonstrated [72], soiling ratio is measured with absolute uncertainty of  $\pm 1\%$  under the mentioned conditions. The average of the irradiance  $G_{av}$  of the whole considered surface of the glass is then given through Eq.1:

$$G_{av} = \sum_{i=1}^{24} \frac{G_i}{24} \quad \text{Eq.1}$$

By measuring solar irradiance  $G$  received by the glass, the soiling ratio ( $SRatio$ ) is determined using the Eq.2:

$$SRatio = G_{av}/G \quad \text{Eq.2}$$

### **b. Soiling losses**

Soiling losses ( $SL$ ) are calculated from the  $SRatio$  (Eq.3) as earlier cited in chapter II.

$$SL = 100. (1 - SRatio) \quad \text{Eq.3}$$

### **c. Energy Production**

The energy production presents the technical factor conditioning the efficiency of a photovoltaic power plant. It is the quotient between the power produced  $E_p$  by the PV module and its nominal power under STC conditions, and it is expressed in  $(Wh/W_p)$  per day. According to [162] and assuming that the glass surface is operating as a PV module, the energy  $E_p$  produced per day is calculated by Eq.4:

$$E_p = P. \Delta t = (\eta. S. G_{av}). \Delta t \quad \text{Eq.4}$$

where  $\eta$  refers to the PV module instantaneous efficiency in real operating conditions, defined below by Eq. 5,  $S$  is the effective surface of the considered PV module, while  $\Delta t$  is the sunshine duration in hours per day. It is defined by Eq.6.

$$\eta = \eta_r. [1 - \gamma. (T_c - T_a)] \quad \text{Eq.5}$$

where  $\eta_r$  is the PV module nominal efficiency at STC conditions ( $T = 25^\circ\text{C}$ ,  $G = 1 \text{ kW/m}^2$  and  $\text{AM} = 1.5$ ),  $T_c$  and  $T_a$  are respectively the PV module temperature and the PV module reference temperature in  $^\circ\text{C}$ , while  $\gamma$  is the temperature coefficient [163].

$$\Delta t = \frac{2\omega}{15} \quad \text{Eq.6}$$

$$\omega = \cos^{-1}(\tan \delta . \tan \Phi) \quad \text{Eq.7}$$

$$\delta = 23.45 \times \sin[0.986 . (n + 284)] \quad \text{Eq.8}$$

where  $\omega$  is the hour angle,  $\delta$  is the solar declination,  $n$  is the year day since January, while  $\Phi$  is the latitude of Rabat.

### **2.2.2. Errachidia region**

The measurements of the soiling rate have been done as well in Errachidia city. The test bench used consists of two identical PV modules with a peak power of  $115 \text{ W}_p$  presented in Fig

IV.4. One of the modules ( $M_1$ ) was subject to regular cleaning while the second one ( $M_2$ ) accumulated soils. In order to get accurate evaluation of the soiling loss in this region, power measurements have been performed. The measurement protocol to evaluate the  $SRatio$  is based on the Eq. 9.

$$SRatio = \frac{P_{max2}}{P_{max1}} \quad \text{Eq.9}$$

where  $P_{max1}$  and  $P_{max2}$  are respectively the maximum power generated by the cleaned module  $M_1$  and the uncleaned one  $M_2$ . Measurements were taken one to three times a day depending on the stability of irradiance using a multimeter.



Fig IV. 3. Set up of the test bench on the building roof of the Technical High School in Errachidia city (with a tilt angle of  $30^\circ$ ).

## **2.3. Results and discussion**

### **2.3.1. Site of Rabat**

#### **a. Soiling ratio**

Measurements of soiling conducted on the solar glass exposed in Rabat have lasted approximately 2 years. In the beginning,  $SRatio$  is almost around 1 which corresponds to the clean state. Its value decreases when soiling increases as shown by the trend lines. Fig IV. 5 shows the evolution of  $SRatio$  during the 1<sup>st</sup> year of exposure, which extends from April 20, 2016, to March 10, 2017. During this year the soiling rate ( $SRate$ ) reached a decrease of 5%. Fig IV. 6 presents the 2<sup>nd</sup> year of the exposure, which runs from March 25, 2017, to February 26, 2018. During this year,  $SRate$  was about 3%. From the results obtained, the average annual soiling rates have been extracted from the evolution of the daily  $SRatio$ . We can conclude that the average annual soiling rate in Rabat is around 4%.

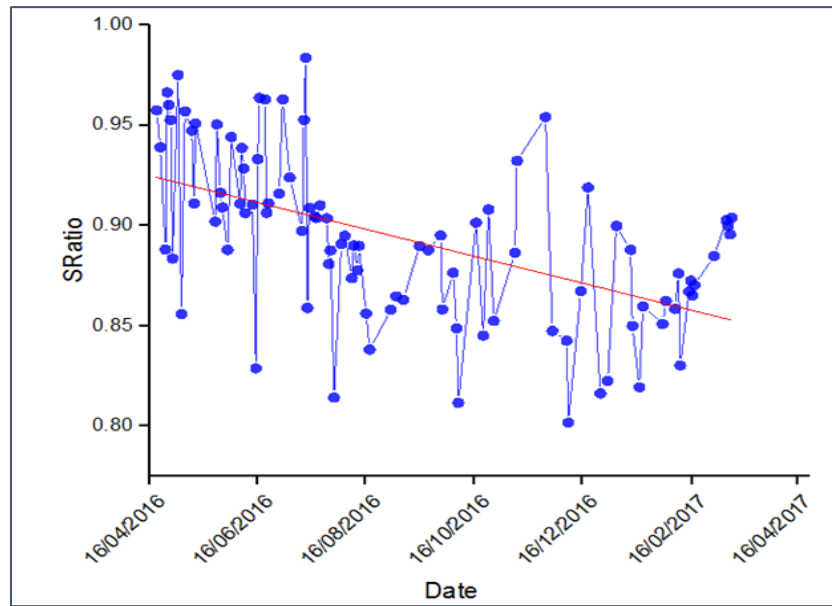


Fig IV. 4. Evolution of SRatio of the solar glass during the first year of the exposure in Rabat from 20/04/2016 to 10/03/2017.

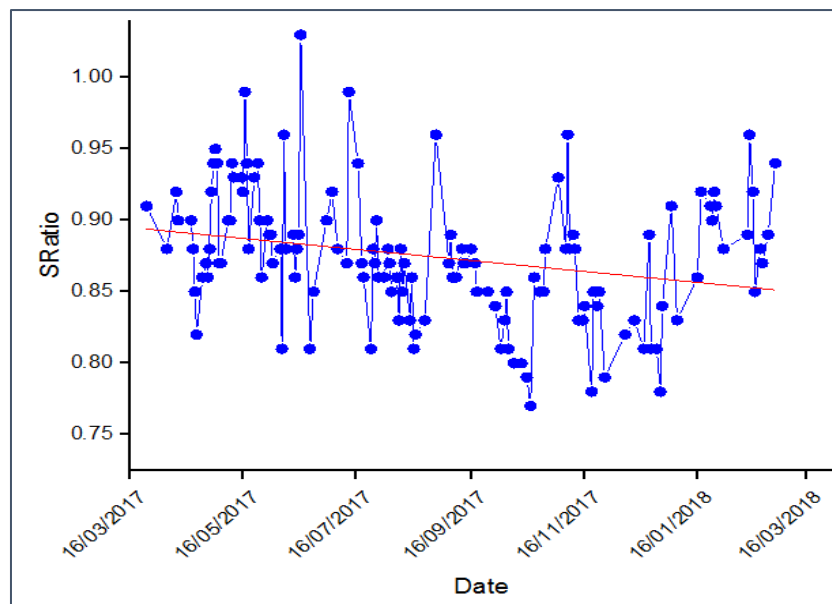


Fig IV. 5. Evolution of SRatio of the solar glass during the second year of exposure in Rabat from 25/03/2017 to 26/02/2018.

In order to compare the obtained results presented in this work with those of literature, we were interested in studies that have presented annual percentages of losses due to soiling cited in the reviews specialized in soiling issues [20,66,164]. Table IV.1 summarizes the annual averages of rainfall, which have been reported from the database Climate-data [165], and their corresponding losses due to soiling by region.

Based on Table IV.1, the percentages of losses due to soiling have been divided into four intervals according to the annual average rainfall as presented in Fig IV.7. These results can be

highly recommended to predict the effect of soiling according to an annual average of rainfall, especially for PV sizing software which, in most cases, do not take into account the soiling effect or, in some cases, consider only a fixed average value for any geographical area.

Table IV. 1. Annual average losses due to soiling by region.

Region	Annual average rainfall (mm)	Annual average soiling rate (%)
Malaga, Spain [166]	520	4.40
Phoenix, Arizona, USA [167]	211	5
North of China [20]	100 - 200	5.32
North of China [20]	600 - 800	2.09
Rabat	523	4

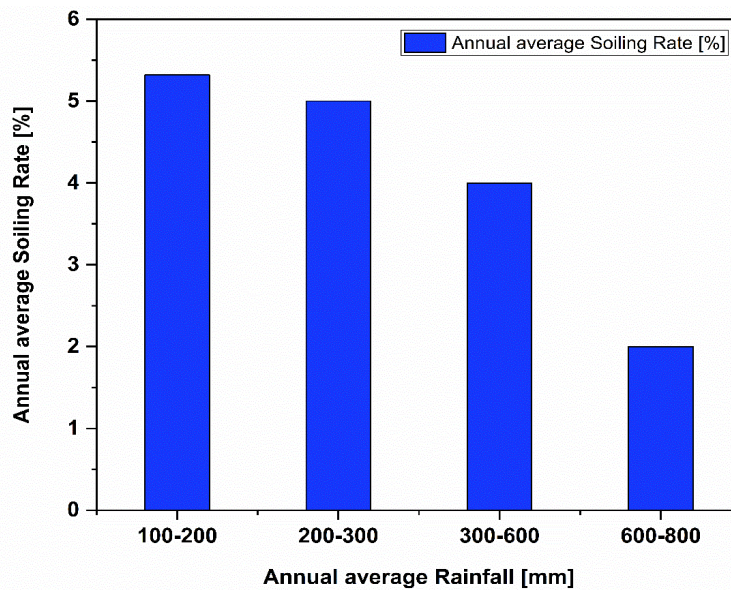


Fig IV. 6. Annual average soiling rates according to the annual average rainfall.

### **b. Effect of climatic conditions on soiling ratio**

As already mentioned, the investigation of the soiling ratio calculated for the solar front-glass with the climatic conditions was among our interests. The rainfall data were partially ordered from the National Meteorology Department while the speed and direction of the wind were recorded from our meteorological station.

According to Fig IV.8, an increase of around 2% is noticed in the soiling ratio during the period (from 09 to 29 November). In fact, this period was characterized by strong rainfall up to 32 mm and a high wind speed up to 1.79 m/s on November 22. The same remark was made for December 5 characterized by a rainfall amount of 10.2 mm and a wind speed of 2.75 m/s. It should be noted that the reduction in soiling is calculated from the day before the occurrence of rainfall until the day after this latter where there were measurements of soiling ratio. Therefore,

the period between 25 and 29 November could not be interpreted due to the unavailability of soiling data even there was a significant rainfall of more than 20 mm. The same percentage increase of 2% in soiling ratio was noticed during the period from 29 November to 13 December. However, to define a threshold of reduction in soiling corresponding to a threshold of rainfall with a cleaning effect, it will be necessary to investigate several periods. In our case, this significant increase during a short period in the soiling ratio can be explained by the double effect of rainfall and wind speed. However, to conclude that the wind speed takes a positive role in reducing the effect of soiling, it was important to determine the wind direction which is an essential climatic parameter in the study of this phenomenon. The most dominant wind direction during this period in our study site is the north. Since the solar glass is oriented south and the direction of the wind is north, the glass is facing the wind. In other words, wind can blow the rainfall on the glass surface which affects positively the soiling ratio and therefore clean the dust as it has been found by [48]. However, the soiling ratio has not shown a raise in the absence of rainfall during the period from 27 September to 4 October even the wind speed was relatively high. In other words, the soiling at the site of Rabat depends more on rainfall than on wind speed. However, both parameters contribute to decreasing the soiling rate then increase the PV module energy production.

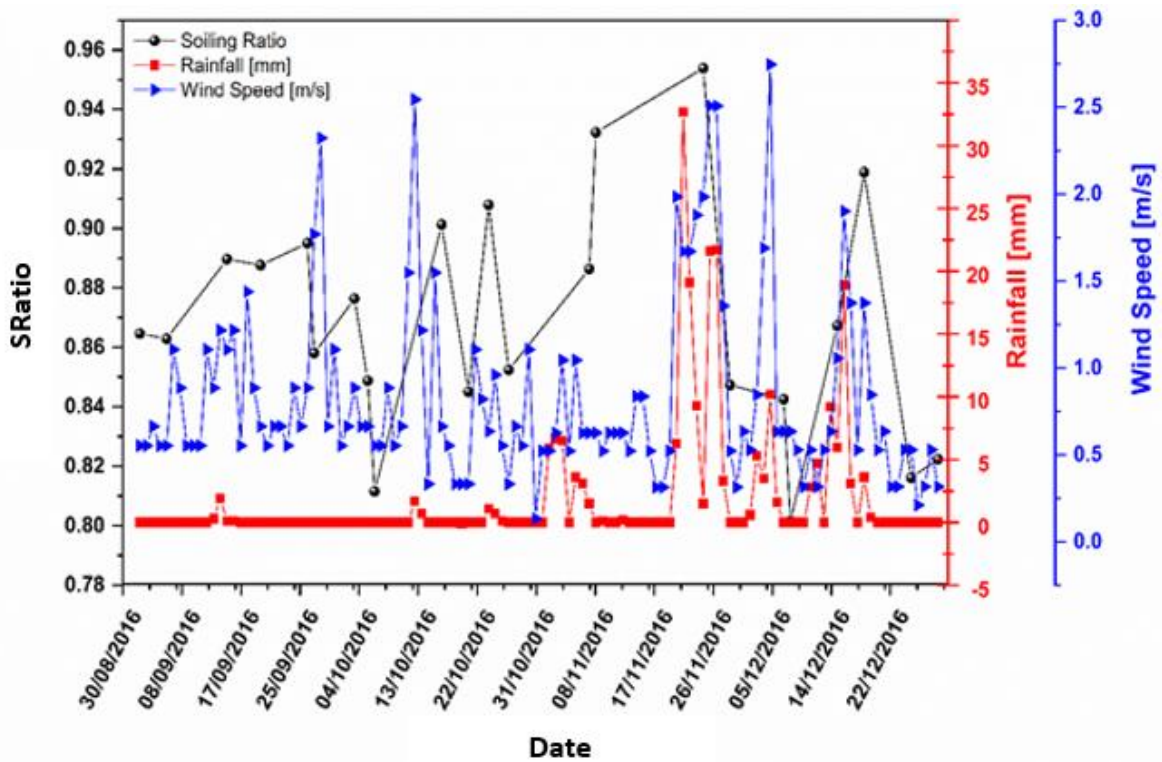


Fig IV. 7. Evolution of the soiling ratio with the recorded rainfall and wind speed on the site of Rabat for the period from September 2 to December 27, 2016.

### c. Energy production

Fig IV.9 shows that the energy production curve has a periodicity during the two years of exposure. It increases during the sunniest seasons and decreases during the winter. Since the duration of sunshine changes from one season to another, and to better analyse the effect of soiling on the energy production, we opted for the period from April to August with almost the same sunshine duration as it is presented in Fig IV.10. Over a period with an important sunshine duration, it is noticed that the effect of soiling on the energy production is slight and can reach up to 2 Wh/W<sub>p</sub> per day during the dry period and it corresponds to the loss of a single PV module.

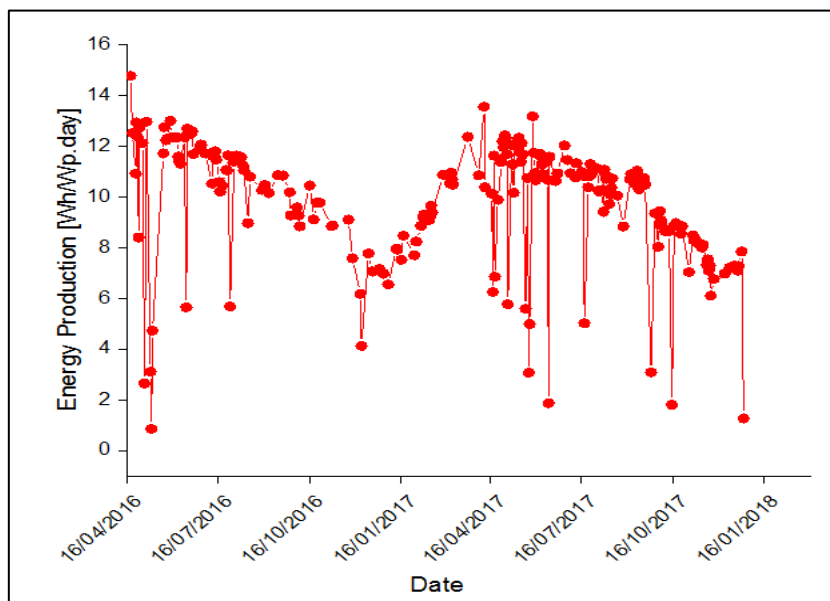


Fig IV. 8. Energy production calculated for the period of exposure of the solar front-glass in the site of Rabat, assuming that it is operating as a PV module.

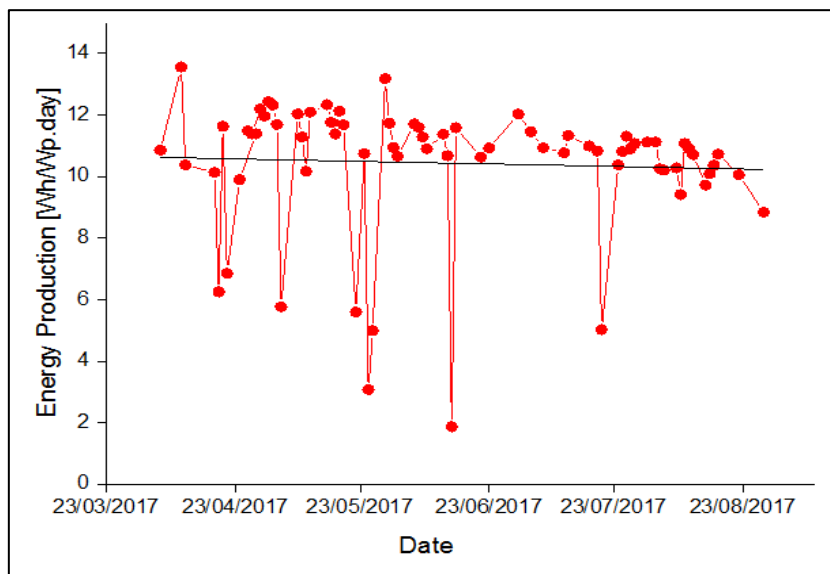


Fig IV. 9. Energy production calculated for the period from April to August 2017.

#### **d. Most abundant soiling types in Rabat**

During the period of solar glass exposure, different soiling materials were observed as shown in Fig IV.11. We have noticed that the most abundant soiling constituents are clay (a) and dust (b), which are deposited on the solar front glass arbitrarily. These soils are differently contributing in the transmitted irradiance decrease which is affected by the density of soils avoiding then irradiance to reach the cells.

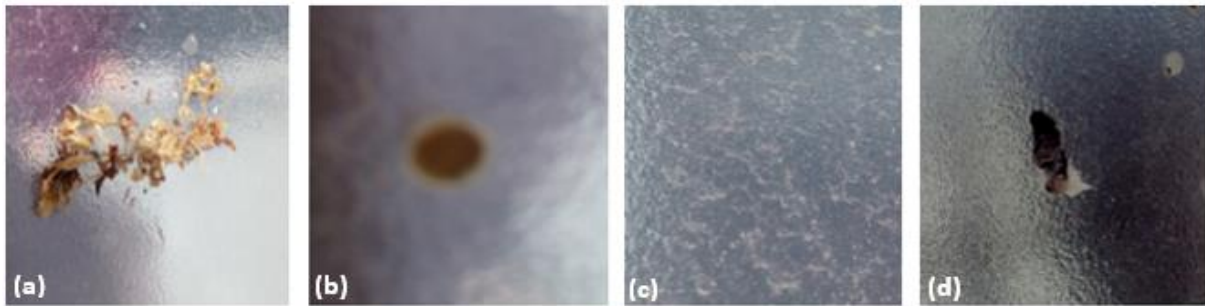


Fig IV. 10. Different soils deposited on the solar front glass during its exposure; (a) Debris of trees, (b) Clay, (c) Dust, (d) Birds droppings.

In order to follow up on what has been previously mentioned about the effect of rainfall, a visualization of the soiling types has been performed after rainfall that recorded 10 mm. Rainfall has different effect on soiling types deposited on the solar glass showed in Fig IV.12. It has well contributed in removing almost all dust but only mitigating the clay traces as clearly shown in Fig IV.13. Comparing this observation with the drop of only 2% with heavy rainfall of 32 mm, clays that are randomly deposited on the surface of the glass still may cause the reduction of the transmitted irradiance.

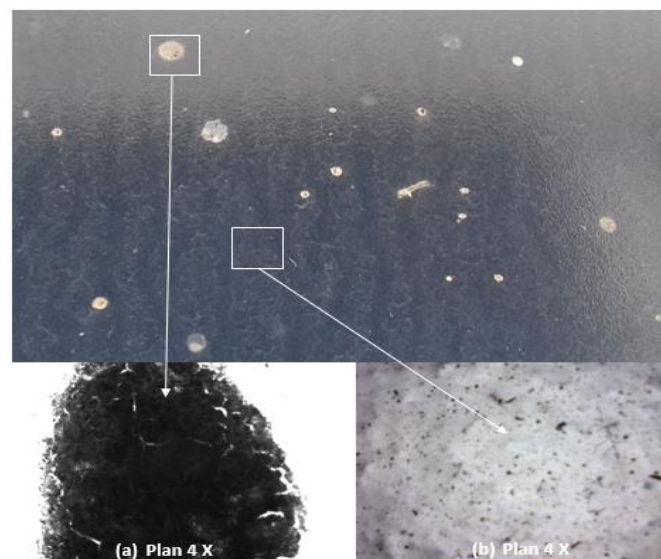


Fig IV. 11. Capture of the solar glass exposed in outdoor conditions in the RDI Solar Energy Platform of PSES in Rabat with visualization by optical microscope of the most abundant deposited soiling materials.

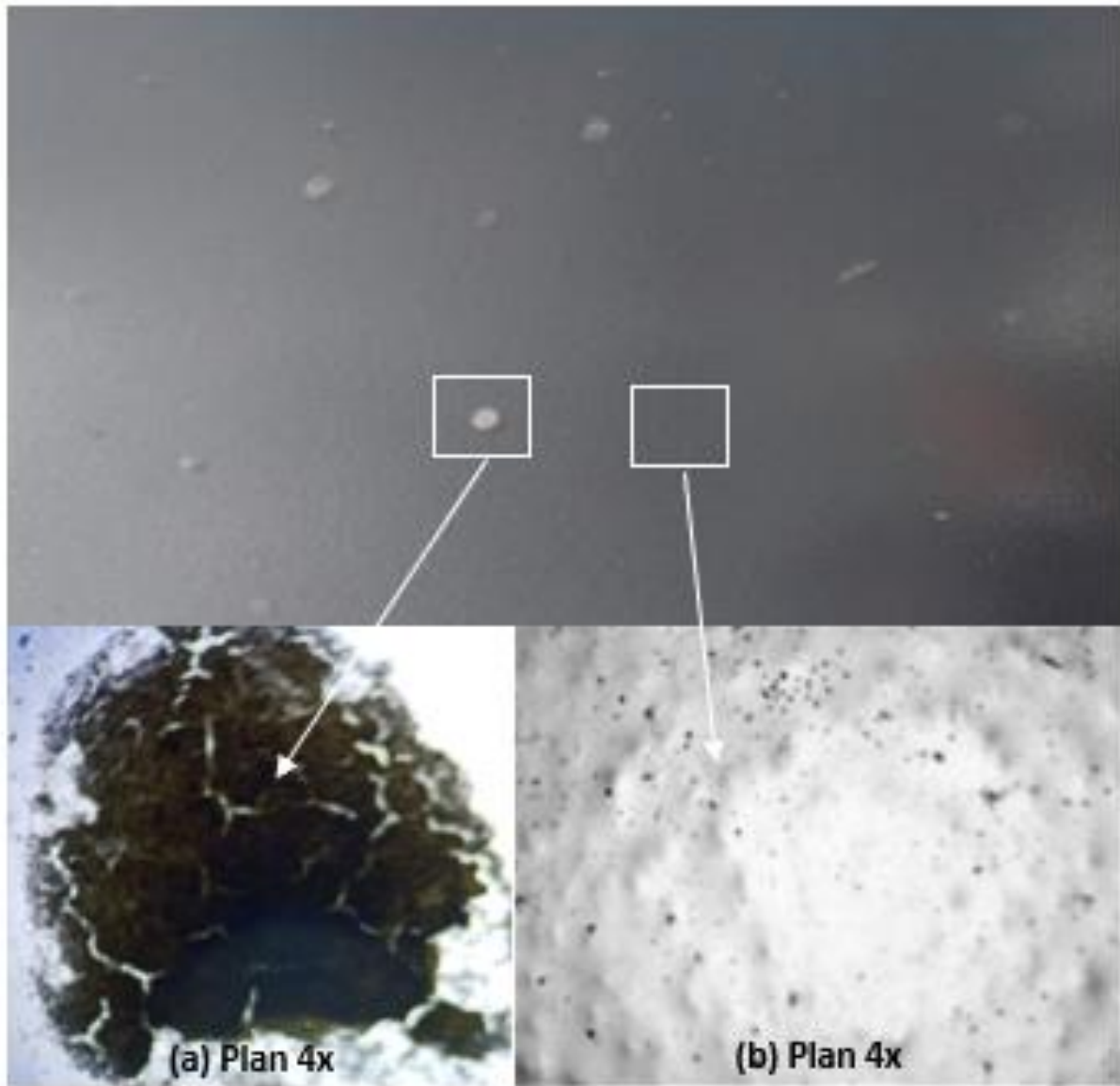


Fig IV. 12. Capture of the solar front glass exposed in Rabat after a considerable amount of rainfall.

Clay is sediment composed of fine particles resulting from the alteration of various Silicate-based rocks. These particles suspended in the atmosphere end up by depositing under the effect of gravity on the surface of the PV modules. This observation has been confirmed from the microscopic point of view via analyzing the composition of soils deposited on PV modules in real outdoor conditions in our RDI Solar Energy Platform in Rabat.

According to the work published by Chaouki et al. [53], the results obtained from X-ray Fluorescence (XF) analysis show that the most abundant element in Rabat soils is Silica which represents 35,5% of the total composition as shown in Fig IV.14. This result can be correlated with the amounts of quartz in the soil.

The knowledge of the density of soils that most affects the power output of PV modules helps to determine the type of cleaning required for a specific geographical area. On the site of Rabat, the clay is affecting the transmitted irradiance seriously and it requires to be humidified first before cleaning.

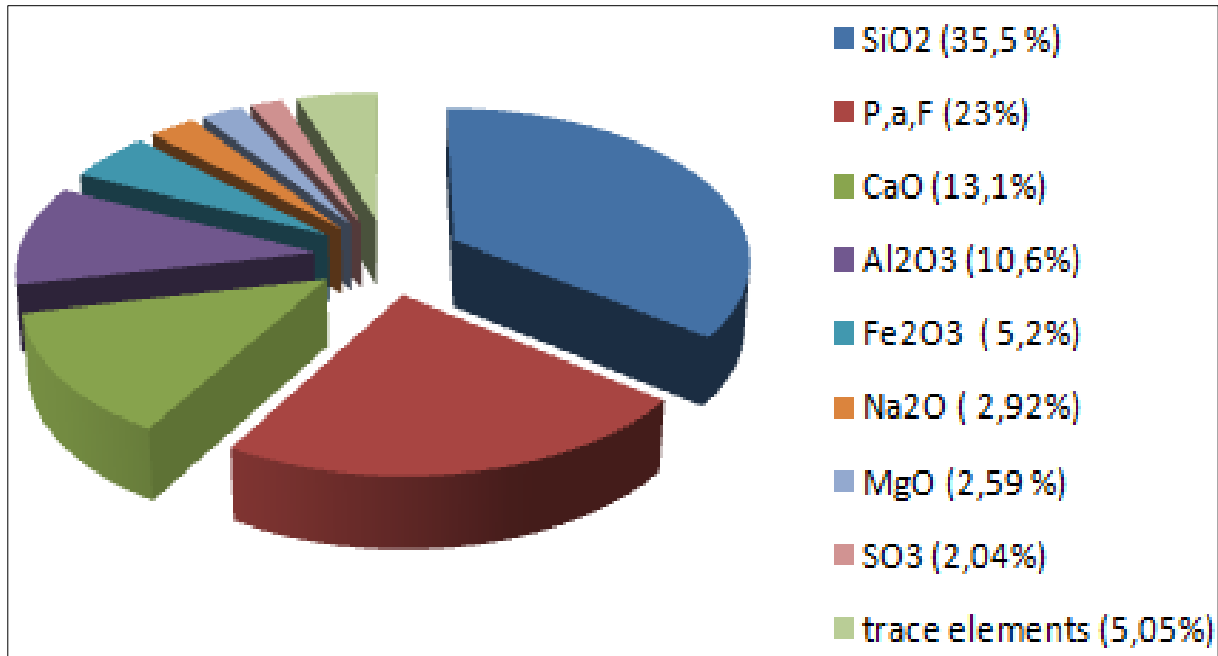


Fig IV. 13. Percentage of components of the dust deposited on PV panels [53].

### 2.3.2. Site of Errachidia

*SRatio* measurements carried out in Errachidia from March 12 to April 05, 2018, are shown in Fig IV.15 with rainfall and wind speed recorded during this period from the National Meteorological Department. According to the same figure, *SRatio* has made a significant decrease, although the period of exposure is short. Indeed, the soiling rate in the region of Errachidia is 23%/month, which is different from the site of Rabat where the highest soiling rate recorded is 5% over a longer period of exposure (Fig IV.16). Contrary to the effect of soiling in the region of Rabat, which is influenced more by rainfall, the soiling of the modules installed in Errachidia is much more influenced by the wind, as can be seen in Fig IV.15, where the increase of wind speed is followed by the increase in *SRatio* values. This is explained by the fact that the dust in Errachidia is drier than that of Rabat and therefore easy to remove out from the panel. Indeed, as previously mentioned, the dirt in Rabat is bonded to the surface of the PV modules by the effect of humidity which makes them harder to remove.

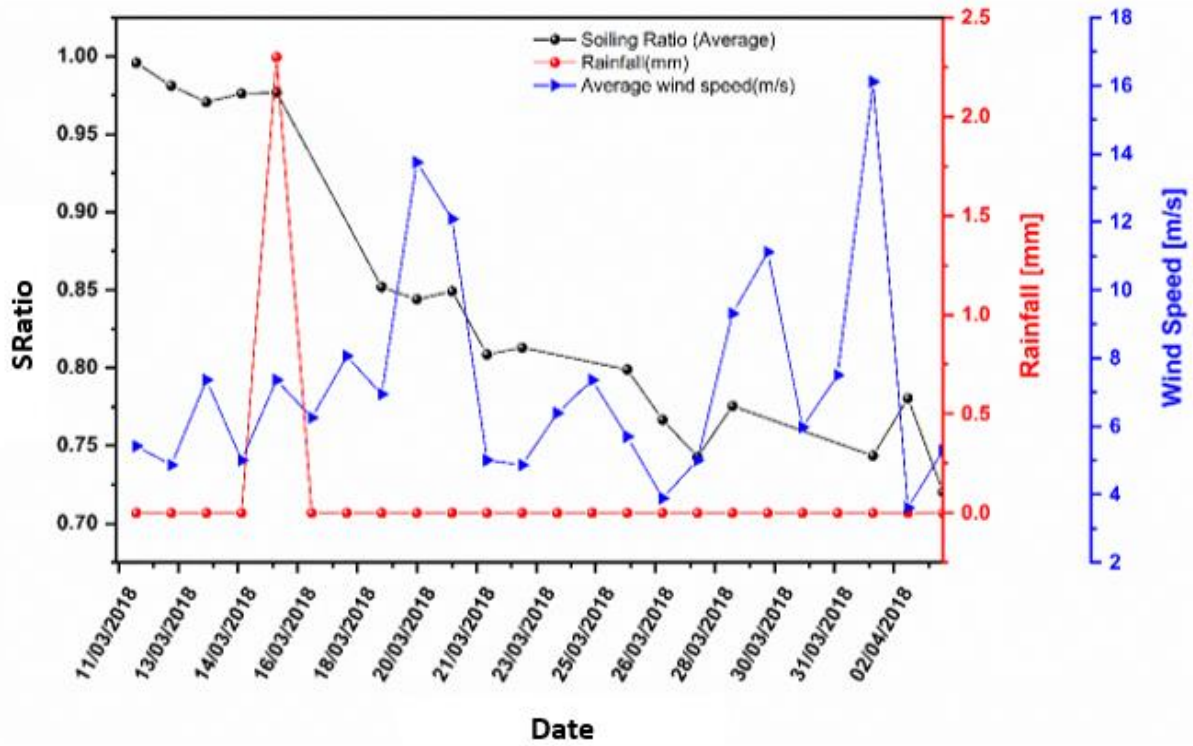


Fig IV. 14. *SRatio* measurements recorded during the period of exposure in the region of Errachidia (Hyper-arid climate) from March 12 to April 5, 2018.

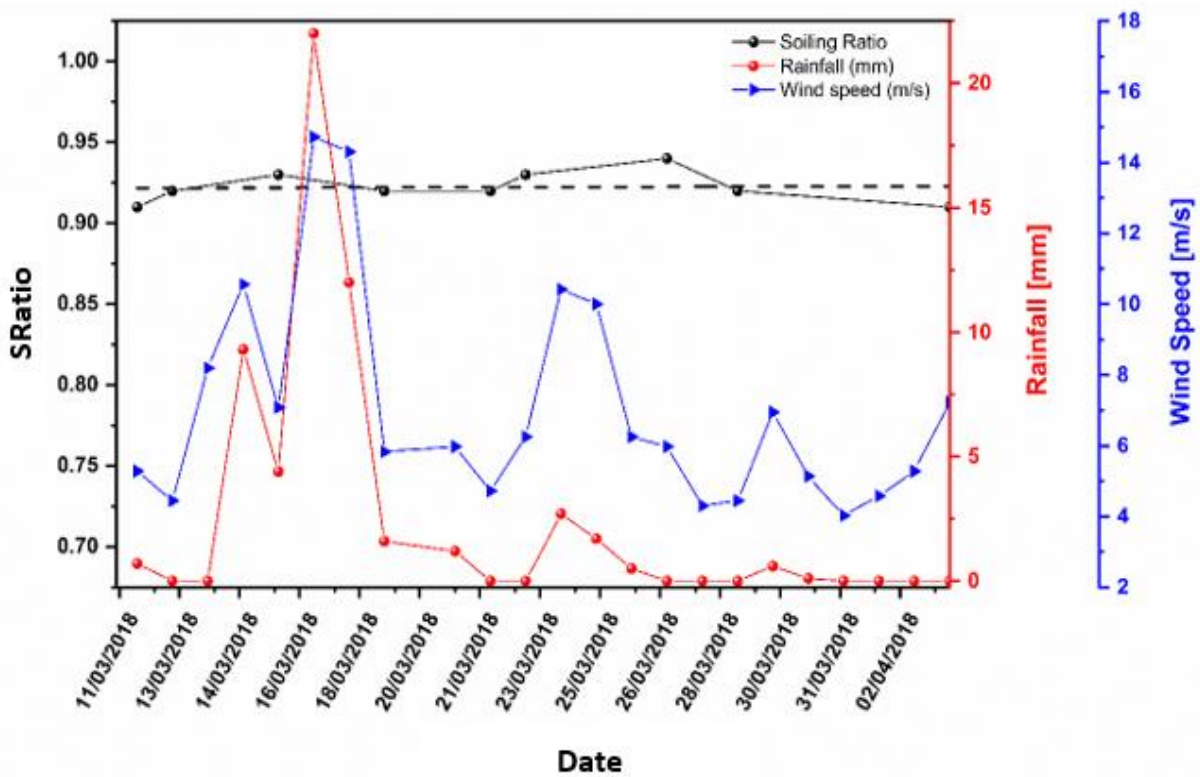


Fig IV. 15. *SRatio* measurements recorded during the period from Marsh to April 5, 2018 on the site of Rabat.

### 2.3.3. Cleaning of PV

#### a. Dry and humid cleaning

By comparing Fig. IV.16, which shows the 25<sup>th</sup> month of the exposure period in Rabat, and Fig. IV.15, which shows the 1<sup>st</sup> month of exposure in Errachidia, we can remark that the increase in wind speed causes significant increases in *SRatio* in the region of Errachidia. However, even there are important rainfalls in Rabat, the *SRatio* increases are slight. Apart from explaining this fact by the effect of humidity, the exposure period also has an important role in increasing the attraction bonds of particles to the surface and making them difficult to remove as it has been mentioned previously.

Through the results obtained from the comparison between Errachidia and Rabat sites (Table IV.2), the cleaning method could be defined for each climate type. In desert or hyper arid areas, dry cleaning can be sufficient which is of ultimate importance with the scarcity of water in this type of site. For humid sites, the use of water remains essential, but thanks to the lower soiling rates, its use is very limited and cleaning frequencies will be reduced.

Table IV. 2. Summary of the effect of rainfall and wind speed in Rabat and Errachidia sites according to the period of exposure.

Exposure		Site of Rabat	Site of Errachidia
Short period of Exposure	Rainfall	+++	++
	Wind speed	++	+++
Long period of Exposure	Rainfall	++	+
	Wind speed	+	Period of exposure should be more extended
Type of cleaning		Humid cleaning	Dry cleaning

+++ : Significant cleaning effect

++ : Average cleaning effect

+ : Weak cleaning effect

#### b. Cleaning based on dew

Dew formed on PV modules surfaces has been reported to have a negative effect related to soiling since it increases the adhesion of particles to the surface [119,168]. However, it could have a positive effect if it is exploited as a substitute of water used in PV modules cleaning operations. From the results presented above, moistening the soils on the surface of the PV modules is a must specially to remove the clay traces, therefore using water is highly required

for cleaning in such site as Rabat (semi-arid climate). This is on the one hand. On the other hand, the observation we have made for the PV modules exposed in Rabat, has proved that cleaning using dew water is efficient as clearly shown in Fig IV.17. Therefore, exploiting dew in cleaning can add an ecological aspect to the cleaning methods in order to optimize the use of such precious natural resource. However, dew is subject to climatic and geographical limitations, it is enough for the air to be slightly humid and that the sky is reasonably clear so that the dew has favorable conditions for its development. We have deepened into the formation of dew to confirm our hypotheses concerning the type of cleaning already mentioned above. Lekouch et al. [169] have applied an appropriate model considering the parameters affecting dew formation to estimate the quantities of dew which can occur in various climates. It has been shown that the formation of dew is ensured in the humid regions (Agadir, Casablanca, Rabat, Tangier and Nador), while this is not the case for non-humid areas (Errachidia and Ouarzazate). That therefore well confirms our hypotheses of defining the type of cleaning for each climate. The efficiency of the cleaning based on dew water will be investigated in next sections.



Fig IV. 16. Cleaning tests of small PV modules exposed in RDI Solar Energy Platform of PSES at ENS-Rabat.

### 3. Synthesis

The impact of soiling on the energy production of photovoltaic systems using a solar front-glass was investigated in outdoor conditions. The study was conducted in Rabat (Morocco) which is characterized by semi-arid climate. The evaluation of the soiling effect directly via the transmitted and the received irradiance has given annual average soiling rate of approximately 4% which is perfectly compatible with the literature performed. Based only on the annual average rainfall of each area which is supposed hosting PV power plants, the soiling rate may well be estimated as has been shown. Nevertheless, it will be necessary to validate these results in several sites having different climatic conditions.

The climatic parameters have well contributed to the explanation of soiling rate evolution. Our simple approach has confirmed that even in such site which knows continued rainfall, the soiling is present especially in dry periods. Based on the appropriate approach presented in this work, the losses in energy production have been calculated for-one PV module. They are around 2 Wh/W<sub>p</sub> per day.

Through the study performed in Errachidia, it has shown that the soiling is much more significant for the hyper-arid or desert sites which reached 23%/month even if the period of exposure is short. Also, soiling in these areas can be eliminated by blowing (effect of wind). Therefore, dry cleaning of PV modules could be sufficient and it is of ultimate importance with the scarcity of water in such areas. For semi-arid sites as Rabat, the use of water is essential to humidify soils before removing the dust out from the front surface of PV modules. However, thanks to a low soiling rate, the use of water is very limited and the cleaning frequency will be reduced.

The experimental approach detailed in this section aims at elaborating a simple and low-cost soiling measurement protocol for PV modules. To confirm the assumptions about the different types of cleaning proposed for different regions, it is necessary to experience each type of cleaning in the appropriate area. Furthermore, it will be convenient to conduct cleaning frequency studies to deduce the most appropriate one that could be combined with the proposed cleaning type.

#### **4. Evaluation of soiling for PV on solar trackers**

##### **4.1. Installation: dual-axis tracker**

The dual-axis tracker used in this study is manufactured by our industrial partner Helioslite that is specialized in the development of solar tracking systems [170]. The one installed in our

Platform is characterized by Roll and Tilt kinetic (Fig IV.18). 16 polycrystalline Silicon PV modules from two different manufacturers are mounted on this tracker.



Fig IV. 17. PV generator of 4.28 kWp equipped with dual-axis tracker.

#### **4.2. Experimental methodology**

In order to determine the soiling losses ( $SL$ ) of PV modules on tracker, one module was subject to daily manual cleaning, while the adjacent one was accumulating soiling naturally. The output of each PV module is recorded using the power optimizers P300W of SolarEdge which enable displaying the energy production of the modules separately. 16 power optimizers, all connected with the inverter SE4K of SolarEdge, have been used. This methodology has been applied separately on both classes of PV modules provided by 2 different producers. Fig IV.19 shows the measurement protocol, the electrical scheme of the power optimizers connected with the PV modules, and the energy production displaying, monitoring and processing. As previously explained,  $SRatio$  is determined based on the maximum power output of the reference PV module ( $P_{max0}$ ) and the soiled one ( $P_{max1}$ ) according to Eq. 9. It should be noted that  $SRatio$  can be measured with uncertainties on the order of  $\pm 1\%$  or better depending on several factors and operating conditions [72]. Once  $SRatio$  determined, the daily soiling losses ( $SL$ ) can be deduced in percentage.  $SRate$  has been calculated based on the derivative of  $SRatio$  in dry periods [171]. It describes the rate at which the daily  $SRatio$  varies during periods without rain events as already mentioned.

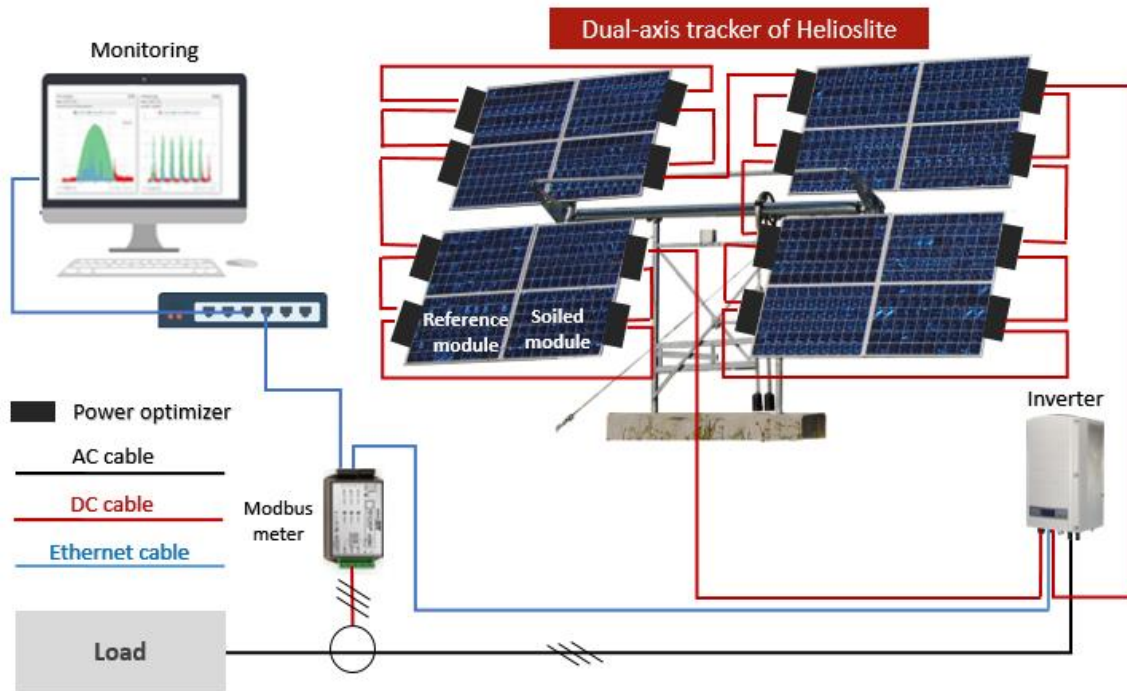


Fig IV. 18. Measurement protocol used to evaluate the effect of soiling for PV modules mounted on the dual-axis tracker of Helioslite.

### 4.3. Results

*SRatio* measurements have lasted for more than ten months from February 19 to December 3, 2018. Fig IV.20 presents the evolution of *SRatio* with the reported rainfall during this period. According to the *SRatio* measurements, it has been noticed that the soiling effect did not significantly appear before a period of about three months from the beginning of the study. In other words, *SRatio* did not considerably drop during the first months of exposure. This first period of the study has experienced significant rainfall up to 40 mm and an average rainfall of 20 mm that kept *SRatio* very close to its initial value. During the dry period ranging from July 2 to August 27, 2018, *SRatio* has significantly dropped as presented by the red line with a *SRate* of about 0.1%/day. Rain events have occurred in mid-September (4.3 mm), recovering partially the *SRatio*. It can be deduced that a cleaning once a year during the dry period is sufficient given the rain events that knows this study site.

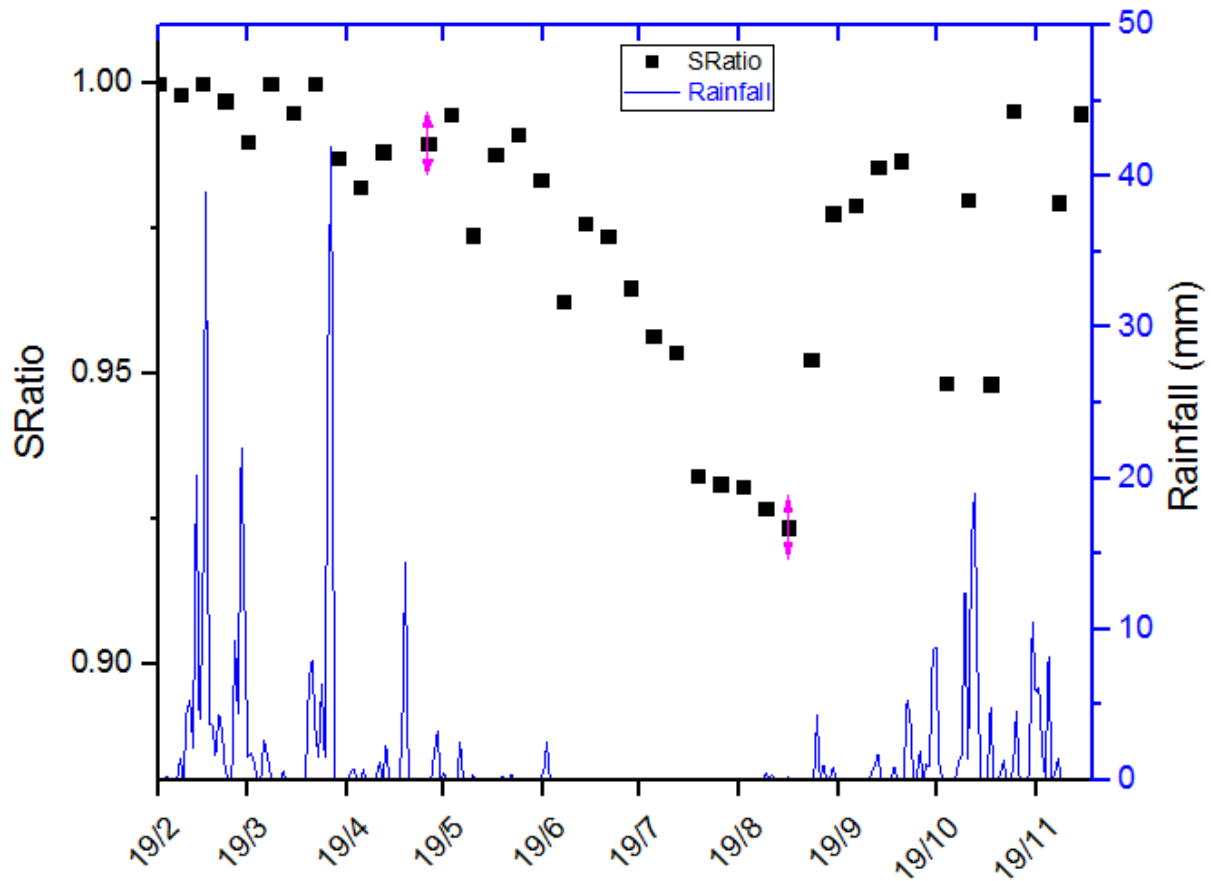


Fig IV. 19. Evolution of  $SRatio$  of PV modules mounted on dual-axis tracker in Rabat, data ranging from February 19 to December 03, 2018. The  $SRate$  is displayed by a red line corresponding to the period with absence of rainfall.

#### 4.4. Soiling losses for fixed and tracking structures

Soiling for fixed system has been evaluated based on a solar front glass exposed in the same conditions as the solar tracker presented above (Fig IV.18). The evolution of daily soiling losses for both fixed PV and PV on tracker is presented in Fig IV.21. It is deduced that  $SL$  are ranged from 2 to 7% in the case of PV with tracking and from 7 to 21% in the case of fixed cover glass titled  $30^\circ$ . The average of soiling losses for fixed system and tracking were respectively 15% and 5%. Note that similar results have been found in Tudela-Spain [76] which is characterized by a semi-arid climate as Rabat in Morocco. In Fig IV.22, the  $SRatio$  for both fixed PV and PV on tracker is presented for the dry period only for identifying well the difference in both trends. This non-rainy period is largely sufficient to deduce the  $SRate$  in such site [172]. For fixed PV, a  $SRate$  around 0.22%/day has been found which is twice greater than that of PV on tracker as shown in the previous section with a value of 0.1%/day.

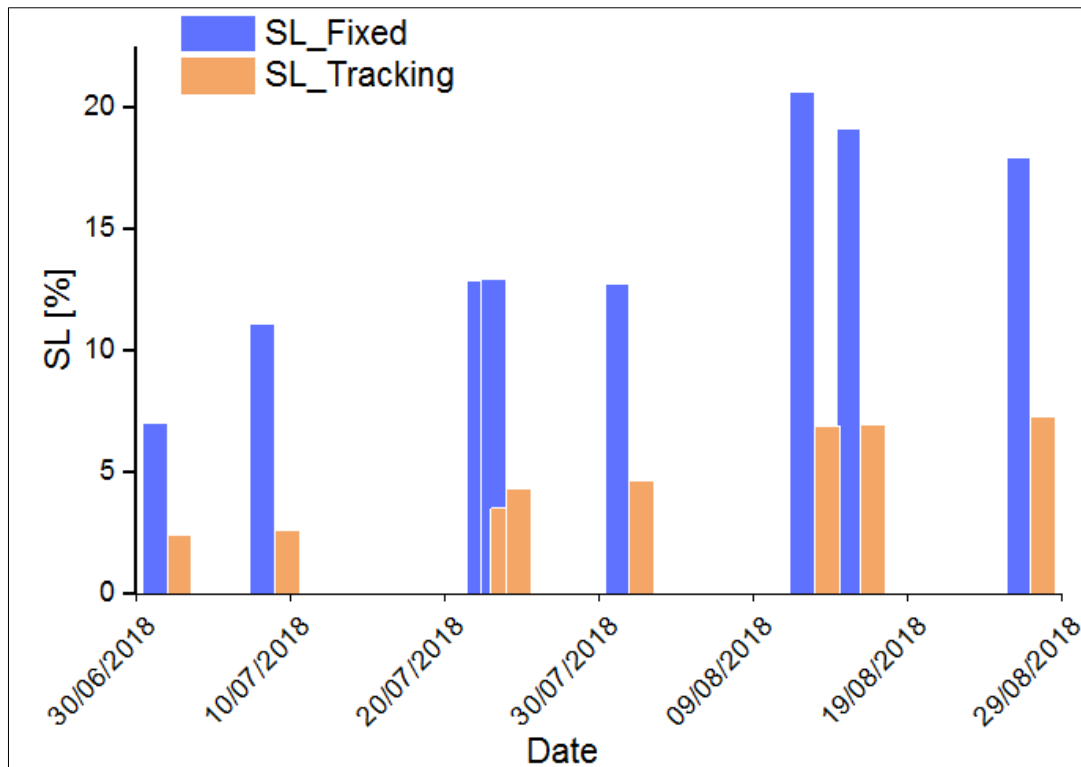


Fig IV. 20. Daily Soiling Losses ( $SL$ ) for fixed PV and PV on tracker in clear days.

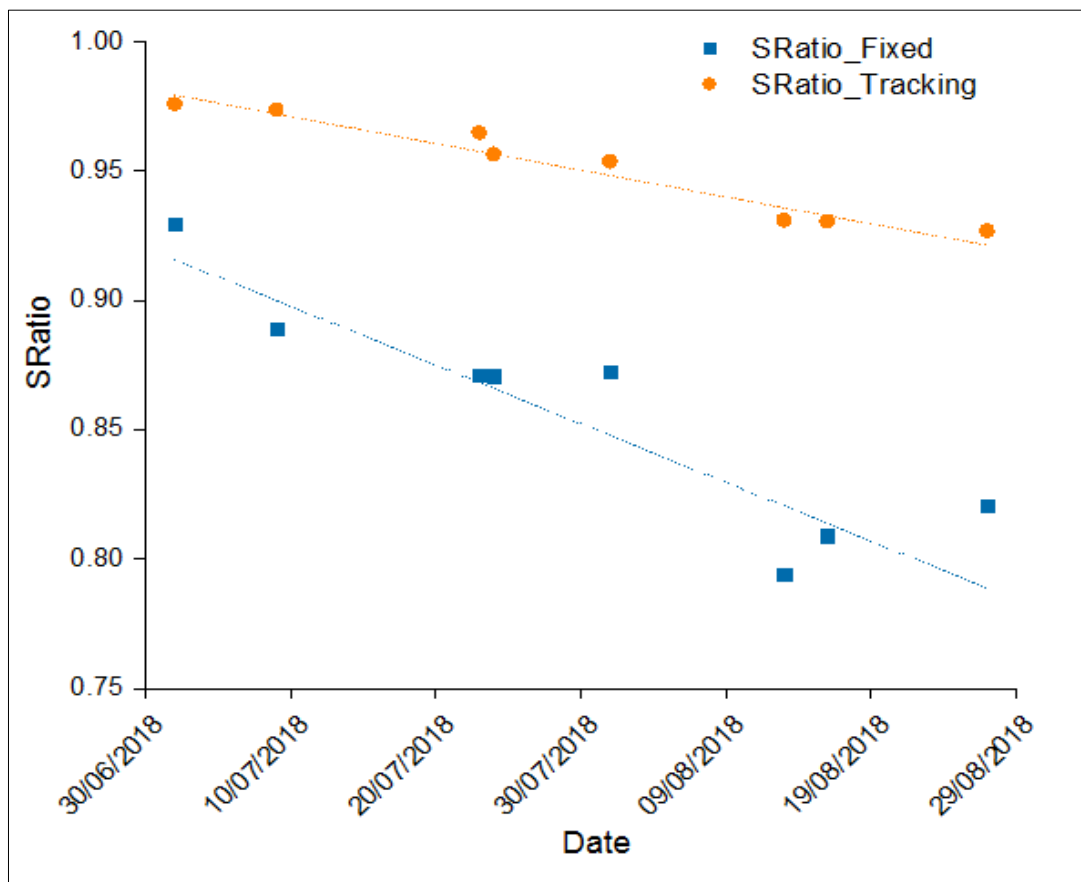


Fig IV. 21. Comparison of  $SRatio$  between fixed PV and PV on tracker installed in Rabat for the dry period ranging from July 2 until August 27, 2018.

As mentioned earlier, the stowage position of dual-axis tracker used in this study is horizontal upward during night, even though the tracker was effective in minimizing dust accumulation. Indeed, it has been noticed for this tracker the presence of a high quantity of dew water on PV modules surfaces in the morning, when they face the sun-rising (face-up to vertical position). Fig IV.23 is a view of the front surface of a PV module covered with dew after the tracker being east-oriented in the morning. The rather good performance of the tracker regarding the reduction of soiling losses has been attributed only to rainfall that is showing good cleaning effect on the surfaces of PV on tracker than those on fixed structure. In this work, the dew effect could be a possible cleaning agent combined with the stowage position.

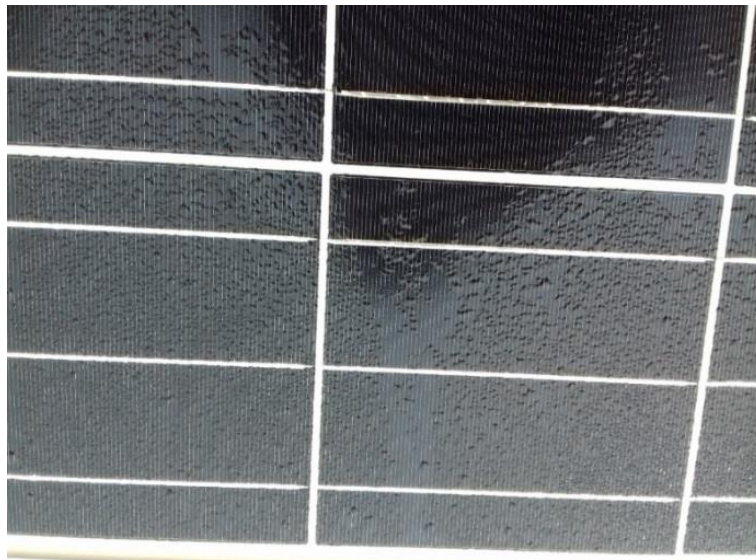


Fig IV. 22. Part of a PV module, covered with dew after being east-oriented by the tracker at sunrise.

## **5. Investigation of the use of dew in cleaning**

### **5.1. Experimental set up and methodology**

In this section, the description of the experimental approach aiming to test the possibility of cleaning PV modules using dew flowing is presented. This approach is based on changing, before sun-rising, the tilt angle of PV modules from horizontal position over the night into the appropriate tilt angle during the day. So, 3 glass samples of 280 mm x 375 mm surface and 3 mm thickness have been carefully prepared and exposed in the same area and conditions at Solar RDI platform of PSES Research Team. Using an appropriate metallic holder with tilt angle modifier made up locally (Fig IV.24), the first sample was placed parallel to the ground. This horizontal position is chosen after sunset in order to promote dew formation over the night and collect the maximum dew water on the sample front surface. Immediately after sunrise, the

sample takes the tilt angle of 30° oriented south to simulate the appropriate orientation of PV panels exposed in Rabat. This tilted position allows flowing dew formed on the glass surface. The other two glass samples remain all the time 30° titled and south oriented as shown in Fig IV.24. One of them, used as a reference, is regularly cleaned, while the other continuously accumulates dust all over the period of test. The methodology followed in this study is presented in Fig IV.25

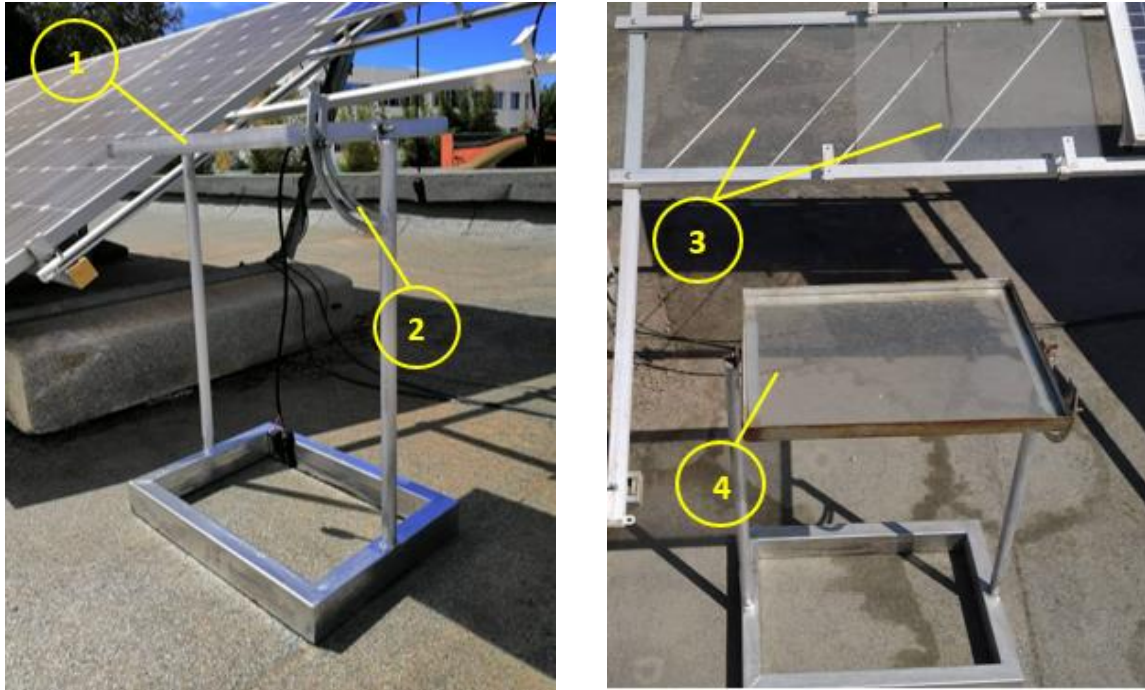


Fig IV. 23. Metallic holder of glass with tilt angle modifier used in this study. (1) Glass sample holder, (2) Tilt angle modifier, (3) Fixed glass samples, (4) Glass sample with tilt angle modification.

The measurements have been performed at midday in clear sky and sunny days, under a stable incident solar irradiance in order to determine the glass *SRatio* as presented previously. The methodology followed for this study is presented in the chart of Fig IV.25. Meteorological parameters have been used to discuss the evolution of *SRatio*. Rainfall and relative humidity (RH) data were recorded from local meteorological station Davis Vantage Pro2 Plus installed at our RDI Solar Energy Platform, while the clearness index *Kt* data were obtained from international accurate database [173].

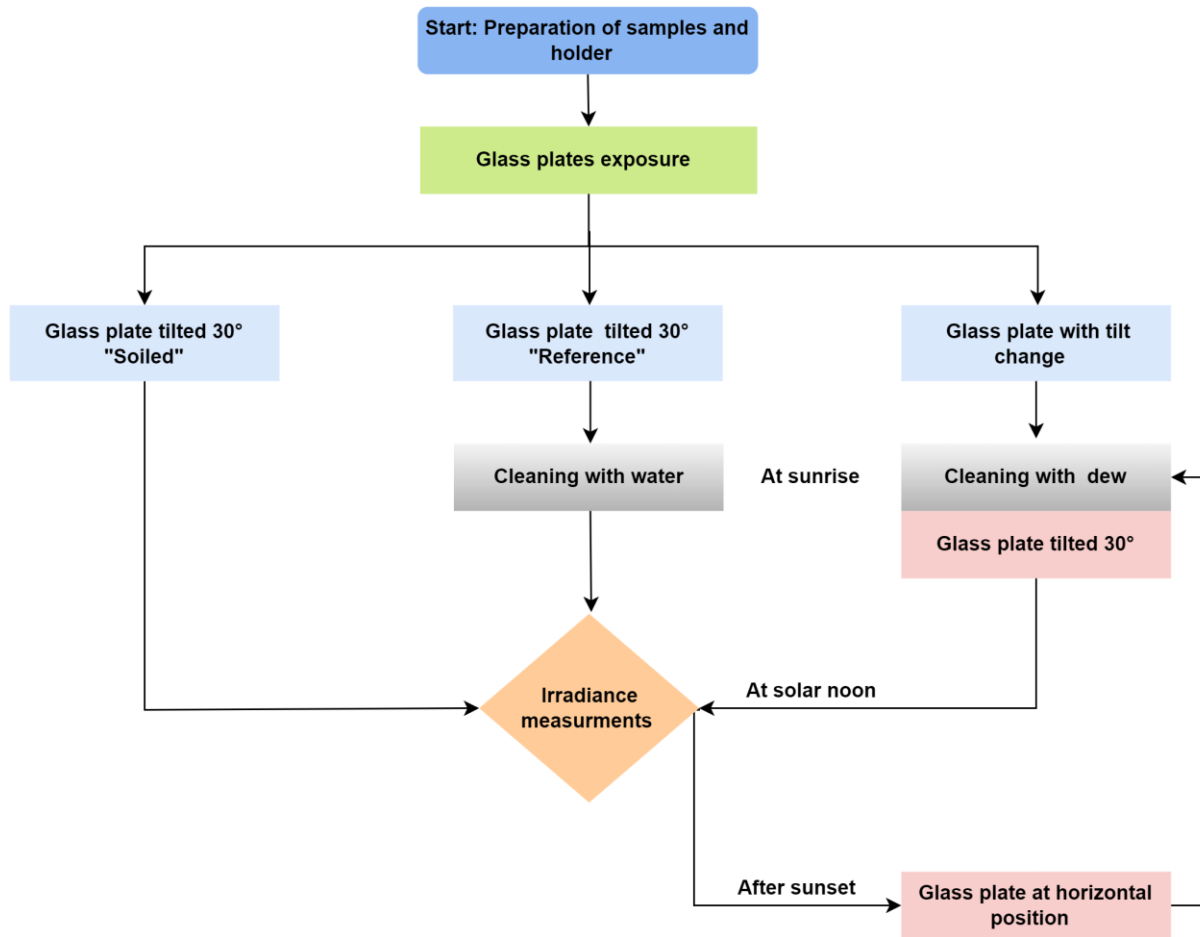


Fig IV. 24. Methodology flowchart applied in the study.

## 5.2. Results of dew cleaning investigation

*SRatio* measurements on the glass samples have been performed from April 1 to July 19, 2021. Fig IV.26 shows the evolution of *SRatio* during this period. "Fixed tilt" corresponds to the measurements performed on the fixed glass sample which continuously accumulate soiling, while "Varied tilt" is related to those obtained from the unfixed one with the change of the tilt. Rainfall has been added to the graph in order to well explain the patterns since the *SRatio* depends strongly on rain events. The graph shows that both glass samples have similar *SRatio* trends. Indeed, *SRatio* values of the Varied tilt in most case are clearly higher which correspond to a clean state maintaining. Depending on the amount of rainfall, *SRatio* of both glass plates knows partially or full recovery. During the dry period from May 30 to June 11, 2021 when no rainfall event has occurred, *SRatio* of the Varied tilt was absolutely higher than the Fixed tilt. This could be explained by the fact that when the tilt angle of the unfixed glass sample changes in the morning, dew flows on the surface and removes part of soiling performing then an efficient cleaning.

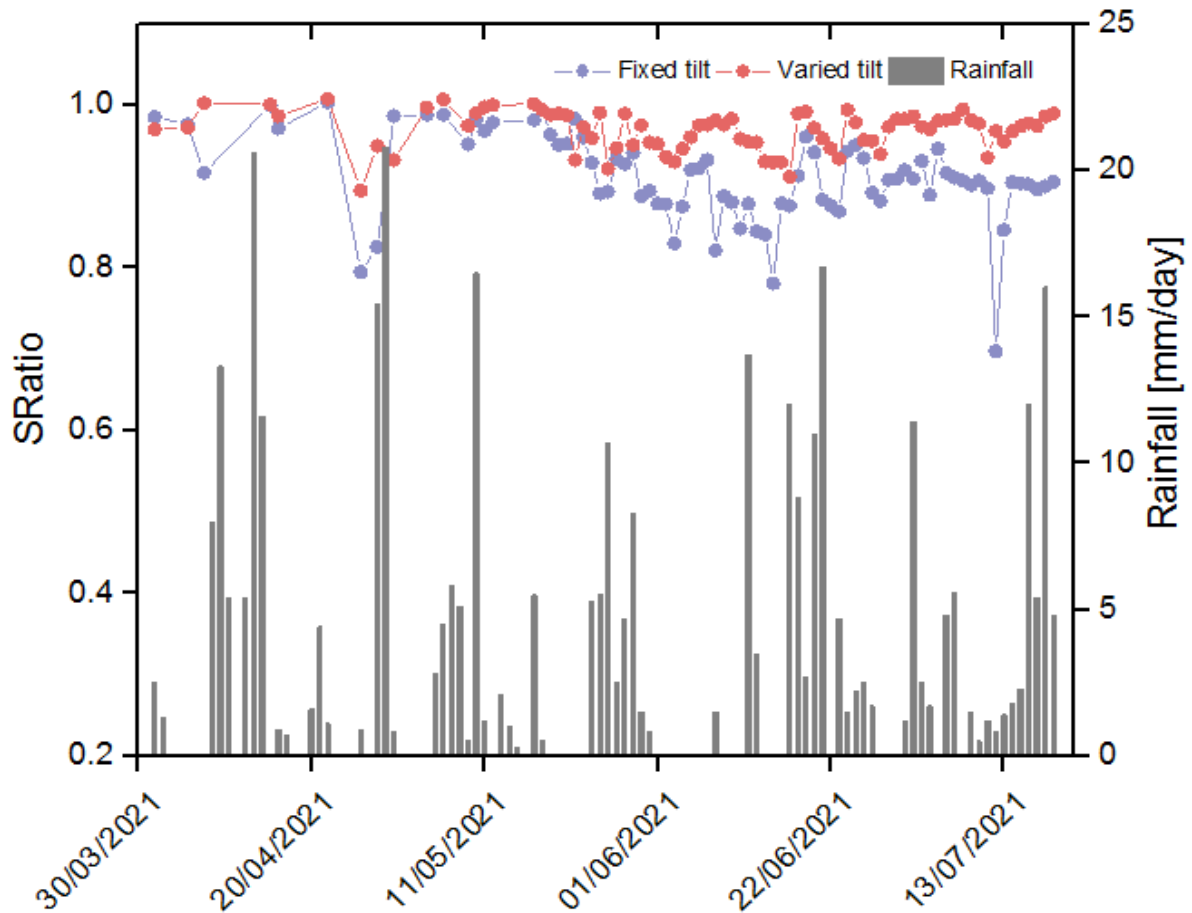


Fig IV. 25. Evolution of  $SRatio$  with recorded rainfall in Rabat from April 1 to July 19, 2021.

Fixed tilt corresponds to the  $SRatio$  of the fixed glass sample, while Varied tilt is corresponding to the unfixed glass, which exploits dew flowing after tilt angle changing to ensure cleaning early in the morning.

Actually, the high  $RH$  values ( $> 60\%$ ), as shown in Fig IV.27, are favoring the formation of dew on the glass surface by night [101]. In some measurements processes illustrated by small triangles in Fig IV.27 and IV. 28, it seems that  $SRatio$  of the Varied tilt has dropped even  $RH$  has achieved high values up to 65%. In fact, apart from  $RH$ , the sky conditions affect also significantly the formation of dew water on a given surface [146]. So, to go further in the analysis of the results, a useful parameter called the clearness index ( $Kt$ ) is required. It corresponds to the cloudless conditions of the sky. A clear sky is defined as  $0.65 < Kt < 1$  while a cloudy sky is in the range  $0 \leq Kt < 0.3$  and partially cloudy sky in the between [174]. Fig IV.28 shows the evolution of  $SRatio$  with  $Kt$  during the same period of exposure. It is found that the days with a reverse effect (Varied tilt less than Fixed tilt) are either characterized by low values of  $Kt$  strictly less than 0.3 or the presence of light rain which worsens soiling.

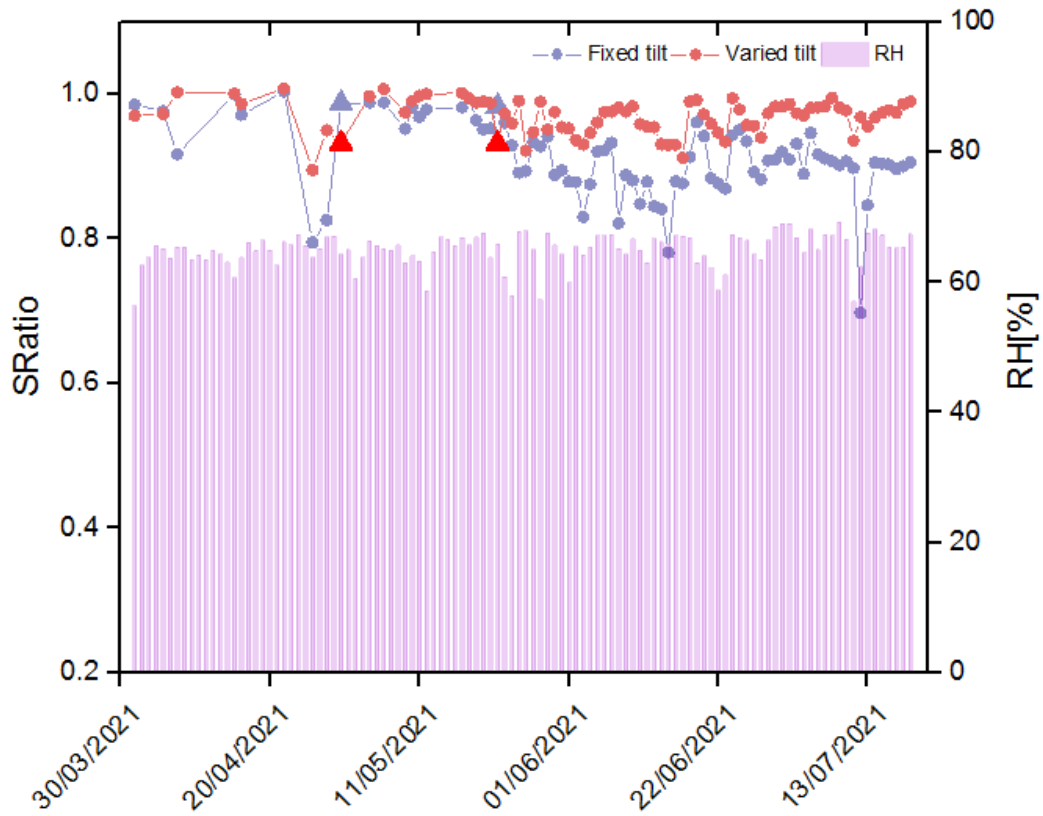


Fig IV. 26. Evolution of  $SRatio$  and the Relative Humidity ( $RH$ ) recorded in Rabat from April 1 to July 19, 2021.

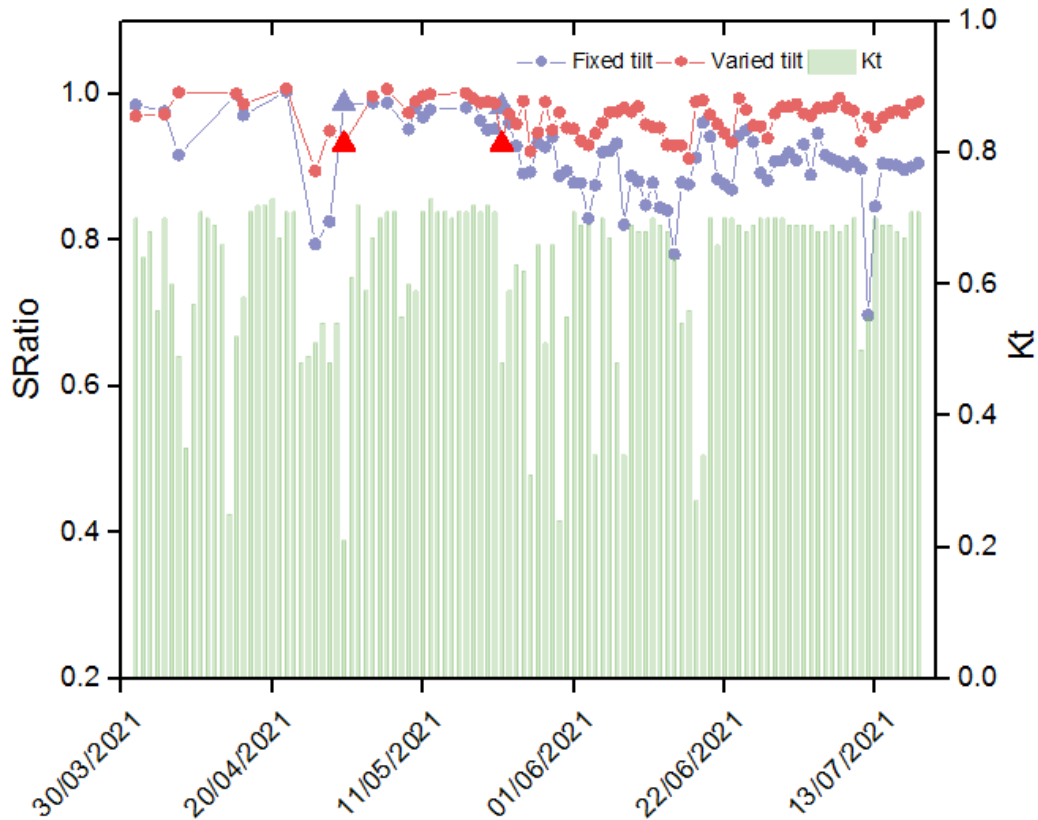


Fig IV. 27. Evolution of  $SRatio$  and the clearness index ( $Kt$ ) recorded in Rabat from April 01 to July 19, 2021.

Fig IV.29 shows the soiling losses ( $SL$ ) in the dry period ranging from May 29 to June 11, 2021. It is clear that  $SL$  values of the fixed tilt glass are always higher than those of Varied tilt one. For Fixed tilt glass, the  $SL$  average value is 3.8% compared to 11.8% for the Varied tilt one. This is because the formation and the accumulation of dew, favoured by the horizontal position all overnight, which makes it possible to wet the glass surface and humidify well the dust. This is required for surface cleaning, in particular in the site of Rabat, as previously demonstrated [8]. So, the exploitation of dew through the approach explained here could significantly reduce (twice) the soiling losses.

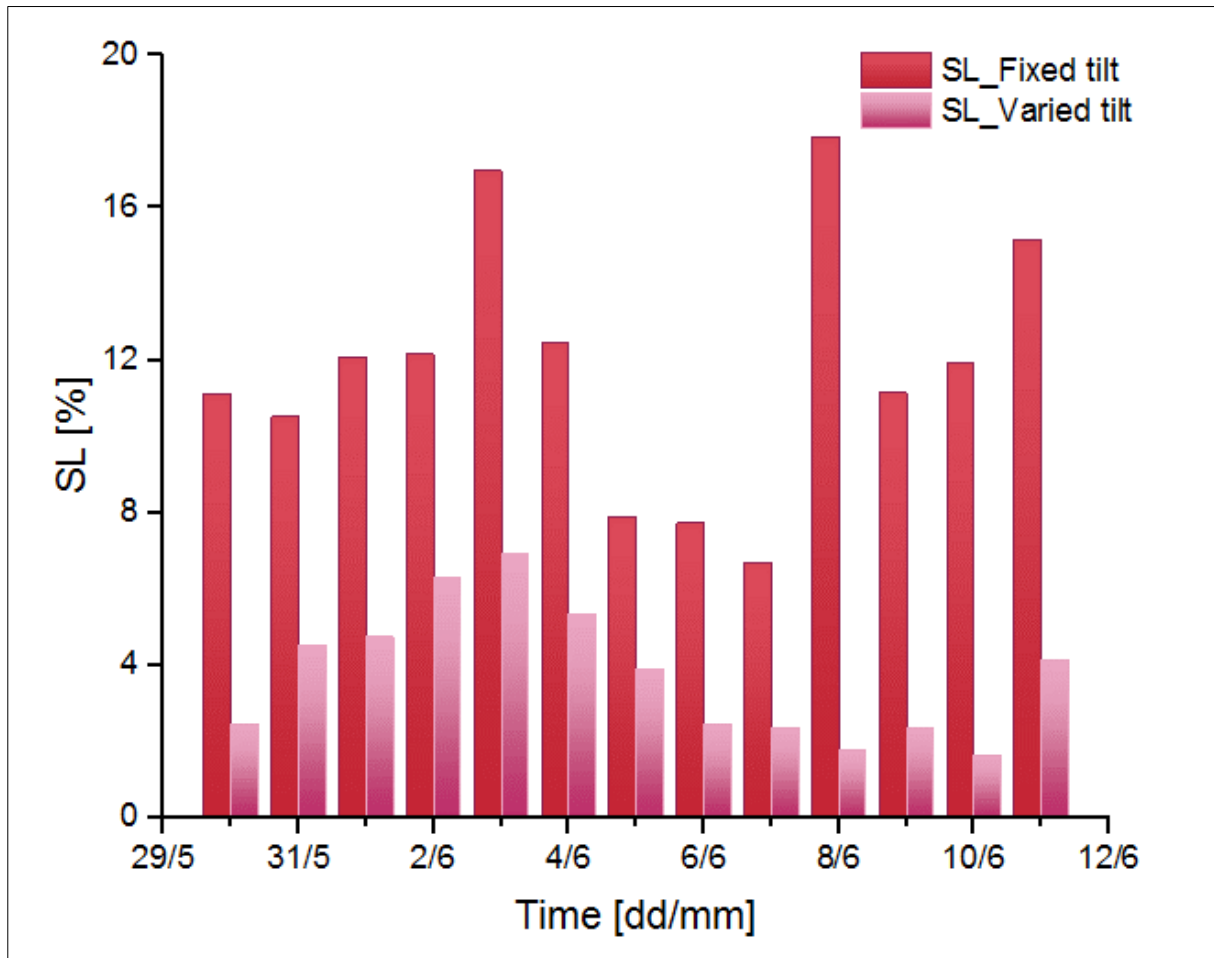


Fig IV. 29. Soiling losses ( $SL$ ) for the dry period ranging from May 29 to June 11, 2021.

### 5.3. Comparison: Fixed tilt, Varied with dew and tracking

This section presents a comparison between the obtained results regarding soiling losses for the fixed glass, PV on dual-axis trackers and glass with tilt angle modification combined with dew flow. During almost a year of study, soiling losses for PV on fixed structures tilted  $30^\circ$  are ranging from 7 to 21% while those for PV on dual-axis trackers are between 2 and 7%. The average of soiling losses for fixed PV and tracking were respectively 15% and 5% for the dry

period. Table IV.3 is a summary of the average of soiling losses that have been found for both dry periods in 2018 and 2021 on dual-axis tracker, fixed solar glass and glass after tilt angle change with dew flow on the surface.

Table IV. 3. Summary of the results relative to the soiling losses in the site of Rabat

	Average of Soiling Losses (%)		
	Fixed solar glass	PV on dual-axis tracker	Glass after tilt angle changing at the morning and dew flow on the surface
Dry period in 2018	15	5	---
Dry period in 2021	11.8	-----	3.8

## 6. Conclusion

This chapter presents several experimental studies of soiling. The longest one in terms of exposure was over a period of two years in Rabat (Morocco) which is characterized by semi-arid climate (according to the aridity index of De Martonne). Based on an appropriate approach, the soiling rate has been calculated directly via the transmitted and the received irradiance and it has given the average annual soiling rate of 4% for fixed structure. The energy production loss has been calculated considering the effect of soiling and it has reached 2 Wh/Wp.day during the dry period. The approach presented in this paper is based on using solar front-glass which is quite efficient, since it presents the advantage of limiting losses that can occur. Strongly depending on the climatic conditions, the soiling ratio has been investigated with rainfall, wind speed and wind direction in both Rabat (semi-arid climate) and Errachidia (hyper-arid climate). Through the first study on fixed PV, several hypotheses have been deduced for the definition of the appropriate type of cleaning of photovoltaic installations; in semi-arid climate (Rabat), humid cleaning is highly required with limited frequency, while in hyper-arid climate (Errachidia) a frequent dry cleaning can be well sufficient.

Due to its high impact on the performance of solar panels thus their maintenance costs, soiling is a challenge for countries having a great potential in solar energy but also high levels of soiling. Several mitigation techniques were the result of the awareness to avoid soiling losses. In this chapter, the effect of dual-axis tracking system to reduce soiling compared to static structures has been also evaluated in Rabat. Indeed, the soiling can be reduced three times if a tracking system is used. Through this study, the cleaning frequency for PV modules on trackers has been deduced that can be once a year during the dry period. This frequency is sufficient to recover the performance given the rain events that knows this study site. Furthermore, it has

been noticed in the site of Rabat high quantities of dew formed on PV mounted on the tracker, which has been tested as a cleaning procedure in such area.

The last section of this chapter presented an investigation of an innovative approach for testing the possibility of soils cleaning by dew which has led to promising results during almost four months of exposure. The soiling can be reduced three times if an inclination angle tilting between 0 and 30° is performed. This result has been found for the tracking system as well. Through this study, it is strongly recommended converting the negative effect of dew which is manifested by dust cementation into a positive effect by relying on the formation and the accumulation of dew during night and flow it off on the PV surface in early morning. The change of PV panels tilt angle associated with dew formation could contribute in mitigating soiling especially in dusty and desert areas where the cleaning is usually required. As has been previously mentioned, the authors of [17] could predict the dew formation in many areas in Morocco. The results obtained in Rabat site in the present study confirm the model's results. Nevertheless, it would be recommended to validate this model in some desert areas for dew formation prediction in order to adopt the change of tilt angle as a novel approach for soiling mitigation of PV panels.

To implement this new approach and make it more attractive as well as facilitating its integration into PV plants, metallic structures with modifiable tilt angle are already existent that can be simply automated. This may also promote the use of such auto-tilted structures especially in remote and isolated areas where the presence of operators would be limited.

**Chapter V: Development of an innovative cleaning system for the dual-axis tracker**

**1. Introduction and study motivation**

Many cleaning systems have been developed to tackle the challenge of soiling. However, most of these cleaning solutions are dedicated to fixed panels and they showed less degree of adaptability to the trackers as shown clearly in Table V.1. According to literature, the cleaning combined with tracking may increase the efficiency of the solar panel by 50% [175]. In order to make these solutions appropriate to trackers, it will be necessary to rely on their adaptation, which will involve a high investment cost and makes the cleaning solution economically less attractive. Few systems that show more adaptability to tracker systems as the case for Hector and Ecoppia T4 [176,177]. Nevertheless, the need for operators is required to perform the distribution tasks for the fleet of solar power plants.

Other solutions have been developed but they are still in the research stage. These show more adaptability to trackers [178,179] since they perform a rotation of 360° during the day, which results in sliding of cleaning system twice over the PV modules. For the autonomous cleaning, robots are considered the most appropriate for the tracking system as they move without restrictions on a given surface and a single robot can scan a large area. However, the passage of a slightly heavy robot on hard soils may not ensure effective cleaning [180]. Furthermore, water-based cleaning methods are nowadays the most commonly used in cleaning of solar collectors [84], but they are considered as less sustainable since they require an important amount of water for large solar plants especially in regions suffering from water scarcity [6].

In this section, after evaluating the soiling losses for dual-axis tracker for the site of Rabat under real environmental conditions, the main objective of this chapter is thus reducing these losses. An innovative cleaning technique has been designed, realized and tested. Indeed, the low-cost aspect was among the most considered criteria in this work through using low cost material and a simple conception which is perfectly appropriate to the used dual-axis tracker.

Table V. 1. Commercial and near commercial mechanical cleaning systems of solar panels, [V]: Verified; [NV]: Not Verified; [A]: Adaptive; [VA]: Very Adaptive.

Cleaning system*	Autonomy	Simplicity of design	Apt for trackers	Adaptability**	Economic attractiveness for trackers	Comments
Nomadd [181]	V	V	NV	NV	NV	The need of twin mounted rails. To be used, this system requires that the PV modules should form a row

*Development of an innovative cleaning system for the dual-axis tracker*

SolaRobot [182]	V	NV	NV	NV	NV	The cleaning system should be guided by rails
SunPower [183]	NV	NV	NV	A	NV	Effective for one-axis tracking solar PV panels
Greenbotics GB1 [184]	NV	NV	NV	NV	NV	Complicated structure which is not compatible with trackers in general
Geva-Bot [185]	NV	V	NV	A	NV	Not compatible with a tracker composed of many modules mounted in wide rows
Washpanel [186]	V	V	V	A	NV	This cleaning system does not require rails and it accepts wide rows. But if the tracker is composed of multiple rows, the use of this system is not considered low cost.
Hector [177]	V	V	V	VA	V	This cleaning system is developed for the cleaning of Heliostats in CSP plants
SunBrush [187]	V	V	V	A	NV	Adaptable for a wide row of PV modules. Multiple units are needed for a tracker composed of many rows.
Solmaks [188]	V	NV	NV	NV	NV	The use of this system requires rails
Miraikikai [189]	NV	V	V	VA	NV	The autonomy of this cleaning system is relative since it needs one operator to be placed on the PV modules surface
Sinfonia Resola [190]	NV	V	V	VA	NV	As a cleaning robot, it needs to be placed on the surface which is subject to cleaning
Aerial Power [191]	VV	NV	V	VA	V	One drone can be used for many trackers. However, it will involve a lot of time in cleaning since it uses a small brush.
hyCleaner [192]	V	NV	V	VA	V	The need for an operator to place the system on the PV panel surface as well as a long time to clean a considerable surface
PSE-BOSO [193]	V	V	NV	A	V	This system presents a smart correction of moving position in real time as well the advantage of turning back after failing to pass an obstacle to 3 times (Security)
Ecoppia T4 [176]	V	V	V	A	V	As a cleaning robot, it needs to be placed on the surface which is subject to cleaning

\* The names of the cleaning techniques mentioned in the table correspond in most cases to the names of the companies. Note that the use of these names is only to compare the compatibility of these techniques with the tracker presented in this work and it does not present any publicity interest.

\*\* Adaptability means the degree of capability to adapt the cleaning system to be used for the dual-axis tracker presented in this work.

## 2. Description of the proposed cleaning technique for dual-axis tracker

### 2.1. Functional analysis

As mentioned before, most of the mechanical cleaning systems are not adaptable for all situations especially in our case as shown in Table V.1. Indeed, the proposed solution has to be appropriate to the mechanical support architecture illustrated in Fig V.1 [170] especially with the mobility of the metallic components of the motion transmission chain indicated by red circles. For this reason, it was essential to carry out a functional analysis (Fig V.2) which aims to express the true need of the solution in terms of different functions that must be stated, grouped and characterized. Other important functions to be considered related to cost and sustainability. In other words, the proposed solution should be low cost and ecological. In the case of a cleaning with contact, this latter should avoid the formation of micro-scratches.

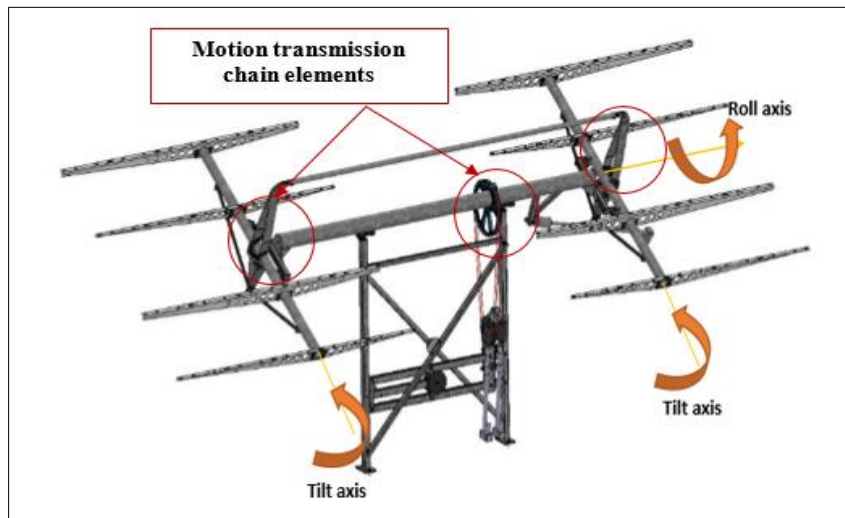


Fig V. 1. Architecture of the dual-axis Tracker from the documentation provided by Helioslite (Appendix 1).

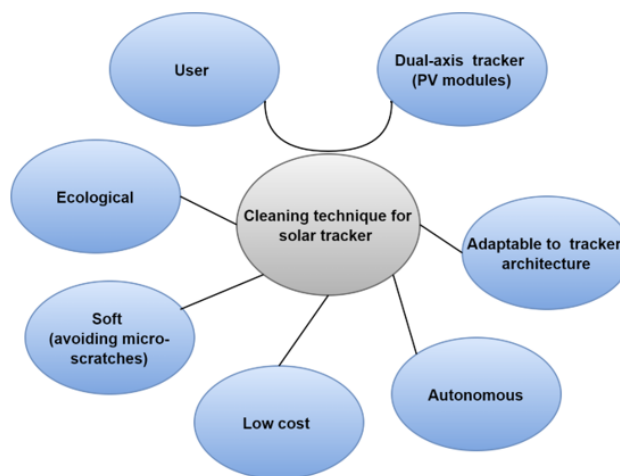


Fig V. 2. Different functions involved in the functional analysis of the proposed cleaning system.

## **2.2. PV cleaning technique based on the telescopic arm**

The design of the cleaning system based on the telescopic arm in the form of a chisel meets all the criteria of the functional analysis presented above. Indeed, we opted for the telescopic arm in the form of a chisel given its rigidity and the fact that we are going to use arms of reduced lengths instead of a single fixed arm, hence the problem of flexion at the extremities of the tracker. Therefore, keeping the arm always horizontal on the surface of the modules as well as ensuring effective cleaning were among the determining criteria for our design proposal for this system.

The arm narrows and deploys using an electric jack to reach the ends of the tracker and then a translational motion is occurred. To be able to rotate from one panel to another, a stepper motor has been proposed to be coupled to a conical gear in order to transform the direction of the rotation. The end of the arm is connected by a mounting connection to rotating nylon brush to prevent scratching on the surface of the PV modules. The proposed brush has a diameter of 400 mm, a large diameter to optimize the number of displacements of the brush on the PV modules surface. The cleaning using this type of brush can be performed on a dry surface as it can be done on a humid surface especially in early mornings where the amount of dew is quite important [8]. As for the time of cleaning, in order to exploit the quantity of dew formed, the cleaning will be performed early morning when the tracker is still in the stowage position (horizontal). Fig V. 3 is illustrating the architecture of the proposed cleaning technique designed for the real dimensions of the dual-axis tracker. The telescopic arm with chisel form will be fixed in the middle of the tracker's bar by a fixing connection.

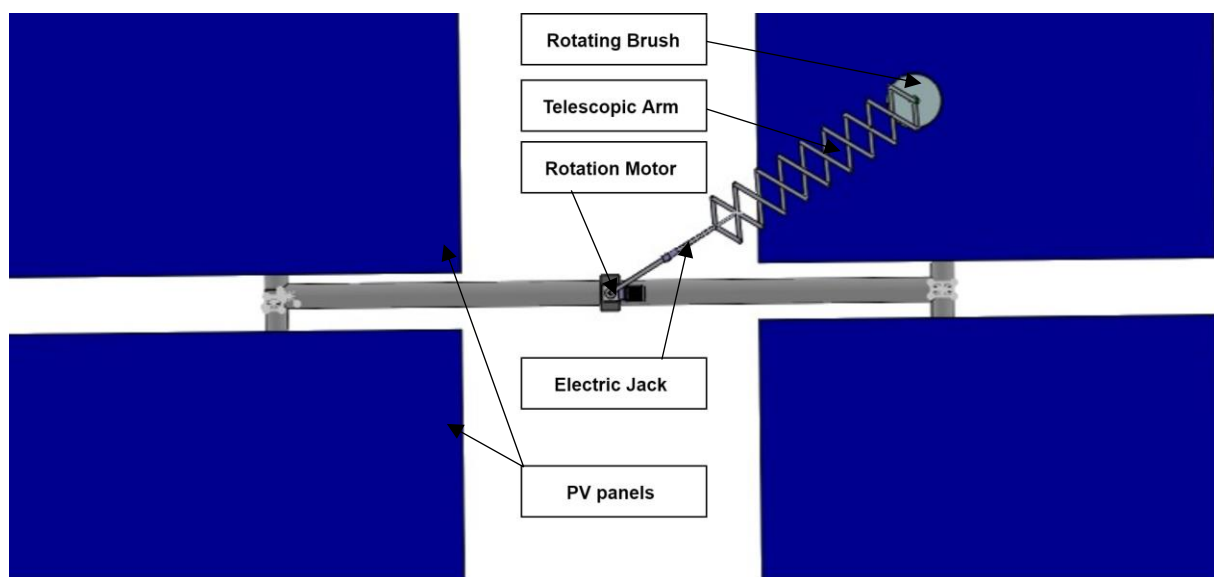


Fig V. 3. Location of the cleaning system on the middle bar of dual-axis tracker.

### **2.3. Dimensioning of the telescopic arm**

In Fig V. 4, an illustration of the telescopic arm position when the tracker is in the horizontal position. Some data related to the tracker are used in this dimensioning as the distance between the PV module and metal central bar ( $h$ ). The diagonal of the 4 PV modules will be designated by ( $D$ ). One of the lozenge angles is designated by ( $\beta$ ). For a good appearance of the parameters on the figure, each parameter is indicated by color adjacent to the parameter in question.

In order to calculate the minimum length ( $a$ ) of the telescopic arm, a mathematical approach has been followed. The length ( $a$ ) will be calculated based on Eq. 1 so that the arm does not cross with the metal bar of the tracker that we already mentioned in Fig V. 1.

$$\cos \beta = \frac{h}{a} \quad \text{Eq. 1}$$

For the case that the telescopic arm is completely narrowed,  $\beta = 5^\circ$  and referring to Eq. 1:

$$h = a = 208 \text{ mm} \quad \text{Eq. 2}$$

By adopting the following hypothesis for a lozenge represented by Eq. 3, where  $d_1$ ,  $d_2$  and  $\alpha, \beta$  are respectively the diagonals and the angles of the lozenge. A condition limit has been as well adopted which is  $d_1 < d_2$ .

$$\begin{cases} \alpha + \beta = \frac{\pi}{2} \\ d_1 + d_2 = Cte \end{cases} \quad \text{Eq.3}$$

To calculate the number of lozenges that will compose the telescopic arm, the 4 modules diagonal ( $D$ ) has been determined using the dimensions of a standard PV module. Eq. 4 presents the total number of lozenges.  $N$  refers to the number of bars of length ( $a$ ) constituting the telescopic arm. Considering that  $D = 3565$  mm, the telescopic arm will be composed of 9 lozenges made of aluminum profile with a length of 208 mm each.

$$N = \frac{D}{a} \quad \text{Eq.4}$$



Fig V. 4. Dimensioning of the telescopic arm taking into account the real dimensions of the tracker.

#### **2.4. System control**

Since the system must be controlled and its use needs to be secure, safe and autonomous, the automated control is extremely required. For the control of the system, a GRAFCET (Control Functional Graph Steps and Transitions) diagram has been developed as shown in Fig V.5. It describes the functioning of the system and represents the developed automatism to control the cleaning system. This diagram contains all the actions and transitions since the beginning of the command which is related to the defined starting conditions until the shutdown. The principle of cleaning of a panel will be the same for the other panels mounted on the dual-axis tracker, which means 4 control loops. Each loop corresponds to the rotation of the telescopic arm from one panel to the other with an appropriate angle. A time delay for an adjustable duration of  $T_s = 3$  s has been chosen to allow the brush to effectively clean the swept surface.

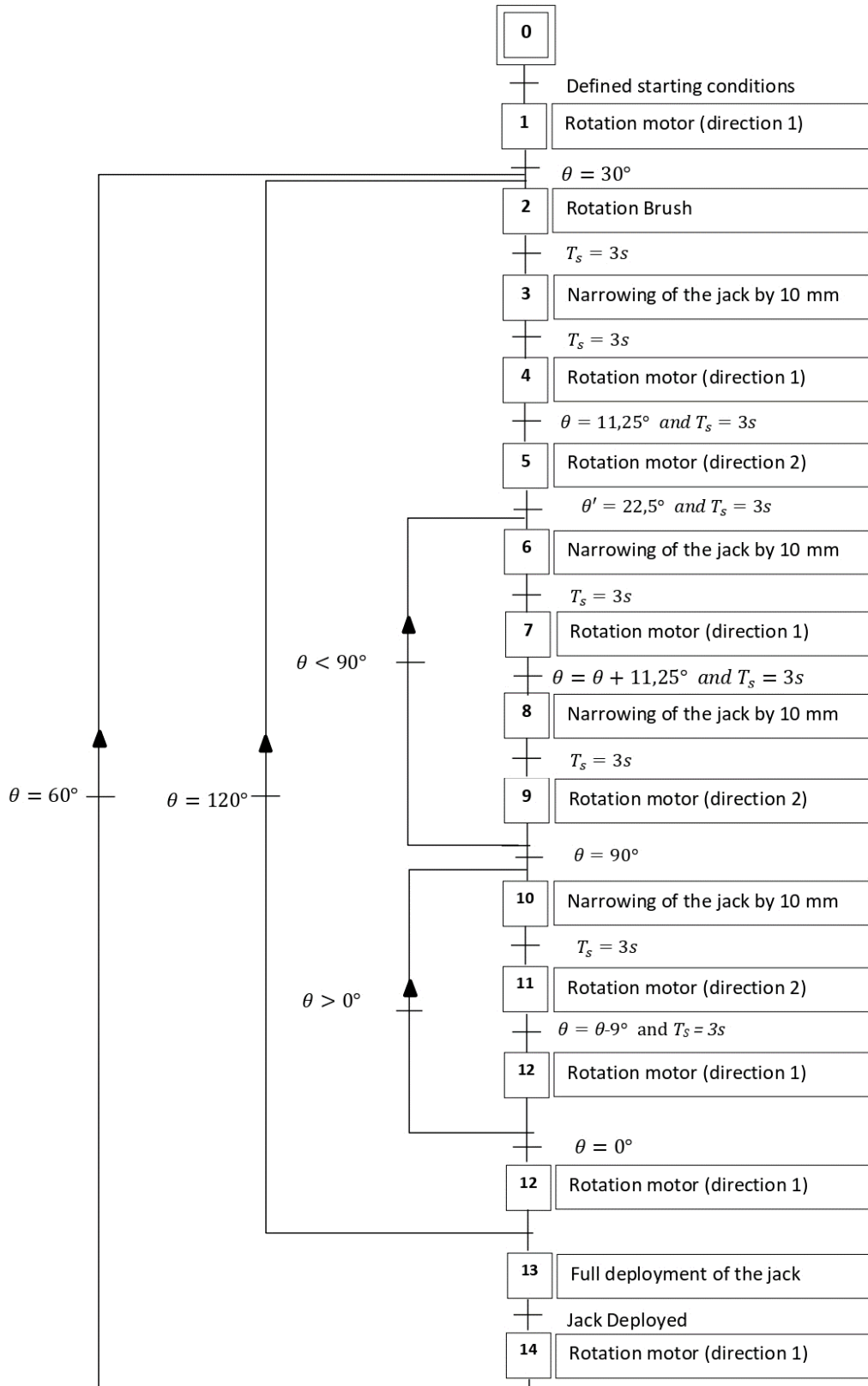


Fig V. 5. GRAFCET representation of the control system. The rotation motor ensures the scan of the PV module surface as well as the rotation of the telescopic arm on the 4 sides of the tracker.

### **3. Demonstration prototype**

#### **3.1. Overview of the realized system**

The purpose of making a demonstration prototype of the cleaning technique is to do tests before investing in the development of the final version of the product. It also makes it possible to validate the technical choices before going into production. Through this reduced prototype, the efficiency of the cleaning technique will also be evaluated. It should be noted that the choice of components for this reduced prototype strongly depends on what is available on the market. Instead of using two PV modules for each side as illustrated in Fig V. 3 and Fig V.4, only two modules for the whole system have been used since the purpose of this realization is testing the cleaning technique and not to reproduce the PV system with its tracking system as shown in Fig V.6. Technical data of the PV modules and the used motors are presented respectively in Table V.2 and Table V.3. A focus on the control board is presented in Fig V.7.



Fig V. 6. Top view of the realized prototype of the cleaning technique based on the use of telescopic arm.



Fig V. 7. A focus on the control board and its location in the realized prototype.

Table V. 2. Technical data of the PV modules used for the tests of the cleaning technique.

Technology	Polycrystalline Silicon
Rated Power ( $P_{max}$ )	40 W
Voltage at $P_{max}$	18.2 V
Current at $P_{max}$	2.20 A
Open-circuit Voltage ( $V_{oc}$ )	22.5 V
Short-circuit Current ( $I_{sc}$ )	2.31 A

Table V. 3. Description of the used motors

Motor	Type	Reference
Rotation motor	Stepper motor	Nema 24HS43-2004S
Electrical jack	DC motor	KCY 100-VB32
Rotating brush	DC motor	ZYT05R 10W

### 3.2. Control of the realized prototype

The control of the cleaning solution presented in Fig V.8 is based on the use of an Arduino Uno board. This card is responsible for processing the various information detected by the Bluetooth sensor, a start button or others. Since the cleaning system consists of three motors of different voltages, the use of the relay-based board is necessary. This 5V relay board is connected to the DC motor of the rotating brush with a voltage of 12V as well as the motor of the jack which ensures the translation of the telescopic arm on the surface of the PV panels. As for the rotation motor which moves the arm from one panel to another, it is directed via a reference TB6600 stepper motor driver. It should be noted that the cleaning solution integrated on the full-size tracker would be supplied by the PV modules mounted on the tracker itself.

Since the prototype produced would be powered from the grid, an AC/DC transformer has been added to the system.

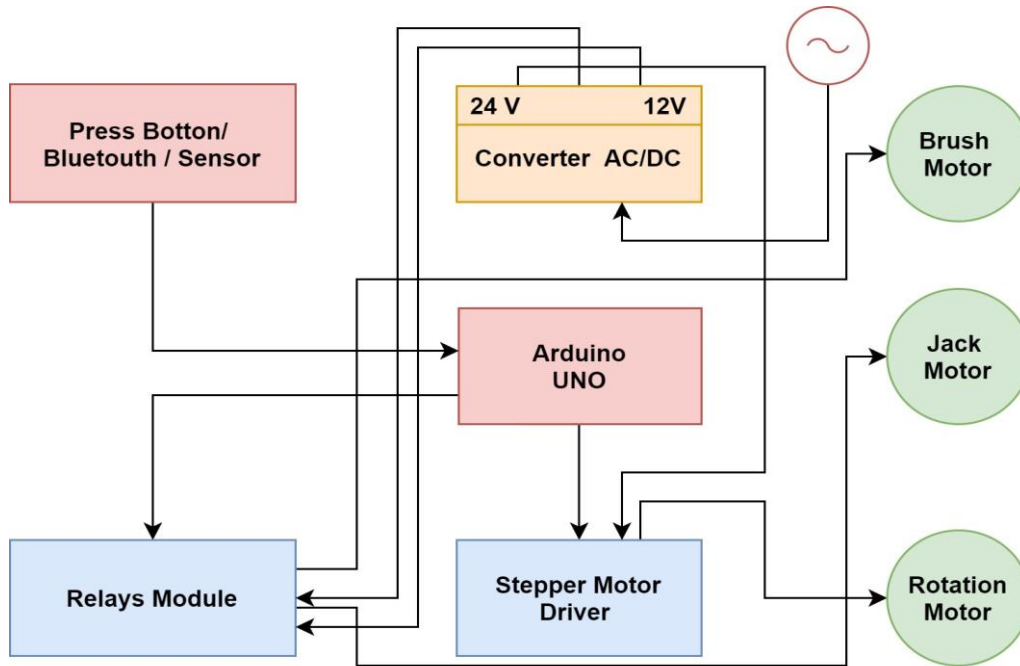


Fig V. 8. Block diagram of the cleaning system control proposed to be integrated into the dual-axis tracker.

### 3.3. Tests of the proposed cleaning technique

#### 3.3.1. Experimental methodology for artificial soiling

The purpose of this section is to test the cleaning carried out by the proposed cleaning based on the telescopic arm with an artificial soiling. The panel surface has been covered in a homogeneous way, with the dust collected from the ground, to simulate the soiling that occurs in outdoor conditions. Note that the operation is done by the same person and with the same amount of dust to be able to keep the same tests conditions. It would be more convenient to the test bench that has been already designed and tested locally for dust deposition [194]. However the dimensions of the PV modules (71.1 cm x 32 cm) are bigger than the dust container. The density of dust is 70 g/m<sup>2</sup> as measured before experiment (Fig V.9). The cleaning technique performance will be evaluated based on measuring the output characteristics of the PV modules with the technical data presented in Table V.2. A multimeter has been used to measure the open-circuit voltage ( $V_{oc}$ ) and the short-circuit current ( $I_{sc}$ ). The PV modules are placed in horizontal to simulate the worst-case scenario of dust accumulation [7]. The methodology followed in this section is presented in Fig V.10.



Fig V. 9. Dust used in the artificial soiling weighted by the precision electronic balance with an accuracy of 0.01g.

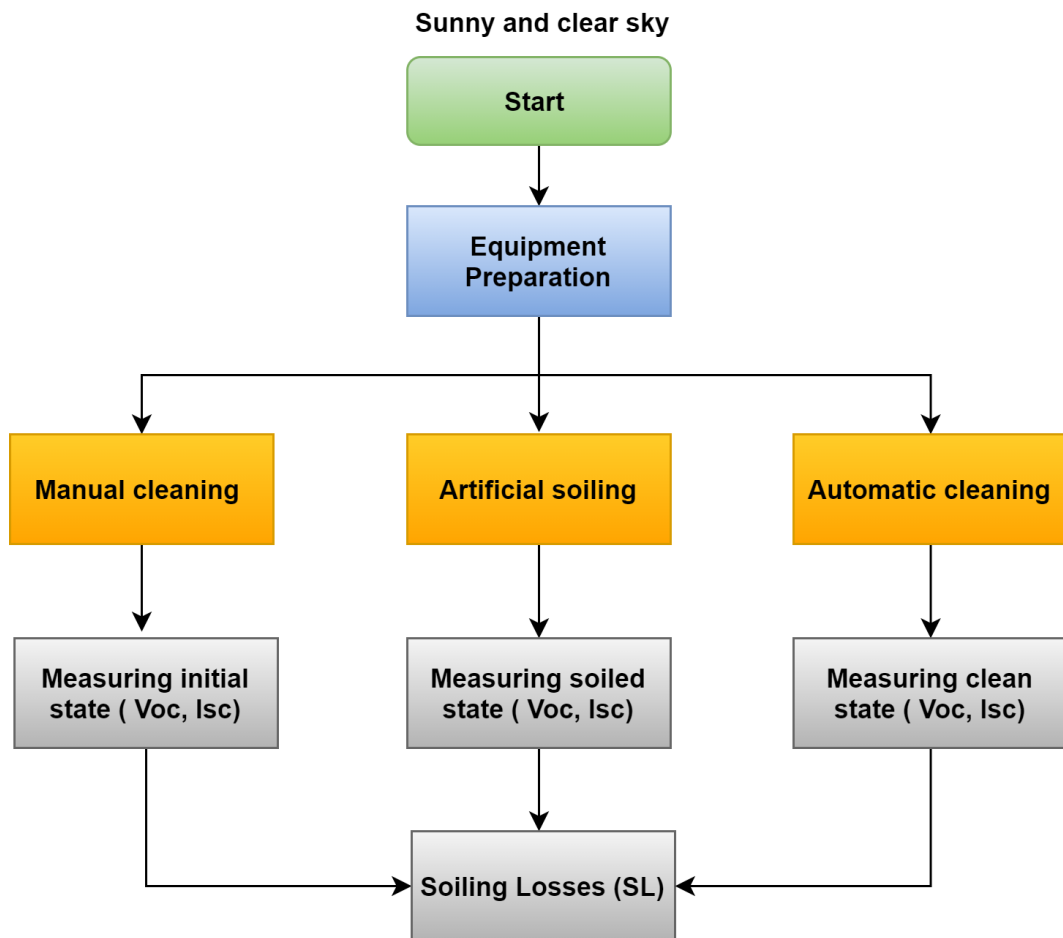


Fig V. 10. Methodology followed to test the realized cleaning technique.

### 3.3.2. Results of artificial soiling

The test results of the artificial soiling are shown in Fig V.11. Actually, *SL* were 31% after covering the surface of the PV panel. A manual cleaning has been done as previously explained leading to only 2.58% in *SL*. The panel has been newly covered with the same amount of dust

to test the realized cleaning system. Through the cleaning carried out by the cleaning system (Fig V.12), the losses due to soiling have been reduced to 3.53%. Indeed, the difference between both automatic and manual cleaning was only 0.95 pp. It should be noted that the automatic cleaning carried out is without water with a very fine brush. However, some fine particles remain on the PV panel surface. Note that the surface of the panel is swept only once in order not to scratch it, as well as to optimize the energy consumed by the motors. Unlike the manual cleaning where we could re-clean the same surface. For the reasons previously mentioned, the difference between both cleaning is well justified.

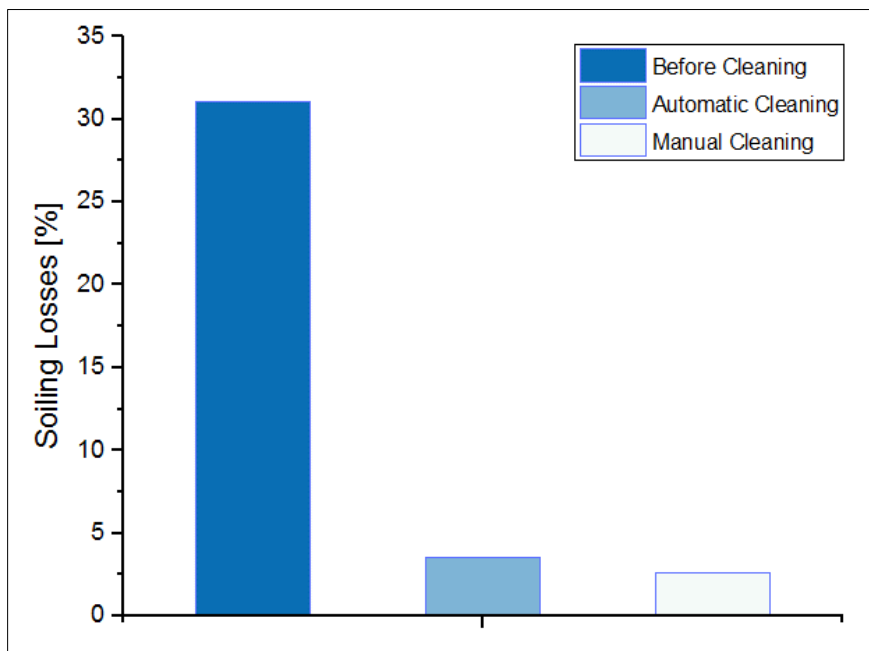


Fig V. 11. Soiling losses recovery by manual and automatic cleaning.



Fig V. 12. View on the PV modules with artificial soiling during cleaning operation.

### **3.3.3. Economic analysis**

The economic analysis is an essential part of this work to evaluate the success of the proposed cleaning technique. It assesses the profitability and feasibility of this technique, including its ability to recover investment and operating costs as quickly as possible. A study of the cost impact for a real case was performed for the dual-axis tracker previously described of 4 kWp installed in Rabat. The cost the proposed cleaning system ( $C_{CS}$ ) is the total of the initial cost ( $C_{initial}$ ) and the maintenance cost ( $C_{maintenance}$ ). This latter is calculated based on the cost of energy consumption ( $C_w$ ) of the solution with a frequency of cleaning of once a month and spare parts replacements. Indeed, the cleaning frequency depends on the geographical area where the PV plant is implemented. In this case, the worst-case cleaning frequency has been adopted to calculate the energy losses due to soiling ( $E_{loss}$ ). The cost of electricity losses ( $C_{El}$ ) is calculated by Eq.7, where ( $C_{oE}$ ) is the cost of electricity per kWh [195].

$$C_{CS} = C_{initial} + C_{maintenance} \quad \text{Eq. 5}$$

$$C_{maintenance} = C_{material} + C_w \quad \text{Eq. 6}$$

$$C_{El} = E_{loss} \times C_{oE} \quad \text{Eq. 7}$$

$$E_{loss} = E_{gc} - E_{gs} \quad \text{Eq. 8}$$

where ( $E_{gc}$ ) and ( $E_{gs}$ ) are respectively the energy generated at clean state and soiled state of the PV modules mounted the dual-axis tracker.

$C_{CS}$  of the proposed cleaning solution was taken to be 11993 MAD on the lifetime of 25 years which is the common period for the operation of PV plants. Considering the automatic cleaning recovery calculated in previous section that can be obtained using the proposed cleaning solution of 3.53%, the gain in energy (or loss in case of absence of cleaning) in energy is 330.44 kWh over the year as can be deduced from Fig V.13 and Fig V.14. Therefore, the automatic cleaning cost will be 1.46 MAD/kWh which is not profitable in terms of payback time compared to the system lifetime. In fact, the cost of the solution should provide a return on investment in less than 10 years. In other words, since in desert and arid sites, soiling is more pronounced then the return on investment is expected to be faster. For this reason, a projection has been made on an arid region where soiling is higher. Assuming that the same tracker is implemented in an arid region with an average soiling losses of around 12% [80]. The gain in energy after cleaning would be 930.8 kWh which implicates 1359 MAD/year. So, a payback

time would be 8 to 9 years. Table V.3 is a summary of the performed economic analysis. It can be deduced that this cleaning solution based on the telescopic arm would show a very important economic attractiveness if only it is implemented in a desert climate where the soiling reaches higher rates.

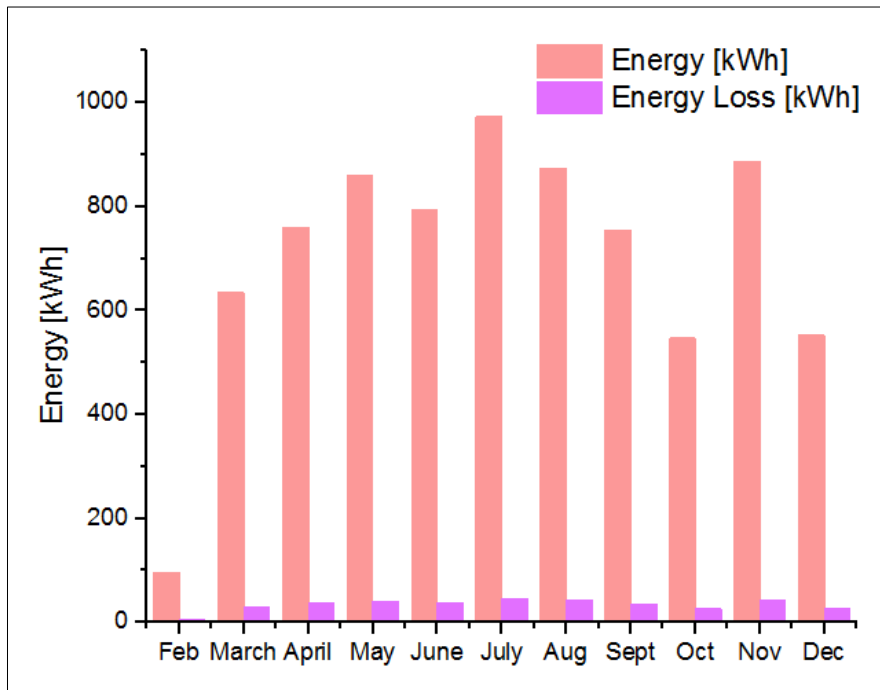


Fig V. 13. Evolution of monthly recorded energy produced by clean PV modules and the corresponding losses due to soiling in the site of Rabat from February to December 2018.

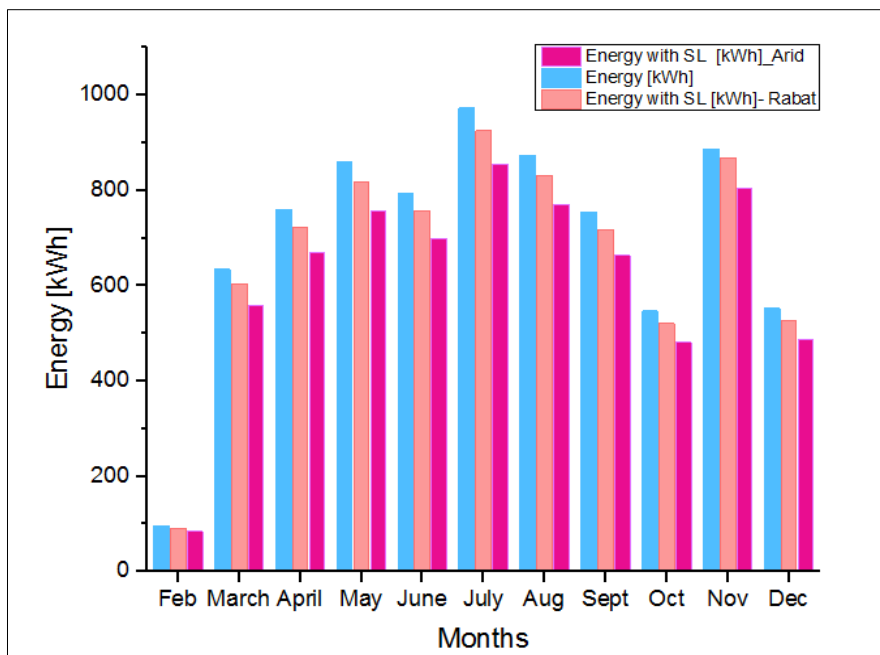


Fig V. 14. Comparison of the energy produced with and without soiling based on the recorded energy for the site of Rabat, the energy with soiling loss in the arid region was calculated based on the soiling losses found in the arid region.

Table V. 4. Gain obtained by cleaning using the solution designed for Rabat Region and in the case that the installation is in an arid area.

	<b>Rabat site</b>	<b>Arid site</b>
Average soiling losses (%)	4.8	12
Lifetime of the cleaning system (years)		25
Price of the solution to be paid (MAD/kWh)		1.46
Gain in energy production (kWh)	330.44	930.8
Payback time	24	≈ 9

#### **4. Conclusion**

Soiling is among the most challenging topics which receive a lot of attention in the research community regarding its significant effect on energy production. Indeed, soiling phenomenon and its effect has been evaluated, studied but not yet resolved. This paper brings to the literature an innovative approach to improve the performance of solar installations. It is not only a question of using a tracking system to maximize the production of PV modules but to integrate an automatic and low cost cleaning system for a higher production.

According to the intensive research carried out, only few cleaning systems that showed their adaptability to the tracker studied in this thesis. However, this adaptability is relative since it will be necessary to invest more to make these cleaning systems completely appropriate to the dual-axis trackers. Therefore, it is of utmost importance to present an innovative cleaning solution to tackle the challenge of soiling especially for countries with great potential in solar energy as the case of Morocco.

The evaluation of the soiling losses for the PV modules mounted on a dual-axis tracker has been done for almost a year at the site of Rabat. For the same tracker, an innovative cleaning technique based on a telescopic arm has been presented. It has been also detailed in this paper, an artificial soiling approach followed to evaluate the gain in energy production using the realized cleaning technique. Considering the cleaning cost including the CAPEX and OPEX which is 1.46 MAD/kWh, through the economic analysis performed in this work, it has been found that the cleaning system is not profitable at the site of Rabat where higher soiling losses do not exceed 7%. However, it would present a very important economic attractiveness if the dual-axis tracker is implemented in desert areas where high soiling levels are frequently reached. In this case the payback time of the cleaning solution is faster (8 to 9 years), hence its profitability.

As mentioned before, the presented cleaning system has been designed to work on a dry surface of PV modules as it can ensure a humid cleaning especially in early mornings where the amount of dew is important and the tracker is still in the stowage position. As perspectives, it is recommended, before implementing the solution into the real size tracker, to test the realized prototype under real conditions in arid or hyper-arid climates to well evaluate its effectiveness and profitability.

## Chapter VI: Summary, conclusions and perspectives

### 1. Summary and conclusions

This thesis project comes to support the steps towards the effective application of the National Energy Strategy initiated by His Majesty King Mohammed VI. It aims to establish a Moroccan energy model that relies on diversifying the sources of energy supply, increasing the proportion of renewable energies in the energy mix, and providing access to a price competitive energy supply, as well as ensuring a sustainable usage and preserving the environment. This strategy was completed in 2009, by the Noor Plan, which unveiled the ambition of Morocco for solar energy. This plan particularly outlined the ambitious goal of establishing a solar capacity of 2000 MW.

To serve renewable energies, particularly solar energy, the main motivation of this thesis work is the optimization of the performance of the PV panels through a low cost and ecological cleaning. This includes many sub-goals related to the investigation of soiling phenomenon, its quantification and how the exposure conditions affect the soiling rates. These objectives are a part of an InnoPV Project co-funded by IRESEN entitled: New solutions to optimize the efficiency of photovoltaic systems by a low cost, ecological and strongly integrated locally cleaning.

The first chapter of this thesis presents a global overview of the global context of the study and the crucial importance of presenting appropriate solutions to tackle the challenge of solar installations soiling. Given the importance of water in cleaning operations and its scarcity at the same time, the present work comes to propose an ecological way to exploit a non-conditional source of water, which is dew, in cleaning the solar power plants.

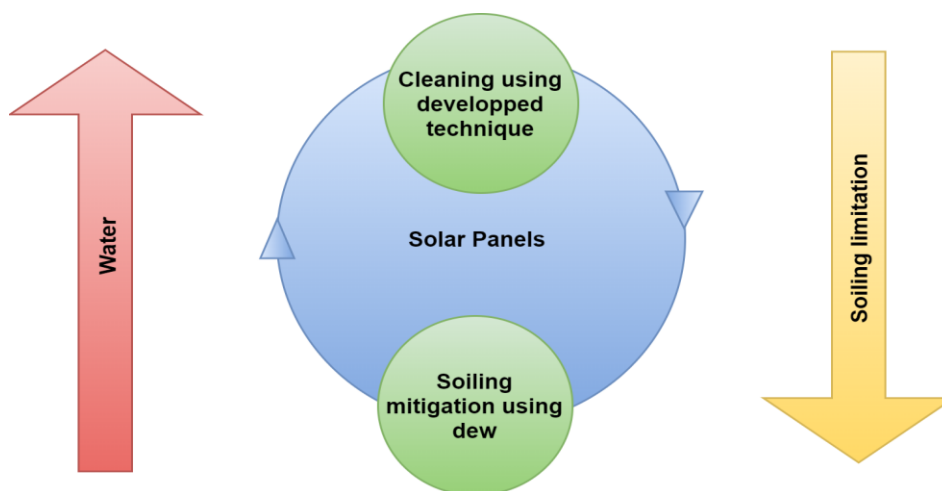


Fig VI. 1. Overall achieved thesis project objectives.

From previous literature, the process of soiling of PV has been studied in details starting from the soiling particles generation to their adhesion on PV panel's surface. The particles diameter involved in the soiling process is ranging from 500  $\mu\text{m}$  to less than 20  $\mu\text{m}$  through different transportation mechanisms. Depending on their diameters, these particles may deposit on the solar panels by different processes such as gravitational settlement, Brownian motion or turbulent deposition. The adhesion mechanism between soiling particles and the surface tends to change with time due to the influence of the environment. According to literature, the main adhesion forces previously explained are van der Waals force and capillary forces. In addition to what has been earlier mentioned, soiling is influenced by diverse site-specific environmental and weather variables such as rainfall, humidity, wind speed and its direction. These factors and their interaction with each other make soiling a complex phenomenon. Cleaning operations and soiling mitigation approaches are nowadays receiving a lot of attention especially with the loss in the photovoltaic yield that can reach its half.

The literature that has been done in this work has shown that any type of cleaning solution has advantages and disadvantages. Apart from the natural cleaning and the manual and considering the objective of the work, special attention has been given to corrective mechanical cleaning and preventive cleaning. Indeed, many mechanical cleaning systems have been developed to reduce soiling. However, the most of these cleaning solutions are dedicated to fixed panels. Thus among the motivations of this work, we cite the investigation of their adaptability to solar trackers. Moreover, the dew use in cleaning has been well investigated. Indeed, dew has a great effect on soiling and it can be positive or negative depending on the characteristics of the installation environment. The conducted survey has shown that the negative effect of dew on soiling, which is manifested by the cementation of dust particles on the glass cover, has been reported by 52% in comparison with 48% of studies that have highlighted the self-cleaning caused by dew. From the analysis conducted of the soiling mitigation based on dew, 61% of papers have recommended its enhancement while only 39% of works have proposed some approaches towards its suppression. Indeed, this second category presents the big challenge of economic feasibility and applicability, in particular that these solutions require being supplied in energy as the case of heating. On the other hand, the enhancement of dew water must attract much more attention since it presents many advantages in particular that they are passive solutions based, that use innovative coatings or films.

Several outdoor experimental studies have been carried out to investigate soiling taking into account the specifications of different climates (Rabat and Errachidia) as well as different

technologies (fixed PV and trackers). Results from the conducted studies have been presented in the fourth chapter of this thesis. In the first study conducted in Rabat, the evaluation of soiling effect directly via the irradiance transmitted through the cover glass has given annual average soiling rate of 4%. This result agrees with the performed literature. Based on the rigorous approach presented in this work, losses of energy production have been calculated per one PV module which is around 2 Wh/Wp per day.

Through the study of Errachidia that has been conducted at the same time as Rabat, a soiling rate of 23%/month was found. Note that the climatic conditions such as rainfall and wind have well contributed to the explanation of the evolution of the soiling ratio, this on the one hand. On the other hand, these parameters have contributed in the determination of cleaning type that can be adopted for each site. Dry cleaning can suffice as a cleaning method in the site of Errachidia where soils can be removed out from the panels based on wind effect. While, for semi-arid sites as Rabat, the use of water is essential to humidify soils before removing the dust.

The soiling effect was also studied for PV mounted on the dual-axis tracker installed in Rabat. During almost a year of study, soiling losses for PV on dual-axis trackers were between 2 and 7% while those on fixed structures tilted 30° were ranging from 7 to 21%. The average of soiling losses for fixed PV and tracking were respectively 15% and 5% for the dry period. Through this study, the cleaning frequency for PV modules on trackers has been deduced that can be once a year during the dry period. This frequency is sufficient to recover the performance given the rain events that knows this study site. Furthermore, regarding the high quantities of dew water that the site of Rabat knows, a simpler approach has been tested to mitigate soiling. This latter consists of inverting the PV module at sunrise which has been in horizontal position to accumulate dew on its surface. The study conducted in Rabat has led to promising results which manifest by reducing the soiling losses three times in comparison with fixed structure.

An investigation of the adaptability of the cleaning systems to dual-axis tracker has been first carried out. In fact, few among the studied cleaning systems that showed adaptability to the tracker. However, this adaptability is relative since it will be necessary to invest more to make these cleaning systems completely appropriate to the dual-axis trackers. Therefore, it is of utmost importance to present an innovative cleaning solution to tackle the challenge of soiling especially for countries with great potential in solar energy as the case of Morocco. Thus the fifth chapter presented the developed cleaning technique to deal with soiling of PV on dual-axis tracker. Through the functional analysis, some functions had to be considered in the

development of this innovative cleaning technique. The cleaning system based on the telescopic arm was very appropriate to the mechanical support architecture of the studied tracker. Other functions have been considered related to cost and sustainability; in other words, the proposed solution has to be low cost and ecological in terms of the water consumption.

Through the economic analysis performed in this work, it has been found that the cleaning system is profitable only when the soiling losses exceed 7%. A study case has been presented with soiling losses of 12% as the case of Benguerir site. While for the site of Rabat where higher soiling losses do not exceed 7%, the developed cleaning system does not present a real economic profit. However, in the case of a desert area where high soiling levels are frequently reached, the payback time of the cleaning solution is faster (8 to 9 years), hence the profitability of the developed cleaning system.

## **2. Perspectives**

Based on the original and promising results and conclusions of this thesis work, the following recommendations are made related to the topic of soiling of PV:

- Depending on the climate of a given area, soiling can be more influenced differently by climatic conditions such as rainfall, wind and humidity. The conducted investigation made in this work in Rabat and Errachidia has led to an interesting hypothesis regarding the type of cleaning that can be adopted for each site. Soiling in Errachidia is more impacted by wind, so the dry cleaning can be applied. While in Rabat, soiling is influenced by rainfall more than wind, thus the wet cleaning is more efficient. It would be then recommended to concretize these assumptions by experimental studies in other areas having the same climate characteristics.
- The cleaning frequency of PV is not well addressed in literature; it will be convenient to conduct cleaning frequency studies to deduce the most appropriate to be combined with the proposed cleaning type. This study can be combined to soiling modeling taking into account the climatic conditions of a given area.
- PV mounted on trackers could present less soiling losses if the stowage position at night considers the effect of dew that can be used for cleaning in early mornings. A comparative study should be conducted to evaluate the effect of upward and facedown stowage positions of trackers.
- Regarding the negative effect of dew water, up to now, the amount of dew which increases soiling has not been studied yet. In most cases, the amount of dew is addressed as a light rain. Nevertheless, some climatic parameters favoring the formation of dew have been set such as the case of the relative humidity. Indeed, dew formation and its yield depend on the combination

of factors that interact with each other. In this case, the threshold should be investigated taking into account the behavior of each factor which can be achieved through a physical or neuronal modeling that have not been well addressed in literature.

- It is highly recommended digging into the solutions of the enhancement of dew water formation especially in the areas that suffer from water scarcity. This recommendation is supported particularly with the positive effect of dew reported by numerous studies that have dealt with dew as a main topic and not as a factor.
- The cleaning system was tested on a dry surface of PV modules (dry cleaning) however it can ensure a humid cleaning. It would be interesting to perform a comparative study to evaluate the cleaning efficiency of both cleaning types. Moreover, it would be interesting to combine the use of the realized cleaning system with the use of dew which is abundant in quantity especially in early mornings when the tracker is still in the stowage position. The mentioned perspectives will confirm the effectiveness and the profitability of the proposed system before the implementation of its preindustrial prototype.

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### Scientific recognition and production

- 1) Waterless cleaning technique for photovoltaic panels on dual-axis tracker  
**D. DAHLIOUI, S. M. ALAOUI, B. LAARABI, and A. BARHDADI**  
 Will appear in the Journal of Environmental Science and Pollution Research, **2022** (Indexed in Scopus)
  
- 2) Ecological cleaning of PV panels by exploitation of dew water in Morocco  
**D. DAHLIOUI, L. TRAORE, B. LAARABI, and A. BARHDADI**  
 Journal of Materials Today: Proceedings, **2022** (Indexed in Scopus)  
<https://doi.org/10.1016/j.matpr.2022.04.024>
  
- 3) New approach towards mitigating photovoltaic panels soiling by dew flowing  
**D. DAHLIOUI, B. LAARABI, L. TRAORE, S. BELIHI and A. BARHDADI**  
 Journal of Environmental Science and Pollution Research, **2022** (Indexed in Scopus)  
<https://doi.org/10.1007/s11356-022-19171-5>
  
- 4) Review on dew water effect on soiling of solar panels : towards its enhancement or mitigation  
**D. DAHLIOUI, B. LAARABI and A. BARHDADI**  
 Journal of Sustainable Energy Technologies and Assessments, **2021** (Indexed in Scopus)  
<https://doi.org/10.1016/j.seta.2021.101774>
  
- 5) Chemical Analysis of Soiling of Photovoltaic Modules in Different Moroccan Areas  
 B. LAARABI, F. SAFSAFI, F. DAOUDI, **D. DAHLIOUI, Y. EL BAQQAL, A. BARHDADI**  
 Applied Solar Energy, **2021** (Indexed in Scopus)  
<https://doi.org/10.3103/S0003701X21020055>
  
- 6) Investigation of soiling impact on PV modules performance in semi-arid and hyper-arid climates in Morocco  
**D. DAHLIOUI, B. LAARABI and A. BARHDADI**  
 Journal Energy for Sustainable Development, **2019** (Indexed in Scopus)  
<https://doi.org/10.1016/j.esd.2019.05.001>
  
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## Technical specifications of Helioslite tracker



### 2 HeliosLite tracker description

**Description :** The dual-axis HeliosLite tracker is based on a tilt & roll configuration and compatible with most PV and CPV modules. Different fixation systems are available depending on the modules and several foundation solutions are possible best meet the installation conditions.

Contact HeliosLite for more details regarding HeliosLite tracker capability to support specific PV and CPV modules and foundation solutions.



Figure 2-1 HL-25-MTP2

## 2.1 HL-25-MTP2 Tracker Technical Data

Type	HL-25-MTP2
Tracking type	Dual-axis tracker (Tilt & Roll)
Certifications	CE (in progress)
Controller	Self correcting hybrid loop
Actuator protection class	IP 55
Guaranteed tracking accuracy (WS = WindSpeed)	<math>\pm 0.1^\circ >99\% \text{ WS} < 4 \text{ m/s}</math> <math>\pm 0.3^\circ >99\% \text{ WS} < 8 \text{ m/s}</math> <math>\pm 0.5^\circ >99\%, \text{ WS} < 14 \text{ m/s}</math>
Equatorial axis range	+/- 85°
Tilt axis range	-30 °N, +65 °S
Structure material	Steel
Protection	Hot deep galvanizing
Max. tracking wind speed	14 m/s
Max wind speed in stow	40 m/s
Operating temperature	-30 °C / + 70 °C
Weight tracker table including drive control (without modules)	605 kg
Max number of H-Track units per row	16
System design life	Up to 20 years

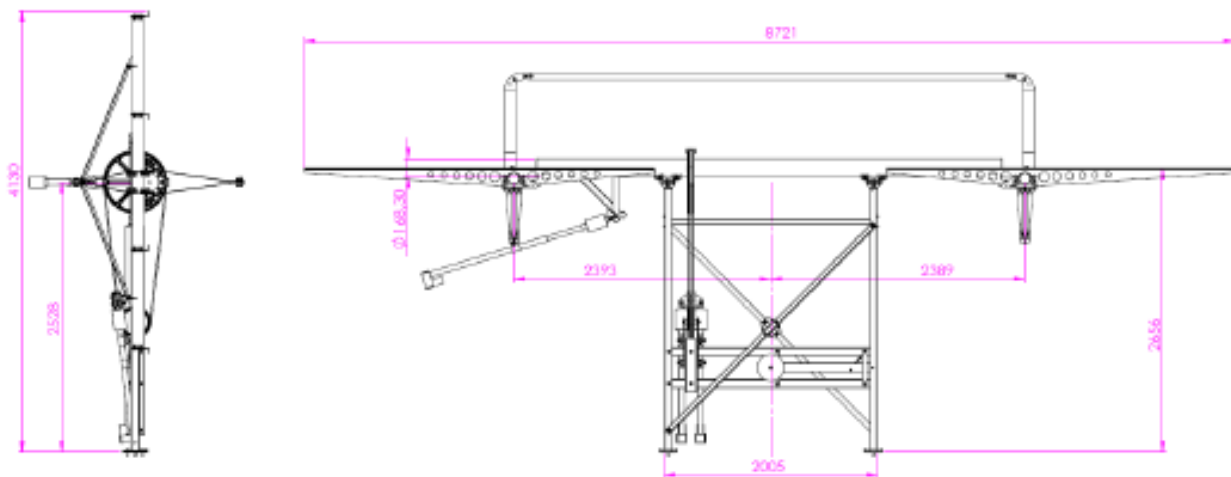


Figure 2-2 HL-25-MTP2 tracker dimensions, front view horizontal position (Right view), side view vertical position (Left view)

### Abstract

In this thesis, soiling of photovoltaic (PV) modules has been studied in details starting from the soiling particles generation to their adhesion on PV as well as the effect of dew formation on soiling of PV. Soiling was investigated in outdoor conditions leading to annual average soiling rate of 4%. Based on this approach, losses of energy production were calculated per one PV module which is 2 Wh/Wp per day. The soiling effect was also studied for PV on the dual-axis tracker in Rabat. During a year of study, soiling losses for the tracker were between 2 and 7% while those on fixed structures tilted 30° were ranging from 7 to 21%. This thesis work has also studied an approach for testing the soils cleaning by dew which has led to promising results. The soiling can be reduced to three times if an inclination angle tilting between 0° at sunset and 30° at sunrise is performed. Similar results were found for the tracking system. An investigation of the adaptability of the cleaning systems to dual-axis tracker has revealed that few among the studied cleaning systems that showed adaptability to the tracker. Therefore, a cleaning technique based on telescopic arm has been developed, realized and tested to deal with soiling of PV on dual-axis tracker. Through the performed economic analysis, it was found that the cleaning system is profitable only when the soiling losses exceed 7% as the case of arid areas where high soiling levels are frequently reached.

**Key Words:** Solar energy; Soiling; Photovoltaic panels; Solar tracker; Automatic cleaning technique; Dew water.

### Résumé

L'objectif de ce travail de thèse est l'optimisation des performances des panneaux photovoltaïques (PV) grâce à un nettoyage écologique et à faible coût. Dans ce travail, l'effet de la formation de rosée sur la surface des modules PV a été étudié vu son grand effet sur l'encrassement. L'analyse menée a montré que l'eau de rosée a un effet négatif se manifestant par la cimentation des salissures et un effet positif dû à l'auto-nettoyage naturel résultant du ruissellement de l'eau de rosée. C'est ce deuxième effet qui a été particulièrement étudié dans cette thèse et les résultats obtenus sont prometteurs. L'encrassement des salissures peut être réduit au tiers si une permutation de l'angle d'inclinaison des modules PV entre 0° (au coucher du soleil) et 30° (au lever du soleil) est effectuée d'une manière systématique. Des résultats similaires sont trouvés pour les modules PV dynamiques montés sur un suiveur solaire biaxe. L'impact des salissures sur les modules PV conduit à un taux d'encrassement annuel moyen d'environ 4% et une perte moyenne de productible journalier d'environ 2 Wh/Wc. En plus de l'approche de nettoyage écologique des modules PV par la rosée, ce travail propose aussi une nouvelle technique de nettoyage, utilisant un bras télescopique facilement intégrable sur le tracker biaxe. Toutefois, l'analyse économique effectuée montre que l'opération de nettoyage n'est vraiment rentable que lorsque les pertes d'énergie dues aux salissures dépassent 7%. C'est particulièrement le cas des zones désertiques où les taux de salissures sont souvent élevés.

**Mots-clefs:** Énergie solaire; Encrassement; Panneaux photovoltaïques; Tracker solaire; Nettoyage automatique; Eau de rosée.