Cyprus University of Technology

Online PEARL PV Workshop WG4:
Photovoltaic Systems in the Built Environment

EnergyLab

Estimating Clear-Sky PV Electricity Production Without Exogenous Data

Stefani Peratikou

Sustainable Energy Laboratory
Department of Chemical Engineering
Cyprus University of Technology

19 January 2022

PV Power Output Variability

Multiple Advantages of PVs

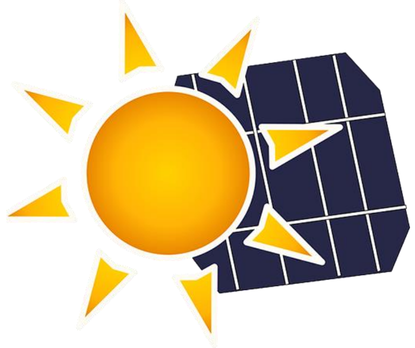
- Energy is free and abundant
- Technical progress
- Fast decline in PV module prices
- Require less maintenance
- Easy to install
- Strong independence
- Long effective life

- The global capacity of installed PV power has experienced enormous growth over the past decade and in some countries, PVs have emerged to noticeably contribute to the national electricity portfolio.

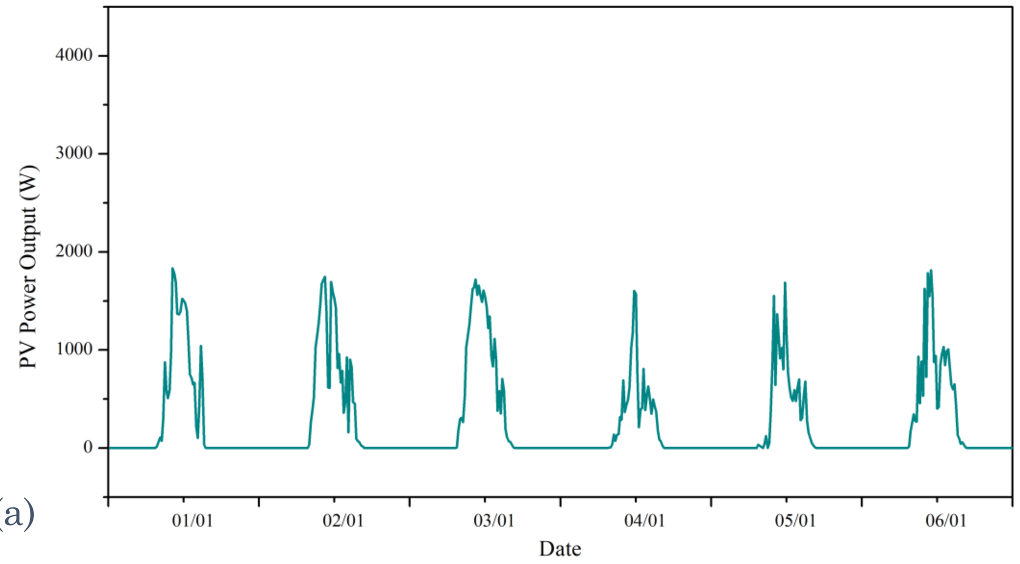
- Nevertheless, issues related to its integration to the grid persist due to its inherent variability and unpredictability.

PV Systems are a function of:

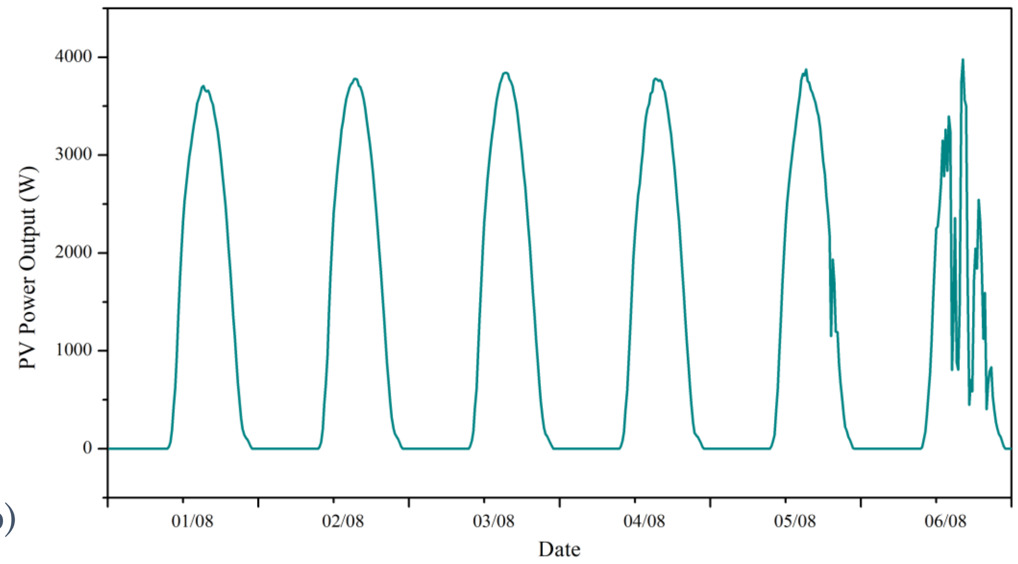
- Location
- Orientation
- Tilt
- Technology
- Unpredictable Environmental Parameters



PV Power Output Variability



(a)



(b)

Figures: PV Power Output for a PV Plant during (a) 01-06.01.2017 and (b) 01-06.08.2017

- The power production of a PV plant might be extremely variable in a specified future time period.

Any grid-connected PV system has to be considered as an **unpredictable power generator** in the utility network.

PV Power Output Variability

Production yield variation can:

- ❑ Adversely affect the power systems stability and reliability
- ❑ Cause control and operation issues as a result of sudden surpluses or drops in power output
- ❑ Generate substantial issues in balancing between the power generation and load demand

A solution to this:

- ❑ Ideally: Independence of PV systems from weather conditions

  ⇩

  Unrealistic

- ❑ Best Option: the electrical power supply to the grid based on the demand

  ⇩

  Costs due to construction of energy storage or the utilization of batteries

» **Forecasting Scheme of the PV power output variability**

Why Clear-Sky Predictions?

The ability to accurately predict the PV power production variability, when it occurs, will help the grid operators to accommodate with the periodic energy to their scheduling, dispatching and regulation of power.

- Can assist to anticipate a case of shortage or abundance of solar power and therefore, can help them to make alternate arrangements for trustworthy plans and to manage the power of demand and supply,
- Evaluate the performance of PVs over time,
- Quickly identifying the sources of system losses and/or the occurrence of partial shading,
- Avoid delays for identifying and correcting system faults, especially when monitoring a PV system.

This can be achieved by predicting:

a. PV power output during clear-sky conditions

b. Future PV electricity production

Clear-Sky Models

- A lot of research has been devoted for the development of an appropriate clear-sky forecasting PV model with the main purpose to achieve:
  - Higher accuracy
  - Minimum complexity with computational cost

- Several papers have been published describing the different types of clear-sky models, analyzing the complexities, and evaluating the accuracy of each model applied to various locations or geographic region.

- In general, there are three categories of clear-sky irradiance models which complexity increases with the number of required atmospheric parameters.

Very Simple Clear-Sky Models	***Simple Clear-Sky Models***	***Complex Clear-Sky Models***
use only geometric calculations	include, in addition to zenith angle, some basic parameters of the atmospheric state	take into consideration various measurable atmospheric parameters

Clear-Sky Models

❑ Most of the studies examined clear-sky models:

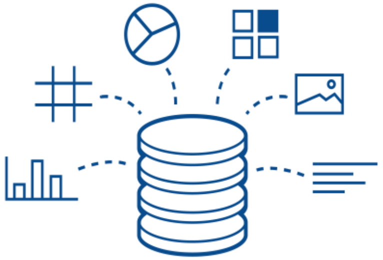
- Provide promising results concerning the error performance
- Need meteorological related variables as inputs:
  - Ground Measurements
    - solar irradiance
    - air temperature
    - humidity
    - cloudiness
    - wind speed and direction, etc
  - Sky-cameras
  - Satellite images
  - Technical characteristics of PVs
  - Info from nearby PV plants

Exogenous Data

<u>Make prognosis significantly challenging since such info:</u>

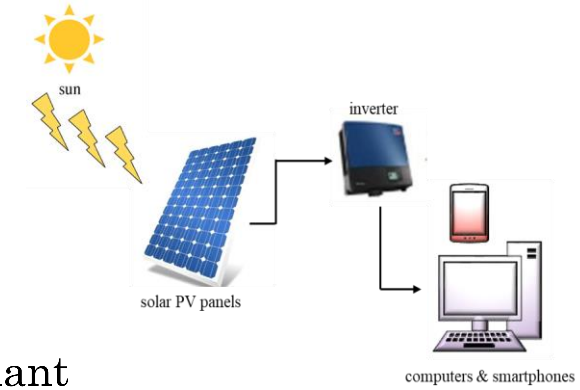
- are not always guaranteed for the location of PV sites examined,
- are rarely available to everyone and thus, must be purchased with an associated cost from the appropriate services,
- may need to purchase the appropriate equipment and there is an extra cost for their maintenance,
- data sourcing, downloading and processing might take a few days to a few months.

The choice of a clear-sky model is driven by the **availability and quality of input data**, which is the **main limiting factor**, and the selection of a specific model is of secondary importance.



OBJECTIVE

- ❑ Some authors proposed statistical clear-sky models for the estimation of the power output under clear-sky conditions.
- ❑ Limited bibliography exists that estimates directly the clear-sky PV power output signal using exclusively endogenous data.



Endogenous Data

- Current and/or past time-series records of the power output of a PV plant

Benefit from the simplicity in data collection since no other data is necessary

Number of installed PV systems and monitoring systems has increased

Unprecedented growth in the amount of historical and live PV power output data available for analysis globally

Objective:

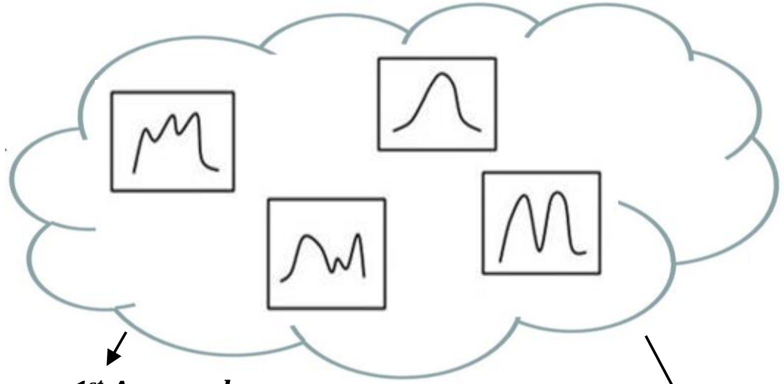
Estimation of the PV power output during clear-sky conditions

adopting data-driven approaches

Proposed Framework

A: PV Data Collection

B: Analysis of the PV Power Output Data

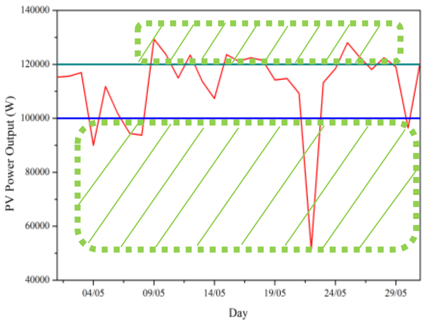


1st Approach

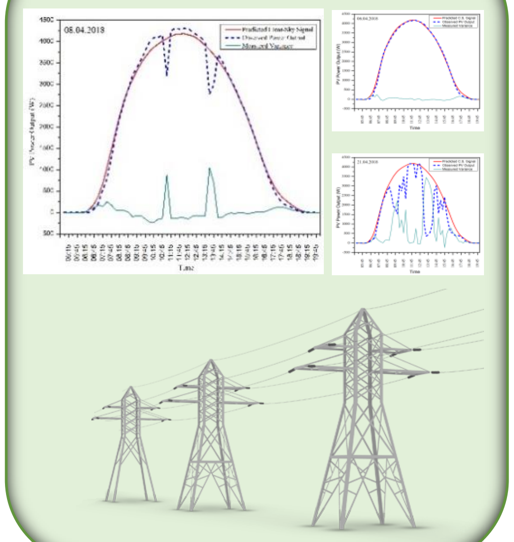
Time	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
00:00	0	0	0	0	0	0
… **…** **…**	… … …	… … …	… … …	… … …	… … …	… … …
07:00	41,9	51,68	29,01	76,13	0,78	55,57
07:15	208,6	167,03	95,02	183,7	81,68	178,81
07:30	402,86	389,08	287,95	396,41	87,46	356,4
07:45	507,54	508,43	428,42	551,11	73,9	503,1
08:00	564,89	583,34	554,22	615,79	223,71	606,23
08:15	865,61	870,73	879,84	705,58	226,16	977,41
08:30	1101,22	1115,66	1089,21	945,41	456,42	1221,46
08:45	1695,11	1718	1664,88	1162,56	730,92	1802,24
09:00	2333,9	2299,45	2185,87	1422,39	773,82	2362,35
… **…** **…**	… … …	… … …	… … …	… … …	… … …	… … …
23:45	0	0	0	0	0	0
Third Quartile-Median	X_1	X_2	X_3	X_4	X_5	X_6

If Avg $X > X_1, X_2, X_3, \ldots\ldots$

2nd Approach



C: Prediction of Clear-Sky PV Energy Output Signal



METHODOLOGY

1. Data Acquisition

- ❑ Historical time-series data from grid connected PVs was collected:
  - Date
  - Time
  - Instantaneous kW production
- ❑ All data was included
- ❑ No pre-processing of the data was performed (e.g., data filtering, missing values, gaps)
- ❑ No utilization of any other data (e.g., meteorological related data) or assumptions was done
- ❑ No knowledge of the technical characteristics of the PVs or specialized equipment.

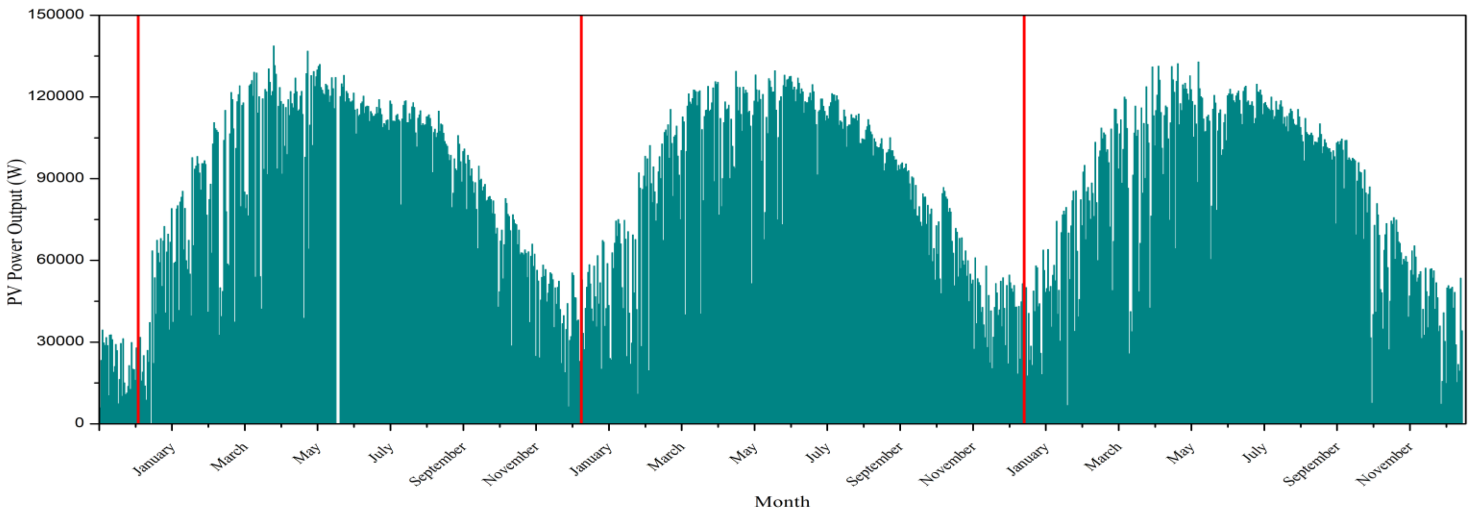


Figure: PV Power Output over the entire period

- A PV plant site located in Limassol, Cyprus
- Installed capacity: 5 kW
- Data: - covers the period from 1.12.2016 to 31.12.2019 (108096 observations)
  - value of solar power output (in Watts) over 15 minutes

Methodology

1. Data Acquisition

- Historical time-series data from grid connected PVs was collected:
  - Date
  - Time
  - Instantaneous kW production
- All data was included.
- No pre-processing of the data was performed (e.g., data filtering, missing values, gaps).
- No utilization of any other data (e.g., meteorological related data) or assumptions was done.
- No knowledge of the technical characteristics of the PVs or specialized equipment.

2. Data Aggregation

- Aggregation of data into monthly intervals for each PV system examined.

3. Analyze Time-Series

- The observed time-series of PV power output used as inputs to the proposed approaches in order to estimate the clear-sky power output signal of the PV system for each month.
- Two approaches were proposed.

Methodology

4A. Analyze data per day

Aim: *exclude the 'bad' days from the data set*

Time	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
00:00	0	0	0	0	0	0
… … …	… … …	… … …	… … …	… … …	… … …	… … …
07:00	41,9	51,68	29,01	76,13	0,78	55,57
07:15	208,6	167,03	95,02	183,7	81,68	178,81
07:30	402,86	389,08	287,95	396,41	87,46	356,4
07:45	507,54	508,43	428,42	551,11	73,9	503,1
08:00	564,89	583,34	554,22	615,79	223,71	606,23
08:15	865,61	870,73	879,84	705,58	226,16	977,41
08:30	1101,22	1115,66	1089,21	945,41	456,42	1221,46
08:45	1695,11	1718	1664,88	1162,56	730,92	1802,24
09:00	2333,9	2299,45	2185,87	1422,39	773,82	2362,35
… … …	… … …	… … …	… … …	… … …	… … …	… … …
23:45	0	0	0	0	0	0
Third Quartile-Median	X_1	X_2	X_3	X_4	X_5	X_6

4B. Analyze Data per Time-Step

Aim: *remove too high or too low PV energy output values at each time step*

Approach	Method	Lower Limit	Upper Limit
1st	1	—	—
2nd	2	Mean	Maximum Value
	3	Mean - 1 SD	Mean + 1 SD
	4	Mean - 0.5 SD	Mean + 0.5 SD
	5	Mean - 0.25 SD	Mean + 0.25 SD
	6	Mean	Mean + 1 SD
	7	Mean	Mean + 0.5 SD
	8	Mean	Mean + 0.25 SD
	9	New Mean	Mean + 1 SD
	10	New Mean	Mean + 0.5 SD
	11	New Mean	Mean + 1.5 SD

Table: Characteristics of the methods used for the prediction of clear-sky signal.

Methodology

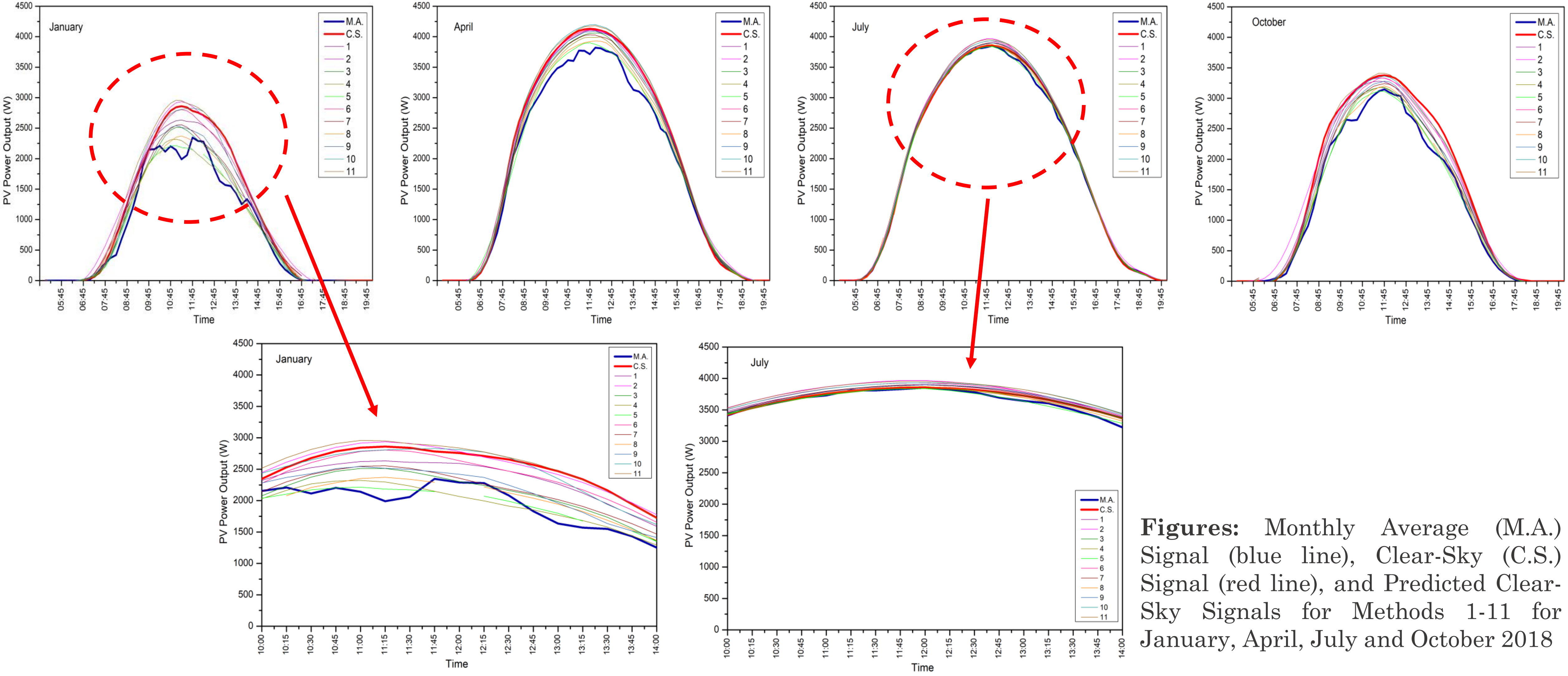
4. Estimation of true clear-sky signal

- ❑ The calculation of the real clear-sky signal would require knowledge not only of the true clear-sky solar irradiance but also of the orientation, tilt, etc of the PV plants.
- ❑ This work is not considering any of these exogenous data, but rather ***averages the PV power time series of each month that are visibly smooth.***

5. Performance Analysis

- ❑ The proposed clear-sky methods were compared to the visibly clear-sky signal to test their accuracy.
- ❑ Three key statistical criteria were used:
  - Root Mean Square Error (RMSE),
  - Mean Absolute Deviation (MAD),
  - Mean Absolute Percentage Error (MAPE).

Prediction Results



Figures: Monthly Average (M.A.) Signal (blue line), Clear-Sky (C.S.) Signal (red line), and Predicted Clear-Sky Signals for Methods 1-11 for January, April, July and October 2018

Prediction Results

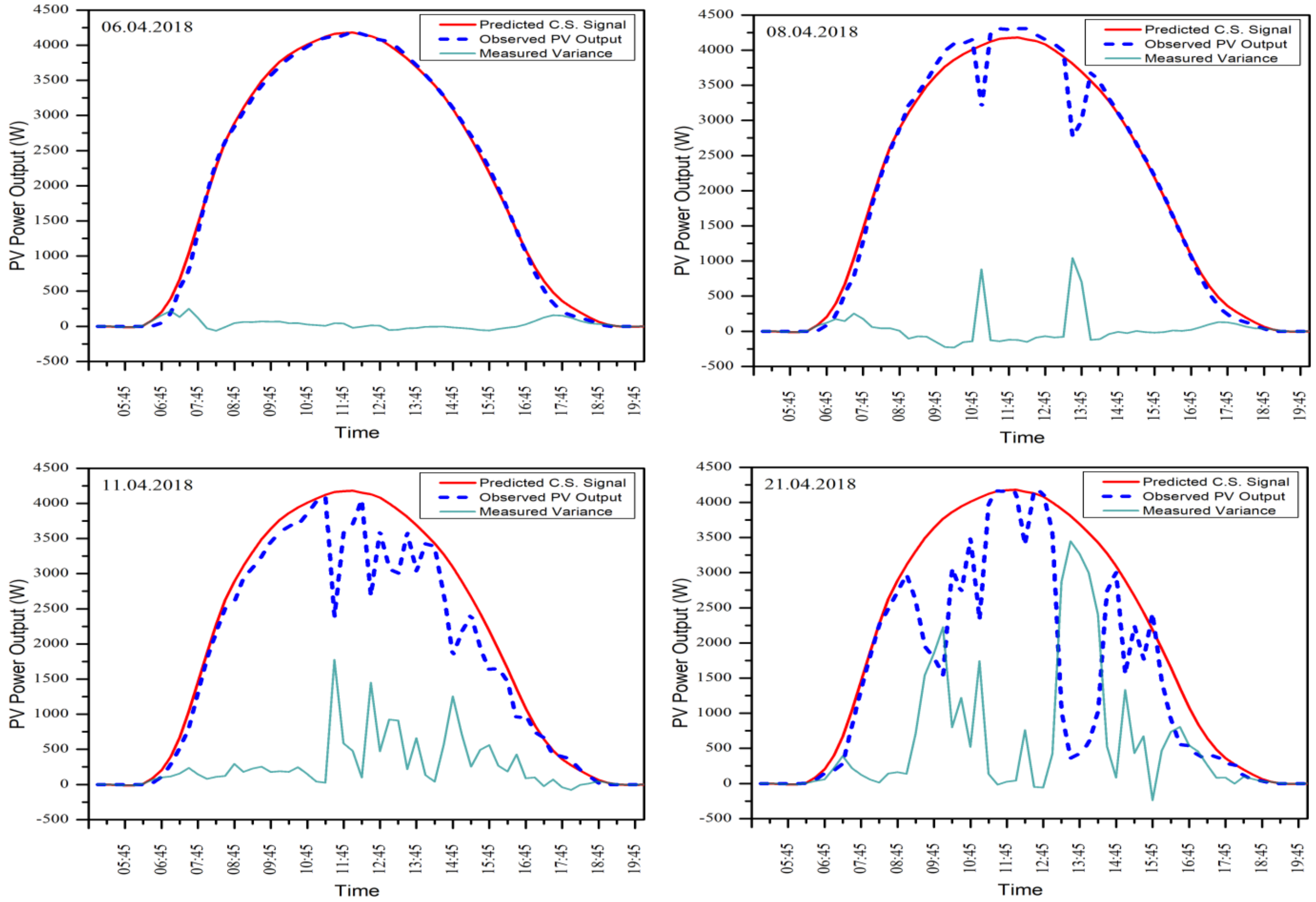
Performance Analysis

- The error metrics of RMSE, MAD, and MAPE have been applied to measure the accuracy of each method.
- The 11th method was selected as the most appropriate method for estimating the clear-sky signal since it:
  - has showed better assessment and provided the lowest value of evaluation criteria through the unsteady conditions of winter months
  - does not have considerable difference in the other months

	2017	2018	2019	Average
RMSE	55.87	82.74	72.02	70.21
MAD	31.49	47.37	37.44	38.77
MAPE	4.38	7.9	3.23	5.17

Table: The average error metrics of RMSE, MAD and MAPE for 11th Method for 2017, 2018 and 2019.

Visual Verification

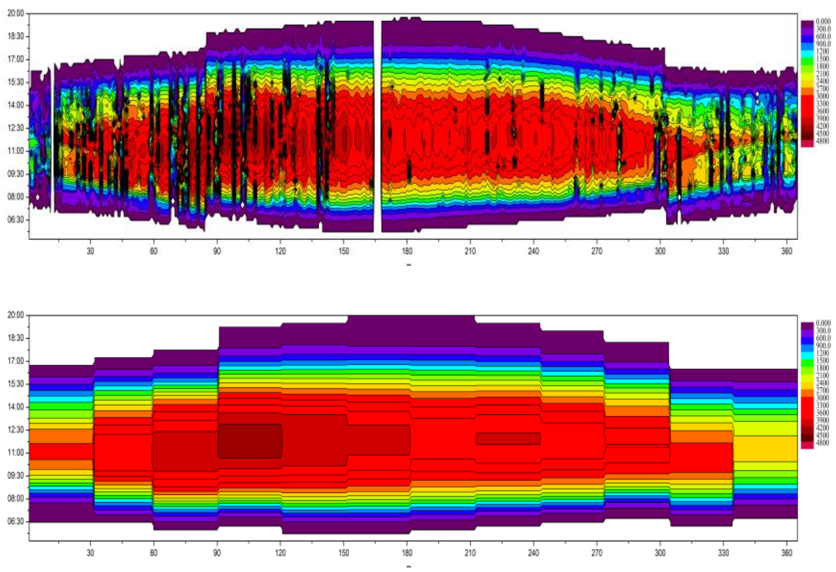


Figures: Measured variance among the predicted clear-sky signal and the observed power output value for 6th, 8th, 11th, 21st of April 2018.

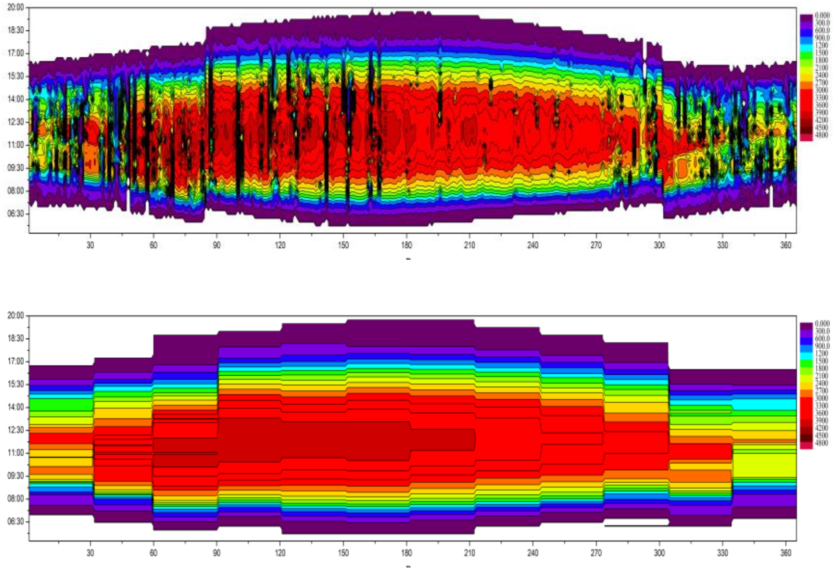
PREDICTION RESULTS

Visual Verification

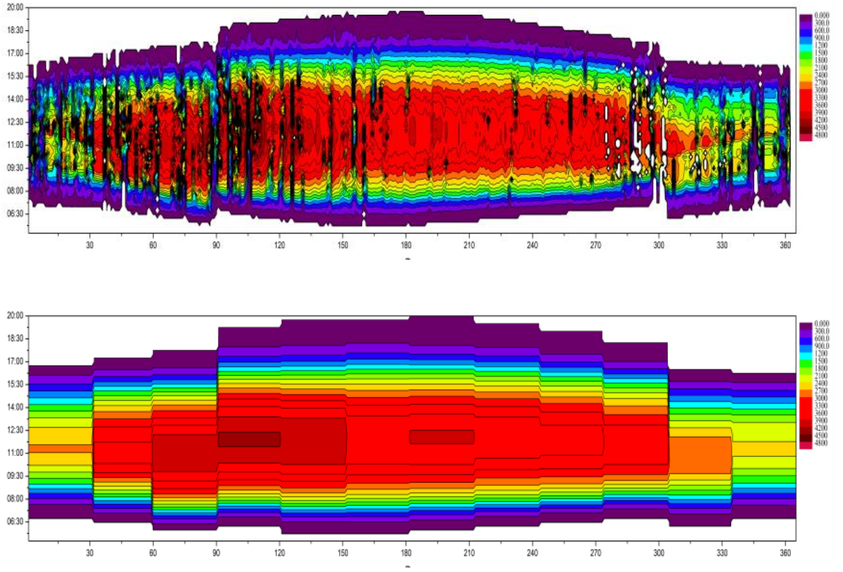
2017



2018



2019



Figures: Top: Observed PV Power Output and Bottom: Predicted PV Power Production under clear-sky conditions as a heatmap during 2017, 2018, and 2019, respectively.

Conclusions

- Accurate predictions of PV power output during clear-sky conditions is a key element since it provides us with ***important information***

- The proposed method has great interest and significance since it ***contributes to the limited bibliography*** that exists in ***evolving methods*** that generate the clear-sky PV power output signal ***without exogenous inputs***
  - Not always available
  - Gathering, processing and analysing requires a lot of time
  - Cost for purchasing data or the necessary equipment

- The implemented methods ***utilized unexploited data*** that can be accessed easily from existing monitoring equipment of PVs, resulting to ***low equipment cost and low time-consuming solution***

- The method developed ***can predict well*** the expected results, considering both a qualitative assessment (visual examination) and a quantitative evaluation (error metrics).

- The methodology is ***not computer-intensive***, since a manual analysis can also be applied. However, a manual analysis is a time-consuming method and this is an important limitation. In this work, the programming language of Matlab was used for the predictions.

Conclusions

- Our method evaluated using also data from different PV stations located at Cuenca, Spain
- Installed capacity ranging from 20kW to 100kW
- Data: - covers the period from 1.01.2018 to 31.12.2018
  - value of solar power output (in Watts) over 15 minutes

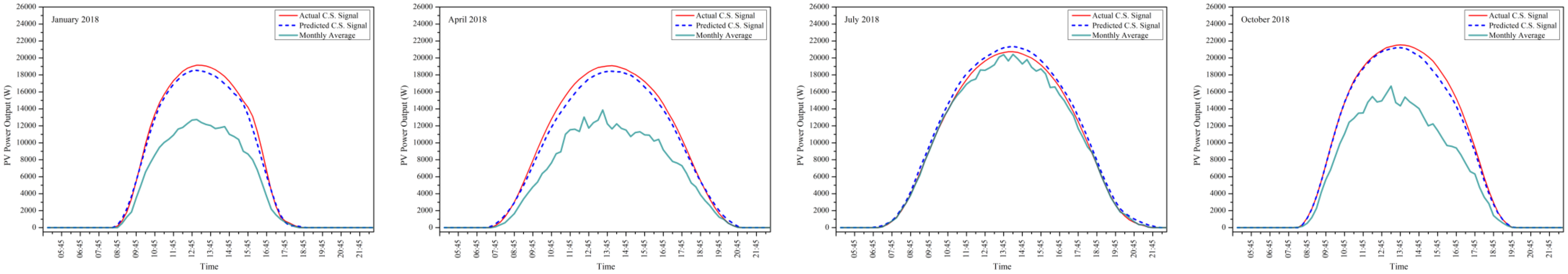


Figure: Monthly Average (green line), Actual Clear-Sky (red line), and Predicted Clear-Sky (blue dot-line) Signals for PV Station 1, Cuenca for January, April, July and October 2018.

❑ Results showed:
- our method is able to ***deliver satisfactory results*** when compared to real PV clear-sky signals
- ***PV data alone*** can provide ***interesting information***
- the proposed methodology has a ***generalization capacity*** → it can be used for different time-series and for several PV stations indicating that is ***site-independent***

Thank you!

Stefani Peratikou, PhD Student
ss.peratikou@edu.cut.ac.cy
Sustainable Energy Laboratory
Cyprus University of Technology

Funded by: SOLAR-ERA.NET RESEARCH & INNOVATION FOUNDATION