European Geosciences Union General Assembly 2017
Vienna, Austria, 23-28 April 2017
ERE3.7/HS5.11 - Renewable energy and environmental systems: modelling, control and management for a sustainable future

Investigation of the stochastic nature of solar radiation for renewable resources management

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1. Introduction

A detailed investigation of the variability of solar radiation can be proven useful towards more efficient and sustainable design of renewable resources systems. This variability is mainly caused from the regular seasonal and diurnal variation the stochastic nature of the atmospheric processes, i.e., sunshine duration caused by the cloud coverage.

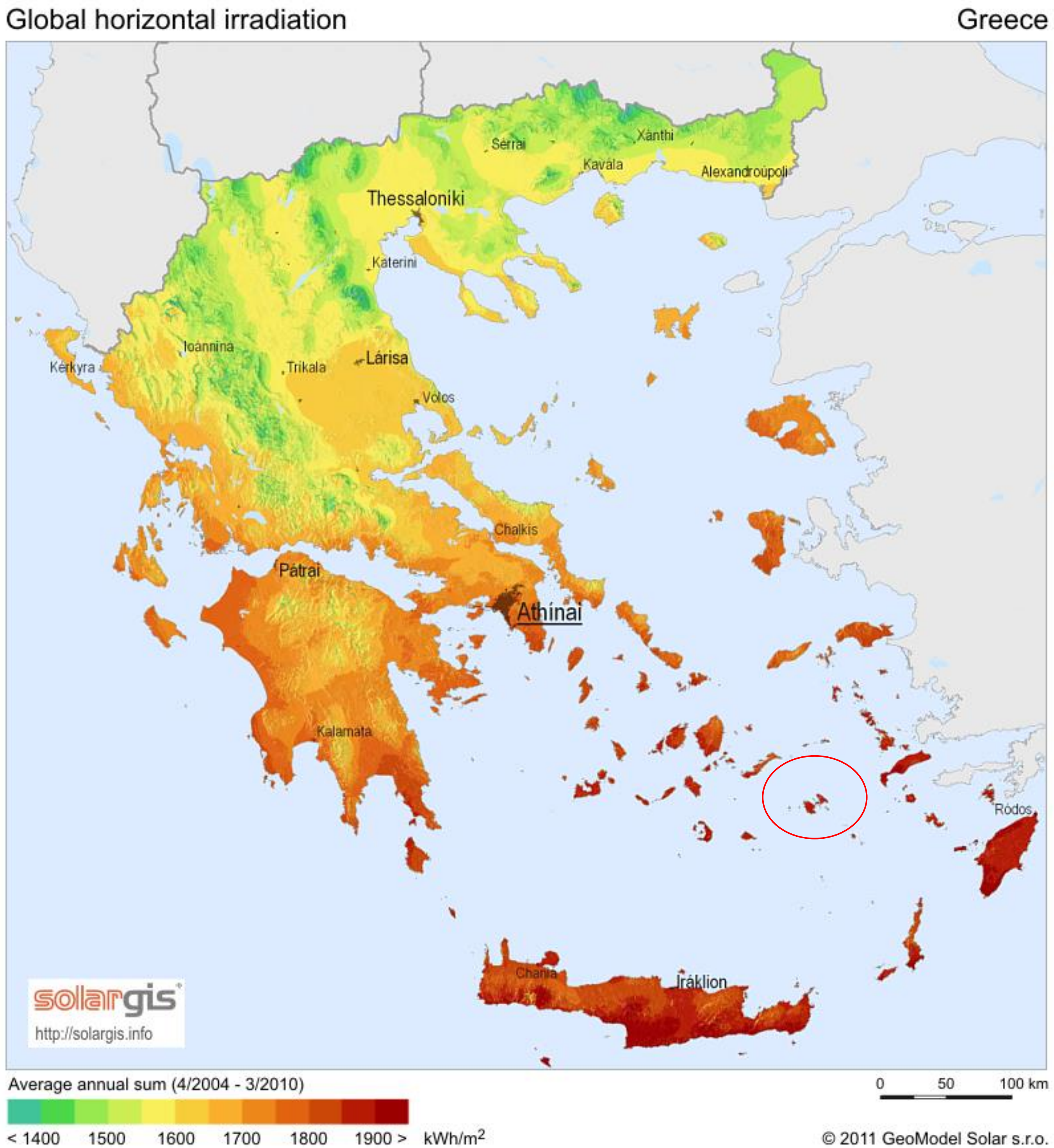
In this context we analyze observations from Greece (Hellenic National Meteorological Service; http://www.hnms.gr/) and around the globe (NASA SSE - Surface meteorology and Solar Energy; http://www.soda-pro.com/web-services/radiation/nasa-sse). We investigate:

- The marginal distribution of the solar radiation process based on a monthly scale.
- The long-term behavior based on an annual scale of the process.
- The double periodicity (diurnal-seasonal) of the process.
- We apply a parsimonious double-cyclostationary (hourly scale) stochastic model to a theoretical scenario of solar energy production for an island in the Aegean Sea.

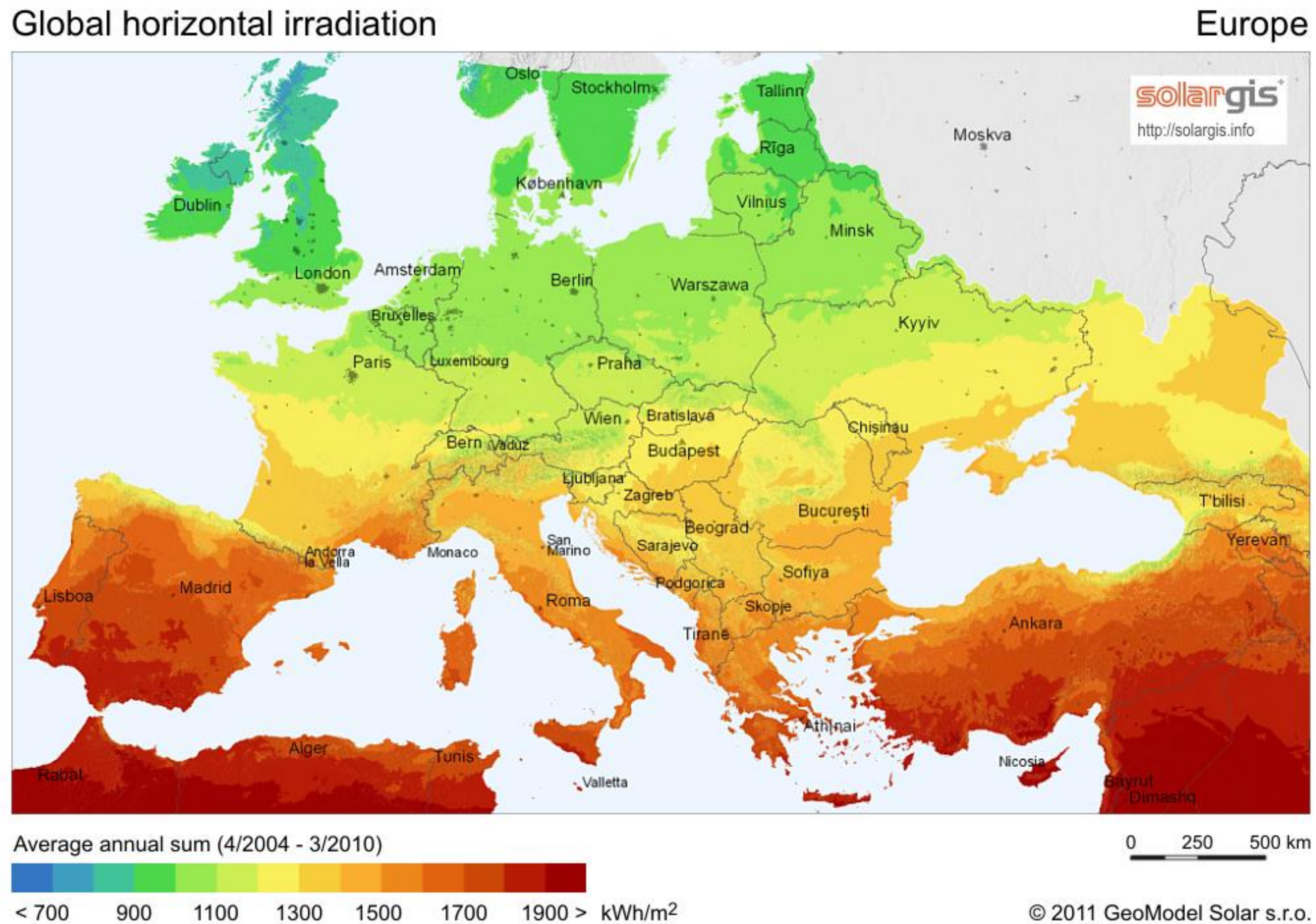
Acknowledgement :

This research is conducted within the frame of the undergraduate course "Stochastic Methods in Water Resources" of the National Technical University of Athens (NTUA). The School of Civil Engineering of NTUA provided moral support for the participation of the students in the Assembly.

2. Potential of horizontal solar irradiation over Europe



Map 1: Greece Horizontal Irradiation (source Wikipedia)



Map 2: Europe Horizontal Irradiation (source Wikipedia)

3. Area of interest

We compare observed timeseries of solar irradiance with the corresponding ones from the NASA-SSE database and we observe a hysteresis of 1 day lag (cross-correlation coefficient for $\varrho_1 = 0.9$) .

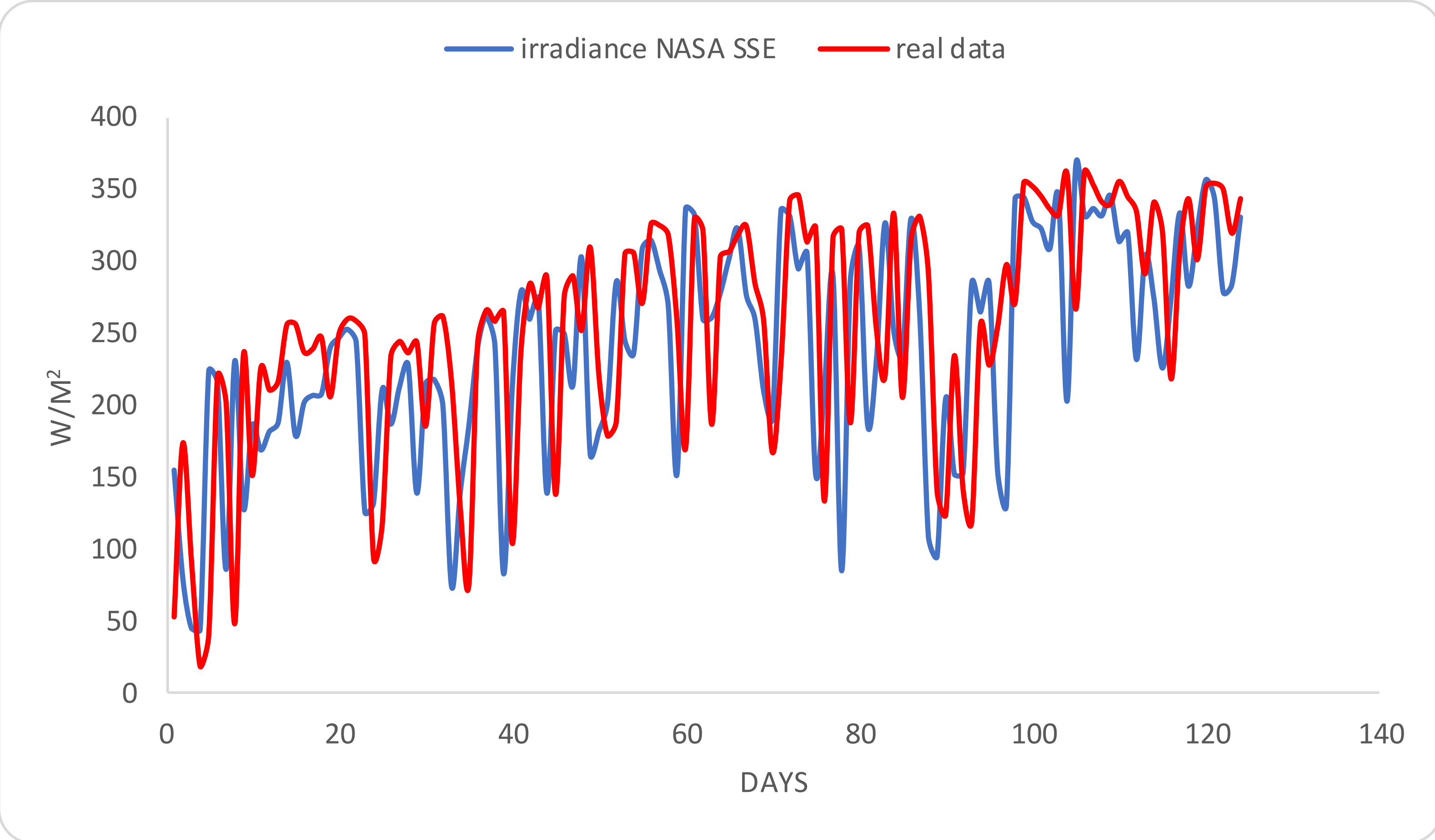


Figure 1: Data comparison

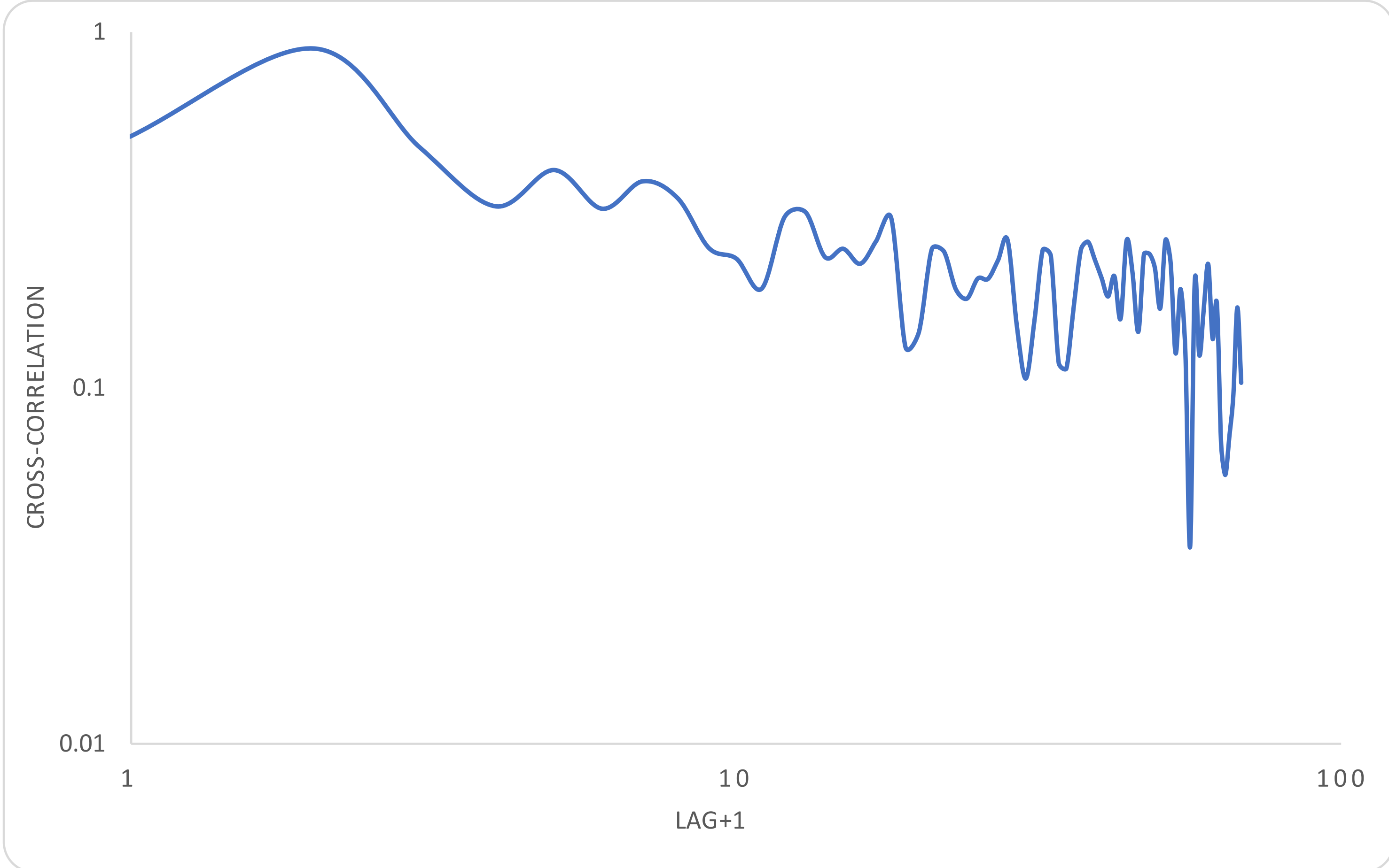


Figure 2: Cross-correlation between Nasa-See & Observed

The study area is the remote island of Astypalaia, south east of the Aegean-Sea, with over 1300 residents (and a popular destination for summer holidays). We extract the solar irradiance timeseries above Astypalaia from the NASA-SSE database, with over 8 thousand days of data and of approximately 22 years of length.

4. Marginal distribution

We estimate the marginal distribution for each month in a daily scale (640 days for 12 months). Through the open-software Hydrognomon (hydrognomon.org), that includes more than 20 popular distributions used in geophysics (such as gamma, Pareto, lognormal, Pearson etc.), we could not adequately fit the right tail of the empirical distribution. This can be explained considering that the solar irradiation process is left and right bounded. Although the left boundary is close to zero, the right boundary varies in an annual scale. Therefore, distributions like gamma and Pareto, although they may exhibit a good fit (based on the Kolomogorv–Smirnov test), they should not be applied for the solar irradiation, since they are not right bounded. We conclude that the Kumaraswamy distribution [1] describes exceptionally well the observed distributions for all months and is justified for its use in solar irradiation since it is both left and right bounded.

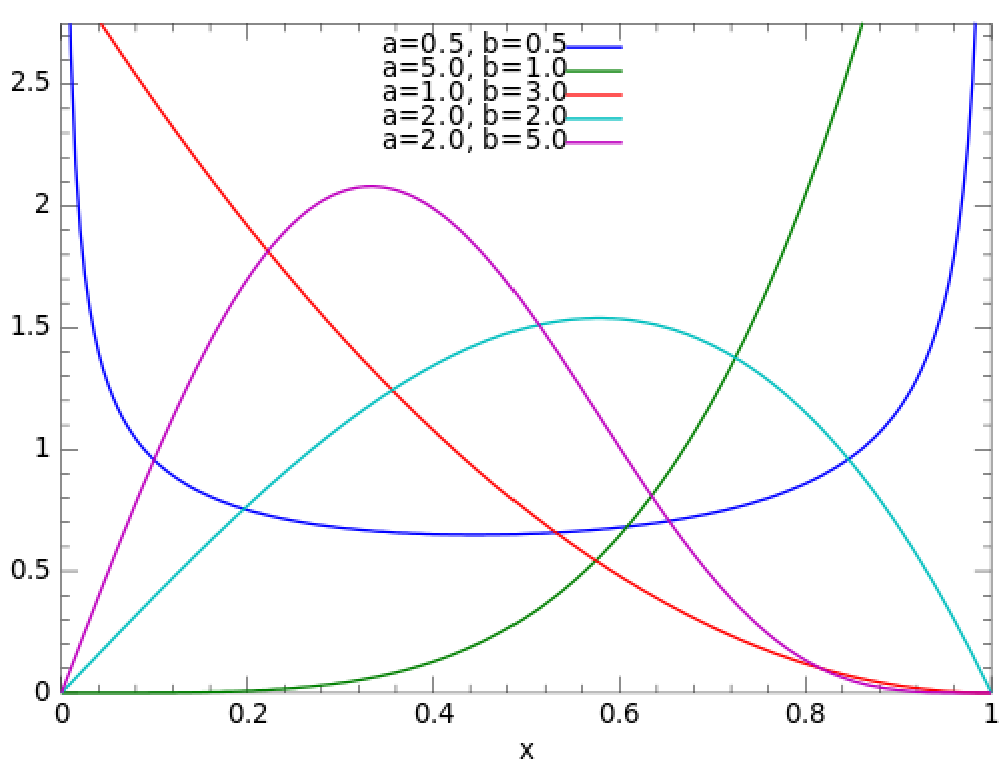


Figure 3: Probability density function (source: Wikipedia)

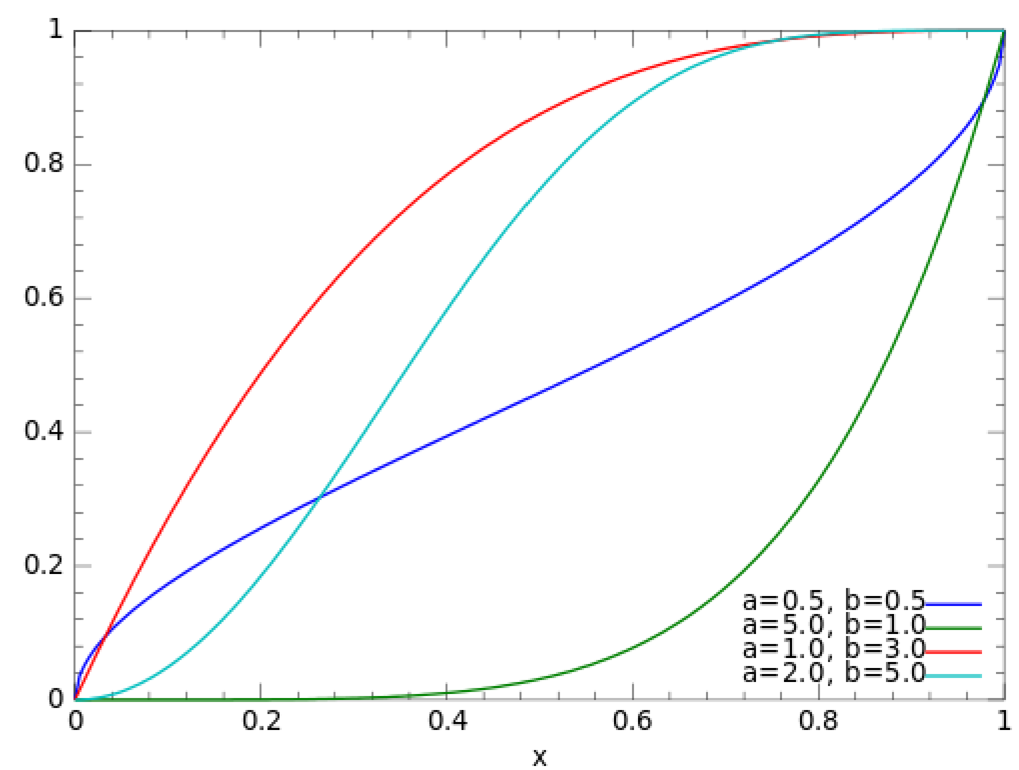


Figure 4: Cumulative distribution function (source: Wikipedia)

Parameters	$a > 0$ (real) $b > 0$ (real)
Support	$x \in [0, 1]$
PDF	$abx^{a-1}(1-x^a)^{b-1}$
CDF	$[1-(1-x^a)^b]$
Mean	$\frac{b\Gamma(1+\frac{1}{a})\Gamma(b)}{\Gamma(1+\frac{1}{a}+b)}$
Median	$\left(1-2^{-1/b}\right)^{1/a}$
Mode	$\left(\frac{a-1}{ab-1}\right)^{1/a}$ for $a \geq 1, b \geq 1, (a,b) \neq (1,1)$

Table 1: Kumaraswamy distribution. (source: Wikipedia)

5. Estimated marginal distribution parameters (I)

Since solar irradiation right boundaries vary in an annual scale, we divide all values of the timeseries for each month with the calculated maximum value of the observed process. We then estimate the parameters of the Koumaraswamy distribution (Table 2) for the dimensionless daily timeseries varying from approximately zero to one.

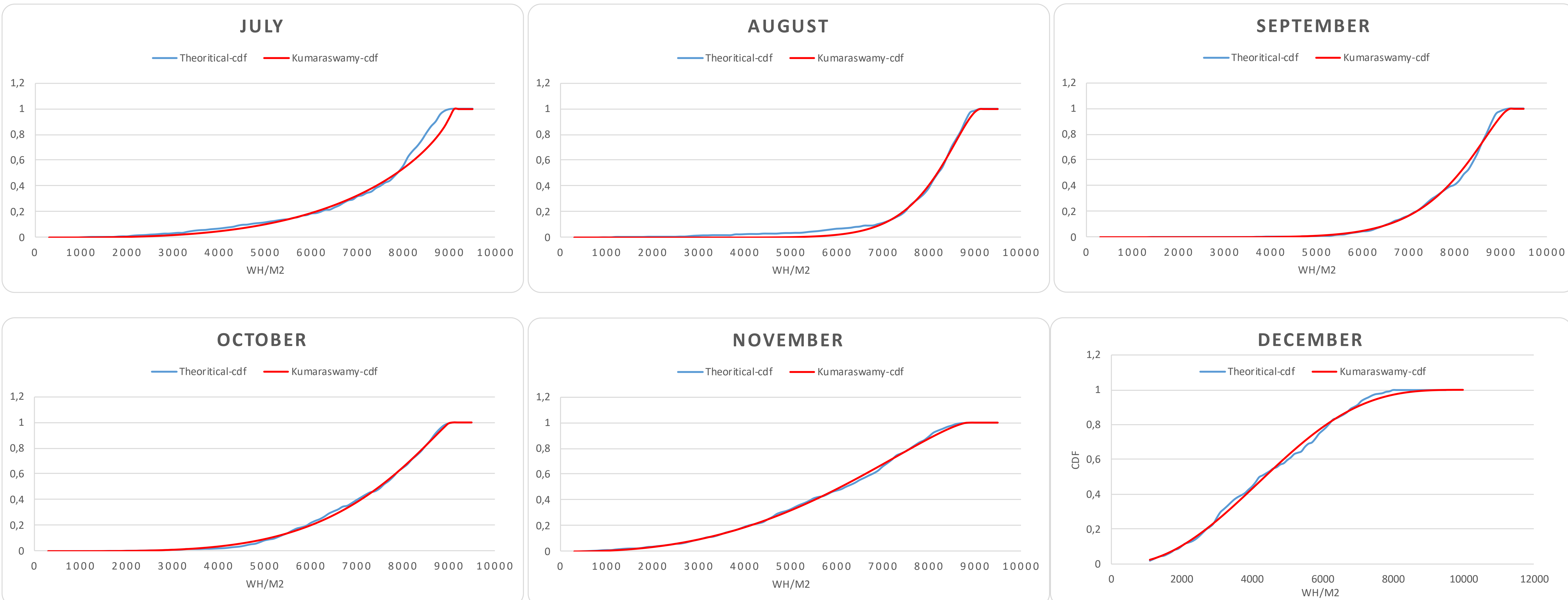


Figure 5: Fitting of the Kumaraswamy marginal distribution for each month.

6. Estimated marginal distribution parameters (II)

Parameters	July	August	September	October	November	December	January	February	March	April	May	June
a	3.28	10.61	8.01	4.23	2.48	1.88	1.99	2.58	2.08	1.65	1.84	2.06
b	0.70	1.81	1.53	1.14	1.4	1.67	8.10	29.21	13.91	4.50	2.80	1.02
max variable (Wh/m^2)	9060	9120	9200	9030	8840	7950	6980	5230	6310	7710	8940	8940

Table 2: Estimated distribution parameters for each month

Figure 5: Fitting of the Kumaraswamy marginal distribution for each month.

7. Statistical moments and dependence structure

	July	August	September	October	November	December	January	February	March	April	May	June
Mean	7223.87	7890.25	7905.33	7163.48	5821.09	4395.08	3250.72	2668.90	2730.48	3543.62	4699.04	5977.26
St.deviation	1078.22	636.10	779.06	1309.39	1765.02	1676.34	1204.09	554.76	795.23	1343.71	1503.50	1563.23
Skewness coeff.	-0.77	-1.01	-0.99	-0.60	-0.32	0.26	0.87	1.12	0.52	0.38	-0.12	-0.41
Excess Kurtosis	-0.79	0.72	0.12	-1.00	-1.25	-1.35	-0.54	0.77	-0.55	-1.27	-1.13	-0.78

Table 3: Statistical moments of each month

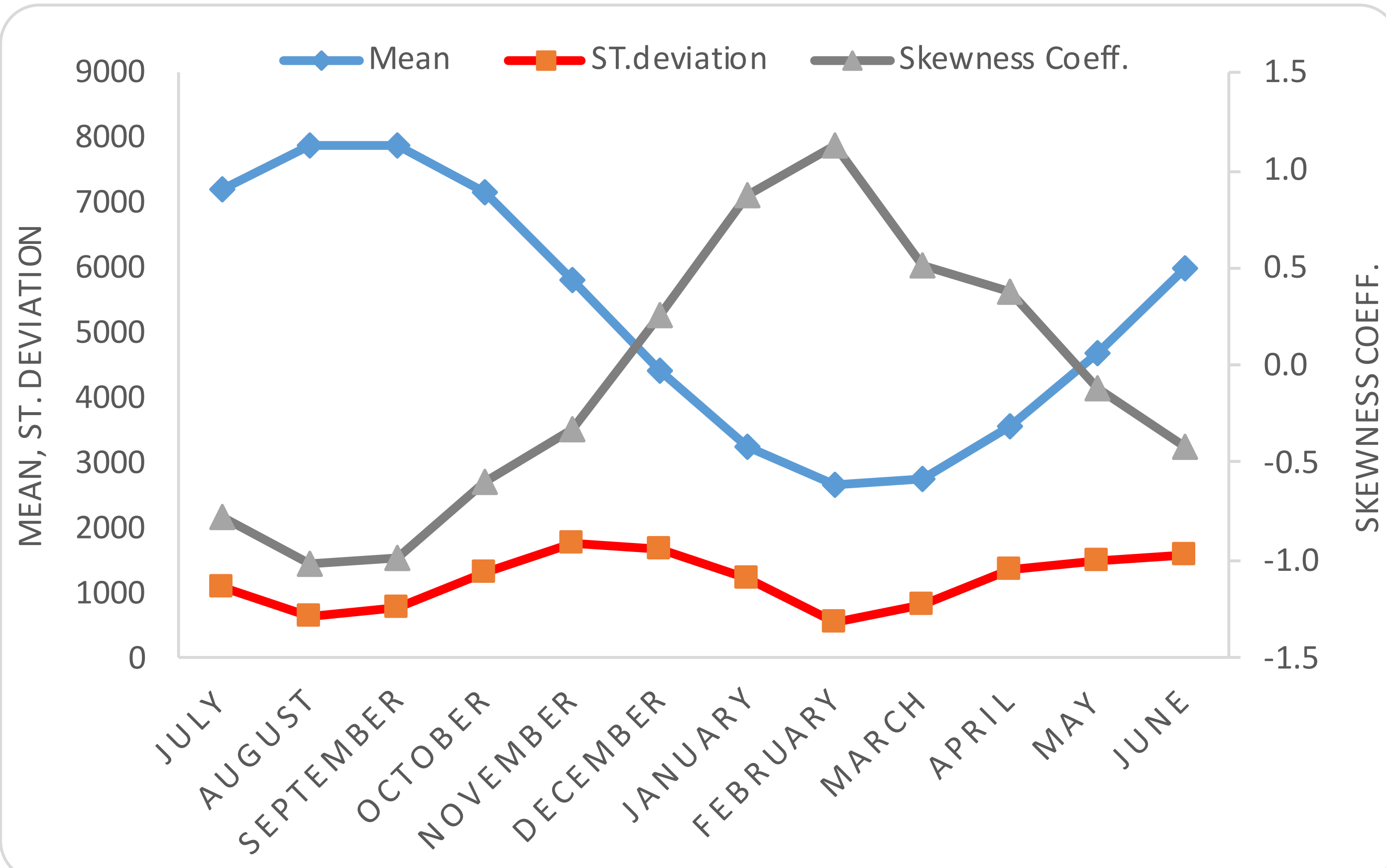


Figure 6: All periodicities for each month starting from July.

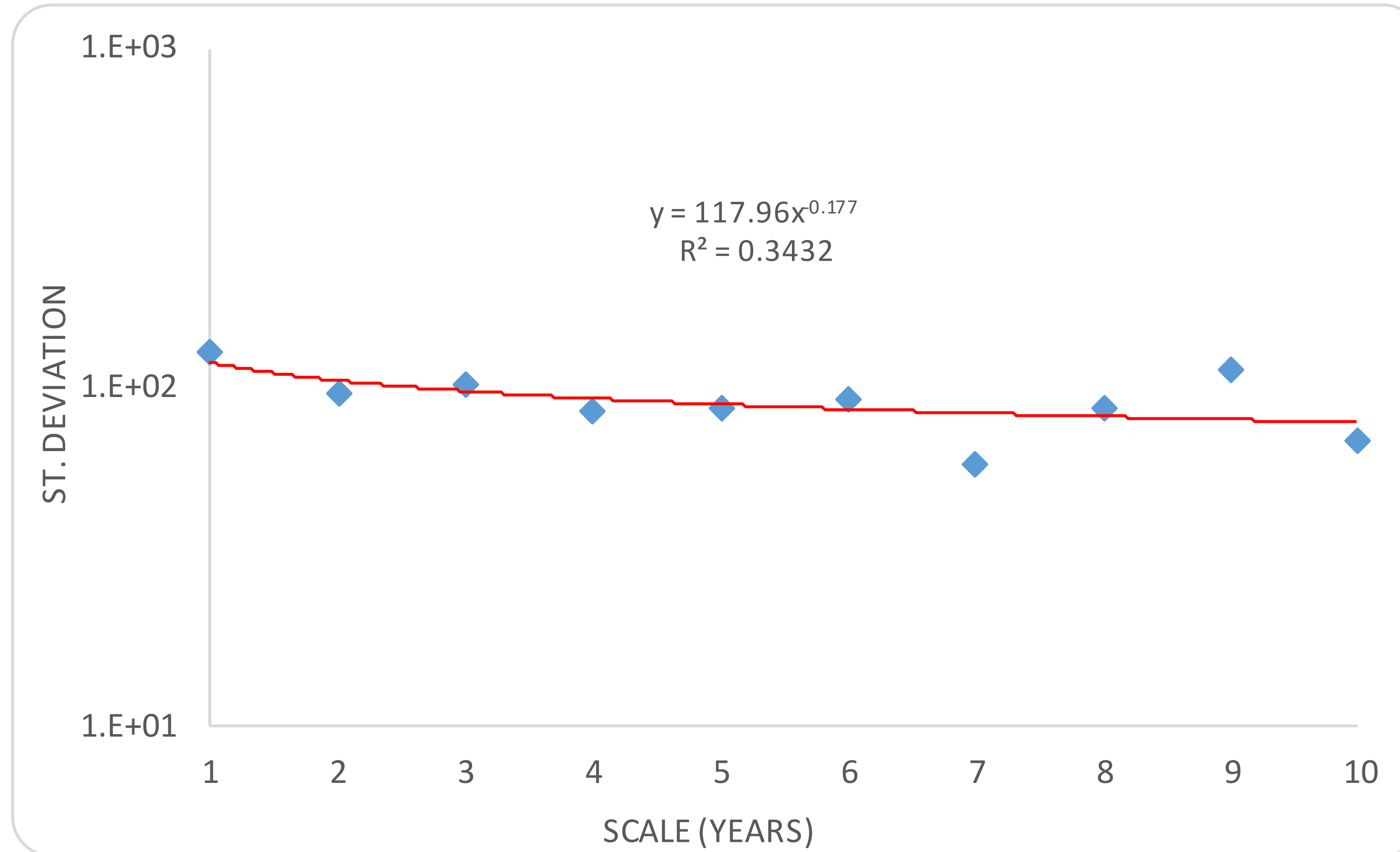


Figure 7: Climacogram for the 22 years timeseries.

Based on the climacogram [2] the empirical Hurst parameter is estimated as 0.82 that indicates a persistent behaviour. Therefore. the annual solar irradiation in Astyapalaia is strongly correlated and cannot be considered as a white noise process.

8. Double cyclostationarity

In order to generate hourly solar radiation [2] from daily solar radiation data we analyze one year hourly observations and split them to 12 timeseries (one for each month).

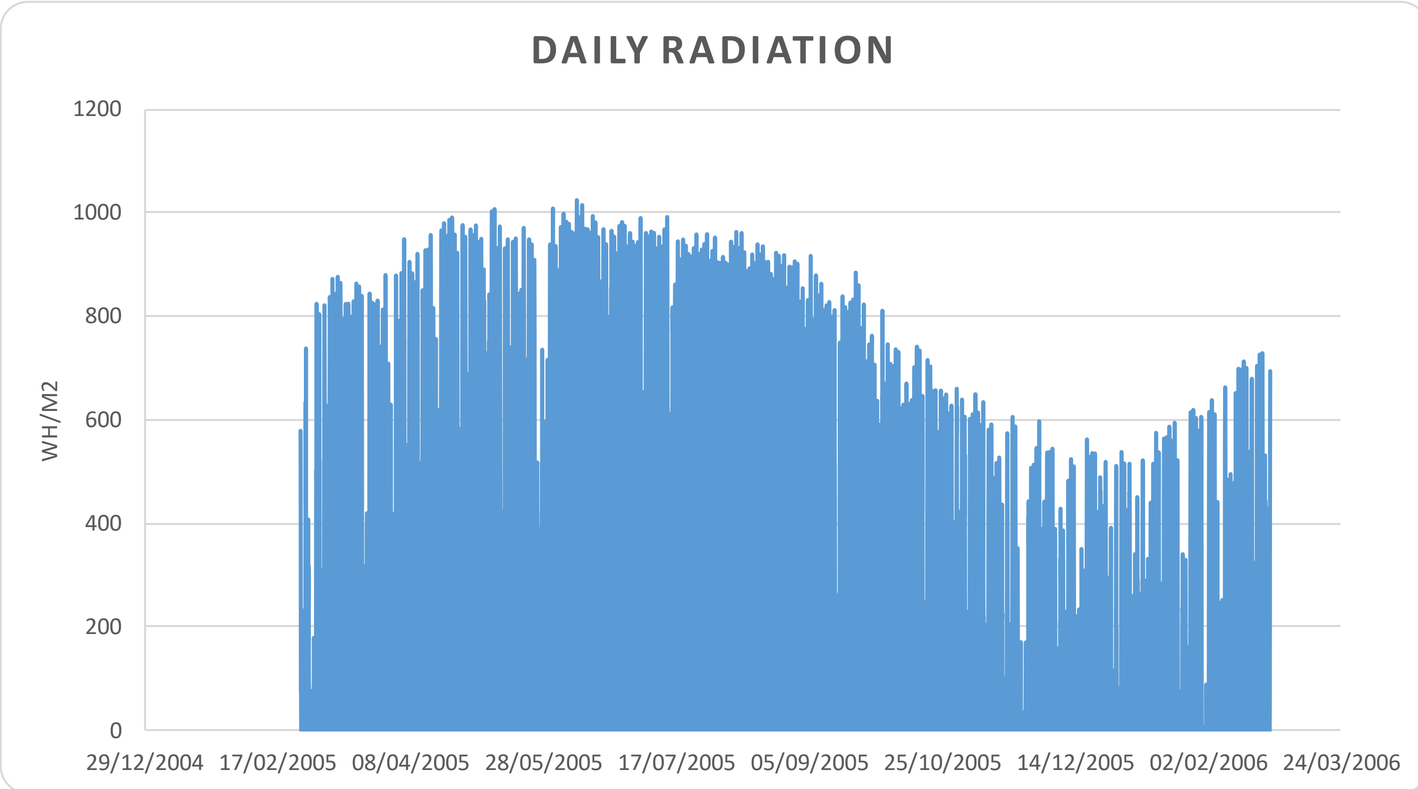


Figure 8: One year observations of solar irradiation

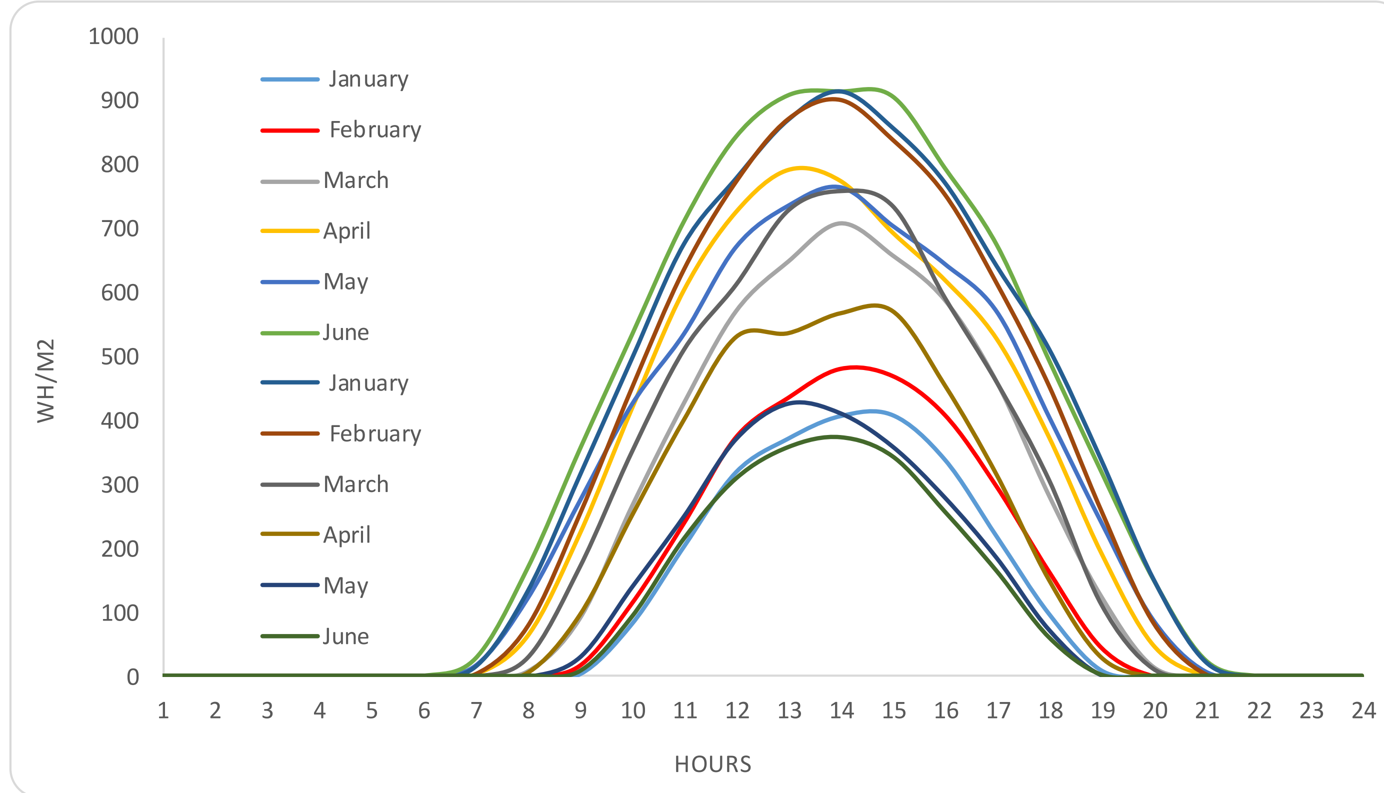


Figure 9: Irradiance per month (double periodicity)

We deduct the mean from each month and divide with the st. deviation in order to investigate the dimensionless pattern of the double periodicity of solar radiance, which resembles that of the Gaussian function:

$$C(x) = 2.6\, e^{-\frac{(x-1.15)^2}{16}} \qquad (1)$$

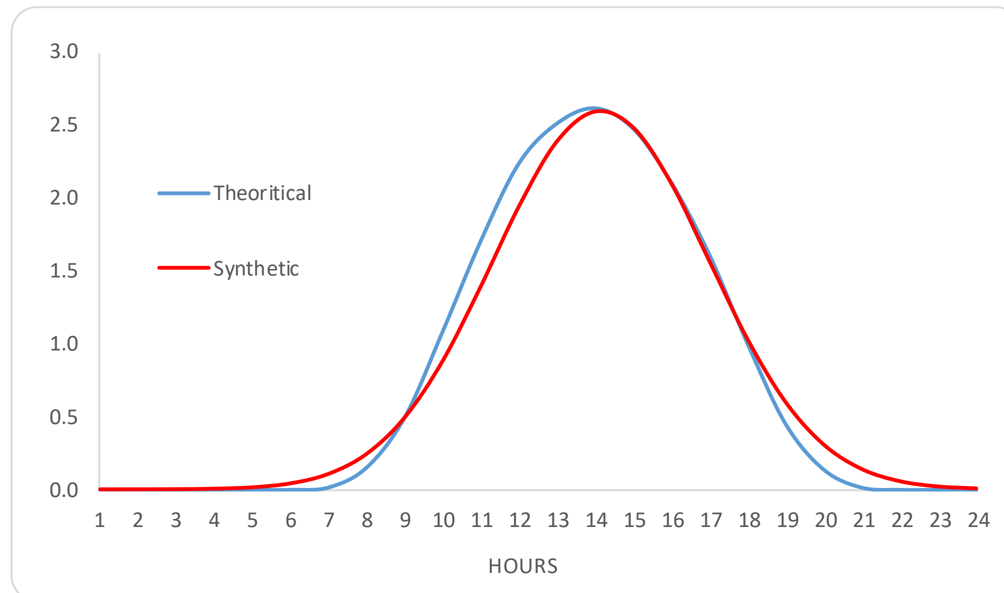


Figure 10: Dimensionless double periodicity

9. Generation stochastic model

The mean-hourly synthetic timeseries are produced using the methodology of [4] suitable for double periodic processes such as the ones examined in this study. Particularly, this methodology preserves the double cyclostationarity (i.e., diurnal and seasonal) of a process through the hourly-monthly marginal distributions, including intermittent characteristics such as probability of zero values, as well as the dependence structure of the processes through the climacogram. For the dependence structure we apply an HK model based on the empirical climacogram of each process. Finally, for the generation scheme we use the CSAR algorithm (cyclostationary sum of finite independent AR(1) processes [5]) capable of generating any length of time series following an HK, or various other processes, and with arbitrary distributions of each internal stationary process of the double cyclostationary process.

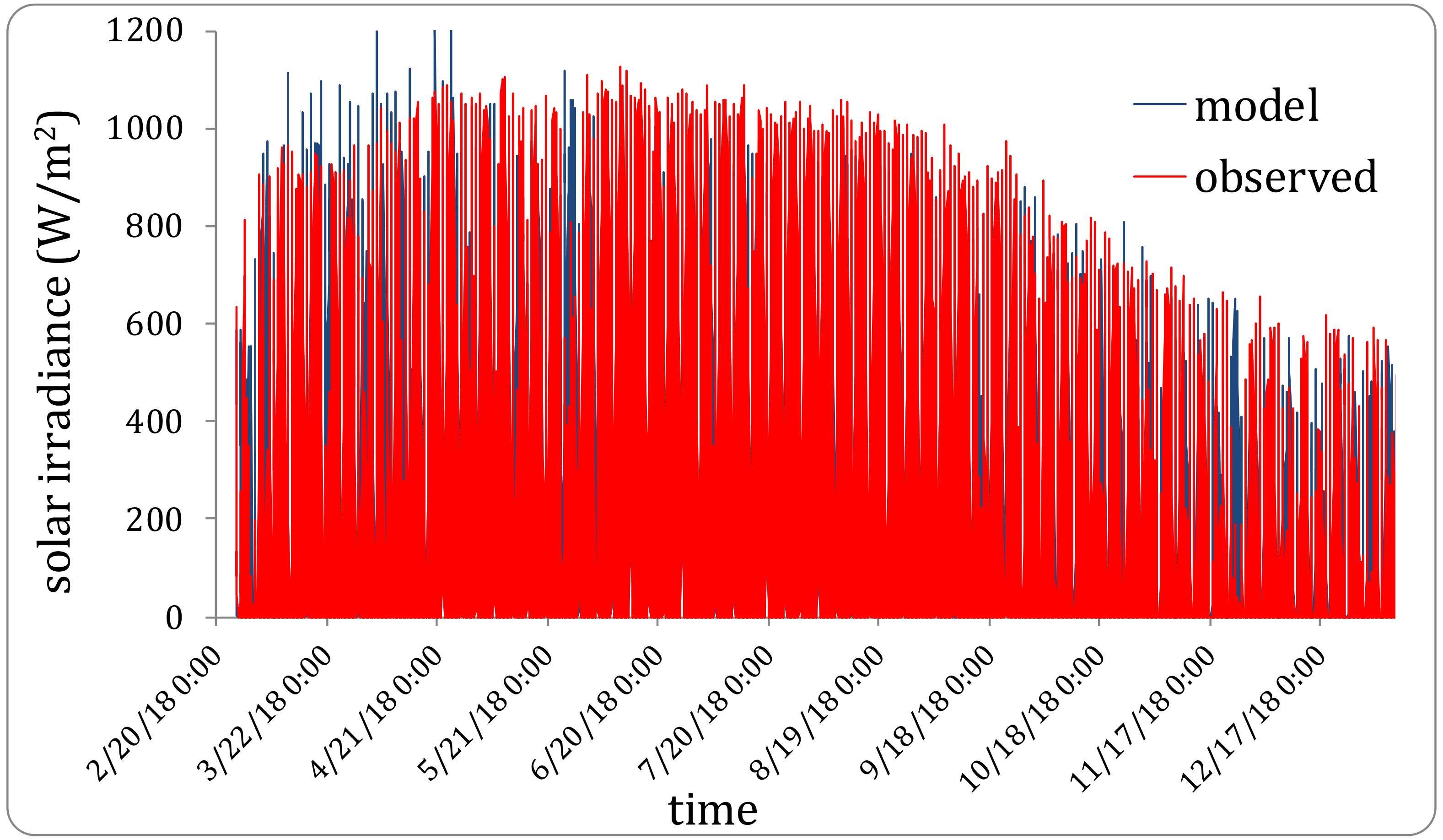


Figure 11: Hourly Synthetic time series generated from daily irradiation

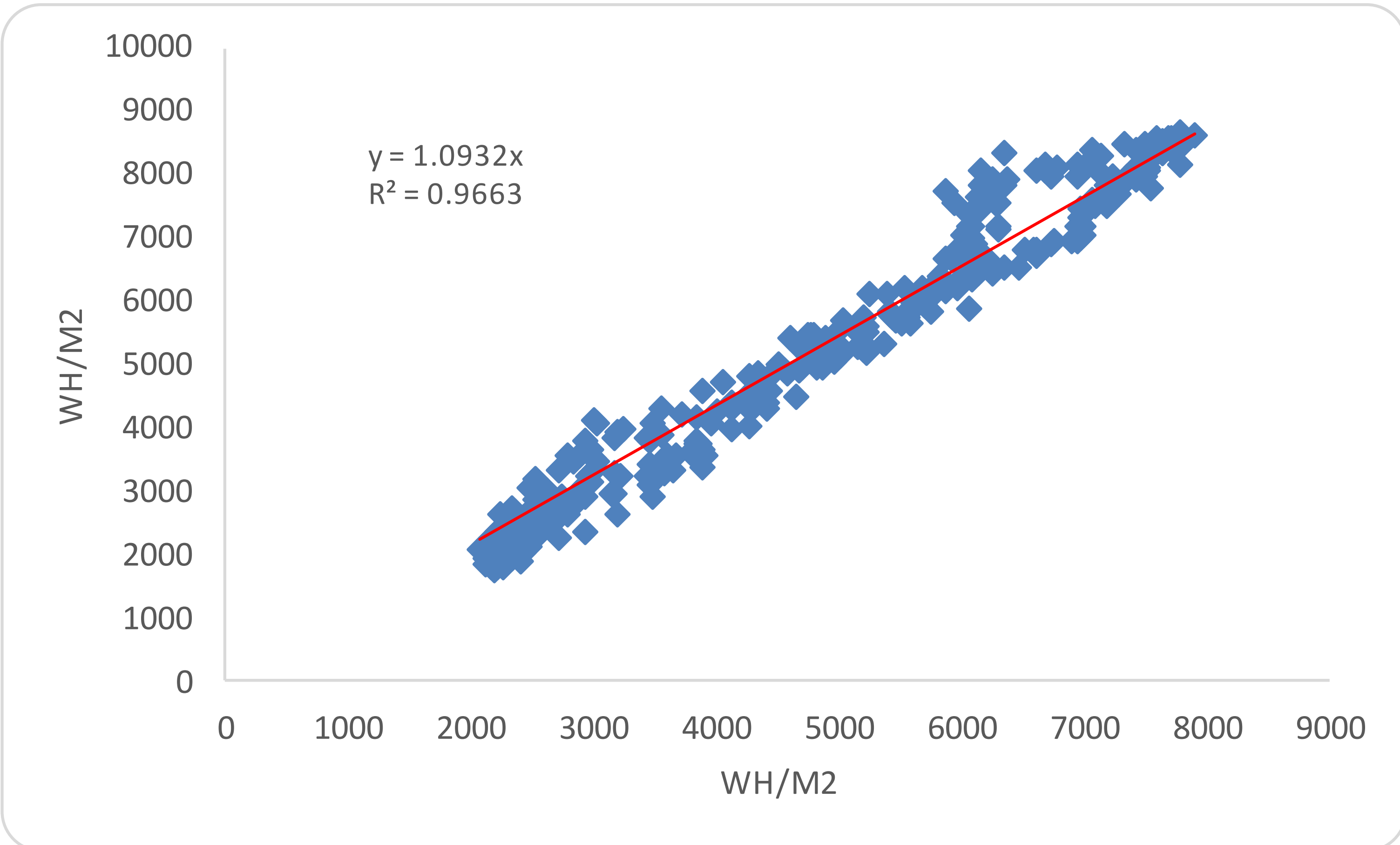


Figure 12: Yearly average of daily observed and synthetic values

10. Renewable Energy Sources in Astypalaia

Our original goal is to make Astypalaia energy independent from non-renewable energy sources such as fuels. We consider many scenarios using only solar energy but we encounter many difficulties, i.e., increase of energy demand during summer due to tourism, solar irradiation is highly uncertain especially during winter due to cloud coverage.

A suggested solution is to install various solar panels through an autonomous system [6], which however is considered very expensive. For example, a 5 MW installed solar energy system requires more than 23,800 solar panels of 210 W each, is expected to fail meeting the energy demand 62.2% in an annual basis.

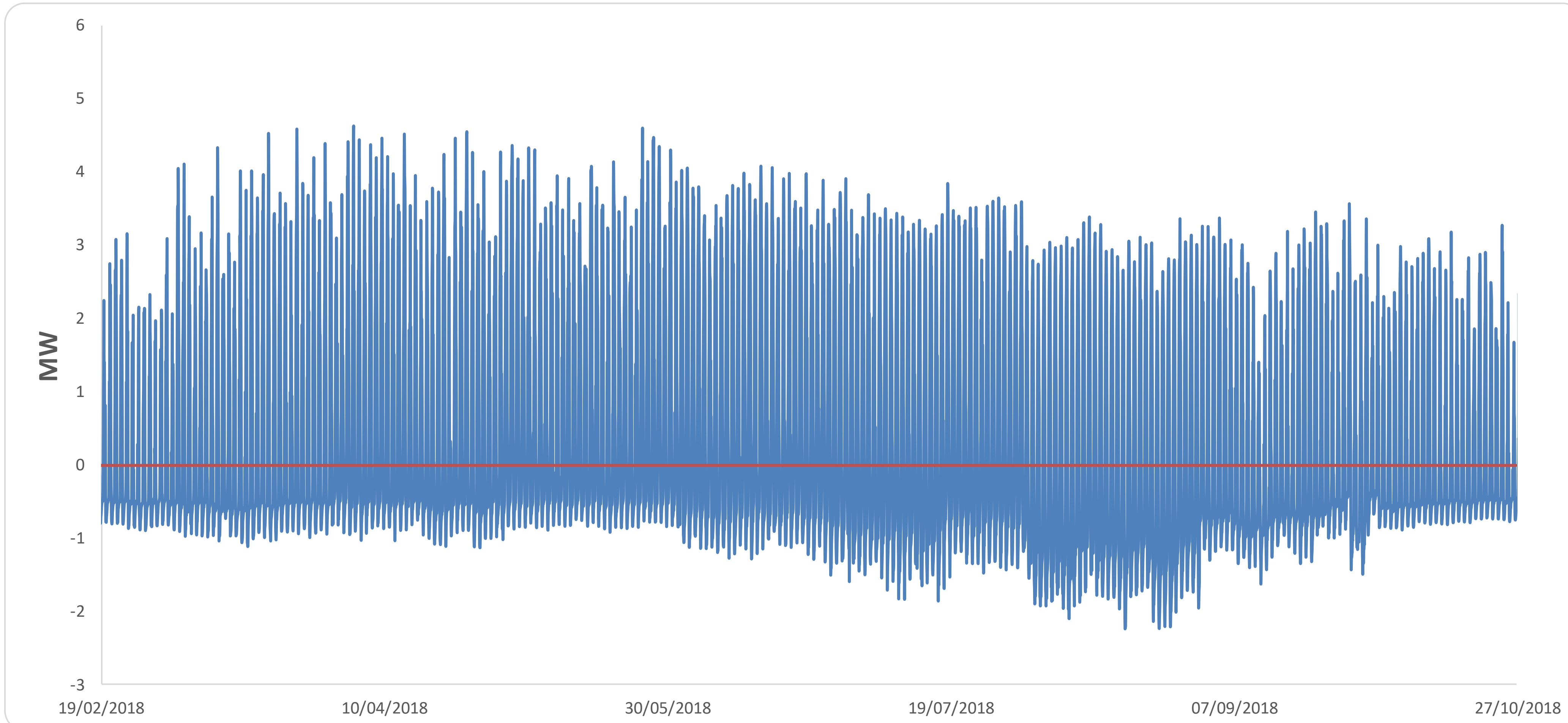


Figure 12: Energy demand minus energy produced from solar panels.

11. Suggested solution

Instead of using solar energy to cover the yearly demand of the island we produce drinkable water with a PV-Reverse osmosis (RO) facility [7,8] during autumn, winter and spring. Nevertheless, during summer that we have the highest demand of energy and the irradiation has its maximum values, the solar system could contribute to cover the peak of demand. We analyze the potential 5MW installed capacity using 100 years hourly solar irradiance synthetic timeseries.

Installed Capacity	**Solar Panels**	**Energy Consumption**	**water volume produced per day (m^3)**	**water volume produced per year (m^3)**	**Energy Produced Summer Per Year**
5MW	23.809	10 KW per m^3	1400	510.998	2997 MW
RO facility cost	**Solar Panels cost**	**Production cost per (m^3)**	**Selling Price per (m^3)**	**Total production cost per year**	**Profit from Selling per year**
2.239.993 €	7.142.857 €	2 €	3.76 €	1.021.996 €	1.921.354 €
Profit from Energy	**Payment in full**				
269.815 €	**8 years**				

Matrix 4: Financial analysis of the suggested solution.

Based on our analysis, the overall suggested system can be paid in full after 8 years. In this solution, we can provide more than 510.998 m^3 of drinkable water per year, covering the excessive needs of the remote island residents as well as touristic needs.

12. Conclusions

- Solar irradiation in monthly scale can be adequately described by the Kumaraswamy distribution.
- Solar irradiation exhibit a Hurst-Kolmogorov behaviour since the Hurst parameter is estimated as 0.82. Such a persistent behaviour indicates the high correlation between successive years.
- The stochastic generation model can capture the double periodicity, marginal characteristics and dependence structure of the hourly solar radiation process.
- Solar energy cannot alone cover the energy demand of a remote island since the uncertainty of solar radiation increases the need (and therefore, the cost) for additional capacity (i.e., solar panels). Nevertheless we can use solar power in hybrid systems, while we can combine it with desalination and additionally produce drinkable water.

References

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