Investigation of the stochastic nature of wave processes, for renewable resources management: a pilot application in a remote island in the Aegean sea

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**

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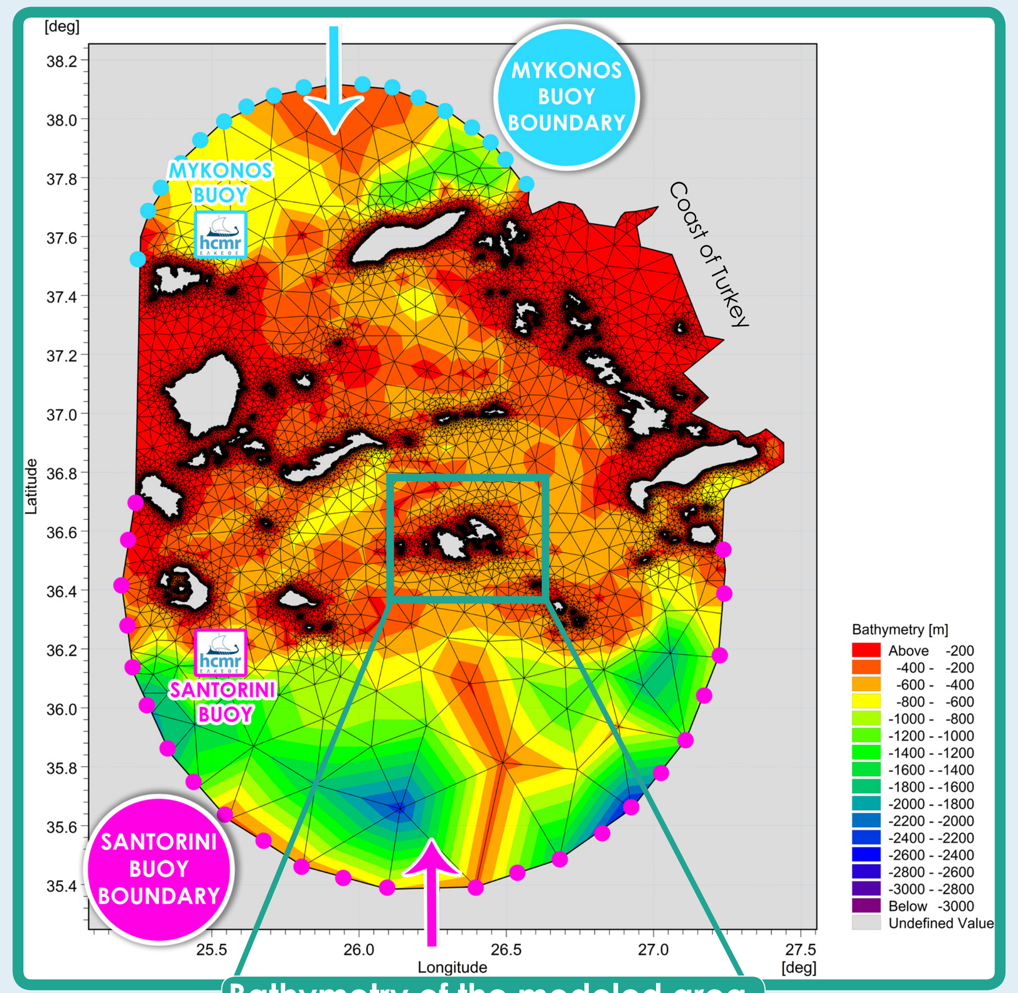
Introduction

Wind-generated waves have always been treated as a phenomenon to protect rather than to benefit from. Recent technological developments and research have not only shown the potential of utilization of wave energy as a renewable resource through Wave Energy Converters (WECs) but also as one possibly antagonistic to the existent renewable energy systems.

In this research we employ numerical as well as stochastic modelling as a combined methodology for assessing the wind and wave resources for a long time period. We apply the methodology in Astypalaia, a remote (non-connected), 1,334 resident, island in the Aegean Sea, in order to evaluate the combined utilization of wind and wave energy.

Analyzing a future 100 year renewable resource management scenario, we conclude that the synergy between wind and wave resource, harnessed through Overtopping WECs and Wind Turbines can sufficiently fuel an autonomous Hybrid Renewable Energy System in remote islands like Astypalaia.

1 Modelling of the wave climate in the coastal region of Astypalaia

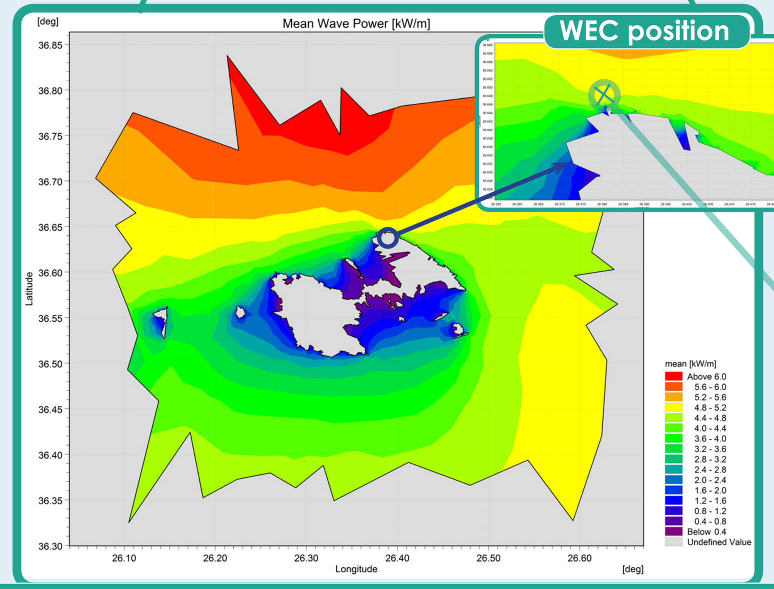


Bathymetry of the modeled area

- Assessment of the wave climate in Astypalaia is done through the third-generation spectral wave ***numerical model MIKE 21 SW*** by DHI. Bathymetry of the model is obtained from the Hellenic National Hydrographic Service with a 15'' spatial resolution, which was interpolated in an unstructured mesh.
- Measured data by the POSEIDON buoy network of the Hellenic Center for Marine Research [1] is utilized to account as input from the northern and southern boundary of the model. Data from the Mykonos and Santorini buoys undergoes a filtering process while missing values are filled through an auto-regressive model, in order to provide the regional wave climate in the 7-year period 2005-2011.
- For the same time period, wind forcing was also taken into account. Wind data was obtained from ECMWF (ERA-Interim) [2] with a 0.125 degrees spatial resolution and 6 hourly temporal resolution.
- The spectral model simulates the effects of refraction, shoaling, wave growth due to wind, wave-wave interaction and dissipation due to bottom friction, white capping and most importantly wave-breaking.

Model Results

A **7-year time period between 2005-2011 is modelled** based on the input available data. The **nearshore region** of the north-east side of the island has access to a **mean wave resource of ~ 5 kW/m**. This resource is maximized during winter months and is minimized during spring months.



Mean Wave Power [kW/m] in Astypalaia (2005-2011)

Characteristic values

Depth	12 m
Mean Wave Power	4.73 kW/m
Wave Power Coeff. of variation	0.455
Mean Wave Height	0.98 m
Mean Wave Period	4.45 sec

A tip of the north area of the island is chosen as the WEC installation position (nearshore), as it provides access to high wind and wave resource on a small depth while avoiding wave-breaking.

2 100-year stochastic estimation of wind and wave resource

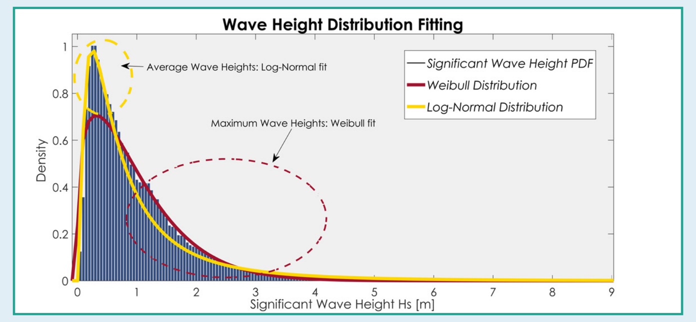
METHODOLOGY

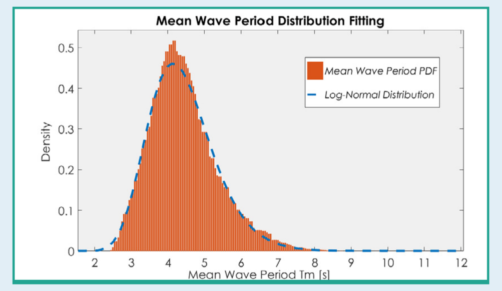
The **mean-hourly synthetic time series** for 100 years, are produced using the methodology developed by *Deligiannis et al (2016)* [4] suitable for double periodic processes such as the ones examined in this study.

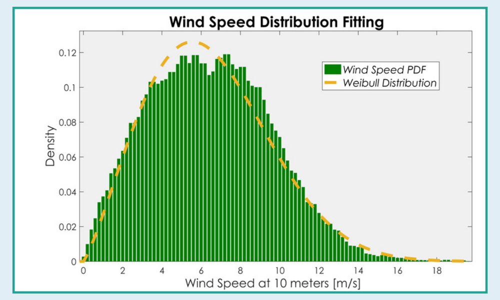
Particularly, the applied method preserves the double cyclostationarity (diurnal and seasonal) of a process through the hourly-monthly marginal distributions (as shown in [4]), including intermittent characteristics such as probability of zero values, as well as the dependence structure of the processes through the climacogram (i.e., variance of the scaled-averaged process as a function of scale [5]).

Additionally, in this study ***we preserve the empirical cross-correlation among wind speed, wave height and wave period:***

- For the wind speed we apply the *two-parameter Weibull distribution* (suitable for small return periods which are of interest in wind energy production and management; [6]).
- For the wave height we apply again the *two-parameter Weibull* distribution while for the wave period we apply the *two-parameter Log-normal distribution.*
- For the dependence structure we apply a Hurst-Kolmogorov [HK] model [7] 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 [3, 8]) 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.



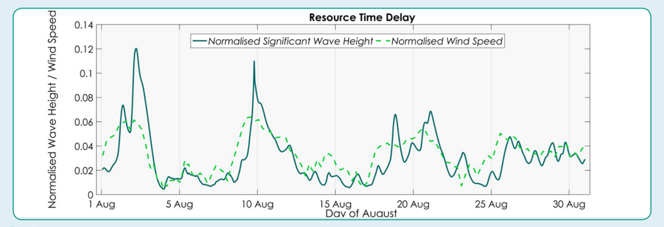




Distribution fitting in the historical wind and wave data produced by the numerical model for the period 2005-2011.

As discussed, the synthetic time series maintain the distributions of the historical ones.

Wave height shows two fits: Weibull for maximum and Log-Normal for average values, only one of which was maintained.



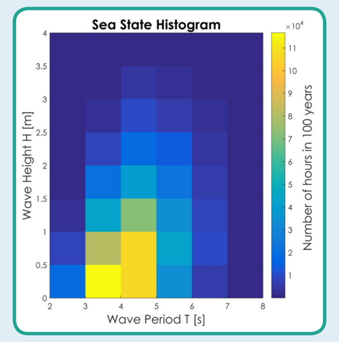
In this plot, cross-correlation between wind and wave resource can be seen. Also the time delay between them, aids for better management, as discussed in [9]

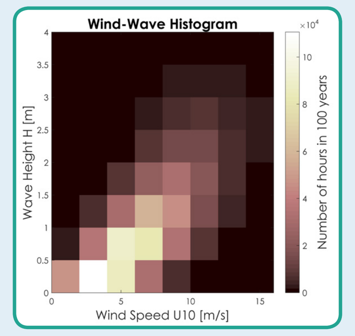
WAVE HEIGHT / WIND SPEED CROSS-CORRELATION FACTOR (1st-order)
0.75

Wave Height - Wave Period, and Wave Height - Wind Speed histograms of the produced synthetic time series.

The synthetic time series maintain the first moments (average, standard deviation) and the first-order auto-correlation factor, as well as the cross-correlations between H_s-T and H_s-u_{wind}, which are high.

Wave height has an uneven distribution with large frequencies at the low values, while wind has a more normalized distribution.



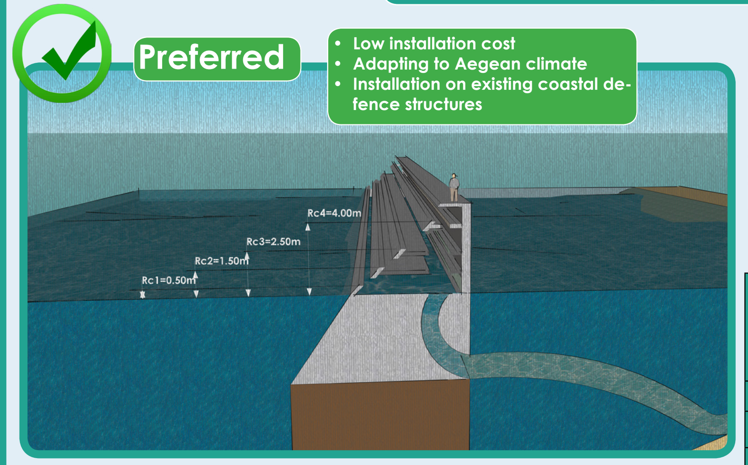


3 Evaluation of Wave Energy Converters

Overtopping WEC

Preferred

- Low installation cost
- Adapting to Aegean climate
- Installation on existing coastal defence structures



Characteristic values

Length	125 m
Rc1	0.50 m
Rc2	1.50 m
Rc3	2.50 m
Rc4	4.00 m

Energy Production

Installed Power	Annual Produced Energy	Capacity Factor
200 kW	649 MWh	37.04%
250 kW	706 MWh	32.25%
300 kW	747 MWh	28.42%

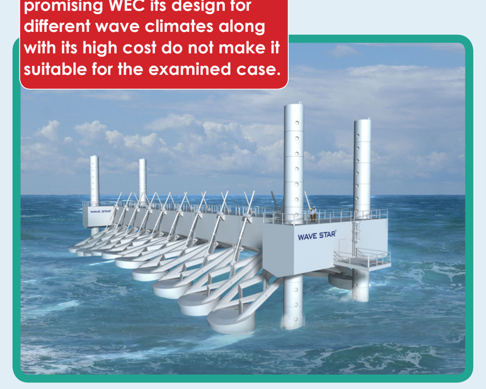
- Operates by collecting water through overtopping and wave-run up processes. Energy is produced by feeding the water into a low-head **Kaplan turbine.**
- OWECs with multiple reservoirs such as the SSG [10] have been proven to produce enhanced results. Here a **4-reservoir OWEC** with 35% total efficiency is supposed.
- *Kofoed (2006) [11]* suggested an equation for calculating the amount of discharge in each reservoir:

$$q_{ov,j} = \int_{R_{c,j}}^{R_{c,j+1}} \frac{dq}{dz} dz = \cdot \sqrt{g \cdot H_s^3} \cdot \frac{A}{B} \cdot e^{C \cdot \frac{R_{c,1}}{H_{mo,t}}} \cdot \left(e^{B \cdot \frac{R_{c,j+1}}{H_{mo,t}}} - e^{B \cdot \frac{R_{c,j}}{H_{mo,t}}}\right)$$

- *Ioannou et al (2014)* [12] examined the installation of an OWEC in Donoussa, another remote island of the Aegean, providing energy autonomy, if used along with a WT.

Wavestar WEC

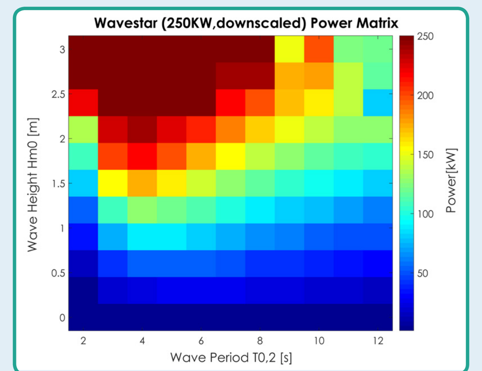
Even though Wavestar is a promising WEC its design for different wave climates along with its high cost do not make it suitable for the examined case.



Energy Production

Installed Power	Annual Produced Energy	Capacity Factor
200 kW	608 MWh	34.32%
250 kW	698 MWh	31.87%
300 kW	787 MWh	29.91%

- Designed by Danish company WaveEnergy. Prototype machine rates 600kW.
- Energy production of the Wavestar is calculated through the power matrix. For wave heights larger than 3m, the machine operates in storm protection mode, producing zero energy.



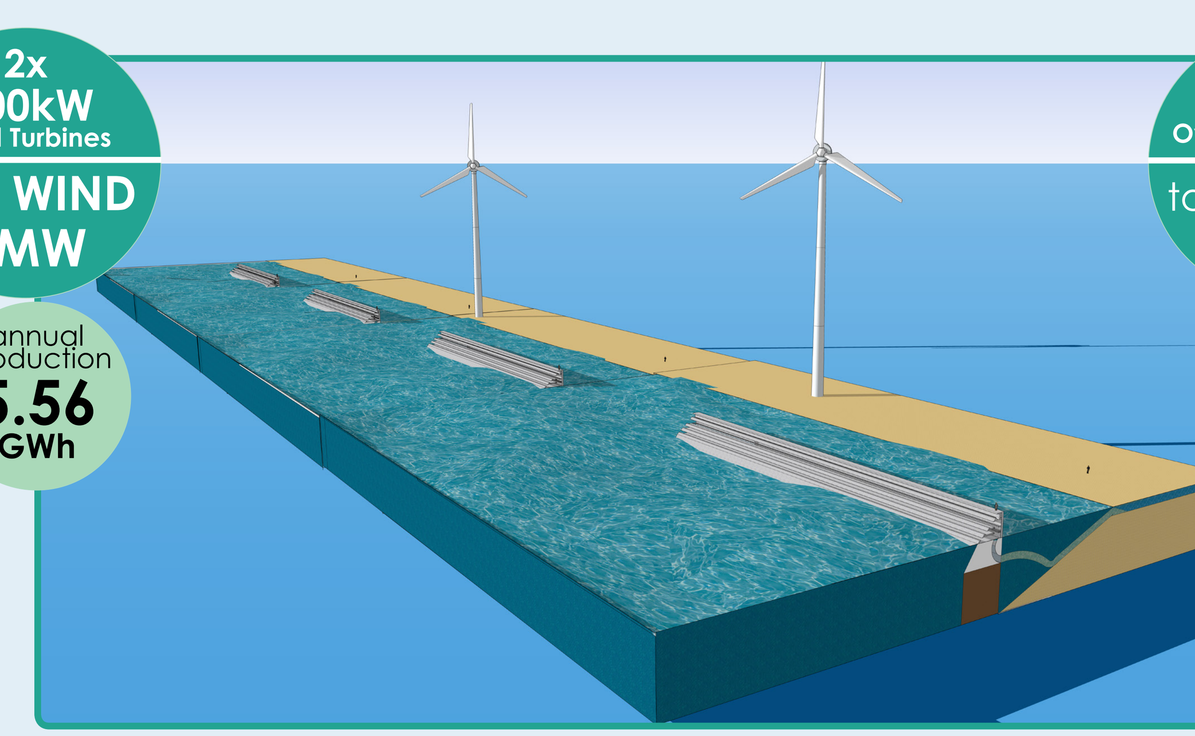
Wavestar Power Matrix (downscaled)

- The 600kW prototype, along with its power matrix, is **downscaled** on a scale λ by applying a Froude criterion of hydraulic similarity, in order to match the lower energy potential of the Aegean sea:

$$\lambda^{3.5} = \frac{P_{downscaled}}{P_{model}} \qquad \lambda = \frac{H_{s_{downscaled}}}{H_{s_{model}}} \qquad \lambda^{0.5} = \frac{T_{m_{downscaled}}}{T_{m_{model}}}$$

- *Friedrich and Lavidas (2015) [9]* evaluated the installation of a Wavestar WEC and a wind turbine as a part of a HES for covering the needs of Astypalaia. Their results show that combined wind-wave resource management can be a possible alternative.

4 A Hybrid Renewable Energy System for remote islands



Today the island is powered through a small fossil-fuel plant.

Alternatively it could be powered by a HRES, consisting of two wind turbines and four OWECs.

Characteristics

	Wind	Wave
Installed Capacity	500kW	250kW *
Height or Length	75m	125m
Can store surplus?	NO	YES

*One OWEC consists of five 50kW Kaplan Turbines distributed through the reservoirs

54% of days in 100 years are covered fully

Brief Cost Analysis

	Wind	Wave
Installation	115,000	375,000
Turbine	840,000	275,000
Foundation	50,000	100,000
Grid connection	120,000	50,000
Total per item	**1,125,000** x2	**800,000** x4
Pump & Reservoir	600,000	
TOTAL	**6,050,000€**	

*Sources for wind: Blanco, 2009; EWEA, 2009; Douglas-Westwood, 2010 and Make Consulting, 2011c
*Sources for wave: G.A. Aggidis 2010 and A.Ioannou 2014

Vending Prices

Wind: **99.45€ per MWh** — Wave: **84.60€ per MWh**

*Sources: Hellenic Transmission System Operator (HSTO); Sismani G.,Karambas Th. (2015)

Payback time*: 10 years

*Considering sold, only the quantity of energy that is integrated in the grid.

Adding Pumped Storage System

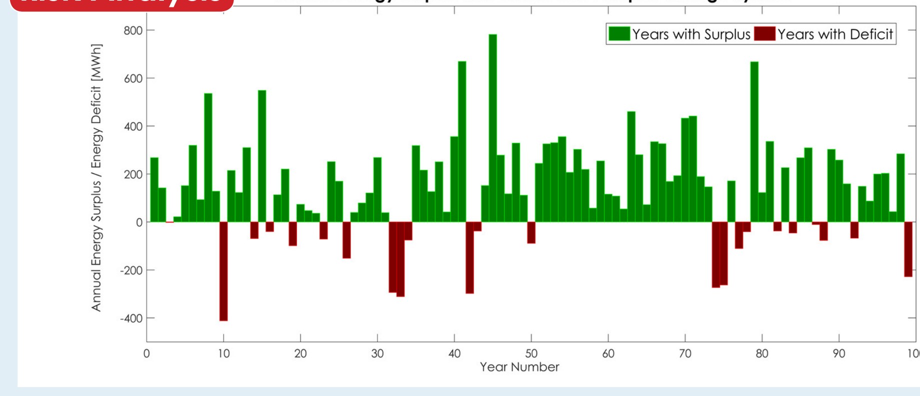
*Alternatively: Battery

A basic disadvantage of renewable energy is that it can not be produced "on-demand". To cover peak demands, surplus wave energy collected through the OWECs can be stored with a pumped storage system. The pump is fed with the surplus energy produced by the wind turbines.
In the diagram below surplus is considered the one provided through wave resource only, as wind resource surplus cannot be stored.

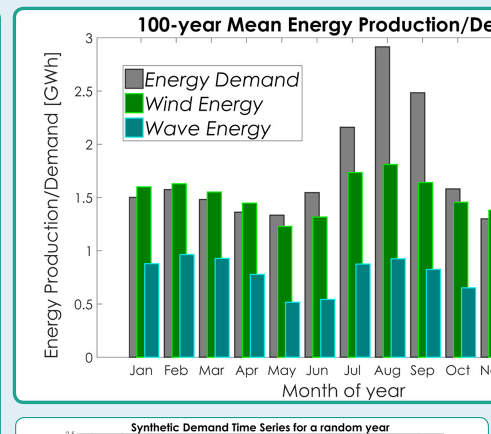
Pump Efficiency 75%

Probability of Failure (annual) 24%

Risk Analysis



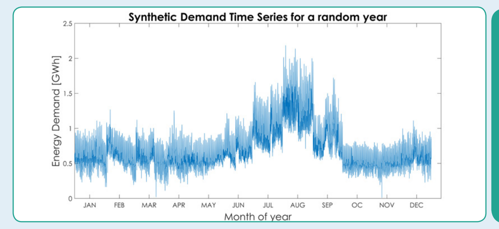
Monthly and yearly deficits can be covered through surplus of former months and years respectively



Highest Energy Demand AUG

Lowest Energy Production MAY

Mean monthly Probability of failure 35%



An annual window of the 100 years synthetic time series of energy demand in Astypalaia produced by *Koskinas et al (2017--this session) [13]*

Comment: The decision of the energy mix must be taken after consideration of additional financial, environmental and sociological issues. The examined solutions have high demand of financial and organisational resources and therefore it is reasonable that thermal stations that are fed with transported oil, are still broadly used in non-connected islands, *Roussis et al (2017 -- this session) [14]*

References

[1] H. Hellenic Centre for Marine Research, Monitoring, Forecasting System, Oceanographic Information for the Greek Seas (POSEIDON), http://www.poseidon.hcmr.gr/
[2] R. Gibson, P. Kallberg, S. Uppala, The ecmwf re-analysis (era) project, ECMWF, Newsl. 73 (1996) 7e17
[3] P. Dimitriadis, and D. Koutsoyiannis, Application of stochastic methods to double cyclostationary processes for hourly wind speed simulation, Energy Procedia, 76, 406–411, doi:10.1016/j.egypro.2015.07.851, 2015..
[4] E. Deligiannis, P. Dimitriadis, O. Daskalou, Y. Dimakos, and D. Koutsoyiannis, Global investigation of double periodicity of hourly wind speed for stochastic simulation; application in Greece, Energy Procedia, 97, 278–285, doi:10.1016/j.egypro.2016.10.001, 2016.
[5] P. Dimitriadis, and D. Koutsoyiannis, Climacogram versus autocovariance and power spectrum in stochastic modelling for Markovian and Hurst–Kolmogorov processes, Stochastic Environmental Research & Risk Assessment, 29 (6), 1649–1669, doi:10.1007/s00477-015-1023-7, 2015.
[6] D. Koutsoyiannis, P. Dimitriadis, F. Lombardo, S. Stevens, From fractals to stochastics: Seeking theoretical consistency in analysis of geophysical data, Advances in Nonlinear Geosciences (accepted).
[7] D. Koutsoyiannis, Hurst-Kolmogorov dynamics and uncertainty, Journal of the American Water Resources Association, 47 (3), 481–495, doi:10.1111/j.1752-1688.2011.00543.x, 2011.
[8] P. Dimitriadis, Hurst-Kolmogorov dynamics in Hydrometeorological processes and in the microscale of turbulence, PhD thesis, Department of Water Resources and Environmental Engineering, National Technical University of Athens, Athens, 2017 (submitted).
[9] D. Friedrich, and G. Lavidas, Combining offshore and onshore renewables with energy storage and diesel generators in a stand-alone Hybrid Energy System, in OSES2015, 2015.
[10] L. Margheritini, D. Vicinanza and P. Frigaard, SSG Wave Energy Converter: Design, Reliability and Hydraulic Performance of an Innovative Overtopping Device, Journal of Renewable Energy, Elsevier, 34(5), pp.1371-1380, 2008
[11] J.P. Kofoed,Vertical Distribution of Wave Overtopping for Design of Multi Level Overtopping Based Wave Energy Converters, in Proceedings of the 30th International Conference on Coastal Engineering, San Diego, 2006.
[12] A. Ioannou, A. I. Kalfas, and T. V. Karambas, "Integrated Overtopping Wave Energy Converter in a Hybrid Offshore Wind Turbine Power Generation System, in Proceedings of ASME Turbo Expo 2014: Turbine Technical Conference and Exposition, 2014.
[13] Koskinas Aristotelis, Eleni Zacharopoulou, George Pouliasis, Ioannis Engonopoulos, Konstantinos Mavroyeoryos, Ilias Deligiannis, Georgios Karakatsanis, Panayiotis Dimitriadis, Theano Iliopoulou, Demetris Koutsoyiannis, and Hristos Tyralis, Simulation of electricity demand in a remote island for optimal planning of a hybrid renewable energy system, EGU 2017
[14] Roussis Dimitrios, Iliana Parara, Panagiota Gournari, Yiannis Moustakis, Panayiotis Dimitriadis, Theano Iliopoulou, Demetris Koutsoyiannis, and Georgios Karakatsanis, Energy, variability and weather finance engineering, EGU 2017

Acknowledgment: 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.