The Role of the Minor Hydrographic System in Increasing the Ecological Network

Original
The Role of the Minor Hydrographic System in Increasing the Ecological Network / La Riccia, L., Ferraris, S. (THE URBAN BOOK SERIES). - In: Post Un-Lock. From Territorial Vulnerabilities to Local Resilience / Brunetta G., Lombardi P., Voghera A.. - ELETTRONICO. - Cham, Switzerland : Springer, 2023. - ISBN 978-3-031-33893-9. - pp. 33-44 [10.1007/978-3-031-33894-6_3]

Publisher:
Springer

Published
DOI:10.1007/978-3-031-33894-6_3

On the complementarity of wind, wave and solar energy in North Tyrrhenian Sea

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***Abstract*—Achieving a fully renewable energy future can potentially benefit from the integration of offshore energy sources (whenever available), such as wave, wind and solar energy, into the current energy mix. These resources offer significant potential to enhance the reliability of renewable energy systems by complementing each across various temporal scales. The inclusion of offshore resources in the current energy portfolio may improve power output stability, reduce periods of energy generation shortfall, and lessen the dependency on energy storage solutions. This study employs innovative complementarity metrics—including total variation, variance, and standard deviation—to evaluate the interactions among wind, wave and solar resources in North Tyrrhenian Sea. Temporal complementarity analysis in the North Tyrrhenian Sea reveals significant differences when considering only two resources or multiple resources and when considering different resource pairings.**

***Index Terms*—Complementarity, wave energy, wind energy, solar energy, offshore renewable energy sources, North Tyrrhenian Sea**

I. INTRODUCTION

Variable renewable energy sources are crucial for meeting global energy demand, and current trends suggest that they will play an increasingly important role in the future. The main challenges related to renewable energy sources are that they are affected by weather and climate, resulting in considerable spatial and temporal fluctuations. Thus, renewable energy sources cannot offer additional and mandatory services to the grid beyond delivering a specific amount of energy. The integration of multiple renewable energy sources within a single power station presents a viable approach to address these issues. It has the potential to manage the natural variability of renewable energy sources, lower the costs of co-locating them within the existing electrical infrastructure and enhance the reliability of the power system. Moreover, the combination of different renewable sources offers a promising solution to provide a stable and diversified alternative to the conventional electricity mix of a given region, particularly in isolated areas that are not yet connected to the national power grid. This strategy relies on the complementary characteristics of renewable energy sources i.e. when one resource is lacking, another can simultaneously offset this shortfall. As the penetration of renewables into the power grids grows, complementarity analysis is gaining significance. This kind of study can potentially aid the process of techno-economic optimization of the deployed renewable technologies, minimize the dependence on storage devices [15], and reduce the overall fossil fuel consumption [1]. Complementarity analysis provides an effective method for evaluating the optimal combination of variable renewable sources in different areas and acts as a decision support tool for new investments.

Various metrics have been proposed in the literature to measure energetic complementarity but most of these methods are not proven to be adequate for evaluating complementarity among more than two time series. Nevertheless, all metrics show that the integration of energy resources with strong complementarity yields many benefits [11]–[13]. In this study, innovative metrics, proposed by Cantor et al. [2], are employed. These complementarity metrics are able to measure the regularity of the sum of all available resources and they rely on mathematical principles of total variation, variance, and standard deviation. This study is carried out at three locations in the North Tyrrhenian Sea with the aim of comparing the potential complementarity among two and three renewable energy sources, i.e. wind, wave, solar. The three locations under study are Elba Island, Livorno and Capraia Island. So far, few studies have been carried out along the Italian peninsula to assess the energetic complementarity between only two energy resources (wind and solar, solar and hydro, wind and wave) [5]–[7]. This is the only study focusing on the North Tyrrhenian Sea that evaluates temporal complementarity between two and three offshore energy sources and it is performed with an hourly resolution data over a time interval of one year.

II. CHOICE OF SITES, DATA COLLECTION AND POWER DENSITIES

The North Tyrrhenian Sea is the focus of the study, with three specific locations selected within the area under analysis of the AIMS project [3]. More in detail, the three locations under study are Elba Island, Capraia Island, and the coastal site near Livorno, whose coordinates are shown in Fig.1. These locations are chosen at a distance of at least 10 km from

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E. Pasta received partial funds as part of the project AIMS: Artificial Intelligence to Monitor our Seas – funded by the European Union - NextGeneration EU - Ministry of University and Research - under the PRIN 2022 PNRR Call for Proposals (D.D.1409 of 14/09/2022).

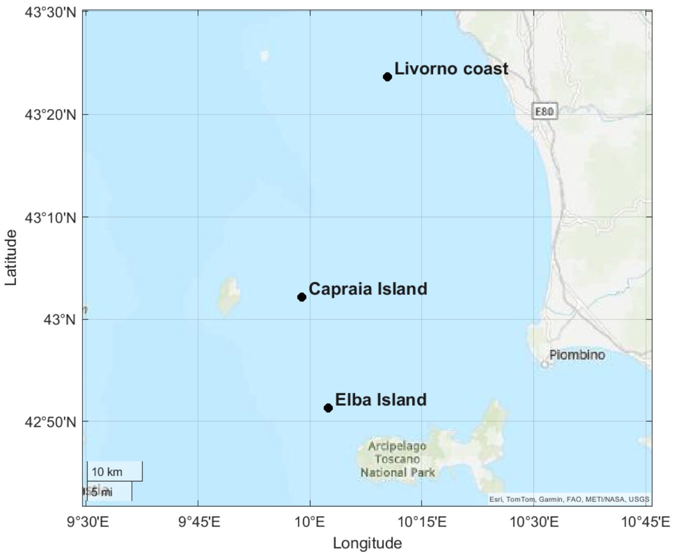

Fig. 1. Locations in North Tyrrhenian Sea under study.

the coast. Hourly data for wave resources are obtained from the AIMS dataset of the area, which was obtained by means of SWAN simulations at regional level [3]. This numerical dataset has been previously validated with available in-situ measurements (wave buoy data). Wind data are retrieved from ERA5 [14], and solar data from Atmosphere Data Store [9]. All data cover a time interval of one year from 01 January 2022 to 31 December 2022.

A. Wave data and power density

Hourly wave data for this project, including wave significant height H_s and energy period T_e are downloaded from SWAN [3]. The power density P_{wave} (kW/m) [8] can be calculated as follows:

$$P_{\text{wave}} = \frac{\rho_{\text{water}} g^2}{64\pi} H_s^2 T_e, \tag{1}$$

where ρ_{water} is water density (1025 kg/m^3) and g is gravitational acceleration (9.81 m/s^2).

B. Wind data and power density

Hourly northward wind vector v and eastward wind vector u at 100 meters above sea level are downloaded from ERA5 dataset. Wind speed is taken at a height of 100 meters as offshore wind turbines hub height typically attain these elevations.

$$U_{100} = \sqrt{u^2 + v^2}. \tag{2}$$

$$P_{\text{wind}} = \frac{\rho_{\text{air}} U_{100}^3}{2}, \tag{3}$$

P_{wind} is wind power density (kW/m^2) and ρ_{air} is air density equal to 1.225 kg/m^3 at 15°C and 1 atm.

C. Solar data and power density

Global horizontal all sky irradiation GHI for solar hourly data is obtained from CAMS solar radiation time-series dataset [9] in true solar time [8].

$$P_{\text{solar}} = GHI, \tag{4}$$

where P_{solar} is the solar power density (kW/m^2).

III. METHODOLOGY

Innovative complementarity metrics have been proposed in [2] to assess the complementarity between more than two time-series. These metrics are total variation complementarity index Φ, variance complementarity index Φ_v, and standard deviation complementarity index Φ_s.

A. Total variation complementarity index

Total variation complementarity index Φ is expressed by the mathematical principle of total variation. The total variation of a time series defined in an interval [a,b] is [2]

$$V_a^b(f) = \sum_{k=0}^{n-1} |f(x_{k+1}) - f(x_k)|, \tag{5}$$

where $a = t_0 < t_1 < \cdots < t_n = b$.

Given two functions (i.e. wind and solar power densities) not constant, their total variation complementarity index is defined as follows:

$$\Phi(f_1, f_2) = 1 - \frac{V_a^b(f_1 + f_2)}{V_a^b(f_1) + V_a^b(f_2)}, \tag{6}$$

where $0 \leq \Phi \leq 1$.

If Φ=1 it means that $V_a^b(f_1 + f_2)$=0 and perfect complementarity exists, while for Φ=0 there is no complementarity between the two time series (comparable to high degree of correlation). The total variation complementarity index can be applied to any number of time series, it is sensitive to the scale of variables, and it works only with dimensionally homogeneous variables. For this reason, the normalised signal of the power densities with respect to the maximum value of the entire time series is applied in this study. In addition, Φ depends both on the autocorrelations and on the cross-correlations of the series [2] [4].

B. Variance complementarity index

The variance complementarity index Φ_v is derived from Eq.6 by substituting the total variation with the variance (σ^2) [2]

$$\Phi_v(f_1, f_2) = 1 - \frac{\sigma^2(f_1 + f_2)}{\sigma^2(f_1) + \sigma^2(f_2)}, \tag{7}$$

Φ_v varies between -1 and 1. Nevertheless, to be consistent in the comparison with other metrics in this study the rescaled index is used $\hat{\Phi}$.

$$\hat{\Phi}(f_1, f_2) = \frac{\Phi_v + 1}{2}, \tag{8}$$

where $0 \leq \hat{\Phi} \leq 1$.

$\hat{\Phi}$=1 means perfect complementarity and $\hat{\Phi}$=0 no complementarity.

In the explicit formula for this metric given in [2] and [10] is noticeable that the variance complementarity index is a function of the cross-correlation coefficient.

C. Standard deviation complementarity index

The standard deviation complementarity index Φ_s assesses the variability of the time series with the standard deviation (σ). Differently from the $\hat{\Phi}$ case, the involved variables maintain their original measurement unit because they are not raised to the square. As a consequence, this metric does not need to be rescaled [2].

$$\Phi_s(f_1, f_2) = 1 - \frac{\sigma(f_1 + f_2)}{\sigma(f_1) + \sigma(f_2)}, \tag{9}$$

where $0 \leq \Phi_s \leq 1$.

Also, in this case, Φ_s=1 means perfect complementarity and Φ_s=0 means no complementarity. This metric applies to multiple time series and can be defined as a function of the cross-correlation coefficient [2].

IV. TEMPORAL COMPLEMENTARITY RESULTS

To illustrate the potential complementarity of interconnecting two or three different energy sources, Φ, $\hat{\Phi}$ and Φ_s are computed for each site. All time series data for each site are normalised to its maximum value throughout the entire analysed time frame to maintain a consistent scale for assessing complementarity [4].

Φ, $\hat{\Phi}$ and Φ_s outcomes for wind-wave mix are shown in Tab. I. Among all sites analysed in the North Tyrrhenian Sea, Elba Island is the most complementary in terms of Φ metric for the combination of wind-wave resources. To understand the reason, smoothed profiles are analysed by applying a seven-day moving average to the already normalised time series. Fig. 3 shows that the smoothed profile of the wave resource at Elba Island is able to better compensate for periods when the wind resource is absent compared to smoothed profiles at Capraia Island (Fig. 2) and along the coast of Livorno (Fig. 4), where the wave resource is more correlated with the wind resource. Instead, Φ metric is higher at Capraia Island than in the other locations for wind-solar, wave-solar and wind-wave-solar resource mix, as shown respectively in Tab. II, III and IV. Among all combinations of energy resources, the total variation complementarity metric Φ reaches its highest value of 0.125 at Elba Island for wind-wave mix, while the lowest value of 0.027 is reached at the Livorno site for solar-wave resource mix. By comparing Fig. 3 and Fig. 5, it can be observed that the wave-wind resource at Elba Island exhibits a higher Φ than the wind-wave-solar resource. This is because the inclusion of solar energy resource increases the temporal overlap (i.e. correlation) of normalised power density profiles, thereby reducing complementarity. Nevertheless, the high temporal availability of solar resource is beneficial as it facilitates the generation of a greater amount of green energy. Metrics based on standard deviation and variance, i.e. Φ_s and $\hat{\Phi}$, overestimate the complementarity with exception of Φ_s values in the wind-wave resource mix, which are lower than Φ. These findings are consistent with results obtained by using the same metrics in [4]. The overestimation occurs because both Φ_s and $\hat{\Phi}$ do not account for auto-correlations within the time series. They also tend to provide similar results even when more resources are mixed together as well as these metrics exhibit greater sensitivity to variations in the time series data. In general, Φ values closer to 1 indicate better complementarity, while values near 0 suggest limited complementarity. However, the significance and goodness of a particular complementarity level should be related to the temporal dynamics of resources, the spatial context, and the intended application. Since Capraia Island exhibits the highest complementarity for the wind-wave-solar combination, a seasonal analysis of temporal complementarity for this energy mix is conducted at this location. Fig. 6 depicts seasonal complementarity indices for wind-wave-solar mix and it highlights that $\hat{\Phi}$ displays significantly greater variations compared to Φ, with the lowest value occurring in winter and the highest values observed in spring and summer seasons. The increased fluctuations in $\hat{\Phi}$ may be caused by a reduction in solar resource availability during the winter, which makes $\hat{\Phi}$ metric more sensitive to changes in the data. This increased sensitivity is also due to the fact that $\hat{\Phi}$ incorporates the square of the variables in its formulation. Moving from two resources to three resources is noticeable that the total variation complementarity metric Φ consistently proves to be the most robust and less variable, as it is function of both auto-correlation and cross-correlation, as mentioned in sec.III-A.

Furthermore, the reported values may vary when evaluating the extracted power from a specific device. To assess complementarity by filtering the raw resource through an energy converter, certain physical and spatial constraints should be considered. For instance, seabed depth can limit the installation of substructures for offshore wind turbines, offshore photovoltaic panels, and wave energy converters. In addition, spatial constraints such as shipping lanes, military zones, disposal sites, and protected areas should be considered. It is also important to consider the requirement of installing devices at a minimum distance from the coastline, even though this constraint has already been addressed, as all analysis have been carried out at locations situated at least 10 km from the coast.

TABLE I

Φ, $\hat{\Phi}$ AND Φ_s RESULTS FOR WIND-WAVE RESOURCE MIX

Locations	Φ	$\hat{\Phi}$	Φ_s
Elba Island	0.125	0.138	0.071
Capraia Island	0.114	0.143	0.070
Livorno	0.094	0.176	0.092

V. CONCLUSIONS

In this study, a temporal complementarity assessment between two and three renewable energy raw resources, i.e.

TABLE II
Φ, $\hat{\Phi}$ AND Φ_s RESULTS FOR WIND-SOLAR RESOURCE MIX

Location	Φ	$\hat{\Phi}$	Φ_s
Elba Island	0.071	0.528	0.221
Capraia Island	0.084	0.531	0.244
Livorno	0.082	0.528	0.234

TABLE III
Φ, $\hat{\Phi}$ AND Φ_s RESULTS FOR WAVE-SOLAR RESOURCE MIX

Location	Φ	$\hat{\Phi}$	Φ_s
Elba Island	0.031	0.527	0.213
Capraia Island	0.032	0.524	0.216
Livorno	0.027	0.524	0.229

TABLE IV
Φ, $\hat{\Phi}$ AND Φ_s RESULTS FOR WIND-WAVE-SOLAR RESOURCE MIX

Location	Φ	$\hat{\Phi}$	Φ_s
Elba Island	0.105	0.497	0.316
Capraia Island	0.115	0.486	0.326
Livorno	0.107	0.487	0.330

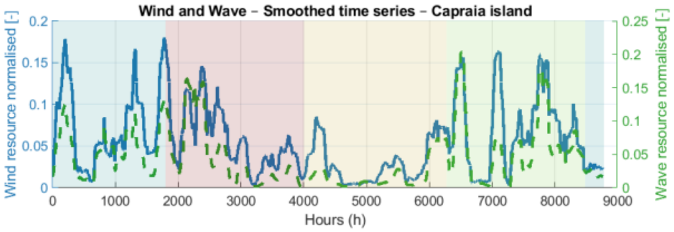

Fig. 2. Smoothed time series of normalised power densities at Capraia Island for wind-wave mix. Background shading indicates seasons: blue for winter, red for spring, yellow for summer, and green for autumn.

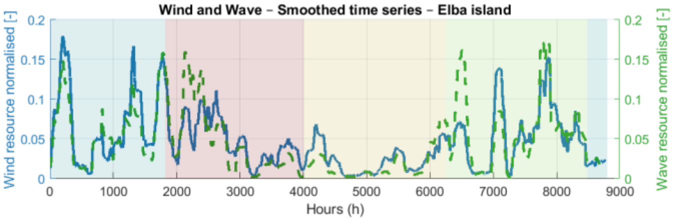

Fig. 3. Smoothed time series of normalised power densities at Elba Island for wind-wave mix. Background shading indicates seasons: blue for winter, red for spring, yellow for summer, and green for autumn.

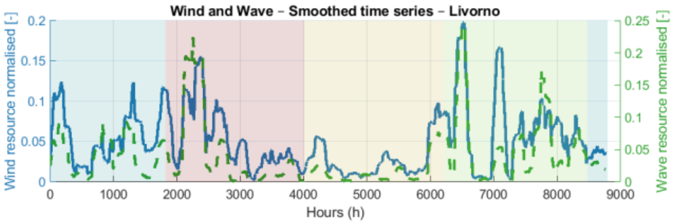

Fig. 4. Smoothed time series of normalised power densities at Livorno for wind-wave mix. Background shading indicates seasons: blue for winter, red for spring, yellow for summer, and green for autumn.

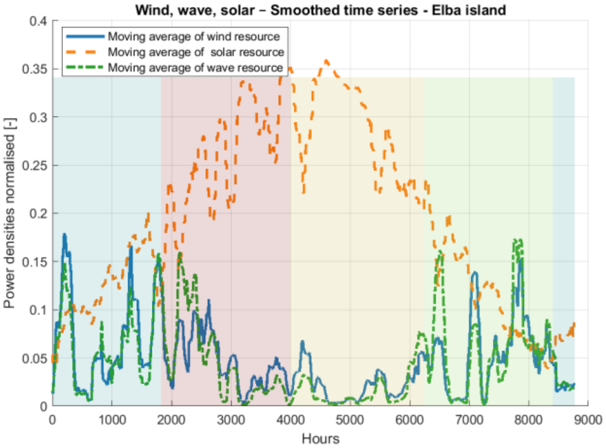

Fig. 5. Smoothed time series of normalised power densities at Elba Island for wind-wave-solar mix. Background shading indicates seasons: blue for winter, red for spring, yellow for summer, and green for autumn.

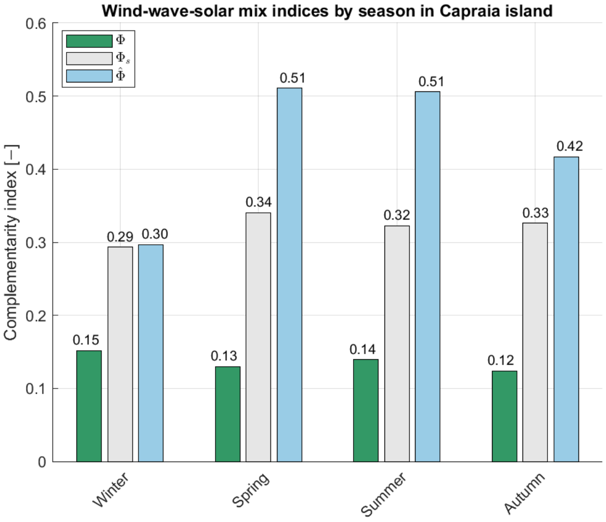

Fig. 6. Seasonal complementarity indices at Capraia Island for wind-wave-solar resources.

solar-wind-wave, in the North Tyrrhenian Sea is presented, and differences in energetic complementarity between three sites within this region are highlighted. The analysis is carried out by implementing three innovative complementarity indices Φ, Φ_s, and $\hat{\Phi}$ which facilitate the evaluation of temporal complementarity across multiple resources at the same time. The total variation complementarity metric Φ shows reliable results compared to Φ_s and $\hat{\Phi}$ metrics, which tend to overestimate complementarity and show higher sensitivity to variations in time series data. Findings show that complementarity between wind and wave raw resources is higher near Elba island than near the Livorno coast and Capraia Island because the temporal distribution of energy resources is such that they balance each other more effectively. Thereby, the analysis reveals that mixing wave and wind resources is most beneficial when they are harnessed in Elba Island. Conversely, results reveal that Capraia Island is more suitable for exploiting wave-solar, wind-solar and wind-wave-solar resources as the temporal complementarity of these energy combinations is higher at this site. Specifically, the highest total variation complementarity value is observed when all three resources are combined, indicating that greater continuity and reliability in energy supply could be achieved through such a multi source integration. However, the outcomes may vary when spatial complementarity is considered, or when complementarity is evaluated based on the actual power extracted by specific energy converters. In such cases, additional constraints should be considered.

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