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A review on the complementarity of renewable energy sources: Concept, metrics, application and future research directions

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ABSTRACT

Global and regional trends indicate that energy demand will soon be covered by a widespread deployment of renewable energy sources. However, the weather and climate driven energy sources are characterized by a significant spatial and temporal variability. One of the commonly mentioned solutions to overcome the mismatch between demand and supply provided by renewable generation is a hybridization of two or more energy sources into a single power station (like wind-solar, solar-hydro or solar-wind-hydro). The operation of hybrid energy sources is based on the complementary nature of renewable sources. Considering the growing importance of such systems and increasing number of research activities in this area this paper presents a comprehensive review of studies which investigated, analyzed, quantified and utilized the effect of temporal, spatial and spatiotemporal complementarity between renewable energy sources. The review starts with a brief overview of available research papers, formulates detailed definition of major concepts, summarizes current research directions and ends with prospective future research activities. The review provides a chronological and spatial information with regard to the studies on the complementarity concept.

1. Introduction and motivation

Over the last years, variable renewable energy sources (VRES) have become a cost-competitive and environment-friendly alternative to supply power to isolated and central/national power grids around the globe. Nevertheless, because of their intermittent/variable/stochastic/non-dispatchable characteristic, they cannot provide the grid with various additional and mandatory services other that delivering a certain volume of energy.[1] In order to explore how to effectively improve VRES integration into the power systems, more needs to be known about the underlying behavior patterns and dynamics of their power generation. Consequently, over the recent years many investigations have focused on the VRES grid integration (Cheng et al., 2019; Denholm et al., 2018; Weitemeyer et al., 2015).

Several solutions worth mentioning were presented by Jacobson and Delucchi (2011) who suggested to apply them in order to facilitate the process of VRES integration:

- interconnecting spatially distributed generators;
- using complementary or/and dispatchable generators in hybrid configurations;
- application of demand-response and flexible loads;
- deploying energy storage;
- oversizing and power to X;
- using the concept of vehicle to grid – use of electric vehicles as storage;
- forecasting of VRES generation.

Notably, two of the referenced concepts mention the use of a combination of VRES sources, which exhibit a complementary nature of their operation. First is the hybridization of energy sources (like solar-wind, wind-hydro, etc.) and the second is the use of spatial distribution

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[1] It is worth mentioning that besides active power, inverters of renewable power generators can also provide reactive power for voltage control and could be programmed to provide inertia (Kroposki et al., 2017).

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of generators to smooth the power output of given VRES. Both concepts are based on the complementary (to various extent) nature of renewable energy sources.

From the literature point of view, we would like to draw attention to works by Hart et al. (2012) and Engeland et al. (2017). Although not explicitly, both considered the concept of VRES complementarity in their analysis. The first paper provided an in-depth analysis from the power system operation perspective, whereas the second looked at it rather from a climate/meteorological perspective.

The objectives of this review paper are to: provide a thorough overview on the past research activities concerning the concept of energetic resources complementarity; analyze and assess the existing state of knowledge; provide guidelines for potential future research directions. More specifically, we aim at answering the following research questions:

- What is and how is the concept of energetic complementarity defined?
- Which are the types of energetic complementarity?
- How did the studies on complementarity evolve and what are major, still unresolved shortcomings?
- Which metrics/indices are used to evaluate complementarity?
- What are potential applications of complementarity metrics?

In our research, we have applied a narrative approach of writing a review paper. Consequently, we have focused on comparing, and summarizing the existing theory/models and formulating conclusions on qualitative level. The investigated topic has been structured based on methodological approaches (indices and methods for complementarity assessment), chronological order and geographical location. To ensure a wide coverage of studies investigating complementarity concept we have used the following search engines: Science Direct, Scopus and Google Scholar. After the initial screening of papers containing the keyword "complementarity", we have performed an additional search based on the references present in those papers and included those relevant to the subject. According to the Cooper's taxonomy (Cooper, 1988) this review can be described as summarized in Table 1.

The rest of this paper is structured as follows: in Section 2 we start with a clear and updated definition of the "complementarity" concept. In Section 3 we present the historical and geographical overview of the research on the complementarity – simply statistics on complementarity research. In Section 4 we analyze and describe the various metrics used to assess the complementarity. In Section 5, we discuss current possibilities of applying the concept of complementary and we formulate further potential applications. The paper ends with Section 6, which summarizes the review and presents potential future research directions. The Appendix A contains a table which gathers all relevant papers and presents their content in a structured way.

2. Definition of the complementarity concept

According to the Oxford dictionary, the term complementarity is: "a relationship or situation in which two or more different things improve or emphasize each other's qualities". Considering the context of energy sources, the complementarity should then be understood as the capability of working in a complementary way. Complementarity can be observed in time, space and jointly in both domains. The graphical explanations are provided in Figs. 1 and 2. On both figures, sine functions with different phase angles were used to "simulate" the theoretical and idealized operation of renewable energy sources. In these particular cases, the time domain (horizontal axis) is irrelevant and can either refer to seconds, hours, months or years. Fig. 1 presents five different situations (charts A-E) where the renewable sources exhibit different level of complementarity (expressed here as coefficient of correlation). For this idealized situation, only the sources presented on chart E are capable of satisfying the load whereas in the remaining cases we observe either oversupply or deficient generation. The solution to overcome the problems presented on charts B-D would be either to oversize the system or apply energy storage. In case presented on chart A both sources reach "0" generation in the same time, therefore only energy storage could be considered, or spatial distribution of generators as visualized in Fig. 2. On this figure two cases were presented, and they show that despite VRES being spatially distributed their generation can still follow the same patterns which will result in load not being covered. Nevertheless, the combination of spatial distribution and temporal complementarity can improve the overall reliability of the system. This issue will be discussed further in later sections.

Based on the above figures and literature review the following paragraphs aim to provide the brief definition of complementarity types:

Spatial complementarity – can be observed between one or more types of energy sources. It is a situation when energy resources complement each other over certain region. Scarcity of one VRES in region x is complemented by its availability in region y at the same time. An example of space complementarity can be the smoothing effect of spatially distributed wind generators whose energy production trends exhibit decreasing coefficient of correlation with an increasing distance between sites.

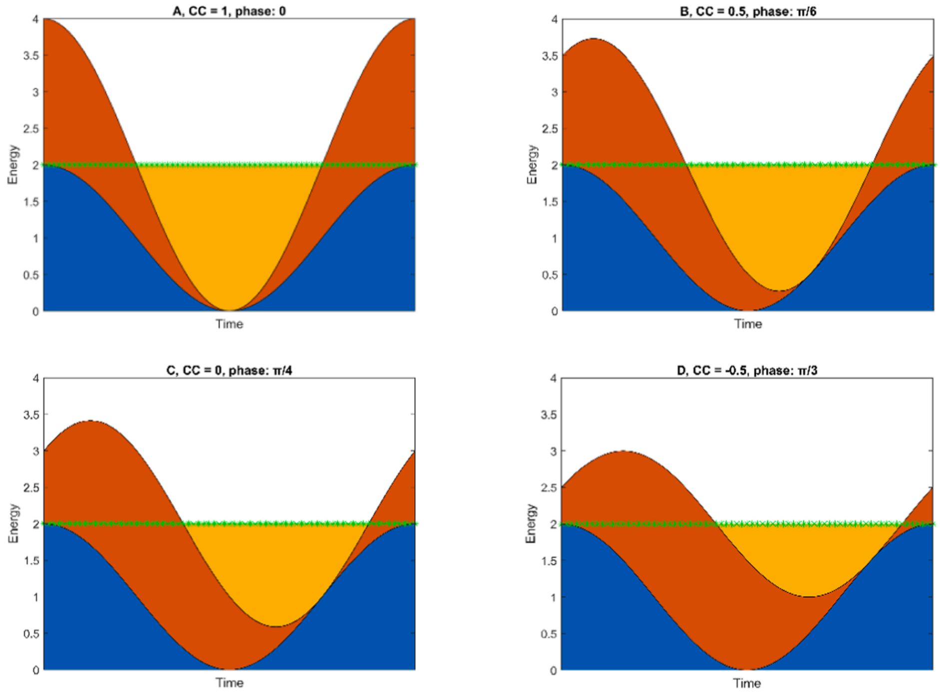
Temporal complementarity – can be observed between two or more energy sources in the same region. It is understood as a phenomenon when VRES exhibit periods of availability which are complementary in the time domain. As an example, it is possible to mention the annual patterns of wind and solar energy availability over Europe, where the former is abundant in Autumn – Winter whereas the latter is abundant in the Spring-Summer period. An example of temporal complementarity for a single source is provided in the note below Table 2. This table presents the characteristics of the different types of complementarity.

Spatio-temporal complementarity – (complementarity in time and space) is considered for a single or multiple energy sources whose complementary nature is investigated simultaneously in time and space domains. A good example is the Brazilian power system and its hydropower resources, which lead to an interconnection of the south-southeastern and north-northeastern subsystems.

The energetic complementarity can be assessed based on various indices and metrics, with the most relevant being described in Section 4.

Table 1
Characteristics of this review based on Cooper's taxonomy.

Characteristic	Cooper's definition	Authors' selection
Focus	The material that is of central interest of the reviewer	Research methods, outcomes, theories and applications
Goal	What the author hopes the review will reveal	Integration of available knowledge, criticism
Perspective	Reviewer point of view	Neutral
Coverage	The extent to which reviewer includes the relevant works	Representative
Organization	Paper organization	Methodological
Audience	Intended paper audience	Specialized scholars/decision makers



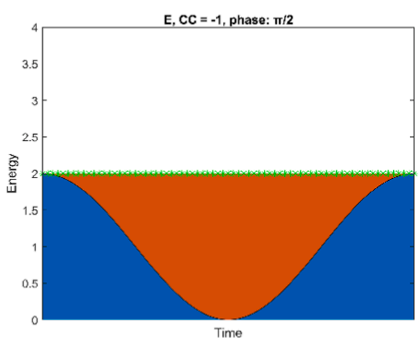


Chart	Load not covered	Min/Max generation
A	31.4%	0/4
B	27.2%	0.27/3.73
C	22.2%	0.58/3.42
D	15.7%	1/3
E	0.0%	2/2

Sources generation range: 0-2. Load: constant 2.

Fig. 1. Complementarity concept explained by means of sine signal. CC – coefficient of correlation.

3. Research on complementarity

3.1. Historical perspective

We have performed an in-depth analysis of available literature on the complementarity concept and found that the first papers dedicated to this topic were published in the late-seventies. Two papers by Kahn (1979, 1978) and a paper by Takle and Shaw (1979) investigated complementarity, mostly focusing on reliability of spatially distributed wind generators. The aim of their works was to answer the question whether spatial dispersed wind parks can provide firm power to the system, thus allowing replacing conventional fuel based generators. Kahn stated that the study of energetic complementarity is a very promising area of research, and its assessment should be considered when pondering VRES integration to power systems. On the other hand, the paper by Takle and Shaw (1979) investigated the temporal complementarity between solar and wind resources in Iowa. Their findings show strong complementary on an annual basis but only slight on a daily scale. Along with the series of studies summarized by Justus and Mikhail (1979), the aforementioned works can be considered as the pioneer research contributions in the area of complementarity between renewable sources. Over the recent years the number of papers dealing with the complementarity concept widely varied, however, the period from 2016 to 2018 has been the most productive, as seen in Fig. 3. This might be associated with the growing importance of renewable sources and their integration in the power systems.

3.2. Spatial coverage

Research case studies on the complementarity concept have not been spatially uniformly distributed across the world. According to the conducted literature review, the majority of research papers concentrates on Brazil, China, USA and Europe. Such concentration of research is not a surprise considering the fact that the mentioned regions either historically had a large share of renewable generation (e.g.: Brazil with hydropower) or are currently putting a lot of effort into increasing the share of renewable resources in their power systems (Figs. 4 and 5). The spatial coverage and statistics presented in this review are the ones found within the search algorithm described in the introduction section, however, it is probable that further works might be available as theses, reports, etc., written in languages different from English.

3.3. Structure of research on complementarity

In this section, we briefly present the reader with the overall statistics regarding the documental database created for this review on renewables complementarity. Overall, the research is dominated by analyses focusing on complementarity between two selected renewable energy sources (over 60% of papers), as seen in Fig. 6. Out of these, 34

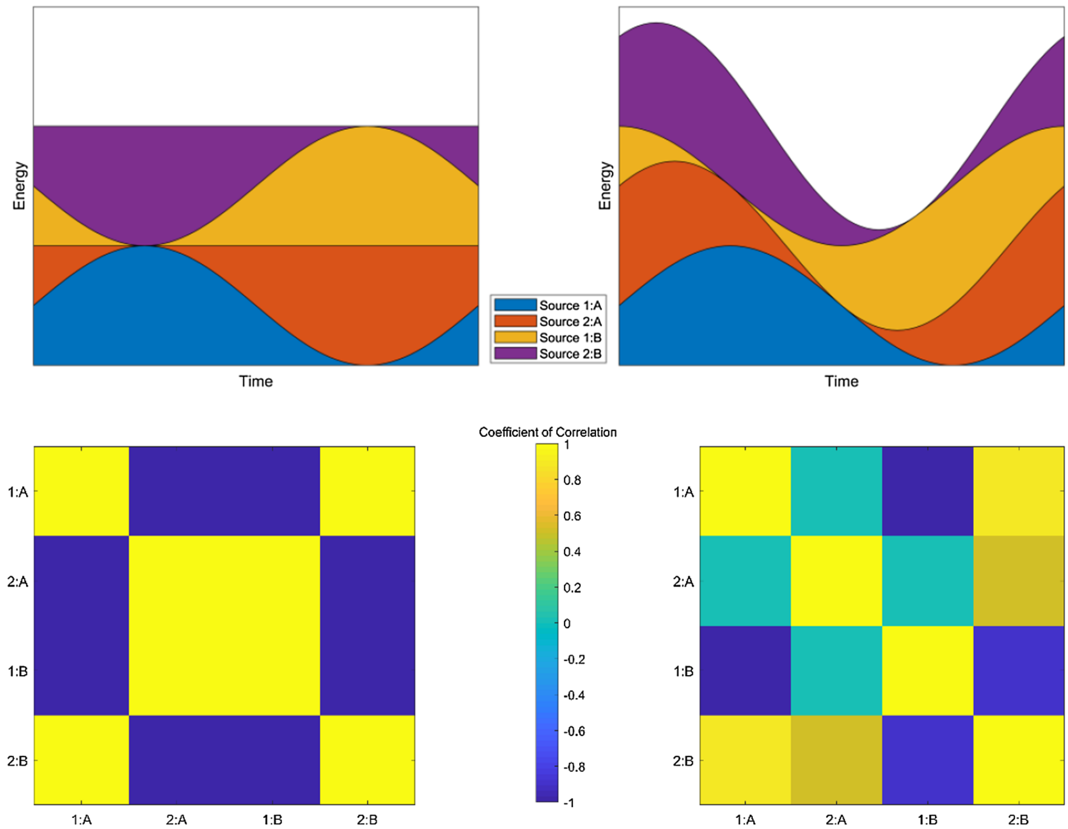


Fig. 2. Conceptual visualization of spatio/temporal complementarity. Legend/axis reads: "1:A" energy source "1" in location "A" etc. Left chart a perfect spatial and temporal complementarity between energy sources. Right chart a perfect complementarity between the same source located in two different sites "A" and "B", good complementarity between sources "1" and "2" in location "B" lack of complementarity between sources "1" and "2" in location "A" as well as between "1" and "2" in locations "A" and "B".

papers focused on solar-wind complementarity, whereas the remaining works evaluated complementarity between solar-hydro and wind-hydro resources. Research on complementarity between more than two renewable sources is gaining popularity in recent years, however, most of these studies focus on complementarity in terms of optimal sizing and/or operation of solar-wind-hydro systems.

The selection of the temporal resolution is extremely important when analyzing the balance between power supply and demand. Most energy analysis models are based on time series with hourly or sub hourly (15 min) time steps. From the documents analyzed in this paper, it is possible to observe that the majority of those works made their analysis based on time series divided in hourly time steps (see Fig. 7) – what is in line with the approach used in modelling activities. It is however important to underline that a significant part of the papers included in this review investigated complementarity for multiple time scales.

Time series for assessing availability and variability of VRES can be obtained from various sources. The most commonly used are ground measurements, satellite measurements and numerical models/reanalysis.

From the consulted references it was found that more than half of the considered studies were based on time series created from ground measurements, whereas the remaining papers relied on mixed data sources or single satellite or reanalysis data sources. For clarification, a reanalysis is a data assimilation project that combines a physical model with historical observational data into a single consistent dataset. Within the considered literature, studies that relied on reanalysis were mostly based on Numerical Weather Prediction (NWP) and physical models, *i.e.* numerical models that use physical laws to simulate the atmosphere, such as MERRA-2 (Global Modeling and Assimilation Office - GMAO, 2015).

4. Quantifying energetic complementarity: indices, metrics and other approaches

Since the early works about energetic complementarity between VRES, authors have been trying to assess this complementarity by means of statistical metrics and other indices. This assessment has become more relevant with the current trend of increasing renewable penetration in national power grids, while maintaining high levels of

Table 2
Characteristics of the different types of energetic complementarity.

Type of complementarity	Number of sources considered	Number of sites/regions considered	Factor driving the existence of complementarity
Temporal	≥2*	=1	Different availability in time
Spatial	≥1	≥2	Different availability in space
Spatio/temporal	≥1	≥2	Time/space different availability

* In case of temporal complementarity, a single energy source can be also considered by using the "flexibility" offered by technology. For example, the complementarity (smoother power output over the day/year) of single PV system can be increased by mounting PV arrays at different azimuths and inclination angles. The same applies to the wind farm where different wind turbines can be used with various hub heights or power curves.

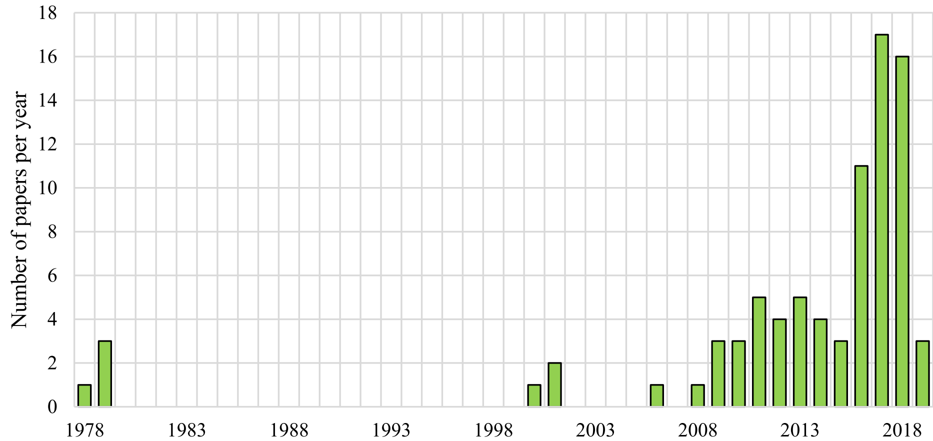


Fig. 3. Number of papers per year in area of renewable energy sources complementarity considered in this review.

reliability and optimizing the financial resources available.

One of the first examples of using metrics for evaluating energetic complementarity can be found in the paper by Takle and Shaw (1979). Besides using superposition to analyze combined solar and wind energy per unit area, these authors have evaluated the product of deviations of the daily total from the expected amount for solar and wind resources, using the monthly and annual averages of these results for drawing their conclusions and suggesting some applications and considerations based on complementarity between the two energy sources.

Since then, several works have been conducted on metrics and indices to evaluate complementarity, as evidenced in Appendix A. In this section, we will present the most common and relevant metrics, indices and approaches that have been applied in assessing complementarity between renewable energy sources.

Throughout the section, we assume given paired data $\{(g_1^s, g_1^{s'}), \cdots, (g_n^s, g_n^{s'})\}$, where g_t^s, $g_t^{s'}$ are generation time series of s and s', that could differ by technology or location. The lower index refers to the time step and the difference between two timesteps Δ_t is typically given in hours or days.

4.1. Correlation

Correlation is the most widely used measure of dependence between two randomly distributed variables. In a broad sense, it can be defined as a metric that directly quantifies how variables are linearly related (Carmona, 2014). Correlation has been the metric most commonly used in papers dealing with complementarity measurements.

The Pearson correlation coefficient r is defined as

$$r_{g^s g^{s'}} = \frac{\mathrm{cov}(g_t^s, g_t^{s'})}{\sigma_{g_t^s}\sigma_{g_t^{s'}}} = \frac{\sum_{t=1}^{n}(g_t^s - \bar{g}^s)(g_t^{s'} - \bar{g}^{s'})}{\sqrt{\sum_{t=1}^{n}(g_t^s - \bar{g}^s)^2}\cdot\sqrt{\sum_{t=1}^{n}(g_t^{s'} - \bar{g}^{s'})^2}}. \quad (1)$$

Also called the simple correlation coefficient, this coefficient measures the association strength between two variables, with values ranging from −1 to +1. A value of 0 implies that no association exists between the two variables; a positive value indicates that as the value of one of the variable increases or decreases, the value of the other variable has a similar behavior; on the other hand, a negative value signifies that as the value of one variable increases, the value of the other variable decreases, and vice versa (Vega-Sánchez et al., 2017).

The most common purposes for calculating the Pearson correlation coefficient regarding energetic complementarity are:

- conducting statistical analyses for evaluating if the renewable energies available in one region could allow the configuration of efficient power systems based on renewables (e.g.: Miglietta et al., 2017; Shaner et al., 2018; Slusarewicz and Cohan, 2018);
- as a tool for improving the operation or planning of existing power plants or systems (e.g.: Cantão et al., 2017; Denault et al., 2009; Jurasz et al., 2018a; Ramírez, 2015);
- as part of the set of equations, parameters and inequalities in an optimization model (e.g.: Aza-Gnandji et al., 2018; Naeem et al., 2019; Zhu et al., 2018b).

A list of papers considering simple correlation for assessing energetic complementarity can be found in the Appendix A at the end of the document.

Another type of correlation coefficient, the Kendall correlation coefficient, usually called Kendall's Tau, with notation τ, is a non-

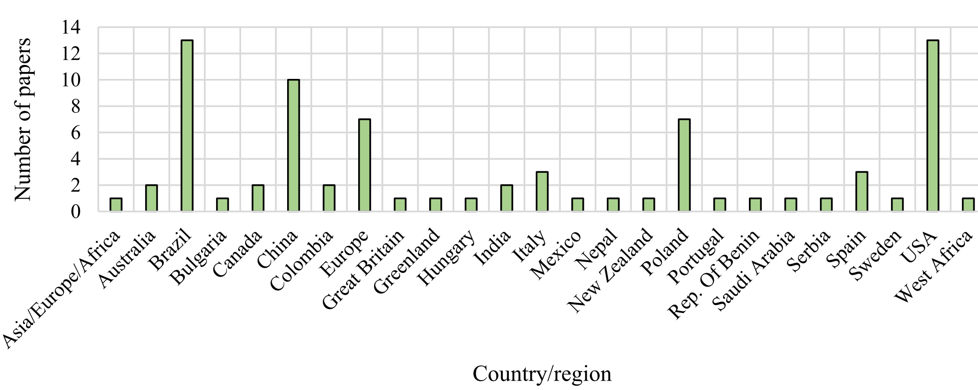


Fig. 4. Number of papers per country/region which investigated the concepts related to energetic complementarity of VRES.

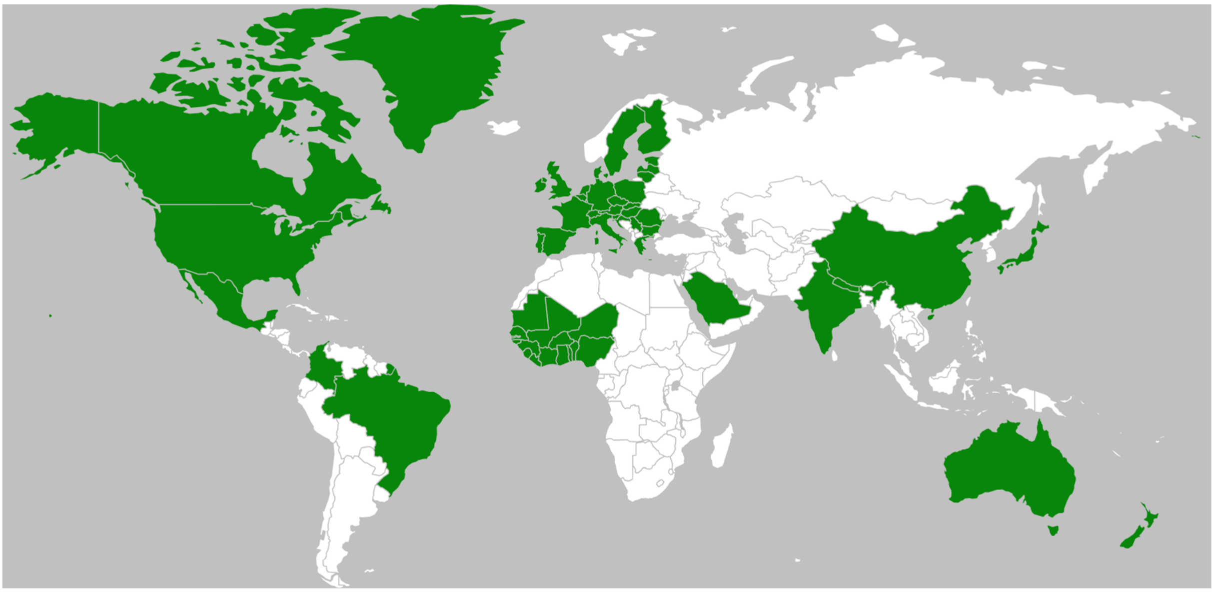


Fig. 5. Spatial coverage of studies considered in this review on renewable resources complementarity.

parametric measure of the rank dependence between two sets of random variables (Carmona, 2014).

Any pair of values $(g_t^s, g_t^{s'})$ and $(g_{t'}^s, g_{t'}^{s'})$ is called concordant, if the ranks of both elements agree, that is either $g_t^s > g_{t'}^s$ and $g_t^{s'} > g_{t'}^{s'}$ or $g_t^s < g_{t'}^s$ and $g_t^{s'} < g_{t'}^{s'}$. Otherwise, this pair is called discordant. Let C be the number of concordant pairs and D be the number of discordant pairs.

Kendall's correlation coefficient is then defined as

$$\tau(g^s, g^{s'}) = \frac{C - D}{\frac{n(n-1)}{2}}. \tag{2}$$

Since $\frac{n(n-1)}{2}$ is the number of possible pairs, $\tau(g^s, g^{s'}) \in [-1, 1]$.

In terms of energetic complementarity, a perfect agreement between two rankings would yield $\tau = 1$, meaning concurrent behavior between resources. Consequently, if one ranking is the reverse of the other, then $\tau = -1$, indicating the best possible complementarity between the sources.

There are some authors that have applied the Kendall correlation coefficient for energetic complementarity assessments. Denault et al. (2009) used it as one of the copulas for modeling the dependence between wind and hydropower resources in the province of Quebec to evaluate the possible effect of wind power in reducing the risk of water inflow shortages. Xu et al. (2017) have assessed the spatial and temporal characteristics of wind and solar complementarity in China in their paper, where they have employed the Kendall rank correlation coefficient as the dependence measure and regionalization index. A recent paper by Han et al. (2019) has compared the results obtained by the method proposed by them with Kendall's tau to describe the complementarity between three renewable sources, including fluctuation and ramp effects in their calculations.

Spearman's rank correlation coefficient is another measure of rank dependence. The Spearman's correlation coefficient can be described as Pearson correlation applied to ranks (Myers and Well, 2003). For a distribution or an infinite population, it is required to transform both variables by their univariate marginal cumulative distribution functions (CDF), allowing to compute the Pearson correlation coefficient for the transformed variables (Ruppert and Matteson, 2015).

First, the ranks $rg(g_t^s)$ and $rg(g_t^{s'})$ for datasets g_t^s and $g_t^{s'}$ are computed, allowing to calculate the Spearman's rank correlation coefficient:

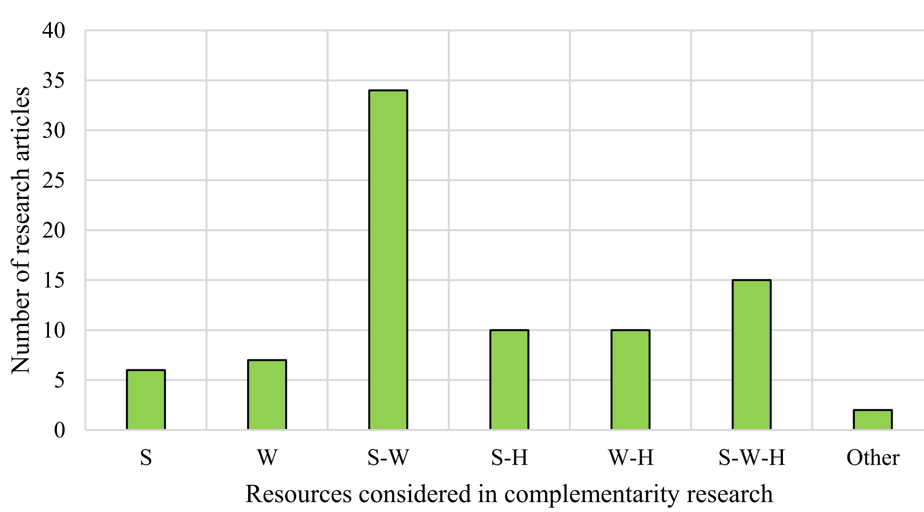


Fig. 6. Number of studies investigating different complementarities (S – Solar, W – Wind, H – Hydropower, S-W – Solar-Wind, etc.). Other refers to combination of solar and/or wind with biomass, wave. – for more details please see Appendix A.

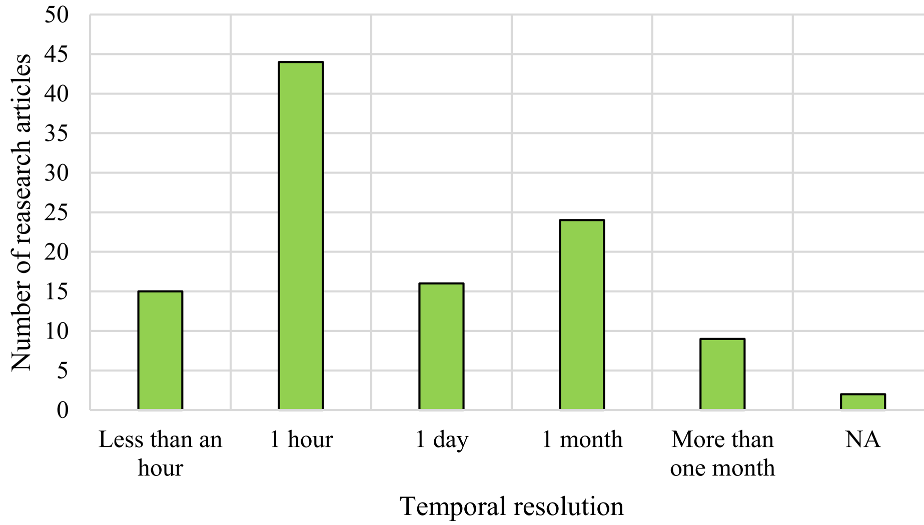


Fig. 7. Temporal resolution of complementarity analysis. Please note that multiple studies considered more than one time-scale. More than one month –refers to inter-annual intra-annual variability.

$$\rho_s(g_t^s, g_t^{s'}) = \frac{\mathrm{cov}(\mathrm{rg}(g_t^s), \mathrm{rg}(g_t^{s'}))}{\sigma_{\mathrm{rg}(g_t^s)}\sigma_{\mathrm{rg}(g_t^{s'})}} \tag{3}$$

For studies related to energetic complementarity, Spearman's rank correlation coefficient has been used by Denault et al. (2009) along with the Pearson and Kendall's tau as the copulas for assessing dependence between wind and hydropower resources in Quebec. Using Pearson's and Spearman's correlation coefficients, Cantão et al. (2017) have produced wind and hydropower complementarity maps for the entire Brazilian territory based on the weather stations used to create Voronoi cells (or Thiessen polygons).

A technique developed in the 1930′s using correlations, the canonical correlation analysis (CCA) can be described as a multivariate statistical technique used for identifying possible links between sets of multiple dependent variables and multiple independent variables (Santos-Alamillos et al., 2015). Whereas multiple regression techniques found the most suitable equation for a single dependent variable based on a set of independent variables, CCA tries to simultaneously estimate the value of multiple dependent variables from the set of available independent variables, using weighted functions for maximizing correlation between these two sets (Santos-Alamillos et al., 2012). Some examples are the relation between governmental policies and the different economic growth indicators, relation of price variables (initial price, salvage value, etc.) of a car and its features, relation between job performance and company characteristics. The CCA method is fully described in Härdle and Simar (2015).

With the southern half of the Iberian Peninsula as a case study, Santos-Alamillos et al. (2012) used CCA with the aim of finding the optimal distribution of wind and solar farms over the region, while keeping a regular energy input into the power system, using coupled spatiotemporal canonical patterns for their analysis. In a follow-up paper, Santos-Alamillos et al. (2015), this time using the region of Andalucia as a case study, used Principal Component Analysis (PCA) coupled with CCA to evaluate if a combination of wind power and concentrating solar power (CSP) could provide an adequate baseload power to the region. PCA is a technique that allows reducing an initial dataset from several quantitative dependent variables (usually correlated) to a few representative variables, known as principal components, which are obtained as linear combinations of the initial variables (Santos-Alamillos et al., 2014).

The cross-correlation function is a measure of similarity that compares two component series of a stationary multivariate time series, where a delayed similarity exists (Li et al., 2009; Ruppert and Matteson, 2015). For two real valued sequences of the same time series and delayed by δt, cross-correlation values range from -1 to 1 and are given by the Pearson correlation of the time series with its time-shifted copy:

$$r_{g_t^s, g_{t+\delta t}^s} = \frac{\sum_{t=1}^{n}(g_t^s - \bar{g}^s)(g_{t+\delta t}^s - \bar{g}_{t+\delta t}^s)}{\sqrt{\sum_{t=1}^{n}(g_t^s - \bar{g}^s)^2}\cdot\sqrt{\sum_{t=1}^{n}(g_{t+\delta t}^s - [\bar{g}_{t+\delta t}^{s\,2}])}}. \tag{4}$$

Cross-correlations can help to understand the relation between the component series or how they are influenced by a common factor. However, like all correlations, they are only a statistical measure of association, not causation, therefore, determining causal relationships requires further knowledge and analysis (Ruppert and Matteson, 2015).

Cross-correlation was the main metric employed by Justus and Mikhail (1979) for assessing spatial energetic complementarity between pairs of sites. In their report, these authors summarized the results from a series of studies made in the 1970′s of wind and power distributions for large arrays of wind turbines in the United States. This metric has been also employed in studies related to assessing the possible benefits of distributed wind power generation in Europe (Su and Gamal, 2013), measuring the complementarity between demands and wind and solar resources in Australia (Li et al., 2009), PV power fluctuations in the Iberian peninsula (Marcos et al., 2012), and calculating complementarity between renewable energy resources in Brazil (Dos Anjos et al., 2015; Silva et al., 2016).

4.2. Indices

An index is a metric used to summarize a set of features in a single value. Some authors have proposed this kind of metrics for evaluating energetic complementarity, and three of them are briefly described in this section.

4.2.1. Time-complementarity index

This index for assessing energetic time-complementarity has been proposed by Beluco et al. (2008). It has been tested for analyzing energetic complementarity between solar and hydropower resources in the state of Rio Grande do Sul, Brazil. The time-complementarity index created by the aforementioned authors is calculated as the product of three partial indices: (1) Partial time-complementarity index (which evaluates the time interval between the minimum values of two sources); (2) Partial energy-complementarity index (which evaluates the relation between the average values of two sources); (3) Partial amplitude-complementarity index (which assesses the differences between maximum and minimum values of the two energy sources). Each one of the partial indices ranges between 0 and 1, therefore, a value of 0 for the time complementarity index indicates that both resources are concurrent, and a value of 1 suggests full complementarity. This index was used in other papers (e.g.: Borba and Brito, 2017; During Fo et al., 2018; Risso et al., 2018) as the energetic complementarity metric, mainly for estimating or reducing energy storage requirements; for creating a spatial representation of complementarity or for evaluating energetic time-complementarity in other regions, as shown in the Appendix A.

The individual components and the value of the metric proposed by Beluco et al. (2008) can be calculated as follows:

(1) First, the partial time complementarity k_t is calculated via

$$k_t = \frac{|d_s - d_{s'}|}{\sqrt{|D_s - d_s||D_{s'} - d_{s'}|}}, \tag{5}$$

where D_s , $D_{s'}$ are the numbers of the days when maximum energy generation from the corresponding sources s and s' were observed, d_s and $d_{s'}$ are the numbers of the days when minimum energy generation from the corresponding sources s and s' were observed.

(2) Second, the partial energetic complementarity k_e is calculated. This parameter estimates the relation between the mean values of the energy resources availability functions,

$$k_e = 1 - \sqrt{\left(\frac{\sum_t g_t^s - \sum_t g_t^{s'}}{\sum_t g_t^s + \sum_t g_t^{s'}}\right)^2}. \tag{6}$$

(3) The last partial component is the partial amplitude complementarity k_a. This component evaluates the relation between the values of the difference (δ) between the maximal and minimal of the two energy sources availability functions.

$$k_a = \begin{cases} \left[1 - \frac{(\delta_s - \delta_{s'})^2}{(1-\delta_{s'})^2}\right] & for \quad \delta_s \le \delta_{s'}; \\ \left[\frac{(1-\delta_{s'})^2}{(1-\delta_{s'})^2 + (\delta_s - \delta_{s'})^2}\right] & for \quad \delta_s > \delta_{s'}; \end{cases} \tag{7}$$

(4) To obtain values of $\delta_{s'}$ and δ_s another formula has to be introduced which reads as follows:

$$\delta_s = 1 + \frac{\max_t^d(g_t^s) - \min_t^d(g_t^s)}{\bar{d}_t^d}, \tag{8}$$

where $\max_t^d$ and $\min_t^d$ refer to the maximum and minimum daily values of the corresponding generation time series and $\bar{d}_t^d$ is the average daily consumption.

4.2.2. Load tracking index

In their scheduling optimization model, Zhu et al. (2018a,b) have combined wind, solar and hydro power output, and defined this ensemble as a virtual power (VP) plant, according to their complementary features. The capacity of the VP output to follow the load is measured by the load tracking index. Lower values of this index indicate a better performance by the VP, thus, the minimization of the load tracking index is the objective function of this model for assessing energetic complementarity in multiple time-scales. The load tracking index is defined asN_r (smaller values of this index indicate the better ability of the virtual power plant to follow the load):

$$N_r = D_t + D_s + D_c. \tag{9}$$

The first term of the load tracking index is defined as

$$D_t = \frac{1}{\bar{d}}\sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(\sum_s g_t^s - d_t\right)^2}, \tag{10}$$

where d is the energy demand. The second term is defined as:

$$D_s = \sqrt{\frac{1}{T-1}\sum_{t=1}^{n}\left(d_t - \sum_s g_t^s\right) - \left(d_t - \bar{\sum_s} g_t^s\right)}; \tag{11}$$

and, finally, the third term is defined as:

$$D_c = \frac{\max_t(d_t - \sum_s g_t^s) - \min_t(d_t - \sum_s g_t^s)}{n\Delta T}. \tag{12}$$

4.3. Metrics related to failures and reliability

In terms of power supply, a failure can be defined as any situation where the total power supplied by the system composed by the generating units and energy storage devices is less than the demand. Some authors have assessed energetic complementarity from that perspective. Stoyanov et al. (2010) have quantified the number of times and total hours of load faults for a case study in Bulgaria, assessing if complementarity between solar and wind resources followed the electrical consumption.

Beluco et al. (2012) have used a failure index to evaluate the performance of a PV-hydro hybrid system, and from their results they have concluded that a smaller failure index is associated to a higher temporal complementarity between the resources.

Assessing the potential of energetic complementarity for increasing system's reliability was one of the first research interests on this subject (Kahn, 1979). Since the early works by Kahn (1979, 1978), a common metric used in papers assessing the reliability of hybrid power systems is the loss of load probability (LOLP), which can be defined as the probability for a system of being unable to meet the demand in a given time. Indirectly, this metric accounts for one of the main concerns about renewables and their complementarity: the power output fluctuation. The LOLP is calculated as

$$\text{LOLP} = \frac{\sum_{t=1}^{n}\max(d_t - \sum_s g_t^s, 0)}{\sum_{t=1}^{n} d_t}, \tag{13}$$

where the numerator is the energy deficit and the denominator is the total energy demand for time intervals from t = 1 to t = n. This metric has been used by Schmidt et al. (2016) as a constraint in the optimization model. The LOLP parameter has also been employed in the paper by Jurasz et al. (2018a) in their analysis on how complementarity affects power system reliability.

By using several descriptive statistics and other techniques like correlation and linear regression, Shaner et al. (2018) have analyzed how the geophysical variability of solar and wind resources affects the system's reliability that can be achieved by different mixes of these two sources. Their findings indicate that energy storage and electricity transmission infrastructure requirements would be a function of the generation mix.

4.4. Assessments based on fluctuations

One of the main concerns related to increasing the fraction of variable renewables in large scale power grids is the disturbance caused by significant oscillations of these sources in time. For example, the temporal variability or fluctuation of the solar resource has two main causes: (1) the daily motion of the sun in the sky and the earth's distance from the sun along the year, which are fairly predictable and traceable; (2) the motion of clouds and weather systems, which is much harder to track and predict (Perez et al., 2016). Similarly, wind speed variability is associated with mesoscale circulations as well as with localized factors like topographic features and thermal contrasts due the proximity to water bodies (Santos-Alamillos et al., 2012). Based on this, some authors have evaluated the potential of spatial and temporal energetic complementarity for limiting or avoiding these fluctuations, and three main approaches (often assessed simultaneously) are briefly discussed in this section, with representative papers for each case.

4.4.1. Output fluctuations

The paper by Gburčik et al. (2006) used the Serbian territory for assessing how complementary regimes of solar and wind energy could be used for reducing these output fluctuations in national grids. Another evaluation of energetic complementarity considering output fluctuations is observed in the model proposed by Widén, (2015) which had the objective of estimating the integrated variability in irradiance continuously distributed over an area, caused by the movement of clouds over the region. The paper by Murata et al. (2009) investigated the relationship between the largest output fluctuation by means of output fluctuation coefficients, using solar power information from 52 sites in Japan. Their findings suggest that the largest output fluctuation of distributed photovoltaic generation can be predicted by using these output fluctuation coefficients and geographical correlation. For calculating the output fluctuation coefficient, the method proposed by these authors requires finding the variable X based on available time series of power output fluctuations. Within this context, output fluctuations are defined as the difference between two timesteps,

$$X_{t,\delta_t} = g_t^s - g_{t-\delta t}^s. \quad (14)$$

Murata et al. (2009) have introduced an output fluctuation coefficient k_M which is defined as the quotient of the largest output fluctuation for a time window with width T divided by the standard deviation of variable X:

$$k_M(\tau) = \frac{\max\limits_{t,\delta_t}(g_t - g_{t-\delta t})}{\sigma_\chi}, \delta t \leq T, \quad (15)$$

Marcos et al. (2012) have demonstrated that short-term power fluctuations produced by a set of large PV plants geographically dispersed are considerably diminished when compared with a single PV plant of the same capacity of the ensemble; both in terms of the largest output fluctuation and the relative frequency. The method for power fluctuations estimation proposed by the authors is based on the output fluctuations as defined before.

4.4.2. Ramp rate assessment

The ramp rate is a common metric in power generation that expresses how quickly the power output changes over time, and is usually expressed in MW/min. This parameter is established to keep an adequate balance between power supply and demand, preventing undesirable effects in the power system and grid due to these rapid fluctuations in loading or discharge, and their impact on the system's reserve (Zhang et al., 2018a). The ramp rate offers a simple metric for analyzing power transients (Tarroja et al., 2013), and because of this, some authors have included ramp rates assessments in their energetic complementarity studies (Tarroja et al., 2013; Widén, 2011; Zhang et al., 2018a). According to Kleissl (2013), the ramp rate of any given plant output is calculated by subtracting values of the power-output time series and dividing it by the timescale. The formula for ramp rate (RR) at time scale Δt reads:

$$RR_t^{s^{\Delta t}} = \frac{1}{\Delta t}\left(\sum_t^{t+\Delta t} g_t^s - \sum_{t-\Delta t}^{t} g_t^s\right). \quad (16)$$

It is vital to understand the importance of the selected time step, because the mean value of RR calculated on short time steps will be smaller than on longer time steps (Kleissl, 2013). It is recommended to analyze the RR values in form of a cumulative distribution plot and pay attention to the extreme values, which are of great importance to the power system operator.

4.5. Other relevant metrics

As seen along this section of the paper, complementarity assessments have been conducted through different approaches. There are some that are not possible to categorize in the previous subsections, but worth mentioning in this document.

The smoothing effect refers to the reduced output variability if several locations of power generation are aggregated. It is a common terminology in investigations on variability and has been commonly studied in a variety of papers. Liu et al. (2013) assessed this feature by investigating the duration curves of the single sites and the duration curve of their sum. They found a considerably smaller spread of values, particularly for wind. Hoicka and Rowlands (2011) quantified smoothing of the joint generation from wind and solar resources compared to single sources in Ontario, Canada and found that instances of high and low production are less frequent when the complementary behavior is considered.

Krutova et al. (2017) evaluated the smoothing effect of Wind-PV mixes in an optimization model, using as case study the entire Afro-Eurasia region. They found a significant balancing potential on these continent-wide scales. Jurasz and Ciapała (2017) observed that is possible to smooth the energy demand curve by means of complementarity, as in their paper they evaluate a hybrid PV-run-of-river system. Spatial and temporal wind and solar power characteristics are analyzed by Tarroja et al. (2013, 2011). Their findings indicate that size and spatial distribution of these power plants significantly reduces the magnitudes of hourly power fluctuations.

In the manuscript by Berger et al. (2018), they show that low wind power production events can be counterbalanced on a regional scale by taking advantage of the different wind patterns across the region (western Europe and southern Greenland in their case study). Their findings evidenced that wind power production on different continents might decrease the number of low wind power production events, making a case for evaluating the potential benefits of intercontinental electrical interconnections.

Glasbey et al. (2001) created a method for the statistical modelling of spatiotemporal variations of global irradiation on a horizontal plane, using covariance as the main metric for assessing the impact of time lag and distance on irradiation complementarity in two sites.

The Power Spectral Density (PSD), which is a measure of power content versus frequency, has been used for characterizing the observed variability of wind and solar power plants as function of different time scales and locations. The procedure and complete formulation is described in detail in Klima and Apt (2015). The PSD metric has been also used by Katzenstein et al. (2010) and Tarroja et al. (2013, 2011) for assessing energetic complementarity.

Risso and Beluco (2017) proposed a method for performing a graphical representation of temporal complementarity of resources at different locations, by means of a chart of complementarity as a function of distance, using a hexagonal cell network for dividing the case study region. In a follow-up paper (Risso et al., 2018), the method was extended, with the graphical representation now portrayed as complementary roses, with the length of the petals denoting the distance to another cell and their color the magnitude of energetic complementarity between these cells.

Spatial and temporal complementarity (synergy) of wind and solar resources in Australia was assessed by Prasad et al. (2017). The Robust Coefficient of Variation was the main metric employed for evaluating the variability of these renewables, and besides this, the method mostly consisted in measuring the occurrence of solar and wind resource above a minimum threshold. The Robust Coefficient of Variation differs from the common Coefficient of Variation in its use of the median instead of the mean. By doing so, affectations caused by extreme values are avoided. Gunturu and Schlosser (2012) provide the Robust Coefficient of Variation (RCoV) equation as follows:

$$\mathrm{RCoV} = \frac{median(|g_t^s - median(g_t^s)|)}{median(g_t^s)}, \quad (17)$$

The RCoV metric can be used to study the variability of wind and solar resources. If two regions (or power plants) are considered and have the same power densities, the one with a lower absolute deviation about the median will be characterized by a lower RCoV, and therefore, it will have a more constant power generation.

The concept of critical time windows, which represent periods within the time series with low average capacity factors, is proposed by Berger et al. (2018) for the systematic assessment of energetic complementarity over both space and time. These critical time windows provide an accurate description of extreme events within the time series, while retaining chronological information. These authors also propose a criticality indicator that quantifies the fraction of time windows during which generation from variable renewables is below a certain threshold, allowing a comprehensive evaluation of energetic complementarity at the different locations over arbitrary time scales.

The local synergy coefficient was a metric employed by Zhang et al. (2018a) for representing the mutual complementarity between VRES at one site, based on the normalized capacity factors of the sources.

The stability coefficient C_{stab} was developed by Sterl et al. (2018) as a measure that quantifies the added value of one VRES to balance the daily power output from another VRES. In their paper, these authors assess the capacity of wind power for balancing PV power in West Africa, based on diurnal timescales of the capacity factors of a hybrid power system with equal installed capacity of PV and wind power. According to these authors, the C_{stab} coefficient can be calculated as follows:

$$C_{\text{stab}}^{s} = 1 - \frac{\sqrt{\sum_t \left(\sum_s \frac{g_t^s}{G^s} - \sum_s \frac{\bar{g}^s}{G^s}\right)^2}}{\sqrt{\sum_t \left(\frac{g_t^s}{G^s} - \frac{\bar{g}^s}{G^s}\right)^2}} \frac{\frac{\bar{g}^s}{G^s}}{\sum_s \frac{\bar{g}^s}{G^s}}. \tag{18}$$

In the C_{stab} formula, G is the absolute capacity, which can be defined as the maximum possible output from a power plant, over a period of time. The interpretation of the results is as follows: by definition the C_{stab} is smaller or equal to 1. $C_{stab} = 0$ indicates that the hybridization of wind and solar sources does not bring benefits in terms of power generation stability, whereas $C_{stab} = 1$ means that a perfect synergy between sources is observed (similarly as in case of coefficient of correlation equal to -1)

4.6. Assessing complementarity between more than two sources

From the previous paragraphs, it can be observed that complementarity is usually measured between two VRES. However, there are authors that have extended the existing methods in literature, in order to allow the assessments of energetic complementarity between more than two sources. Borba and Brito (2017), extending on the method presented in Beluco et al. (2008), proposed a dimensionless index for calculating temporal complementarity between two or more energy resources. In their paper, the complementarity index is calculated as the ratio between the actual generation discarding excess power, and the average generation.

Borba and Brito (2017) remark that the role/contribution of each source may vary over time, but if the combination of all sources is constant, then they operate in a perfect synergy/complementarity. They state that $p(x) = n{\cdot}\bar{g}$ is the measure of how far below average is the current power generation for a set of plants. Next, they formulate the complementarity metric k which does not considers the power generated above the average.

With $g_t = \sum_s g_t^s$, the complementarity metric is defined as:

$$k = \frac{1}{n{\bullet}\bar{g}} \sum_{t=1}^{n} \min(\bar{g}, g_t). \tag{19}$$

Another approach in the literature for assessing energetic complementarity is presented by Han et al. (2019). These authors have evaluated complementarity between wind, solar and hydropower generation by means of comparing fluctuations and ramp rates between individual power generation (*IPG*) and combined power generation (*CPG*). The method has been tested using a region in China as a case study, and their findings suggest that complementarity can be improved by adjusting the proportion of solar and wind power. The method for calculating these metrics can be summarized as follows:

- For quantifying fluctuations at adjacent moments in the time series, the authors define fluctuations as the change in power generation at adjacent time points.

$$\text{FR} = \frac{1}{n-1} \sum_{t=1}^{n-1} |\gamma_t^s|, \tag{20}$$

$$\gamma_t^s = \frac{g_{t+\delta t} - g_t}{G}, \tag{21}$$

where G is absolute capacity.

FR denotes the degree of random fluctuation at adjacent periods. Smaller values of γ_i and FR, account for better stability.

- Next, the complementarity rate of fluctuations (*CROF*) and complementarity rate of ramps (*CROR*) are calculated by Han et al. (2019) by means of the following equations:

$$\text{CROF} = 1 - \frac{\sum_{t=1}^{n-1} \sum_s \alpha_s \gamma_t^s}{\sum_s \sum_{t=1}^{n-1} |\gamma_t^s|}, \tag{22}$$

$$\text{CROR} = 1 - \frac{\text{RROC}}{\text{RROI}}, \tag{23}$$

$$\text{RROI} = 1 - \frac{\sum_s \alpha_s \text{RR}^s}{\sum_s \alpha_s}, \tag{24}$$

where α_k – the proportion of the k^{th} kind of energy in *CPG*, based on the power generation ratio of energies in the combination. The value of *CROF* accounts for the degree of difference in output fluctuation between *CPG* and *IPG*, ranging from 0 to 1, with higher values meaning a better complementary in terms of *CPG*. The *RROC* parameter is the ramp ratio of the *CPG*, while *RROI* is the sum of the ramp rates of individual energies, and RR^k is the ramp ratio of the k^{th} kind of energy. Similar to *CROF,* the *CROR* values range between 0 and 1, with higher values denoting a better complementary.

5. Discussion

The concept of complementarity itself is considered in the scientific literature from several perspectives such as developing/proposing new indices/tools for complementarity assessment/visualization, complementarity assessment with or without further discussion about its potential implications and complementarity being implicitly used, for instance in optimization models, where it is not discussed in details. Typical applications of complementarity are given in Fig. 8.

Most commonly renewable hybrid energy systems consist of a combination of solar and wind generators. Such systems are often considered as a viable supply option for off-grid communities, because they reduce issues of single sources such as the prominent day-night pattern of solar generation, which leads to vast requirements for storage The use of hybrid systems can therefore increase the overall reliability and reduce the cost of electricity or increase its value depending on the operation mode. The underlying principle of hybrid energy sources (utilizing non-dispatchable renewables) is the complementary nature of their energy generation patterns.

(Jurasz et al., 2018a) have recently shown that the varying degree of complementarity can lead to different levels of hybrid system reliability. Fig. 9 shows an example of the varying degrees of complementarity impact on the systems performance and the use of renewable generation. In this work, a wind-PV hybrid system was considered to cover a constant load. Both sources generated the same

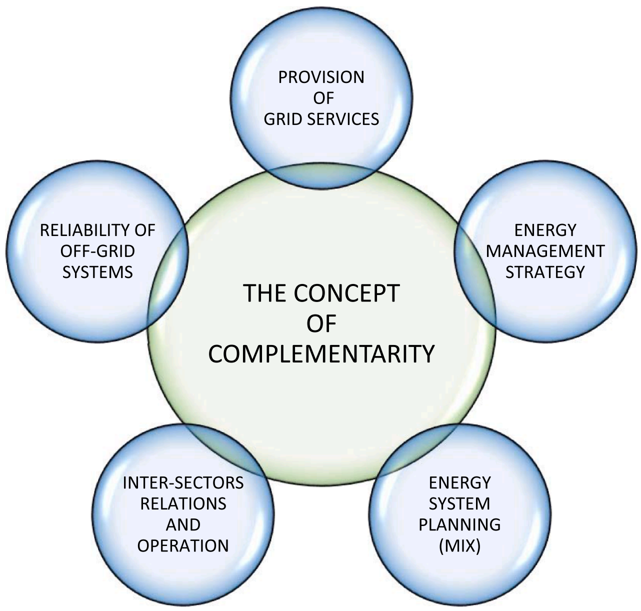


Fig. 8. Use of complementarity in different energy-related research areas.

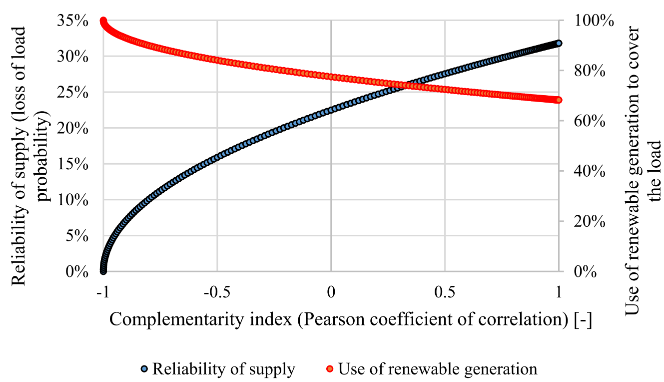


Fig. 9. Reliability and renewable generation utilization for a solar-wind hybrid system with different complementarity values between variable generators. Adapted from (Jurasz et al., 2018a).

overall amount of energy, which on average was equal to the load. As shown, complementary sources provide higher reliability of supply and ensure better utilization of generated energy. An interesting future research direction here is to enhance the knowledge and practical implications resulting from the different levels of complementarity.

Energy systems designed for complementarity can also enhance participation on day-ahead and intraday energy markets by exploiting the partial dispatchability of hydropower coupled with wind or solar generators. As indicated by Jurasz and Ciapała (2017) and Kougias et al. (2016), the power output from variable generators can be smoothed by their joint operation. For example, an appropriate energy management strategy for joint solar-hydro generation can smooth the generation patterns and improve the performance of a power system with respect to power fluctuations, when compared to generation from a PV system alone. Based on the paper by Jurasz and Ciapała (2018), Fig. 10 presents a PV and hydropower station operating as a hybrid station. The optimization objective has been to increase the penetration of variable PV generation by smoothing its power output by means of hydropower to that theoretically observed under clear-sky conditions.

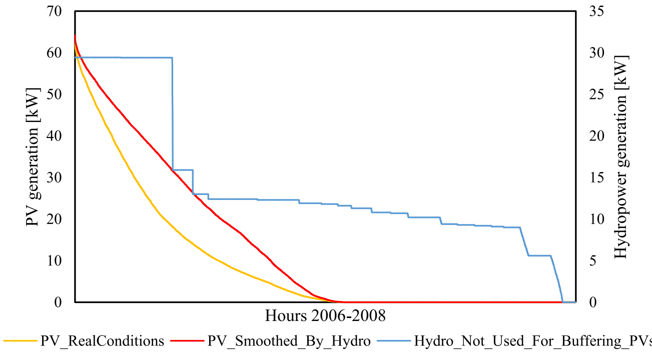


Fig. 10. Duration curves for PV and hydropower station operating as hybrid station. Adapted from (Jurasz and Ciapała, 2018).

The operation was constrained by the potential limitation of the hydropower capacity factor. The considered system comprises PV generators with a capacity of 83.4 kW, a water turbine with a throughput of 0.25 m^3/s and a pondage capacity of 2.64 MWh. For the considered region the hydropower and solar energy tends to exhibit complementarity on an annual (calculated via monthly sums) time scale.

Furthermore, the combination of complementary solar-hydro, wind-hydro and solar-wind-hydro hybrids can enable their participation on intraday and day-ahead markets without the risk of excessive energy curtailment or penalties for not realized bids (if such operation is acceptable within given energy system regulatory framework), and of course, this is only possible if an appropriate operation strategy is implemented. The results of such exemplary system operation are presented in Fig. 11. The bidding of the generation of non-dispatchable generators (wind/solar) is purely based on the forecasted generation and is prone to the forecasting errors. A joint operation with a complementary hydro station is a feasible option to compensate for the forecasting errors of solar/wind generation. The joint operation of PV generators and the hydropower station on a day-ahead energy market is shown in Fig. 11. It can be observed that the small water retention can be increased by an optimal operation of the reservoir without jeopardizing economic performance of both energy sources.

Another example of an energy management strategy for complementary renewables was presented by (Ming et al., 2018). Their management schemes aim at improving the available hydropower utilization, whilst integrating the variable PV generation to the energy system. Fig. 12 shows the results related to the operation of the PV-hydro power station, which was optimized in order to reduce the water consumption. The results of deterministic and stochastic models can minimize the water consumption by 1.5% and 1% compared to the

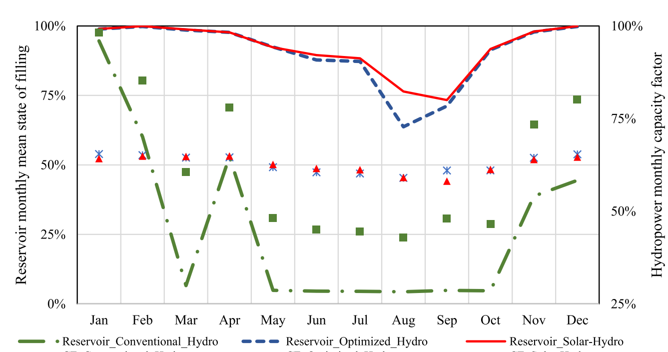


Fig. 11. The joint operation of PV and hydropower station on a day-ahead energy market. CF – capacity factor. Adapted from (Jurasz et al., 2019).

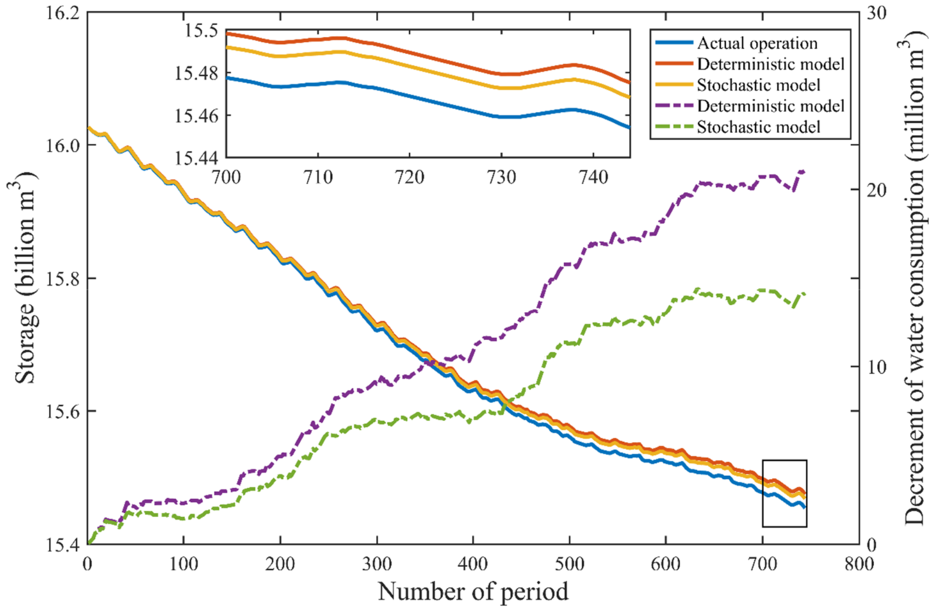


Fig. 12. Operation of PV-hydro power station considering various optimization scenarios. Adapted from Ming et al. (2018).

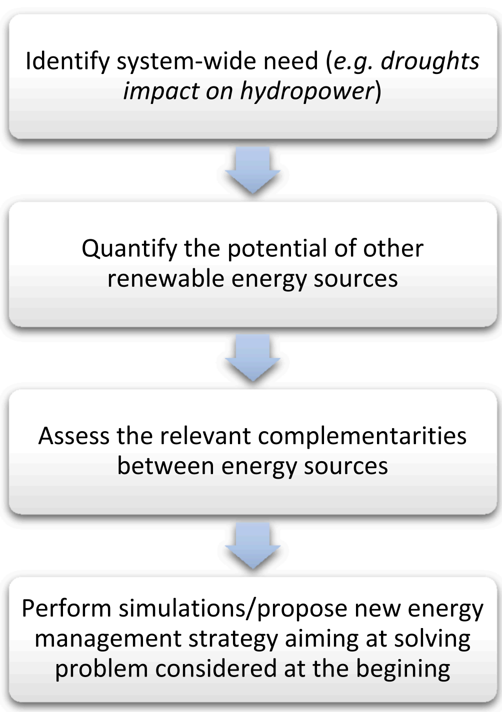


Fig. 13. Simplified procedure which can be applied for studies aiming at solving energy system problem whilst considering the complementarity between energy sources. Approach is applicable also for inter-sector researcher.

current strategy.

Although we have indicated that the concept of complementarity can be used in a large variety across areas of energy-related research activities it is worth to underline that most commonly different aspects are considered. For example, even if the complementarity is analyzed from the perspective of the reliability of an off-grid system, at the same time it is within the interest of the energy management strategies research. Another example is an already mentioned improvement of the energy management strategy of complementary solar-hydro stations, which at the same time addresses the problem of an efficient utilization of water resources (water-energy nexus) and integration of variable renewables.

Based on the conducted literature review it can be observed that the complementarity is playing an especially important role when it comes to the power system planning and decisions/research made at the verge of two (or more sectors). Often it is not directly mentioned by the authors, but it can be concluded that the spatial and temporal ability of VRES to complement each other is the foundation supporting obtained results. From the literature analysis, a following simplified procedure with regards to the research including complementarity on a multi-faceted level can be drawn (Fig. 13):

An example of research which considered the existing relations between energy, water and food sectors was presented by (de Jong et al., 2013). In their analysis they have investigated the potential use of the availability of one source over the course of a certain period to reduce the exploitation of another one which is used for different purposes. A good case is a power system dominated by hydropower, where the reservoirs are often used for energy generation as well as irrigation purposes (food-energy nexus). In such cases, the hydropower generation can be reduced during dry periods by utilizing photovoltaics or wind power (if beneficiary complementary nature of those sources is observed, as shown in Fig. 14).

Another example is the joint operation and scheduling of hydropower-solar/wind stations with biomass facilities. It is a known problem that dry years result in a lower crops harvest which in consequence may cause problems on the supply side of the power stations using biomass. In such situations it may be beneficiary to substitute some hydropower generation by wind/solar and use the water when required for irrigation purposes. The energy will still be generated by the hydropower station although not in such a flexible manner when compared to the usual operation scheme.

Although the concept of complementarity is often not directly discussed, complementarity of renewable resources is often implicitly used in the optimization of energy systems of different scales. Heide et al.

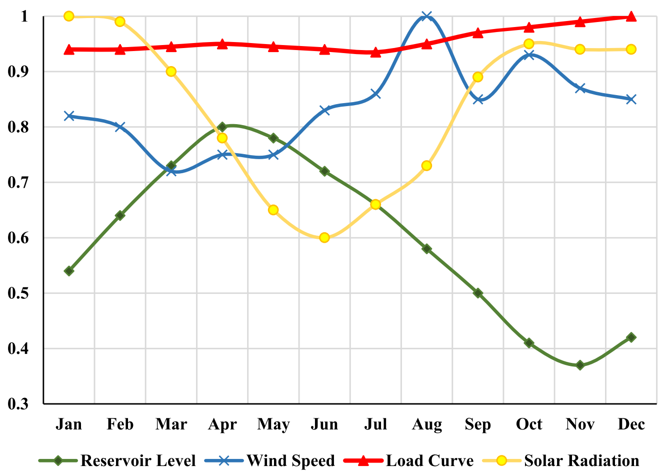


Fig. 14. Relationship between solar/wind and hydropower resources availability compared with the electrical load in Brazil. Clearly significant solar and wind generation from July to August can reduce the use of water in reservoirs, which later can be used for different purposes like irrigation. It must be noted that the figure presents monthly values and in consequence the actual (intraday) variability is not visible. Adapted from de Jong et al. (2013).

(2010) have quantified the standard deviation of generation and need for energy from storage and found it to be lowest at mixes between approximately 40–60% of wind and solar respectively. Compared to wind only and solar only, this is a reduction of the need for storage energy by approximately 50%. For this mix, the standard deviation of generation is reduced by 80% compared to a secenario, where generation is entirely based on wind. The study by Schmidt et al. (2016) has identified the optimal mix in Brazil to be 37% of PV, 9% of wind and 50% of hydropower, where the risk of deficit increases tenfold in a hydro-thermal only scenario. In the paper by Chattopadhyay et al. (2017) these authors optimized the need for balancing energy and storage with respect to tilts/angles of solar modules and found a potential reduction of the balancing need by 11% compared to South-facing optimally inclined with respect to energy yield PV modules alone.

In reality, complementary design and operation of renewables face economic obstacles but they are also subject to incentives and governmental support. Renewable expansion is in many countries supported by feed-in tariffs and net-metering schemes, which provide little incentive for renewable-friendly integration as explained in the works by Kougias et al. (2016) and Hirth and Müller (2016). Some countries have however adapted financial schemes that are better suited to integrate system-friendly complementary renewables such as the market premium recently introduced in Germany. Another option to support the integration of complementary renewables could be a reform of transmission grid charges including incentives for grid-relaxing power injections.

6. Conclusions

From the extensive literature review conducted on papers assessing energetic complementarity between renewable sources, the following conclusions and potential research directions can be formulated:

- There are many geographical areas for which VRES energetic complementarity has not been evaluated yet (mostly parts of Africa and Asia). Furthermore, due to the variety of different indices used by authors a direct (a lack of common/consistent methodology) comparison of results is a challenging task;
- Some of the existing complementarity metrics can be extended to consider other aspects related to VRES like the relation between capacity factor and levelized cost of energy, since better complementarity does not always result in lower overall cost of the system.
- Future studies should extend the complementarity assessments for allowing the user to understand not only on the statistical relationship (complementarity) between the energy sources, but also to obtain additional information related to the practical application of those metrics;
- Complementarity metrics have been included in several optimization models in order to find the best design and/or operation schedule of hybrid power systems. However, the extent of potential applications can be extended to hydrological models (involving water-energy-food nexus) or power system planning;
- Complementarity metrics should be compared based on the same data sample and their performance should be assessed based on the same criterion to clearly formulate their strong and weak sides;
- Since a majority of complementarity studies focusses on the wind/solar/hydro combination, future research should include some additional renewable sources like wave or tidal energy that have gained recent attention
- The research on complementarity should not be based only on historical datasets, but also consider future climate models and the impact of changes in renewables complementarity.
- Climate change will have tremendous impact on renewable resources and likely their complementarity as well. This gives a high priority to studies of renewable complementarity with regard to the climate change.
- Little attention has been paid so far to the question how results on complementarity from measurement-based to model-based data differ. It is possible that some results of wind-solar PV complementarity in models arises from intrinsic model properties such as the parametrization schemes or spatial and temporal resolutions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

This section presents a Table 1A, which summarizes the most relevant information regarding energetic complementarity according to the consulted literature.

Table 1A
Overview of complementarity studies. Resources: S – solar, W – wind, H – hydro. Time-scale: h – hourly, d – daily, m – monthly, i – interannual. Data sources: M – measurements, S – satellite, R – reanalysis. Comp. – Type of complementarity: S – spatial, T – temporal, S/T – spatio/temporal. NA – not available/specified.

Resources	Time scale	Data sources	Comp.	Complementarity metric/approach	Region	Findings/highlights/comments	Reference
W	h	M	S/T	• *Pearson's* • *LOLP*	USA	• Investigation of the wind potential to replace conventional generators • Fundamental work on spatial smoothing increases overall reliability of wind generation	(Kahn, 1978)
W	NA	M	S/T	• *Pearson's* • *Cross correlation*	USA	• Spatial cross-correlations for climatological reduction	(Justus and Mikhail, 1979)
S-W	d	M	T	• *Product of deviations from expected energy* • *Energy density superposition*	Central Iowa (USA)	• Daily complementarity is insignificant, whilst seasonal enables much greater compensation	(Takle and Shaw, 1979)
W	h	M	S/T	• *Pearson's*	California (USA)	• Reliability of variable generators results from geographical dispersal, and it is limited by regional saturation and wind speed correlations	(Kahn, 1979)
S-W	h, d, m	M	T	• *Pearson's*	Dhahran (Saudi Arabia)	• Correlation indicates efficient use of hybrid systems. • Input data with exceptional 1-minute resolution.	(Sahin, 2000)
W	h	M	S/T	• *Pearson's* • *Cross Correlation*	Europe	• Smoothed wind generation can cover 20% of European demand, whilst curtailing only 10% of the generation.	(Giebel, 2001)
S	1/6h, 1/1200 h	M	S/T	• *Covariance between sites*	Pentland Hills and Edinburgh (Scotland)	• Study shows how knowledge about the operation of dispersed solar generators can be used to control the power system	(Glasbey et al., 2001)
S	m	M/R	S/T	• *Pearson's* • *Field significance* • *Pattern correlation*	Europe	• The North-Atlantic oscillation has a significant impact on spatial and temporal variability of winter solar irradiation. • Maximum response has been recorded for the Iberian Peninsula, the British Isles and Scandinavia	(Pozo-Vázquez et al., 2004)
S-W	m	M	T	• *Output Fluctuation*	Serbia	• The fluctuation output of solar-wind generators can be smoothed by their cumulative and complementary operation	(Gburčik et al., 2006)
S-H	m	M	T	• *Beluco index*	Rio Grande de Sul (Brasil)	• Introduction of a comprehensive index for complementarity assessment including the complementarity in time, power and energy	(Beluco et al., 2008)
W	h	M	S/T	• *Descriptive statistics for aggregate arrays* • *Wind speed duration curves*	Midwestern USA	• Reliability was studied with the generation duration curve • Interconnecting wind power plants for this region could provide approximately a third of this energy as baseload	(Archer and Jacobson, 2007)
S-W	½ h	M	T	• *Pearson's* • *Cross Correlation*	Australia	• This study shows that combined solar/wind generation can reliably cover load when grid faces peak demand	(Li et al., 2009)
S	1/60 h	M	S	• *Pearson's* • *Output Fluctuation*	Japan (52 sites)	• By introducing the output fluctuation index the paper proposes a method to estimate the fluctuations of dispersed generators	(Murata et al., 2009)
W-H	h	M	S/T	• *Pearson's* • *Kendall's* • *Spearman*	Canada	• The addition of wind capacity to the hydropower dominated system minimizes the deficit of inflow deficit	(Denault et al., 2009)
S	1/12 h	M	S/T	• *Pearson's* • *Ramp rate* • *Power Spectral Density* • *Coherence spectrum*	Colorado (USA)	• A distributed generation could provide a significant smoothing effect, but the expected high frequency fluctuations in PV power output are relatively larger than those expected from wind turbines. • Solar power is unsuitable for supplying baseload for Colorado but has potential to provide intermediate or peak load.	(Lave and Kleissl, 2010)
S-W	h	M	T	• *Quantity and duration of faults*	Bulgaria	• One of the first approaches for general methodology of power systems coupled with larger scale renewable generators	(Stoyanov et al., 2010)
W	1/60 h and 1/4h	M	S/T	• *Pearson's* • *Power Spectral Density*	USA	• The results indicate that simple interconnection of power plants does not ensure reliability of supply • 3–10% of installed capacity can be provided as firm power due to the dispersion and interconnection effect	(Katzenstein et al., 2010)
S-W	h	R	S/T	• *Optimal mix*	Europe	• Presents various scenarios of solar and wind in autonomous mode, connected to PSH or hydrogen facility, connected to fossil and nuclear power stations	(Heide et al., 2010)
S-W	m, i	R/S	S/T	• *Pearson's*	Europe	• For Europe, the influence of the NAO has been found to be less linear and more complex for wind than for solar irradiation.	(Pozo-Vazquez et al., 2011)
S-W	h	M	T, S/T	• *Smoothing effect*	Ontario (Canada)	• Spatial distribution and hybridization in single location, between locations smoothens the joint power generation profile	(Hoicka and Rowlands, 2011)

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Table 1A (*continued*)

Resources	Time scale	Data sources	Comp.	Complementarity metric/approach	Region	Findings/highlights/comments	Reference
						• No benefits/drawbacks are visible when comparing solar and wind in different locations with both of them in a single location	
S-W	m	M	T, S	• *CIWS*	Oklahoma (USA)	• New interesting index is proposed which is suitable for both GIS and hybrid optimization related research.	(Li et al., 2011)
S-W	h	M/R	T	• *Optimal mix*	New York (USA)	• This paper does not directly investigate the complementarity concept, but it is clearly used in the modelling procedure	(Nikolakakis and Fthenakis, 2011)
W	1/6h	R	T, S	• *Smoothing effect* • *Power Spectral Density*	California (USA) – one site	• The relative wind power fluctuations can be reduced by dispersing the wind generators over geographic	(Tarroja et al., 2011)
S-W	h	M/R	S/T	• *Power ramp* • *Pearson's*	Sweden	• Wind and solar are negatively correlated on all time scales from hours to years however the strongest complementarity is observed for monthly sums	(Widén, 2011)
S	$T = 2^j$ [s] $j = 1,2,\ldots,12$	M	S/T	• *Ramp rates* • *Coherence spectrum* • *Wavelet analysis*	San Diego (USA)	• Paper presents a framework for quantifying geographic smoothing by means of coherence spectra and wavelet analysis. • Using storage with the purpose of ramp rate reduction will lead to a decrease in magnitude and occurrence of extreme ramp events.	(Lave et al., 2012)
S	20 s, 1/60 h, 1/12 h, 1/4h	M	S/T	• *Pearson's*	USA	• Paper presents assess the correlation between irradiance variability at two neighboring sites as a function of their distance and considered time scale. • The findings suggest that relationship between correlation, distance and time can be predictable for irradiance variability.	(Perez et al., 2012)
S-W	h, m, i	R	T, S, S/T	• *Canonical correlation analysis*	Spain	• Optimal location of solar and wind parks will significantly reduce the power output fluctuations • Balancing between solar and wind exists but exhibits a significant seasonality	(Santos-Alamillos et al., 2012)
S-H	N/A	N/A	T	• *Beluco* • *Failure index*	N/A	• The complementarity characteristic can be used for designing the hydro-PV hybrid stations • A supply reliability is presented in the function of complementarity index	(Beluco et al., 2012)
S	1/3600 h	M	S	• *Cross Correlation* • *Output Fluctuation*	Spain (South of Navarra)	• Large output fluctuations and fluctuations frequency is reduced by the spatial dispersion of PV plants • 6 km distance between plants is found to be sufficient to ensure uncorrelated power fluctuations	(Marcos et al., 2012)
W-H	m	M/N	S/T	• *Optimal mix*	Brazil – multiple locations	• Paper proposes a model to analyze hydro-wind complementarity and the portfolio effect on financial profits and risk exposures	(Ramos et al., 2013)
S-H	m	M	T	• *Beluco index*	N/A	• Papers provides a theoretically analysis of the effects of complementarity which are: (1) reduction of failing to meet demand, (2) reduction of storage capacity	(Beluco et al., 2013)
S-W	h	M	S/T	• *Pearson's* • *smoothing effect*	China – 22 locations	• Paper investigates complementarity between wind and solar PV as compared to single sources alone	(Liu et al., 2013)
S-W	Several time scales	R	S/T	• *Optimal backup and energy storage capacity*	Europe – 16 locations	• The authors study the interplay between grid and storage extensions for integrating VRES in Europe using a simple model.	(Steinke et al., 2013)
S	1/12 h	M	S	• *Power Spectral Density* • *Ramp rate*	USA – 8 locations	• In the paper, a spectral method is used to distinguish between cloud- and diurnal-cycle induced transients.	(Tarroja et al., 2013)
W	h	M	S/T	• *Principal component analysis (PCA)*	Southern Iberian Peninsula	• By using PCA, authors present a method for analyzing the potential of wind power resources to supply baseload power within a region.	(Santos-Alamillos et al., 2014)
S-W	h, d, m	M	T, S, S/T	• *Pearson's*	Italy	• Complementarity between wind and solar resources for a sample year in Southern Italy is assessed. Authors find strong advantage of complementarity.	(Monforti et al., 2014)
S-W	h	R/S	S/T	• *Optimal mix and energy storage capacity*	USA – multiple locations	• Paper estimates storage size, backup requirements and transmission requirements and their interplay to design a low-cost renewable system.	(Solomon et al., 2014)
W-H	h	M/R	S/T	• *Beluco index*	Brazil – multiple locations	• Complementarity between wind and hydro resources in Brazil is assessed. Paper provides a map of spatially resolved complementarity in time.	(Eifler Neto et al., 2014)

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Table 1A (*continued*)

Resources	Time scale	Data sources	Comp.	Complementarity metric/approach	Region	Findings/highlights/comments	Reference
S-W-H	m	M	T	● Qualitative analysis	Nepal	● Complementarity of wind, PV and hydro is investigated. Results indicate that a well-planned transmission system could exploit the complementarity.	(Kunwar, 2014)
S-W-H	m, i	R	T	● *Pearson's*	Colombia	● MERRA reanalysis data is used to study the complementarity of wind/solar and hydro resources in Colombia	(Ramírez, 2015)
S-W (CSP)	h, m, i	R	T, S, S/T	● *Canonical correlation analysis*	Spain	● PCA and CCA are used to find optimal locations of CSP plants and wind farms in Southern Spain.	(Santos-Alamillos et al., 2015)
S	10 s	M	S/T	● *Correlation models* ● *Integrated variability*	Sweden	● Paper presents a mathematical model for assessing spatially integrated variability in solar irradiance continuously distributed based on the properties of virtual radiation networks. ● The model is able to reproduce and explain certain previously reported empirical results.	(Widén, 2015)
S	1/60 h and 1/30 h	M	S	● *Pearson's* ● *Power Spectral Density*	Gujarat (India)	● 13 months of observed power production from utility-scale plants in Gujarat, India are used to analyze the potential of geographic smoothing of solar PV.	(Klima and Apt, 2015)
S-W	d	M	T	● *Cross Correlation*	Fernando de Noronha (Brazil)	● Analyses correlations between wind speed and solar irradiation. Results indicate existence of complementarity between both sources.	(Dos Anjos et al., 2015)
W-H	1/6h (wind), d (hydro)	M	S/T	● *Pearson's*	2 sites hydro, 15 wind, (New Zealand)	● Paper studies the correlation between the spatiotemporal distribution of renewable energy resources and electricity demand and prices.	(Suomalainen et al., 2015)
H-W (off-shore)	m	M/S/R	S, T	● *Pearson's*	Brazil	● The possibility of complementing hydro power with offshore wind is investigated for Brazil.	(Silva et al., 2016)
W-H	h	M/S	S/T	● *Optimal mix, backup and energy storage capacity*	California	● Demonstrates advantages of wind and solar complementarity for highly renewable grids in combination with energy storage.	(Solomon et al., 2016)
S-W-H (hydrokinetic)	h, d, m, i	M	T	● *Pearson's*	Poland – two cities	● Investigates complementarity between solar and hydro-kinetic energy for two sites in Poland.	(Jurasz et al., 2016)
S-W-H (run-of-river)	d	M/R	T	● *Pearson's* ● *Optimal mix*	Europe – 12 regions	● The paper studies the Integration of run-of-the river (RoR) power in the solar/wind power mix and shows that this integration significantly increases the penetration rate.	(François et al., 2016b)
S-H (run-of-river)	h, d, m	M	T	● *Pearson's* ● *Optimal energy storage capacity*	North-Eastern Italy	● Run-of-the-river power and solar PV are used to smoothen energy balance in North-Eastern Italy. Results indicate that the optimal share depends on the considered time scale.	(François et al., 2016a)
S-H	d	M	T	● *Beluco index*	Brazil	● 50 years of long-term data are used to study seasonal and inter-annual variability as well as solar-hydro complementarity in Brazil.	(de Mouriño et al., 2016)
S-W-H-wave	h	M/R	S/T	● *Optimal backup*	Spain/Portugal	● Wave, wind and solar PV resources on the Iberian Peninsula are assessed and the optimal mix with respect to the need for balancing energy is determined.	(Kies et al., 2016)
S-H	m	M/R/S	T	● *Pearson's* ● *Optimal configuration*	Hungary – one site	● A methodology is developed to assess the complementarity between solar PV and small hydro. In addition, an optimization algorithm maximizes complementarity while allowing for small compromises in solar energy output.	(Kougias et al., 2016)
S-W-H	d	M/R/S	S/T	● *Optimal mix* ● *LOLP*	Brazil	● Solar and wind sources can reduce the Brazilian power system probability of failing to supply the energy due to large share of hydropower	(Schmidt et al., 2016)
S-W-H	d, m, i	M/R	T	● *Pearson's*	Poland – one site	● Authors study multiannual, monthly and daily of solar, wind and hydro resources in a region in Poland.	(Jurasz and Piasecki, 2016)
S-W	m, quarterly	R	T, S/T	● *Pearson's*	Great Britain	● Findings are bimodal wind-irradiance distribution, weak anti-correlation of wind speed and cloudiness and that more solar than wind power capacity increases variability in summer.	(Bett and Thornton, 2016)
S-H	h,i	M	T	● *Optimal mix*	Northern Italy (four catchments)	● The skill of different hydrological prediction methods to predict complementarity between run-of-the-river hydropower and solar power in mountain basins of the Eastern Italian Alps is studied. From results, performance depends on temporal scale.	(François et al., 2017)

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Table 1A (*continued*)

Resources	Time scale	Data sources	Comp.	Complementarity metric/approach	Region	Findings/highlights/comments	Reference
S-W	h	R/M	T	• *Pearson's*	Europe	• Authors use three years on 100 m wind taken from ECMWF analyses/forecast to assess the possibility of combined solar/wind energy use over Europe.	(Miglietta et al., 2017)
S-H	h	M	T	• *Optimal mix and operation*	China – one location	• A cost-benefit analysis is performed to optimize the size of utility-scale PV power. Variation in downstream water level consequently used to restrict PV integration.	(Ming et al., 2017)
H-S-W	annual	M/S	S/T	• *Beluco index*	Brazil	• The complementarity between wind, solar and hydro in the Brazilian state of Rio Grande do Sul is studied. Mathematical dimensionless ratios which focus on intra-annual periods, are proposed to measure complementarity.	(Bagatini et al., 2017)
S-W	h	R	S/T	• *Coefficient of variation* • *% of time some thresholds are exceeded*	Australia	• A strong temporal synergy of solar and wind resources in Australia is shown and that greater synergy characteristics are in close proximity to established transmission infrastructure.	(Prasad et al., 2017)
W-H	m	M	T, S, S/T	• *Pearson's* • *Spearman*	Brazil	• Voronoi diagram (Thiessen polygons) for representing complementarity through correlation maps.	(Cantão et al., 2017)
S	h, d, weekly	S/R	S/T	• *Optimal mix, backup and energy storage capacity*	Europe	• Paper assess the impact of different PV module configurations on backup and energy storage requirements.	(Chattopadhyay et al., 2017)
S-H	h	M	T	• *Smoothing effect* • *Optimal mix*	Poland –single location	• A MINLP model for a PV-ROR hybrid power system optimization, avoiding large deficits or energy excesses.	(Jurasz and Ciapała, 2017)
S-W	h	M	T	• *Kendall's*	China	• Complementarity maps of wind and solar resources were created, using Kendall's tau as the regionalization indicator.	(Xu et al., 2017)
S-W	h	R	S/T	• *Optimal mix*	India – 10 regions	• Their findings show that energetic complementarity, transmission lines and backup can be used to overcome difficulties related to monsoon.	(Gulagi et al., 2017)
H-W	m	N/A	S/T	• *Beluco index* • *Complementarity charts based on distance*	Brazil – Rio Grande do Sul	• A method is outlined for the spatial representation of temporal complementarity as a function of distance between power plants.	(Risso and Beluco, 2017)
S-W-H	h, d (hydro)	M	S/T	• *Pearson's* • *Optimal mix*	Brazil – Rio de Janeiro	• An LP model for optimizing the mix of three different renewables. • A correlation matrix was created for the 13 plants considered in the case study.	(de Oliveira Costa Souza Rosa et al., 2017)
S-W	h	R	S/T	• *Smoothing effect* • *Optimal backup*	Africa/Europe/Asia (selected locations)	• Paper evaluates the balancing potential of a solar and wind power based supergrid covering Eurasia and Africa.	(Krutova et al., 2017)
S-W-H	h (not clear)	M	T	• *Beluco index extended to three sources*	Rio Grande do Sul (Brazil)	• Based on the index created by (Beluco et al., 2008), the method allows the calculation of complementarity between more than two sources.	(Borba and Brito, 2017)
S-W	h, m, i	S/M	S	• *Pearson's*	Lower Silesia (Poland)	• Results suggests wind and solar complementarity combined with PSH might justify developing a Hybrid power system for the region in study.	(Jurasz et al., 2017)
S-W	m	S/M	S/T	• *Pearson's*	Latin America	• The study evaluates possible impacts of climate change on future wind and solar regimes in Latin America, and its effect on the complementarities between these two energy sources. • Findings shows that climate change is not a hindrance to the development and integration of renewable energy sources in Latin America.	(Paredes et al., 2017)
S-W	d	S/M	S/T	• *Pearson's*	Poland – multiple locations	• Results indicates that complementarity between wind and solar resources in Poland is only significant on a monthly time scale.	(Jurasz and Mikulik, 2017)
S-W	m	M	S/T	• *Pearson's*	Mexico	• Correlation maps were prepared for the entire country and for each season.	(Vega-Sánchez et al., 2017)

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Table 1A (*continued*)

Resources	Time scale	Data sources	Comp.	Complementarity metric/approach	Region	Findings/highlights/comments	Reference
S-W-H	h	M	T	• *Optimal operation*	Yalong river (China)	• An optimization model is proposed, aiming at minimizing excess wind and photovoltaic power and maximizing the stored energy.	(Zhang et al., 2018b)
S-W	h	R	S/T	• *Pearson's* • *LOLP* • *Descriptive statistics*	USA	• Findings indicate that solar and wind power are not enough to provide a highly reliable energy system in continental USA without adequate ancillary infrastructure.	(Shaner et al., 2018)
W-H	m	M	S/T	• *Beluco index* • *Complementarity Roses*	Brazil – Rio Grande do Sul	• A method is proposed for the representation of spatial complementarity in time in the form of complementary roses.	(Risso et al., 2018)
H-S-W	h	M	T	• *Optimal mix and operation*	China	• The complementary coordinated operation model aims at maximizing the renewables consumption through an adaptive simultaneous peak regulation strategy.	(Wang et al., 2018)
S-W	1/4h	R/S	T	• *Pearson's* • *LOLP*	86 locations (Poland)	• Paper assesses how solar and wind resources temporal complementarity impacts on system reliability in terms of covering fixed load. • Evaluates relations between energy storage, complementarity and system reliability.	(Jurasz et al., 2018a)
S-H	h	S	T	• *Beluco index*	N/A	• The paper studies the influence of time-complementarity on the energy storage requirements of hydro-PV hybrid power systems. • HOMER software used for performing simulations.	(During Fo et al., 2018)
W	Time windows 1 h to 10d	R	S/T	• *Critical time windows* • *Criticality index* • *Smoothing effect*	France and South Greenland	• The critical time windows represent periods within the time series with low average capacity factors. • The criticality indicator quantifies the fraction of time windows with renewable generation below a defined value.	(Berger et al., 2018)
S-W-H	h	M	T	• *Pearson's* • *Optimal Operation*	China	• An optimization model is proposed for the complementary operation of a hydro-wind-solar hybrid power system.	(Zhu et al., 2018b)
S-W	h	R/M	T, S	• *Stability coefficient*	West Africa	• The stability coefficient quantifies the complementarity of PV and wind power for balancing power output and reduce energy storage needs.	(Sterl et al., 2018)
S-W	h	M/R	S/T	• *Optimal operation*	Lower Silesia (Poland)	• A model for simulating and optimizing operation of a large scale solar-wind hybrid power system coupled with PSH. • The local consumption index incorporates grid-related cost.	(Jurasz et al., 2018b)
S-W-H	1/4h, h	M	T	• *Load Tracking Index* • *Optimal scheduling*	China	• Renewable power outputs are bundled as a virtual power (VP). • The Load Tracking Index represents the ability of the VP to efficiently track the load curve.	(Zhu et al., 2018a)
S-W	d	M	S/T	• *Pearson's* • *Optimal locations based on complementarity*	Republic of Benin	• Paper proposes a method for selecting optimal locations for renewable generation based on complementarity, using Particle Swarm Optimization.	(Aza-Gnandji et al., 2018)
S-W	h	R	S/T	• *Local synergy coefficient* • *Ramp rates*	China – multiple locations	• The paper presents the framework used in the development of an open-source tool, named Quantitative Synergy Assessment Toolbox for renewable energy sources.	(Zhang et al., 2018a)
S-W-H	h	M	T	• *Optimal mix and operation*	China – single location	• Propose an optimization model aiming at maximizing renewable generation and steady output of a system based on complementary wind/PV/hydro sources.	(Dou et al., 2018)
S-W	1/2h	R/S	T, S	• *Pearson's*	Texas (USA) multiple locations	• The findings suggest possible alternatives for making renewables projects able to maximize reliability with minimal investment in storage technologies.	(Slusarewicz and Cohan, 2018)
S-W-H	h	M	T	• *Kendall's* • *Ramp Ratio and Fluctuation rate of combined power generation*	Single location in Northern China	• Two indices are presented to describe complementarity between two or more energy sources.	(Han et al., 2019)
S-W-H-Biomass	h, m	M	S/T	• *Optimal mix and operation*	Brazil (whole country)	• The model proposed optimizes the renewable mix and operation of hydropower reservoirs, based on daily and yearly variations. • Optimal mix is calculated from a complementarity perspective.	(da Luz and Moura, 2019)

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Table 1A (*continued*)

Resources	Time scale	Data sources	Comp.	Complementarity metric/approach	Region	Findings/highlights/comments	Reference
S-W	m	R	S/T	• *Pearson's* • *Optimal mix and operation*	Ireland	• An optimization model uses the complementary characteristics of variable renewables to achieve an economic and reliable operation of a grid-tied microgrid.	(Naeem et al., 2019)
S-H	m	M	T	• *Optimal operation*	Qinghai province (China)	• Authors propose a multi-objective optimization model using stochastic dynamic programming for obtaining the operation decisions that maximize the total energy production and guaranteed output (minimizing fluctuations). • Uncertainty of streamflow and PV power outputs was considered, and the results show that method was able to improve the long-term complementary operation of the system.	(Li et al., 2019)
S-H	h	M	T	• *LOLP* • *Optimal investment*	Iran	• Paper assesses the impact of four common data records sampling scenarios on the optimal design of a stand-alone hybrid PV-hydro system, using NSGA-II as the optimization tool.	(Shabani and Mahmoudimehr, 2019)
S-H	h	M	S/T	• *Optimal mix*	Qinghai Province (China)	• The study presents a multi-objective mathematical model for optimal sizing of the hybrid system, minimizing the difference between the characteristic load and the daily output, while maximizing complementary guarantee output rate • Model uses genetic algorithms for solving the optimization problem.	(Zhang et al., 2019)
S-W	h, d, m	R	S/T	• *Kendall's* • *Extreme value analysis*	China	• Paper presents a comprehensive assessment of the complementarity between wind and solar resources over China, evaluating the effects of distance and time scale on Kendall's coefficient.	(Ren et al., 2019)
W	1 h, 6 h,1 d, 7 d.	R	S/T	• *Complementarity factors* • *Critical time windows*	South Greenland, Denmark and France	• Paper introduces a method for assessing the benefits of connecting remote locations to major demand centers, from a resource availability perspective. • Results suggests that interconnecting remote areas with renewable energy potential might be beneficial for a secure and reliable electricity supply in future power systems based on VRES.	(Radu et al., 2019)
S-W	h, d, m	R	T	• *Complementarity coefficient* • *Variation coefficient* • *Improvement coefficient*	Shandong Province (China)	• A progressive approach based on three coefficients is used to quantitatively assess the complementarity of wind and solar energy resources. • Capacity factors of wind and solar power are obtained through virtual energy system models.	(Cao et al., 2019)

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