EVALUATION OF ENERGY COMPLEMENTARITY BETWEEN WIND, SOLAR AND WATER RESOURCES IN THE MUNICIPALITY OF LAGES (SANTA CATARINA, BRAZIL)

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ABSTRACT

Purpose: Evaluate the energy complementarity between hydro, wind, and solar resources, and size a wind system and a photovoltaic system to meet the same production of the CGH Caveiras, (Lages/SC).

Methods: Wind and solar systems were sized in order to meet the production of CGH Caveiras, from commercial models of equipment and considering data from 2017 to 2019. To assess complementary, data from the same period were obtained from the river monitoring station of ANA and the meteorological station of INMET.

Results and Conclusion: In order to meet the demand of CGH Caveiras, only 1 medium sized wind turbine or 915 photovoltaic modules of the chosen models for the study would be necessary, and both systems could be used to compensate for periods of low hydroelectric production. The complementarity was confirmed through Pearson coefficients, where -0.39 was obtained between hydro and wind, and -0.32 between hydro and solar. Temporal complementarity indices, in turn, indicate complementarity between hydro and solar (κhs = 0.778) and between hydro and wind (κhe = 0.611).

Research Implications: Both wind and solar resources exhibit complementarity with the hydro patterns of the study area, and either of the proposed systems, wind or photovoltaic solar, could be used in a hybrid manner with the existing hydroelectric system, especially during periods of droughts.

Originality/value: Considering the scarcity of energy complementarity studies in Santa Catarina, as well as the impact of climate change on the hydrological regime and hydroelectric power generation, research of this nature is essential for the region’s energy security.

Keywords: Hybrid Systems, Renewable Energy, Energy Complementarity, Energy Security.

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de complementaridade temporal, por sua vez, indicam complementaridade entre as fontes hídrica e solar (khs = 0,778) e entre as fontes hídrica e eólica (khe = 0,611).

**Implicações da Pesquisa:** Os recursos eólico e solar apresentam complementaridade ao regime hídrico do local de estudo, e qualquer um dos dois sistemas propostos, eólico ou solar fotovoltaico, poderia ser utilizado de forma híbrida ao sistema hidrelétrico existente, especialmente durante períodos de secas.

**Originalidade/valor:** Considerando a escassez de estudos de complementaridade energética em Santa Catarina, bem como o impacto das mudanças climáticas sobre o regime hídrico e a geração hidrelétrica, pesquisas dessa natureza são essenciais para a segurança energética da região.

**Palavras-chave:** Sistemas Híbridos, Energia Renovável, Complementaridade Energética, Segurança Energética.

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**EVALUACIÓN DE LA COMPLEMENTARIEDAD ENERGÉTICA ENTRE RECURSOS EÓLICOS, SOLARES Y HÍDRICOS EN EL MUNICIPIO DE LAGES (SANTA CATARINA, BRASIL)**

**RESUMEN**

**Objeto:** Evaluar la complementariedad energética entre los recursos hídricos, eólicos y solares, y diseñar un sistema eólico y un sistema fotovoltaico para atender la misma producción que CGH Caveiras (Lages/SC).

**Métodos:** Se diseñaron sistemas eólicos y solares para abastecer la producción de CGH Caveiras, con base en modelos de equipos comerciales y considerando datos de 2017 a 2019. Para evaluar la complementariedad, los datos del mismo período provinieron de la estación fluviométrica de ANA y de la estación meteorológica del INMET.

**Resultados y Discusión:** Para satisfacer la demanda de CGH Caveiras se necesitaría sólo 1 aerogenerador de tamaño mediano o 915 módulos fotovoltaicos de los modelos elegidos para el estudio, y ambos sistemas podrían compensar períodos de baja producción hidroeléctrica. La complementariedad se confirmó mediante coeficientes de Pearson, obteniendo -0,39 entre recursos hidráulicos y eólicos, y -0,32 entre recursos hidráulicos y solares. Los índices de complementariedad temporal, a su vez, indican complementariedad entre fuentes hídricas y solares (khs = 0,778) y entre fuentes hídricas y eólicas (khe = 0,611).

**Implicaciones de la Investigación:** Los recursos eólicos y solares complementan el régimen hídrico del sitio de estudio, y cualquiera de los sistemas propuestos, eólico o solar fotovoltaico, podría usarse de manera híbrida con el sistema hidroeléctrico existente, especialmente durante períodos de sequía.

**Originalidad/valor:** Considerando la escasez de estudios de complementariedad energética en Santa Catarina, así como el impacto del cambio climático en el régimen hídrico y la generación hidroeléctrica, investigaciones de esta naturaleza son esenciales para la seguridad energética de la región.

**Palabras clave:** Sistemas Híbridos, Energías Renovables, Complementariedad Energética, Seguridad Energética.

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1 INTRODUCTION

Sustainability is a commitment to the development of alternatives that make it possible to use natural resources without compromising them for future generations, aiming at achieving progress aligned with the socio-environmental perspective. In this context, services considered essential for public welfare, such as electricity supply, are key to countries' development and...
should efficiently link economic, financial, environmental and social aspects. The electric sector is mainly composed of the generation, transmission and distribution segments, being operated by public or private companies (Ribeiro et al., 2017). In this highly competitive environment with significant economic, environmental and social impacts, energy companies play an important role in promoting socio-environmental responsibility. By promoting sustainability-oriented management practices in this sector, the opportunity is created to extend the maturity of the organization in the rational use of resources, especially energy and water, and in the reduction of waste, while generating economic development (Grejo & Lunkes, 2022).

In Brazil, hydroelectric power plays an essential role in the energy scenario, being the main source of the country, representing 60.2% of installed capacity (Brazil, 2022). However, it must be considered that hydropower plants cause several negative environmental impacts, such as: changes in river flow patterns and pathways, relocation of people and terrestrial fauna, retention of sediments and nutrients upstream of reservoir dams, algal blooms, interruption to free flow of aquatic organisms, changes in water quality, among others (Sayed et al., 2021). Lima & Carvalho (2016) further point out that Brazil's leading role in the large-scale exploitation of water, aimed at energy purposes, has ended up concentrating energy production in a single way, resulting in degradation of the environment, compromising the natural water cycle, and paving the way for water crises. In addition, the dependence on hydropower makes the system susceptible to energy crises during periods of scarce rainfall, resulting in the activation of thermoelectric plants, which are more expensive, non-renewable and more polluting (Getirana et al., 2021). In this way, the quest for sustainability and for meeting the objetives of the ODS ends up being jeopardized when they depend only on the hydraulic source.

To mitigate these problems, Brazil has sought to diversify its energy matrix, with a forecast to reduce the dependence on hydroelectric and thermoelectric power, increasing the participation of sources such as wind, solar and thermal (Brazil, 2022), aiming at greater security in the distribution of energy through the use of renewable sources. Furthermore, one must take into consideration the privileged position in which Brazil finds itself, having available in its territory a wide variety of renewable energy sources (Lima & Carvalho, 2016). However, there is no exploitation of energy resources with zero impact. The use of wind and solar energy also has adverse effects, such as the modification of the natural landscape, the use of productive areas, high energy consumption and the emission of CO2 in the production of equipment, bird mortality, difficulties in the recycling of devices, among others. However, when comparing
with fossil sources, it can be observed that renewable sources produce much less negative environmental impacts, especially during the generation of electricity (Sayed et al., 2021).

It is also important to consider that all renewable sources are dependent on climatic conditions (solar radiation, wind, water), which show temporal and spatial variability, according to the region and the period of the year. However, this characteristic can be mitigated by taking into account the complementarity between energy sources (Beluco et al., 2019). Complementarity makes it possible to use two or more alternative sources for the generation of electricity, forming hybrid systems that act in a combined manner both in time and in space. Thus, individual generation variations are compensated, decreasing dependence on a single source, minimizing disadvantages related to its spatio-temporal variabilities, as well as environmental impacts produced (Beluco et al., 2019; Eifler Neto et al., 2020).

Studies in various parts of the world have evaluated the existence of complementarity between different energy sources, most notably Aza-Gnandji et al. (2018), which assessed the complementarity between solar and wind energy in the Republic of Benin, using Particle Swarm Optimization to determine the best geographical locations in terms of complementarity. Also Zhang et al. (2018) utilizing the wind, solar and hydroelectric resources in the Yalong River basin and their complementarity of production as a case study, they formulated an optimization model with the aim of minimizing excess energy from wind farms and photovoltaic installations, maximizing energy stored in cascading hydroelectric plants. Henao et al. (2019) presented an optimization model to increase the uptake of complementary renewable energy sources in Colombia, aiming to minimize system costs, CO2 emissions and blackout events. Canales et al. (2020) evaluated the temporal complementarity between three energy sources (solar, wind and hydraulic) for the continental portion of Colombia, through correlation and commitment programming techniques. The results indicated that the energy sources analyzed showed significant time complementarity. This means that at certain times, one or more energy sources were available in larger quantities, which would make better use of the hybrid system possible. In a study also conducted in Colombia, Parra et al. (2020) compared the complementarity evaluated by Person's coefficient and complementarity indices, noting similarity between the methods, but there are also discrepancies in some cases, especially under interference of energy complementarity and amplitude parameters.

In Brazil, studies on energy complementarity began with the development of complementarity indices, and their application in mapping studies developed for the State of Rio Grande do Sul (Beluco et al., 2008; Bagatini et al., 2017; Risso et al., 2018; Beluco et al.,
2019). Mouriño et al. (2016) also conducted complementarity studies to evaluate the regularization of the level of the Itumbiara hydroelectric reservoir in São Paulo for complementarity with the solar resource, indicating that the storage of photovoltaic energy in potential hydraulic energy could be sufficient to be equivalent to the production of a small hydroelectric power plant. Canton et al. (2017) have developed correlation maps to represent the complementarity between hydraulic and wind sources throughout the national territory, allowing visualization of regions with great potential for complementarity between these sources. Rosa et al. (2017) have developed studies of complementarity between hydraulic, solar photovoltaic and wind resources for the State of Rio de Janeiro, obtaining from Pearson’s correlation coefficients that the combination between the different sources could reduce the daily energy variability by up to 61%. Eifler Neto et al. (2020) also developed time complementarity maps between water and wind resources for the Northeast region, in which they identified that more than 40% of the region showed high levels of complementarity.

Considering the scarcity of studies on the complementarity between energy sources in Santa Catarina, as well as the impact of the severe drought that occurred in 2018 in the mountainous region of Lages (SC), which strongly affected the local hydroelectric power generation, it becomes essential to carry out research of this nature aiming at the proper management of water and energy resources. Thus, the objective of the present study was to evaluate the temporal complementarity between water, wind and solar resources, and to verify the compatibility of serving the energy produced by the Skulls Hydroelectric Generator Power Plant through the other sources, located in the municipality of Lages (SC), aiming to mitigate the effects of water scarcity on energy generation.

2 THEORETICAL FRAME

The next section sets out the classical concepts involving energy complementarity, as defined in a reference study in the area (Beluco et al., 2008). Initially, the definition of the term complementarity will be addressed, outlining the different types and indices that can be used to assess this relationship.

2.1 COMPLEMENTARITY
Complementarity is the ability to work in a complementary way. The term energy and time complementarity between energy sources refers to the capacity of two (or more) energy sources to have complementary availability to each other. This complementarity can occur in time, space, or both, and can occur between sources of the same type or different types.

2.2 TYPES OF COMPLEMENTARITY

Spatial complementarity can be observed when the energy availability of one or more sources complement each other in a given geographical area. Temporal complementarity occurs when the availability of energy from two or more types of sources presents periods of availability that are complementary over time in the same region.

In addition, complementarity can be observed when the availability of energy from only one source is considered over a wide geographical area and over time. For example, the availability of hydroelectric power in Brazil is one of the main reasons for the interconnection of the electricity supply systems of the south-southeast and north-northeast regions. This represents an example of complementarity in both time and space.

2.3 PARTIAL TIME COMPLEMENTARITY INDEX

The complementarity index necessarily involves time and is designed to express the degree of complementarity between two energy sources. He considers three elements: the phase difference between the energy availability values of the two sources, the relationship between the average availability values and the relationship between the variation amplitudes of the availability functions.

The Partial Time Complementarity Index (0TCI) evaluates the time interval between minimum availability values of the two energy sources. If this range is exactly half of the period, the index equals one. If the range is null, that is, if the availability minima match, the index is zero. Intermediate values are linearly related.

3 METHODOLOGY

3.1 FIELD OF STUDY
The study area is the sub-basin of the River Caveiras that is part of the river basin of the Canoas, where is located the CGH Caveiras (27°48'38" S and 50°28'55" W), rural area of the municipality of Lages, mountainous region of Santa Catarina, Brazil (Figure 1). This CGH is owned by CELESC Geração S.A. (Centrais Eléctricas de Santa Catarina), and is made up of a dam of the type threshold free and a power house, containing 4 turbines model Francis horizontal axis. Table 1 shows the CGH specifications and Figure 2 shows an aerial view of the reservoir and power house.

Table 1

*Data from CGH Skulls, located in the municipality of Lages, SC*

<table>
<thead>
<tr>
<th>Characteristics of CGH</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage area</td>
<td>10 400.00</td>
<td>km²</td>
</tr>
<tr>
<td>Main reservoir area</td>
<td>37,800</td>
<td>m²</td>
</tr>
<tr>
<td>Minimum operational level</td>
<td>856.85</td>
<td>m</td>
</tr>
<tr>
<td>Vertical Level</td>
<td>859.85</td>
<td>m</td>
</tr>
<tr>
<td>Gross drop</td>
<td>34.10</td>
<td>m</td>
</tr>
<tr>
<td>Generation capacity (installed power)</td>
<td>3.829</td>
<td>MW</td>
</tr>
<tr>
<td>Start of operations</td>
<td>1940 to the present day</td>
<td>-</td>
</tr>
</tbody>
</table>

Source: Diel (2020)
Figure 1

Study area location map

Source: Prepared by the authors (2023)

Figure 2

View of CGH's Strength House and Reservoir Skulls

Fonte: Google (2023)

3.2 METEOROLOGICAL AND HYDROLOGICAL DATA
In the present study, meteorological (wind and solar radiation) and hydrological (rain and flow) data from 2017 to 2019 were used. The criterion for choosing the three years was defined on the basis of the minimum period required to size wind systems. It should also be noted that the present study used data of solar radiation, wind speed, rain and flow in a period when the transition between El Niño and La Niña occurred, allowing to evaluate the influence of the climatic variations of the region.

The wind and solar radiation data were obtained from the automatic station (code A865) of the National Meteorology Institute (INMET), located in the municipality of Lages/SC (27.80 S and 50.34 W). It should be noted that during the verification of the time series, several shortcomings were noted, which were disregarded in the present work. It is also noted that the A865 meteorological station is located in the central region of Lages (SC), approximately 11 km away from CHG Skulls. The rainfall and flow data, in turn, were obtained from the rainfall (code 2750007) and fluvimetric (code 71655000) stations under the responsibility of the National Agency for Water and Basic Sanitation (ANA). Both data were used in the dimensioning of the photovoltaic wind and solar system, and also in the evaluation of the energy complementarity between resources.
3.3 CGH POWER GENERATION DATA

The installed capacity of CGH Skulls was used as a reference to scale the photovoltaic wind and solar systems, which during the study period was approximately 2,0 MWh day⁻¹. Therefore, the capacity to generate wind and solar photovoltaic energy should be sufficient to supply the capacity produced by CGH. Based on these values, the complementarity between the respective energy sources was analyzed.

3.4 WIND SYSTEM DESIGN

For the design of the wind system, the EWT company's Directwind 500/52 model was chosen. This model was chosen because it is a medium-sized wind turbine, thus considered a more compatible equipment with the site's relatively low energy demand. This is a horizontal-axis (HAWT) wind generator, with 3 propellers and pitch control, features a rated power of 500 kW, and 50 m of hub center height. The turbine power curve was obtained from the product datasheet (EWT, 2024), and is shown in Figure 3.

Figure 3

*EWT DW 500/52 wind generator power curve*

Fonte: EWT (2024)

The method for sizing the wind system, as Pinto (2013), consists of initially correcting the wind speed by the logarithmic law, considering the vertical variation of the height in relation to the ground, as presented in Equation 1.
\[ v_2 = v_1 \frac{\ln(h_2)}{\ln(h_1)} \]  

(1)

Where:

\( v_2 \) is the speed variation with the vertical height \((\text{m s}^{-1})\), \( v_1 \) is the speed at a reference height \((\text{m s}^{-1})\), \( z_0 \) is the ground roughness length \((\text{m})\), \( h_1 \) is the reference height itself \((\text{m})\) and \( h_2 \) is the desired height at capture \((\text{m})\). The values considered for \( h_1, h_2 \) and \( z_0 \) were respectively 10 m, 95 m and 0,2 m. The roughness, which corresponds to the height at which the wind assumes zero value near the surface, according to the relief and the presence of obstacles in the surroundings, was estimated for the coordinates of the study site (-27.81055556, -50.48194444) through the Global Wind Atlas (GWA, 2024).

To assess the wind potential of the region, the Weibull probability distribution was used. For this, it was necessary to calculate the shape and scale parameters of the distribution, through Equations 2 and 3, respectively. In this way, one can calculate the frequency of the wind speed by the Weibull distribution, for each wind class considered, by means of Equation 4.

\[ k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \]  

(2)

\[ A = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \]  

(3)

\[ f_v = \frac{k}{A} \left(\frac{v}{A}\right)^{k-1} \exp\left(-\left(\frac{v}{A}\right)^k\right) \]  

(4)

Where:

\( k \) is the shape parameter (dimensionless); \( v_m \) is the mean wind speed \((\text{m s}^{-1})\); \( \sigma \) is the standard deviation of the wind speed \((\text{m s}^{-1})\); \( A \) is the scale parameter \((\text{m s}^{-1})\); \( f_v \) is the expected frequency for each wind speed class, according to the Weibull distribution; and \( v \) is the wind class range \((\text{m s}^{-1})\) which, in this study, ranged from 0 to 25.

The last step was the calculation of the annual energy generated (EAG) by the wind generator, estimated according to the location of the study, and the expected capacity factor. It should be noted that estimating energy production is one of the most important tasks in a project for the generation of wind power, since it allows for the evaluation of the quantity of wind turbines needed to meet a given demand. Likewise, the capacity factor makes it possible to evaluate the region’s wind potential and can be interpreted as the percentage of expected
recovery in relation to the maximum installed power, which makes it possible to indicate if there is viability in the local wind recovery.

The annual energy generated (EAG) can be calculated by Equation 5, which requires the turbine power for each wind speed class, derived from the power curve of the test wind generator. The calculation of the capacity factor, in turn, is done by means of Equation 6.

\[
EAG = \sum (f_v P_t) \times 8760
\]

\[
FC = \frac{EAG}{(P_{n-a} \times 8760)} \times 100
\]

Where:

- EAG is the annual energy generated (kWh year\(^{-1}\)); \(f_v\) is the Weibull frequency for each wind speed class;
- \(P_t\) is the turbine power for each wind speed class, according to the wind generator power curve (kW);
- FC is the wind system capacity factor (%) and \(P_{n-a}\) is the nominal (maximum) wind generator power (kW).

The number of wind generators needed to meet the CGH generation demand was calculated by Equation 7, with \(E_{dem}\) being the energy generated by CGH per year (MWh year\(^{-1}\)).

\[
N_a = \frac{E_{dem}}{EAG}
\]

### 3.5 SCALING OF THE SOLAR PHOTOVOLTAIC SYSTEM

To size the generation capacity of the photovoltaic system, the methodology proposed by Pinho & Galdino (2014) was used. The photovoltaic panel model chosen was the BiHiKu7-CS7N-655MB-AG, with a rated power of 655 W, from Canadian Solar, as it is a model aimed at solar utility-scale applications, that is, more suitable for centralized generation (non-residential), characteristics of power plants and solar parks. The amount of modules required for installation was calculated by Equation 8.

\[
N_m = \frac{E_{dem}}{HSP \times P_{n-m} \times TD}
\]

Where:
Edem is the daily power demand of the hydroelectric power plant (kWh day\(^{-1}\)); HSP is the number of hours of full sun (h day\(^{-1}\)); \(Pn\)-m is the nominal power of the chosen module (kW); and TD is the system-wide performance rate (%).

HSP was calculated from local solar radiation (Equation 9) which, in turn, was obtained by means of a monthly average of three years of global radiation data (kJ m\(^{-2}\)), and later converted to its daily mean value, G, in kWh m\(^{2}\)d\(^{-1}\).

\[
HSP = \frac{G}{1 \text{kW/m}^2}
\]  

(Equation 9)

The system's performance rate, in turn, subtracts existing losses from the entire conversion. For this, it was considered around 14.9% losses related to: deviation in module yield (5%), effect of air temperature on module (5%), losses in AC side conductors (1%), inverter efficiency (0.9%), shading effect (0.5%), diodes and connections (0.5%) and effect of dirt on modules (2%). Thus, the performance rate used in the calculations was 85.1%.

In addition, it is important to emphasize that the proposed photovoltaic system considers optimal fixed positioning of modules. In this way, the panels were considered oriented towards the geographical north, and the inclination in relation to the horizontal plane was considered equivalent to 32°, that is, with an increase of 5° in relation to the local latitude (27°), according to the proposal by Villalva & Gazoli (2012).

For the definition of the panels, was considered a three-phase 125 kW string inverter, model CSI-125KTL-G1-E Canadian Solar brand. The maximum number of modules per panel was calculated from Equations 10, 11, and 12:

\[
Q_{\text{max}} = \frac{P_{\text{max-inv}}}{P_{n-m}}
\]  

(Equation 10)

\[
Q_{\text{max-s}} = \frac{V_{\text{max-inv}}}{V_{oc_{\text{max-m}}}}
\]  

(Equation 11)

\[
Q_{\text{max-p}} = \frac{Q_{\text{max}}}{Q_{\text{max-s}}}
\]  

(Equation 12)

Where:

\(Q_{\text{max}}\) is the maximum number of modules that can be connected to the inverter; \(Q_{\text{max-s}}\) is the maximum number of modules that can be connected in series; \(Q_{\text{max-p}}\) is the maximum number of modules that can
be connected in parallel. Pmax-inv is the maximum power of the inverter; and Pn-m is the maximum power of the photovoltaic module. Vocmax-m is the highest open current voltage produced by the module, generated at the lowest temperature day at the installation site, according to Equation 13.

\[
V_{oc\text{max-m}} = V_{ocm} \left[ 1 + (T_{min} - 25) \times \frac{C_{Voc}}{100} \right] \quad (13)
\]

Where:

Vocm is the open current voltage of the module (45.2 V); Tmin is the lowest temperature observed at the site during the study period. Between 2017 and 2019, the minimum temperature reached was -3.0°C, according to data from the automatic station of Lages (code A865) of INMET. CVoc is the temperature coefficient for the Voc of the module (-0.26%/°C).

3.6 ASSESSMENT OF ENERGY COMPLEMENTARITY BETWEEN ENERGY SOURCES

The presence or absence of complementarity between the three energy sources was verified visually in the temporal graphs of flow (m³ s⁻¹), wind speed (m s⁻¹) and solar radiation (kWh m²d⁻¹). An analysis of hydraulic, wind and solar resources was also made using Pearson's coefficient, as discussed by Jurasz et al. (2020) and Gallardo (2022). The analysis of the occurrence of the absence or presence of complementarity was verified by means of Equation 14.

\[
\rho = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2} \sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad (14)
\]

Where:

xi and yi are the measured values of the resources to be compared (which can be wind, solar radiation and/or flow data), and "\bar{x}" and "\bar{y}" are the arithmetic means of the resources to be compared (wind, solar radiation and/or flow).

The method of comparison by complementary indices was also used, according to the one proposed by Beluco et al. (2019). The complementarity index between resources can take into account 3 different indices: the temporal complementarity index (0SD); the energy complementarity index (0SD); and the amplitude complementarity index (0SD). Among them, it was judged that the evaluation of the temporal complementarity index was more in line with the objective of this work, and more in relation to the Pearson coefficient (Parra et al., 2020), so it was chosen to calculate only this parameter. The temporal complementarity index between
two resources (r1 and r2) is calculated from the differences between the months of least availability of each resource, according to Equation 15.

\[
\kappa_t = \min\left\{\frac{|m_1 - m_2|}{6}; \frac{12 - |m_1 - m_2|}{6}\right\}
\]  

(15)

Where:

m1 and m2 represent the months in which the lowest energy availability of resources 1 and 2 occurs, the values of which vary between 1 and 12. Thus, \(\kappa_t\) shows how far in time the minimum values of the r1 and r2 resources are between each other. Values close to 1.0 indicate greater spacing between resource minima and consequently that there is temporal complementarity between them. On the other hand, values close to zero indicate smaller gaps between the minima of the resources and, therefore, that they are not complementary to each other.

4 RESULTS AND DISCUSSION

4.1 WIND SYSTEM

For the design of the wind system, the Weibull probability distribution was first obtained (Figure 4) according to the frequency of observed wind speeds at the site. The mean velocity and the other wind parameters are shown in Table 2.

Figure 4

Weibull probability distribution for wind speed classes on site

Source: Prepared by the authors (2024)
Table 2

Parameters used in wind sizing

<table>
<thead>
<tr>
<th>Variable</th>
<th>Acronym Value found</th>
<th>Acronym Value found</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGH annual electrical production</td>
<td>$E_{dem}$</td>
<td>719.67 MWh ano$^{-1}$</td>
</tr>
<tr>
<td>Average wind speed at the location (from 2017 to 2019)</td>
<td>$v_m$</td>
<td>4.12 m s$^{-1}$</td>
</tr>
<tr>
<td>Standard deviation of local wind speed</td>
<td>$\sigma$</td>
<td>2.23 m s$^{-1}$</td>
</tr>
<tr>
<td>Shape parameter of the Weibull distribution</td>
<td>$k$</td>
<td>1.94</td>
</tr>
<tr>
<td>Weibull distribution scaling parameter</td>
<td>$A$</td>
<td>4.64 m s$^{-1}$</td>
</tr>
<tr>
<td>Nominal power of the wind turbine</td>
<td>$P_{n-a}$</td>
<td>500 kW</td>
</tr>
</tbody>
</table>

Source: Prepared by the authors (2024)

It is verified by the Weibull probability distribution that the wind speed remained normal in all classes. The results show that the wind regime presents a uniform and intense distribution over a wide range of wind speeds. Regarding the shape parameters ($k$) and scale ($A$) of the Weibull distribution, lower values (1.94 and 4.64 m s$^{-1}$, respectively) are observed than those obtained by the study by Cuadros et al. (2023) which, when analyzing the wind potential in Huila, Colombia, achieved higher values (3.22 and 6.31 m s$^{-1}$, respectively) than those found in the present study. This disparity can be attributed to the greater uniformity and intensity of winds in Huila. In addition, it is worth noting that the average wind speed at the site was 6.5 m s$^{-1}$, while in this work it was 4.12 m s$^{-1}$.

Table 3 presents the result of the wind system sizing required to meet the power generation capacity of CGH Skulls.

Table 3

Scaling of the wind system

<table>
<thead>
<tr>
<th>Variable</th>
<th>Acronym Value found</th>
<th>Acronym Value found</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual energy generated by wind turbine</td>
<td>$E_{AG}$</td>
<td>951.06 MWh ano$^{-1}$</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>$FC$</td>
<td>21.71%</td>
</tr>
<tr>
<td>Number of wind turbines</td>
<td>$N_a$</td>
<td>1 aerogerador</td>
</tr>
</tbody>
</table>

Source: Prepared by the authors (2024)

It is observed that only 1 medium-sized wind generator (EWT DW 500/52) is already sufficient to supply the annual electricity production of CGH Skulls. This is because the turbines are available for generation day and night, being only dependent on the occurrence of wind. For the wind regime of the site during the 3 years observed in this study, the production of a single wind generator would exceed by more than 30% the energy required.

As to the capacity factor, the world average is 30%, and in Brazil the values differ a lot in relation to positioning. In the Northeast region, for example, where the winds show a good
distribution every year, the average is much higher, reaching close to 50%. In the South, though, the figures are in the region of 30%. The EPRI (Electric Power Research Institute) suggests the value of 32.5% as a feasibility reference (Pinto, 2013). However, these are accepted values for larger systems, characteristic of high power wind generators. Small- and medium-scale wind generators result in lower annual capacity factors, and in this case, values above 17% are considered acceptable for this size of wind systems (Ko et al., 2015). In this way, the FC obtained from 21.71% indicates that there is technical feasibility of exploring medium-sized wind energy at the study site.

4.2 SOLAR PHOTOVOLTAIC SYSTEM

For the dimensioning of the photovoltaic solar system, it was necessary to determine some parameters (Table 4), which were obtained from data from the study site, and from the characteristics of the photovoltaic module and inverter chosen.

Table 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Acronym</th>
<th>Value found</th>
</tr>
</thead>
<tbody>
<tr>
<td>CGH annual electrical production</td>
<td>$E_{dem}$</td>
<td>719.67 MWh ano$^{-1}$</td>
</tr>
<tr>
<td>Average annual solar radiation at the location</td>
<td>$G$</td>
<td>3.92 kWh m$^{-2}$</td>
</tr>
<tr>
<td>Full sun hours</td>
<td>$HSP$</td>
<td>3.92 h dia$^{-1}$</td>
</tr>
<tr>
<td>Solar module power</td>
<td>$P_{n-m}$</td>
<td>655 W</td>
</tr>
<tr>
<td>Performance Rate</td>
<td>$TD$</td>
<td>85.1%</td>
</tr>
<tr>
<td>Maximum inverter power</td>
<td>$P_{máx-inv}$</td>
<td>125 kW</td>
</tr>
<tr>
<td>Maximum inverter voltage</td>
<td>$V_{máx-inv}$</td>
<td>1500 V</td>
</tr>
<tr>
<td>Maximum module open current voltage</td>
<td>$V_{O máx-m}$</td>
<td>48.5 V</td>
</tr>
</tbody>
</table>

Source: Prepared by the authors (2024)

It is verified that the average annual solar radiation incident in the study location, of 3.92 kWh m$^{-2}$, is below the national average (4.5 kWh m$^{-2}$ to 6.3 kWh m$^{-2}$) and the average for the Southern Region of Brazil (4.44 kWh m$^{-2}$), according to Pereira et al. (2017). However, this value is still considered acceptable for photovoltaic system projects, according to Pinho & Galdino (2014), as it is within the minimum solar irradiation requirements for photovoltaic generation, which are 3 to 4 kWh m$^{-2}$ d$^{-1}$. In Germany, for example, annual irradiation is equivalent to around 1200 kWh m$^{-2}$, which corresponds to 3.28 kWh m$^{-2}$ d$^{-1}$, and despite
having less favorable meteorological conditions than Brazil, its installed capacity is much higher. higher education (Júnior & Souza, 2020).

Table 5 presents the result of the sizing of the solar photovoltaic system necessary to meet the energy generation capacity of CGH Caveiras.

### Table 5

**Sizing of the photovoltaic solar system**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Acronym</th>
<th>Value found</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of modules</td>
<td>$N_m$</td>
<td>915 módulos</td>
</tr>
<tr>
<td>Maximum modules per panel</td>
<td>$Q_{máx}$</td>
<td>190,84 módulos</td>
</tr>
<tr>
<td>Maximum modules in series</td>
<td>$Q_{máx-s}$</td>
<td>30,93 módulos</td>
</tr>
<tr>
<td>Maximum modules in parallel</td>
<td>$Q_{máx-p}$</td>
<td>6,17 módulos</td>
</tr>
<tr>
<td>Number of modules per panel</td>
<td>$Q_m$</td>
<td>180 módulos/painel</td>
</tr>
<tr>
<td>Number of panels</td>
<td>$N_p$</td>
<td>6 painéis</td>
</tr>
<tr>
<td>Number of inverters</td>
<td>$N_i$</td>
<td>6 inversores</td>
</tr>
</tbody>
</table>

Source: Prepared by the authors (2024)

For photovoltaic use, a total quantity of 915 modules was determined to meet the annual demand of CGH Caveiras, occupying a total area of less than 0.0028 km², and arranged in 6 photovoltaic panels to be compatible with CGH’s average daily generation. The panels are distributed in 5 panels with 180 modules and 1 panel with 15 modules, according to the maximum quantities determined for the series (up to 30 modules) and parallel (up to 6 modules) arrangements, and according to the inverter model considered.

It is observed that the number of modules and panels is compatible with the electrical demand required by centralized systems, and that the system also appears to be viable for the proposed purpose. For comparison purposes, the system proposed by Landera et al. (2018) resulted in an estimated annual energy of 1581 MWh year$^{-1}$, from 3780 Si modules, highlighting the differences in sizing, such as in the nominal power of the selected modules (250 W), and in the irradiation at the study site (5.0 kWh m$^{-2}$ in Santa Clara, Cuba).

### 4.3 ANALYSIS OF COMPLEMENTARITY BETWEEN ENERGY RESOURCES

The implementation of alternative energy systems, through wind turbines and photovoltaic panels, can be a viable solution for a safer energy supply in the region, as the multiplicity of productive energy sources increases the ability to overcome natural setbacks that cause energy crises, weakening all sectors that depend on it (Lima & Carvalho, 2016). Thus, by combining resources that are most available at different times of the year, energy production
becomes more regular over time, and less vulnerable to extreme weather events. Within the scope of this study, for example, there was a severe drought in 2018, and it can be seen how strongly the energy production of CGH Caveiras was affected (especially in the months of May and June), as shown Figure 5. During this period, interannual climate variability occurred, resulting in several extreme events (intense rains and severe droughts), due to the transition from La Niña (2017 to 2018) and El Niño (2018 to 2019).

**Figure 5**

*Monthly electrical energy production at CGH Caveiras for the period from 2017 to 2019*

In the graphs in Figure 6, one can compare the historical series of hydraulic, wind and solar resources, determined by the moving average for the period from 2017 to 2019. In the months of April to June, the average monthly rainfall was greater than 60 mm, which caused an increase in the flow of the Caveiras River, with a maximum of 95.8 m$^3$ s$^{-1}$ in June. The wind regime, however, presented a higher average speed between the months of August and December, reaching a maximum value of 3.8 m/s in the month of November. This result is consistent with the study by Wahrlich et al. (2018), who analyzed wind patterns for several municipalities in SC, over a period of 42 years of data observed at meteorological stations. These authors found that, in the locality of Lages, winds tend to have greater speed during spring (from September to December). Just like wind energy, the highest average intensities for solar energy at the site extended from October to March, reaching a maximum irradiation of 6.4 kWh m$^2$ d$^{-1}$ in December.

In this way, two clear trends of temporal complementarity can be seen: 1) between hydraulic and wind sources, since the first exceeds the occurrence of the second from late
autumn to early winter, and the opposite occurs during spring; 2) between hydraulic and solar resources, which have a more favorable period during the summer, counterbalancing the greater hydraulic regime in autumn/winter. Thus, there is an indication that, in the middle of the year, local climatic conditions favor hydroelectric generation, and that from the end to the beginning of the year, electrical generation through wind turbines and photovoltaic modules becomes more advantageous.

**Figure 6**

*Complementarity between energy resources: (a) hydraulic and wind; (b) hydraulic and solar*

![Graph](image)

Source: Prepared by the authors (2024)

Complementarity between sources can also be confirmed using the Pearson coefficient and temporal complementarity indices (Table 6). The negative values for the Pearson coefficients obtained in the comparison between hydraulic and wind resources, and between hydraulic and solar resources, confirm the existence of complementarity between them. In other words, when the river flow decreases, there is greater availability of wind and solar radiation in
the region. Regarding solar and wind sources, there is no complementarity, as the Pearson coefficient was positive (0.41), indicating that the resources are similar in terms of availability.

Cantão et al. (2017), however, did not observe the existence of complementarity between wind and hydraulic resources for the Southern Region of Brazil, obtaining positive values for the Pearson and Spearman coefficients. In this sense, it is important to emphasize that the occurrence of complementarity is strongly associated with the study location, as it can be influenced by several geographic factors, making it a highly spatially specific parameter. Therefore, very comprehensive studies from a spatial point of view may not have the necessary resolution to verify temporal complementarity.

For this reason, it was decided to also evaluate the temporal complementarity index, to ensure the occurrence of energy complementarity between the sources studied. For this evaluation, it was observed that the minimum values for the solar resource, during the three-year period considered, occurred in the months of May and June. For the wind resource, the minimums occurred in the months of June and July. And for the hydraulic resource, the minimums occurred in the months of September and December.

Table 6

Analysis of complementarity between resources

<table>
<thead>
<tr>
<th>Resources</th>
<th>Pearson coefficient</th>
<th>Pearson Coefficient Temporal Complementarity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Energy</td>
<td>0.41</td>
<td>0.167</td>
</tr>
<tr>
<td>Hydraulic Energy</td>
<td>-0.39</td>
<td>0.611</td>
</tr>
<tr>
<td>Hydraulic Energy</td>
<td>-0.32</td>
<td>0.778</td>
</tr>
</tbody>
</table>

Source: Prepared by the authors (2024)

The results for \( k_t \) prove the occurrence of temporal complementarity between hydraulic and wind resources, as well as between hydraulic and solar resources, where in both cases, the indices were closer to 1.0 than to zero. In contrast, solar and wind sources showed similarity to each other, that is, they present behavior opposite to complementarity. The result is consistent with the study by Bagatini et al. (2017), who mapped the temporal complementarity indices for the State of Rio Grande do Sul. As in the current study, complementarity was also observed between wind and water sources (reaching values of 0.5 to 0.83 in more than half of the area of the study site), and complementarity between solar and water sources (reaching values above 0.8 in around 33% of the evaluated area). Furthermore, no complementarity was observed between solar and wind sources.
With this, it is proven that any of the alternative sources considered, both wind and solar photovoltaic, could be used in a complementary way to existing hydroelectric generation, in order to ensure energy availability for the region.

5 CONCLUSION

To meet the energy generation demand of CGH Caveiras, located in the region of Lages (SC), two alternative energy systems were designed (wind and solar photovoltaic), aiming to ensure greater stability in the region's energy supply, in particular, due to a possible insufficiency of the water resource. With this, it was established that 1 medium-sized wind turbine (500 kW), or 6 photovoltaic panels (totaling 915 solar modules), would be sufficient to supply hydraulic generation in periods of low production.

To compare the availability of the energy resources under study, the occurrence of temporal complementarity between them was evaluated, based on data on solar radiation, wind speed and flow for the period from 2017 to 2019. Analysis of the graphs allowed us to verify that the Hydraulic and wind energy sources, as well as hydraulic and solar sources, present annual complementarity (i.e., intercalation between the maximum and minimum values of each resource), with greater water availability in half of the year, and greater wind and solar availability in the middle of the year. Beginning and end of the year. Both indicators calculated for this purpose, the Pearson coefficient and the temporal complementarity index $t$, proved that the solar resource and the wind resource are complementary to the hydraulic resource.

It is worth noting that the present study used data on solar radiation, wind speed, rainfall and flow during a period in which the transition between El Niño and La Niña occurred, allowing us to evaluate the influence of climatic variations in the region. In this way, the use of energy sources that are less polluting and have an impact on the environment can become a key element in the management of energy generation in Brazil, whose electrical matrix is predominantly hydraulic, therefore, strongly dependent on climatic conditions.

ACKNOWLEDGEMENTS

The Authors are grateful for the support from the Santa Catarina State Research and Innovation Support Foundation (FAPESC) under Grant Agreement No. 2023TR294.
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