

GEOSPATIAL MODELLING OF SOLAR RADIATION USING SATELLITE-DERIVED DATA

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Rezumat. Studiul analizează distribuția spațială și variabilitatea interanuală a resursei solare în România prin utilizarea seriilor temporale orare derivate din date satelitare și a modelării geostatistice în mediu GIS. Analiza vizează principalele componente ale bilanșului radiativ la suprafață — radiația globală pe plan orizontal (GHI), radiația directă normală (DNI), radiația difuză pe plan orizontal (DHI) și componenta directă pe plan orizontal (BHI), derivată din DNI — calculate pentru intervale sezoniere și anuale pentru perioada 2004–2025. În contextul disponibilității reduse a observațiilor radiometrice la sol, integrarea datelor satelitare multianuale cu instrumente GIS și tehnici de modelare geostatistică permite o analiză integrată a configurației spațiale și a variabilității interanuale a radiației solare în România și oferă, totodată, un cadru analitic pentru evaluări ulterioare ale potențialului energetic solar.

Abstract. This study analyzes the spatial distribution and interannual variability of the solar resource in Romania using hourly time series derived from satellite data and geostatistical modeling in a GIS environment. The analysis focuses on the main components of the surface radiation balance—global horizontal irradiance (GHI), direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and the direct horizontal component (BHI), derived from DNI—calculated at seasonal and annual scales for the period 2004–2025. Given the limited availability of ground-based radiometric observations, the integration of long-term satellite data with GIS tools and geostatistical modeling techniques enables an integrated analysis of the spatial patterns and interannual variability of solar radiation in Romania, while also providing an analytical framework for subsequent assessments of solar energy potential.

Keywords: solar resource assessment, satellite-derived irradiance, geostatistical interpolation, interannual variability, Romania.

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1. Introduction

The global transition towards low-carbon energy systems has intensified research into the identification, quantification, and effective utilisation of renewable energy resources. Within this broader context, solar energy has assumed a central

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role, owing to its abundance and widespread availability at the Earth's surface [1]. The energy potential associated with incoming solar radiation greatly exceeds current global energy demand [1]. Its effective exploitation, however, depends on a rigorous characterisation of the spatial distribution and temporal variability of the main radiative parameters [2].

Solar resource assessment represents a fundamental phase in the planning and design of both photovoltaic and concentrating solar power systems, as the technical performance and economic viability of such installations are directly conditioned by the level and temporal stability of incident radiation [3].

Solar resource assessment has long relied on ground-based radiometric observations, which are still regarded as the reference source for solar resource characterisation [4,5]. Nevertheless, the sparse density and uneven spatial distribution of measurement stations often limit the coherent description of solar resources at regional and national scales [6,7,8]. These constraints led to the widespread adoption of solar irradiance products derived from satellite observations and atmospheric modelling, which provide continuous spatial coverage and temporally consistent records over extended periods [6,9]. Such products, however, remain subject to uncertainty, as their performance is influenced by the representation of clouds and aerosols, as well as by the radiative parameterisations embedded in the underlying models, potentially leading to systematic regional or seasonal biases [10,11]. Despite these limitations, satellite-derived time series enable robust multiannual assessments with high spatial comparability, thereby supporting the identification of the climatological characteristics of solar radiation and the analysis of its interannual variability [12,13].

Beyond data availability, another important aspect of solar resource assessment lies in the integration and spatial analysis of radiative information in relation to geographical and topographical factors. Geographic Information Systems (GIS) provide the technological framework required for the processing, modelling, and spatial representation of continuous climatic variables, enabling the integration of satellite-derived data with topographic, administrative, and infrastructural information [14,15]. Numerous studies have demonstrated the utility of GIS for mapping radiative parameters, analysing the influence of topography on their spatial distribution, and assessing solar energy potential at regional scales [14,16,17]. Through the application of geostatistical techniques, GIS also enables the estimation of the spatial distribution of radiation in areas lacking direct observations, while accounting for spatial autocorrelation and the influence of explanatory variables.

Within this context, the integration of hourly satellite-derived solar radiation data within a GIS framework [18], combined with the statistical analysis of interannual variability [19], provides a robust analytical basis for solar resource assessment at the national scale. Such an approach enables not only the

quantification of mean radiation levels, but also the evaluation of their temporal stability, an aspect that is essential for energy planning and for assessing the risks associated with climatic variability.

Against this background, the present study examines the spatial distribution and seasonal variability of solar radiation in Romania using satellite-derived hourly data for the 2004–2025 period together with geostatistical modelling within a GIS framework. The analysis relates the geospatial organisation of the principal radiative components and the statistical expression of their variability, with the aim of evaluating the solar resource at national scale.

2. Data and Methodology

2.1. Satellite-Derived Solar Radiation Dataset

The solar radiation data used in this study were obtained from the CAMS Solar Radiation Time Series service, developed within the Copernicus programme under the Copernicus Atmosphere Monitoring Service (CAMS) and accessed through the Atmosphere Data Store (ADS) [20]. This product provides hourly estimates of surface radiative parameters derived from the integration of satellite observations with numerical atmospheric models, thereby ensuring temporal consistency and continuous spatial coverage at both regional and national scales [20,21,22].

The dataset includes global horizontal irradiance (GHI), direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and beam horizontal irradiance (BHI), representing the principal components of the surface radiative balance and forming the basis for solar resource assessment as well as for the design of photovoltaic and concentrating solar power systems [2,23]. The data are provided on a regular latitude–longitude grid with a spatial resolution of $0.1^\circ \times 0.1^\circ$, corresponding to an average cell size of approximately 10–12 km at the latitude of Romania, and are available at hourly temporal resolution [20].

For the purposes of this study, the available period 2004–2025 was selected, providing a 22-year time series suitable for the climatological characterisation of solar radiation and for the analysis of interannual variability. Hourly values were extracted for a set of 207 locations distributed across Romania, selected to represent the diversity of the country's topographical and climatic conditions, and were subsequently processed at seasonal and annual scales.

2.2. Time-Series Processing and Variability Indicators

The hourly solar radiation time series were temporally integrated to derive seasonal and annual totals (kWh/m²), following standard methodologies used in solar resource assessment. In addition to mean radiation levels, the temporal stability of the solar resource constitutes an important aspect of energy potential

analysis. The interannual variability of GHI was assessed by calculating the standard deviation [24] and the coefficient of variation [25], two statistical indicators commonly used to characterise the absolute and relative dispersion of annual values around the multiannual mean.

By combining the multiannual mean with measures of variability, the analysis identifies areas characterised by high radiation levels and assesses the degree of interannual stability, which is directly relevant to long-term energy planning.

2.3. GIS-Based Spatial Processing

The spatial processing and cartographic representation of radiative parameter distributions were performed in ArcGIS Pro using Romania's national Stereo 1970 projection system. Annual and seasonal radiative parameters were interpolated using Empirical Bayesian Kriging Regression Prediction (EBK-RP), a geostatistical approach that integrates regression-based modelling with Bayesian semivariogram estimation [26].

EBK enables the modelling of uncertainty associated with the spatial autocorrelation structure through the automatic generation of multiple semivariogram simulations, thereby reducing reliance on fixed assumptions concerning the spatial distribution of the analysed variable [27]. Recent applications of EBK-RP in spatial prediction studies indicate that the inclusion of explanatory covariates may improve interpolation performance relative to EBK, particularly in contexts characterised by uneven sampling density and by spatial variability controlled by auxiliary factors [26,28].

The analysis of relationships between radiative variables and geographical factors was conducted within a GIS framework through a series of spatial operations and statistical procedures. Point-based data were aggregated into spatial units (grid cells, elevation classes, and administrative divisions) and subsequently analysed using zonal statistics. Raster surfaces were compared through cell-by-cell calculations, raster differencing and ratio analysis, as well as through derived indicators describing spatial distribution patterns.

Accordingly, the analysis incorporated the Digital Elevation Model (DEM) together with modelled solar radiation parameters, including Area Solar Radiation and its direct and diffuse components calculated and applied at seasonal scale, as explanatory covariates [15], given the influence of topography on radiation distribution through variations in elevation, slope, and aspect [14]. Final raster layers were generated at a spatial resolution of 200 m using a mask corresponding to Romania's administrative boundaries and uniform processing environment settings (extent, snap raster, and cell size), thereby ensuring the consistency of the results.

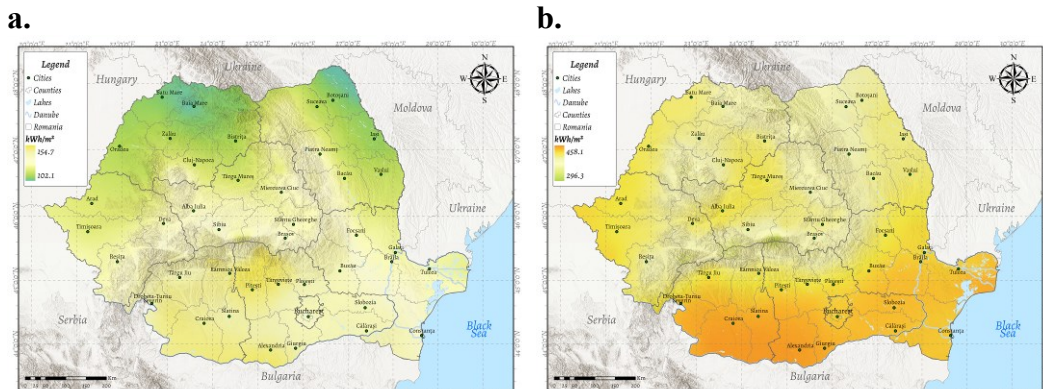
The integration of hourly satellite-derived time series, statistical indicators of variability, and geostatistical modelling within a GIS framework enabled the spatial and seasonal distribution of the solar resource to be analysed within a unified analytical framework, suitable for assessment at both national and regional scales.

3. Results and Discussion

3.1. Integrated Spatial Distribution of Radiative Components

Spatial analysis of the radiative components provides insight into the territorial structure of solar resources and the relationships among the principal components of the radiative balance. The cartographic representations derived from the interpolation of multiannual time-series data offers an integrated depiction of the national-scale distribution of global, direct, and diffuse radiation, thereby facilitating comparison of their spatial patterns and the identification of areas characterised by differing radiative potential. These distributions are interpreted comparatively by examining the absolute values of each component in relation to the broader spatial structure of the radiative regime.

The multiannual spatial pattern of GHI reveals a marked south-to-north gradient in solar resources across Romania, together with a pronounced contrast between the extra-Carpathian regions and the mountainous areas (Fig. 1). Maximum values are concentrated in the southern and south-eastern parts of the country, with a distinct core over Dobrogea and the Romanian Plain, whereas minimum values are associated with the Carpathian Mountains and the northern regions. The observed range (approximately 1098–1502 kWh/m²) indicates substantial spatial variability of the global solar resource at national scale, reflecting the combined influence of latitude, regional atmospheric conditions, and orographic factors on the distribution of solar radiation.



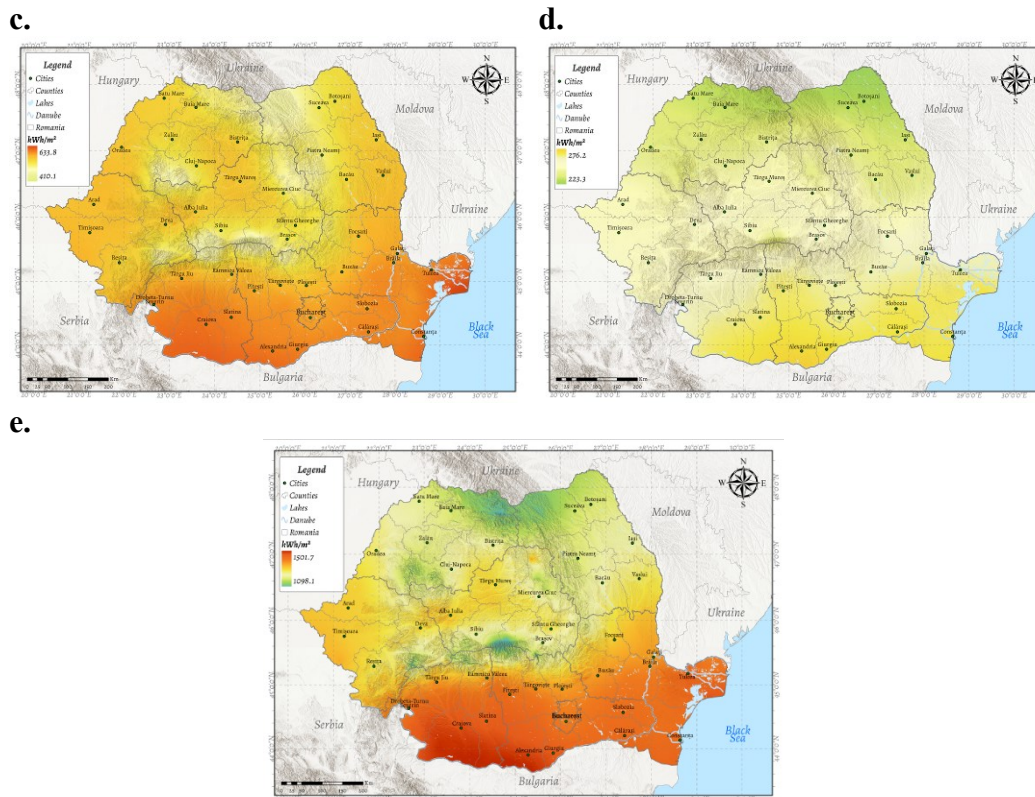


Fig. 1. Seasonal and annual climatological multiannual mean global horizontal irradiance (GHI) in Romania: (a) Winter, (b) Spring, (c) Summer, (d) Autumn, and (e) Annual (source: created in ArcGIS Pro).

In relation to the overall structure of the global solar resource, the distribution of the direct component provides a more sensitive perspective on the influence exerted by atmospheric transparency and cloud regime.

Thus, the annual distribution of DNI follows the same broad spatial configuration, although territorial contrasts are more pronounced, with high values concentrated in the southern and south-eastern parts of Romania and a marked reduction in the mountainous, northern, and north-eastern regions (Fig.2). This enhancement of spatial contrast is physically consistent, as the direct component is more sensitive to cloudiness, the frequency of stable synoptic conditions, and atmospheric transparency. The annual DNI range (approximately 1239–1624 kWh/m²) reflects the marked spatial variability of the direct component and indicates its substantial contribution to the radiative balance of the southern and south-eastern regions. At seasonal scale, the same general spatial configuration is maintained, although the intensity of the contrasts varies according to the radiative regime specific to each season.

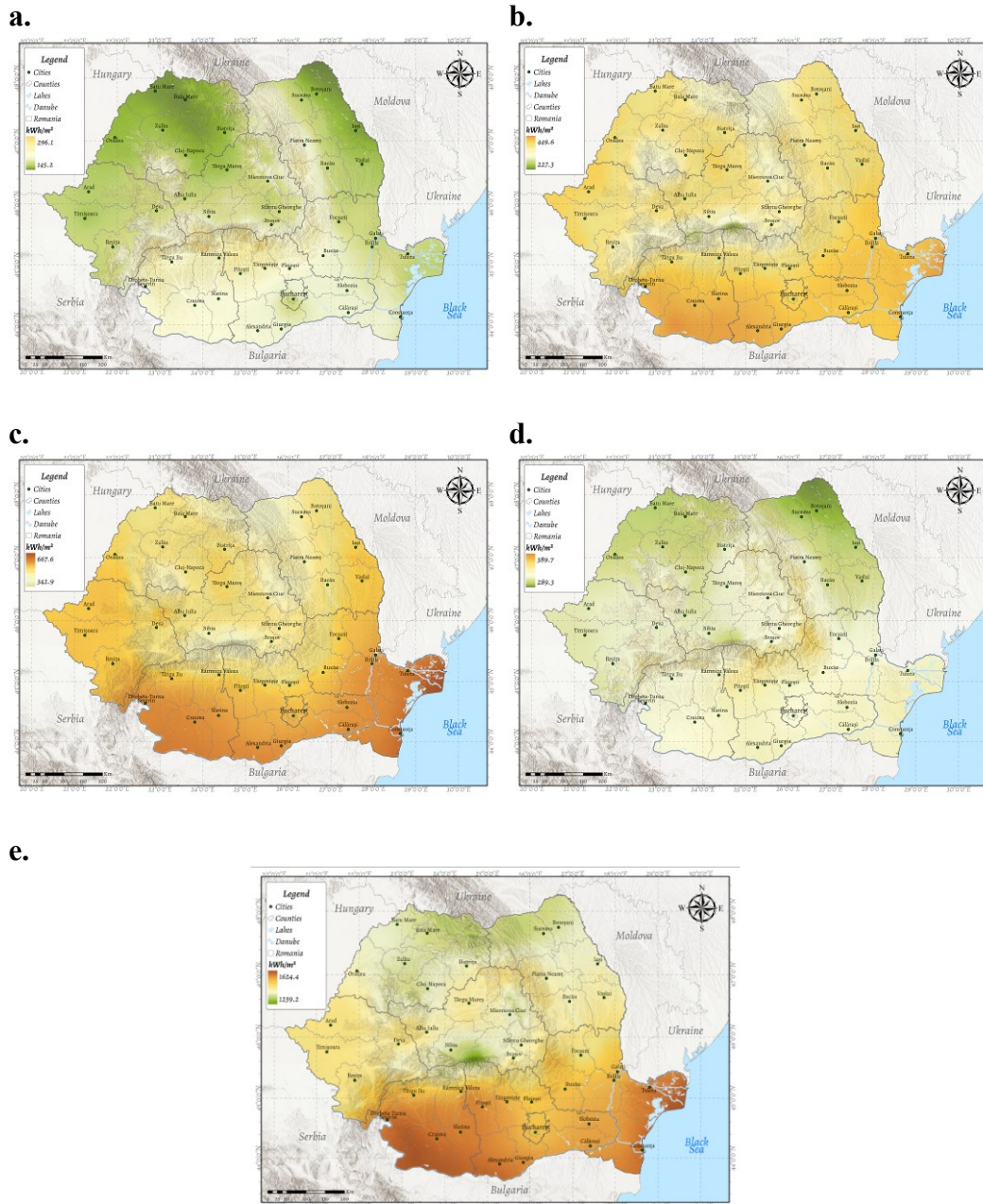
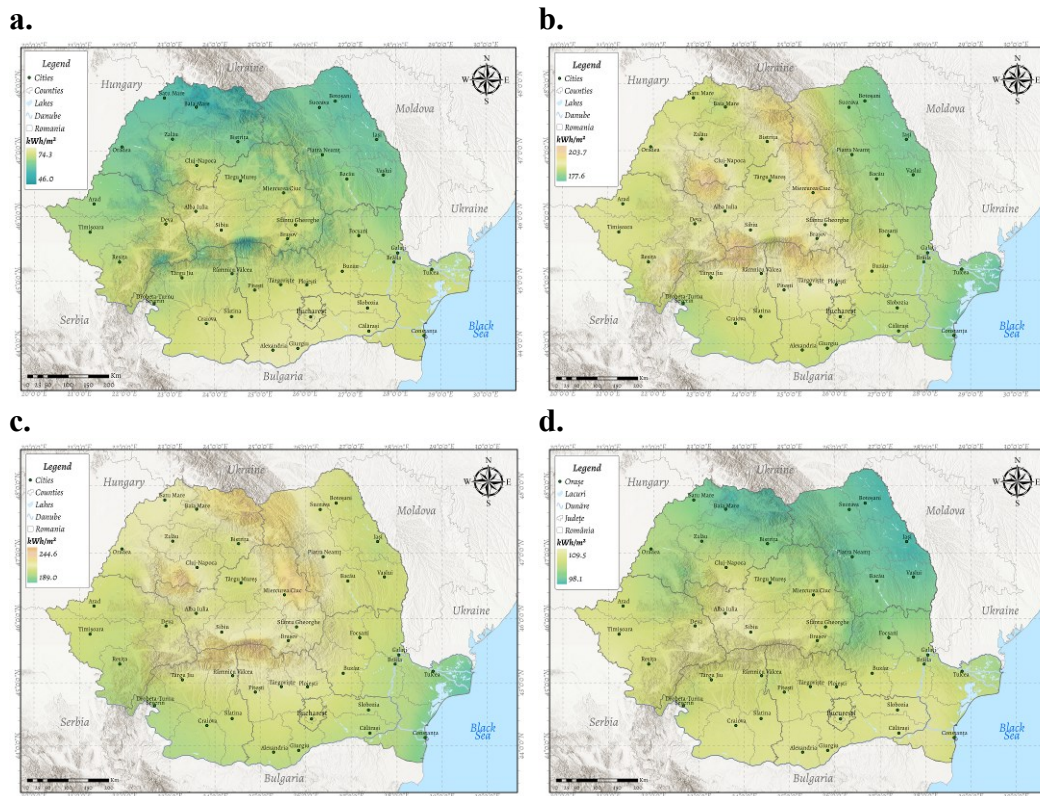


Fig. 2. Seasonal and annual climatology of multiannual mean direct normal irradiance (DNI) in Romania: (a) Winter, (b) Spring, (c) Summer, (d) Autumn, and (e) Annual (source: created in ArcGIS Pro).

The diffuse component (DHI) exhibits a distinct spatial distribution, with relatively higher values in the northern and mountainous regions than in southern Romania (Fig. 3). This configuration reflects the physical complementarity between the direct and diffuse components of the radiative balance: where DNI is lower, the relative contribution of diffuse radiation increases, whereas in regions characterised by higher atmospheric transparency, the direct component contributes more strongly to the overall radiative balance. In terms of radiative structure, the spatial relationship among these three components indicates a coherent spatial organisation of the direct–diffuse ratio and complements the interpretation of the territorial pattern of GHI.



e.

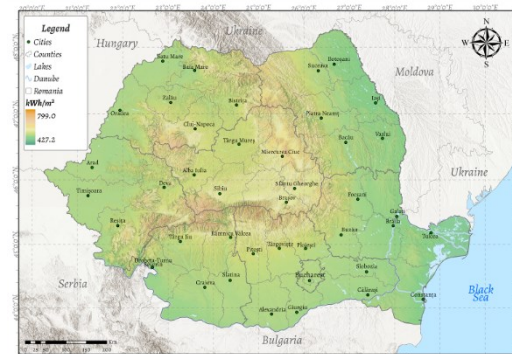
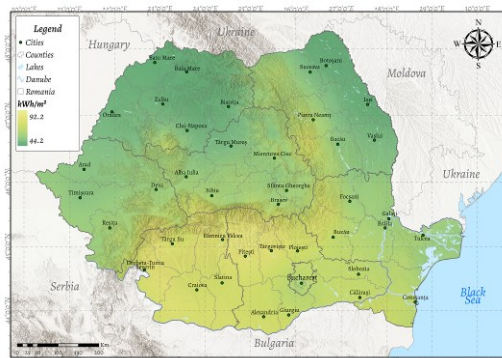


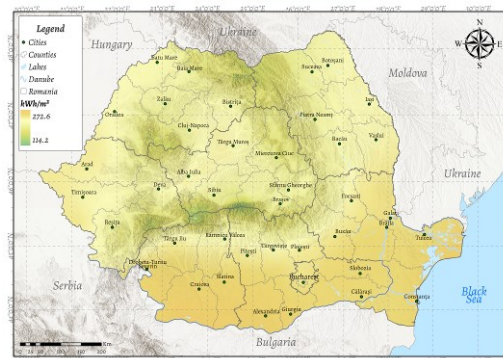
Fig. 3. Seasonal and annual climatological of multiannual mean diffuse horizontal irradiance (DHI) in Romania: (a) Winter, (b) Spring, (c) Summer, (d) Autumn, and (e) Annual (source: created in ArcGIS Pro).

The spatial distribution of BHI (Fig. 4) is generally aligned with that of DNI, reflecting the contribution of the direct component to the radiative regime on a horizontal surface. The highest values are concentrated in the southern and south-eastern parts of the country, particularly over the Romanian Plain and Dobrogea, whereas minimum values occur in the north, north-east, and in certain mountainous areas, where frequent cloudiness and orographic effects reduce the contribution of direct radiation. The BHI pattern therefore confirms the dominant role of direct radiation in shaping the high GHI levels observed in the extra-Carpathian regions and further highlights the spatial consistency of the relationship among the principal components of the radiative balance.

a.



b.



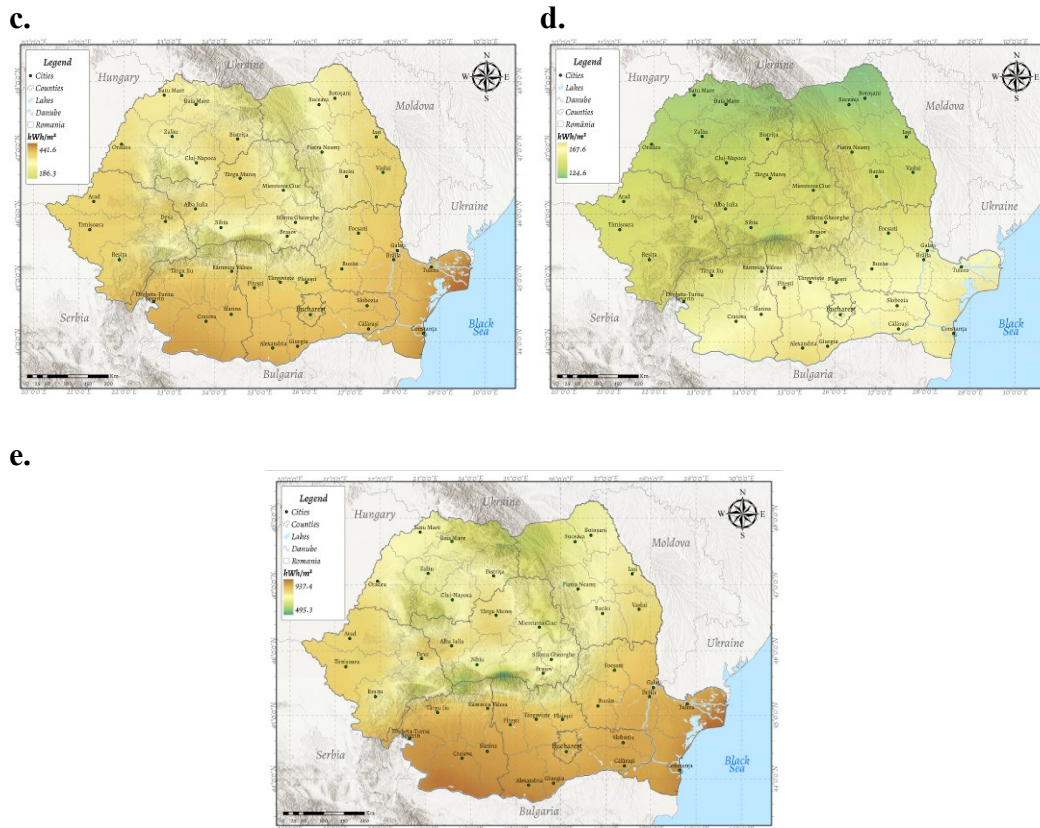


Fig. 4. Seasonal and annual climatology of multiannual mean beam horizontal irradiance (BHI) in Romania: (a) Winter, (b) Spring, (c) Summer, (d) Autumn, and (e) Annual (source: created in ArcGIS Pro).

Seasonal differentiation of the radiative time series confirms and further accentuates the spatial contrasts identified at the multiannual scale. During the warm season, GHI and DNI reach their maximum spatial extent, with high-value areas expanding across southern and south-eastern Romania, whereas during the cold season the absolute radiation levels decrease and the influence of regional atmospheric controls on spatial distribution becomes more pronounced. Under these conditions, DHI exhibits a relatively more homogeneous distribution in winter, suggesting an increased contribution of the diffuse component to the radiative balance under conditions of more frequent cloud cover and reduced atmospheric transparency.

Considered comparatively, these distributions highlight distinct territorial differentiations as well as the structural relationships among the components of the radiative balance. The spatial correspondence between GHI and DNI indicates a strong positive association, suggesting that areas with high global radiation potential generally also exhibit high direct radiation potential. However, the

intensity of the contrasts is greater in the case of DNI, reflecting the higher sensitivity of this component to atmospheric conditions. In turn, the relationship between GHI and DHI points to a redistribution of the diffuse fraction in regions where the direct component is reduced, confirming the structural balance among the components of the radiative balance. The spatial pattern of BHI further confirms the role of the projected direct component on the horizontal surface in shaping the spatial structure of GHI, thereby reinforcing the physical consistency of the relationships among the analysed variables.

Overall, the results indicate a stable spatial configuration of the solar resource at the national scale, characterised by a persistent core of favourable conditions in the southern and south-eastern regions and by relatively low interannual variability of the global component. The coherent correspondence among GHI, DNI, DHI, and BHI supports the internal consistency of the dataset and lends further support to the integrated approach based on satellite-derived data and geospatial modelling.

3.2. Interannual variability of GHI

The interannual behaviour of GHI, assessed from national mean values derived from the set of analysed locations, reveals a moderate and statistically significant positive linear trend. This trend is characterized by a regression slope of approximately 4.98 kWh/m²/year, a coefficient of determination (R^2) of 0.352, and a significance level of $p = 0.00363$ (Fig. 5). Statistically, this result indicates that about 35% of the interannual variability of the mean GHI can be explained by the linear component of the trend, while the remaining variation reflects year-to-year fluctuations associated with climate variability.

The annual dispersion, represented by the interval ± 1 standard deviation, indicates moderate interannual fluctuations without evidence of a progressive increase in spatial heterogeneity. Although certain years (e.g., 2007, 2012, 2022) show a wider range of variation, the overall amplitude of the dispersion remains relatively constant over time, suggesting a stable spatial structure of the resource. These results indicate that, although mean GHI tends to increase over time, the degree of spatial differentiation among locations remains relatively stable. From a methodological perspective, this finding is significant as it indicates that the increasing signal identified at the mean values is not accompanied by a corresponding increase in absolute spatial dispersion.

The coefficient of variation (CV) remains within a relatively narrow interval of approximately 5–7% throughout most of the study period, indicating a moderate level of relative variability of the GHI at the national scale. The lack of a clear upward trend in the CV, despite the increase in mean GHI, suggests that the intensification of radiation level is not accompanied by a proportional increase in interannual instability.

Combined analysis of these indicators indicates that the analysed series is characterised by a gradual increase in mean global radiation, while simultaneously maintaining a relatively stable structure of spatial dispersion and relative variability. From an energy-planning perspective, this behaviour may be regarded as favourable for medium- and long-term decision-making, given the limited degree of interannual uncertainty.

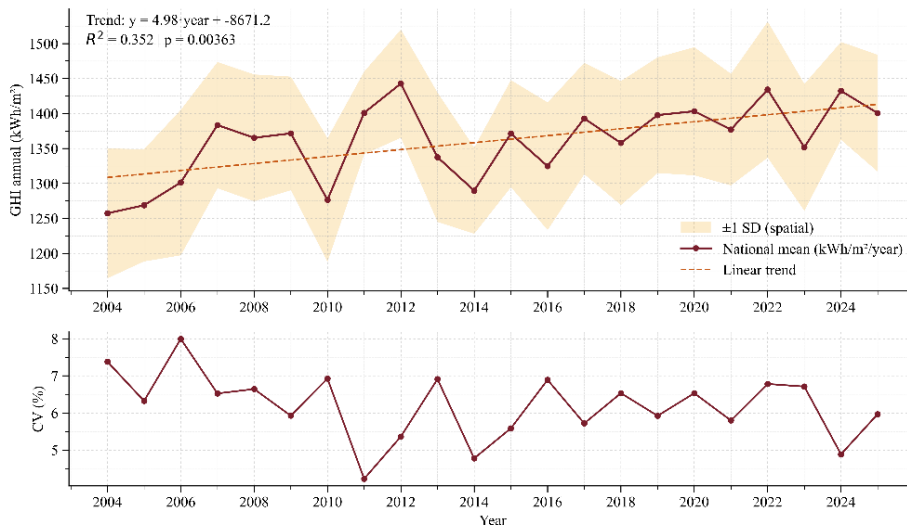


Fig. 5. Interannual variability and trend of national mean GHI and its spatial variability expressed in absolute and relative terms.

Conclusions

The results indicate a clearly differentiated spatial distribution of solar resources across Romania, characterised by a pronounced south-to-north gradient and persistent contrasts between the extra-Carpathian regions and the mountainous areas. The high values of GHI, DNI, and BHI in the southern and south-eastern parts of the country, particularly in Dobrogea and the Romanian Plain, confirm the favourable solar radiation potential of these areas, whereas the relatively higher values of DHI in the northern regions and in the mountainous areas reflects the greater contribution of the diffuse component under less favourable atmospheric conditions. Comparative analysis of the radiative components further highlights the internal coherence of the radiation budget and the functional complementarity between its direct and diffuse components.

At the interannual scale, GHI exhibits a moderate yet statistically significant positive linear trend, while spatial dispersion and relative variability remain within moderate bounds. The absence of a systematic increase in the coefficient of

variation suggests that the intensification of mean global radiation is not accompanied by a comparable increase in interannual instability.

Overall, the results confirm that the use of multiannual satellite-derived products, integrated with GIS tools and statistical indicators of variability, provides a robust methodological framework for solar resource assessment in regions where dense networks of ground-based radiometric observations are lacking. Beyond the descriptive value of the maps, this approach enables the identification of structural relationships among radiative components, the estimate of the interannual stability of the resource, and the support of further analyses related to energy potential, project feasibility, and the influence of climatic variability on solar resources.

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