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Stochastic Investigation of Solar and Wind Processes for Renewable Energy Storage in Greece

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Research Question

Over the past decade, Greece has significantly expanded its installed renewable capacity. However, the stochastic nature of Renewable Energy Sources (RES) creates a critical dual challenge:

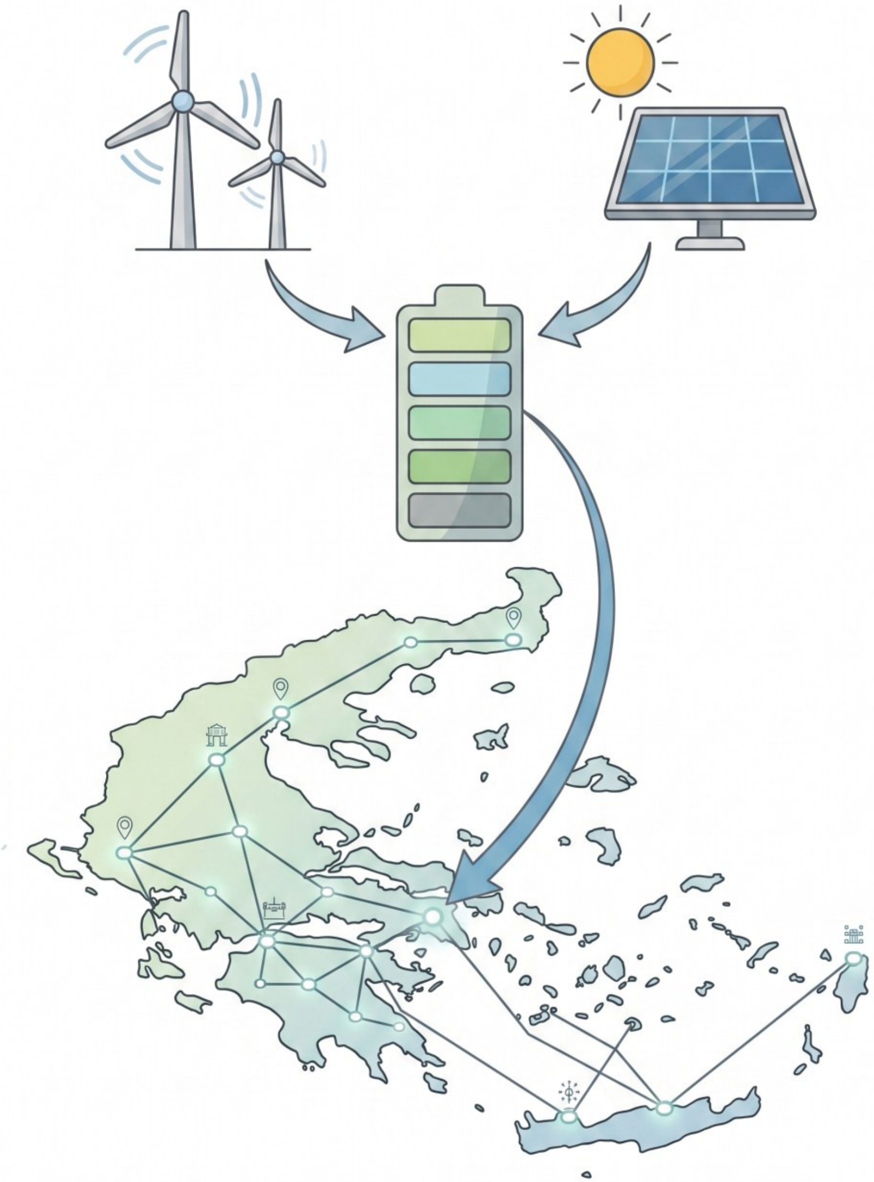
•Energy Curtailment: Frequent overproduction exceeds grid demand, resulting in wasted clean energy.

•Fossil Fuel Reliance: During periods of low weather-driven generation, the absence of energy storage forces the grid to rely on conventional power plants.

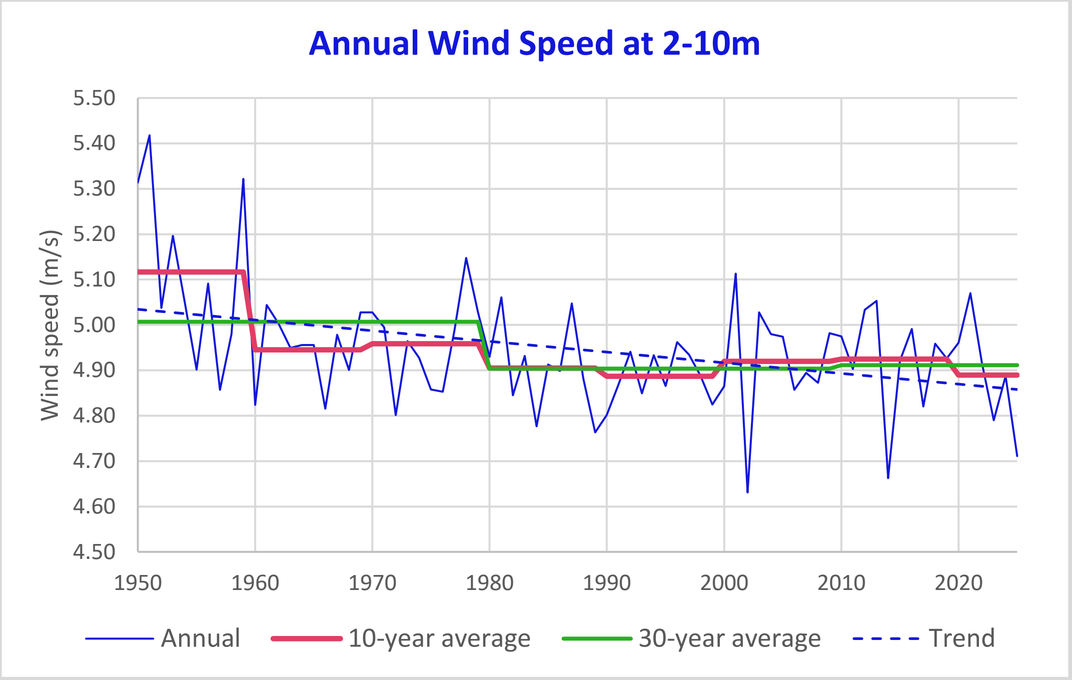
This study investigates Greece's optimal energy storage needs and formulates a robust storage model by examining:

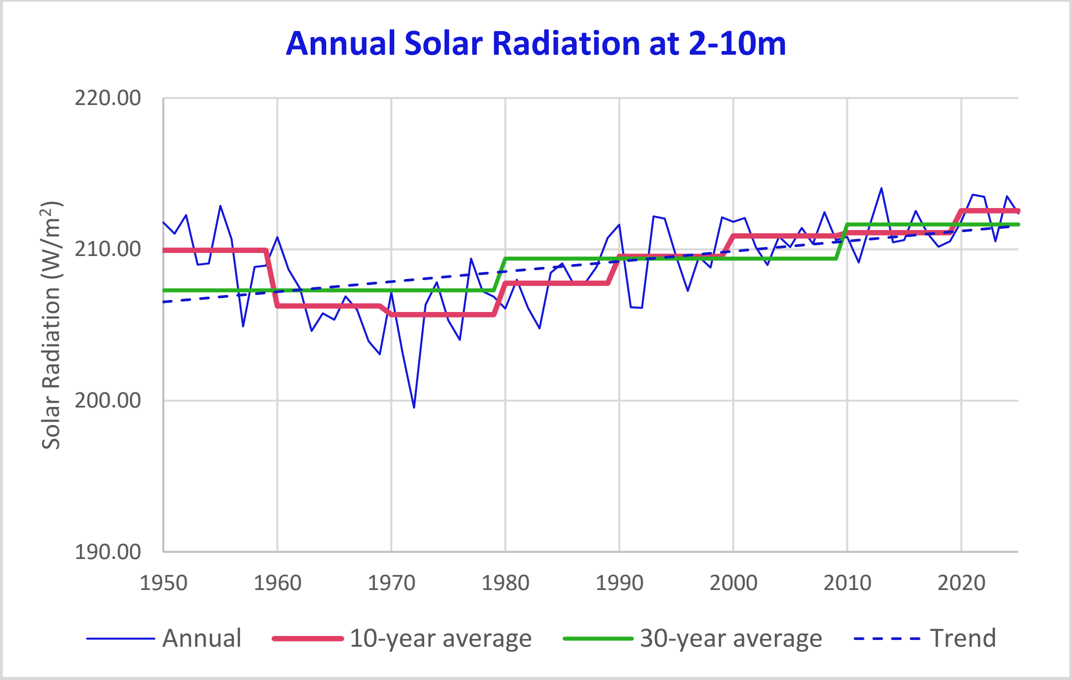
1. **Climatic Analysis & Energy Droughts:** Evaluating historical meteorological and generation data to identify and quantify prolonged periods of low RES availability.

2. **Supply-Demand Dynamics:** Analyzing the hourly relationship between actual energy production and consumption to determine the system's energy deficits and storage capacity requirements.



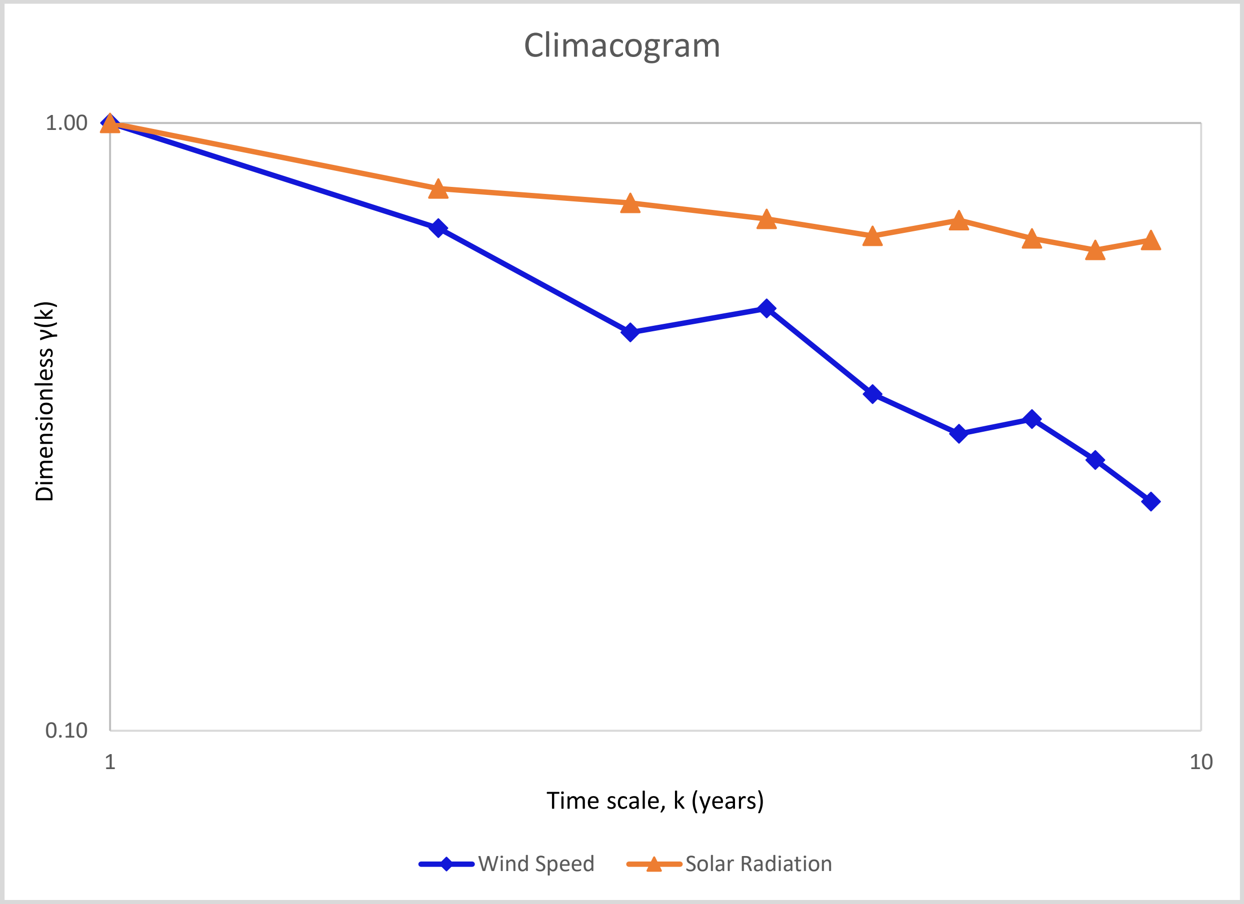
Climatic Patterns





Stochastic Parameters	**Annual Wind Speed (m/s)**	**Annual Solar Radiation (W/m^2)**
Average	4.95	209.03
Standard Deviation	0.13	2.92
Skewness	0.88	-0.64
Slope	-0.002	0.067

Climatic Pattern: Hurst-Kolmogorov process

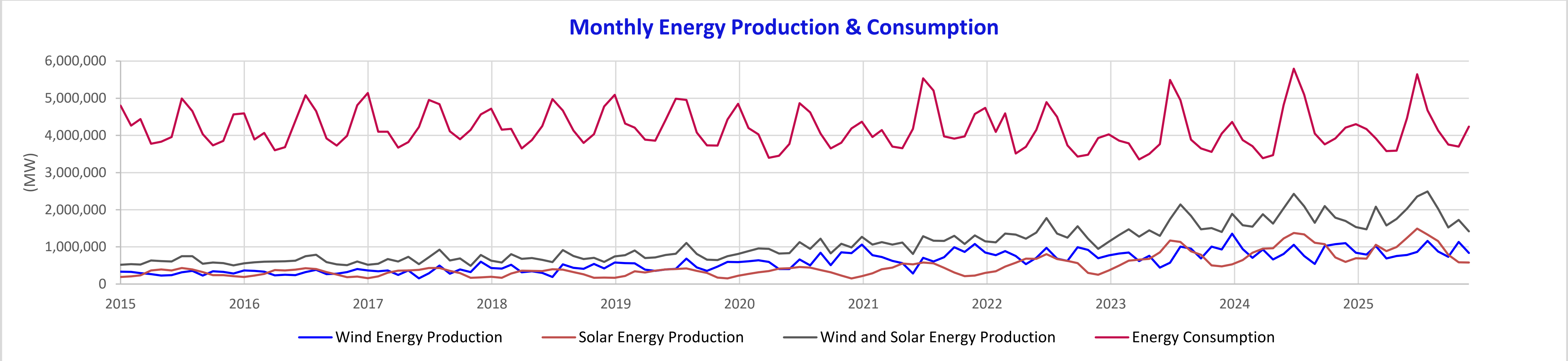


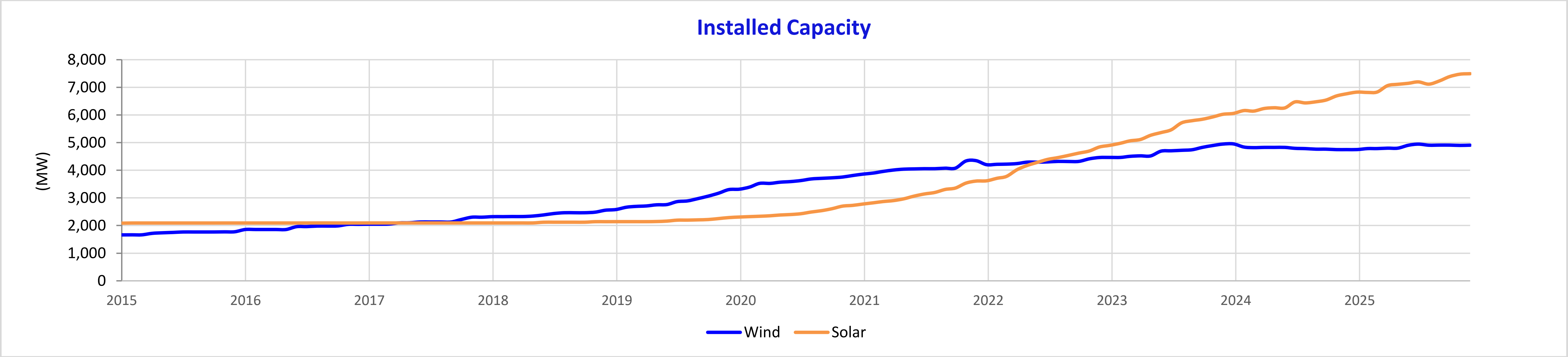
By implementing the **Hurst-Kolmogorov model** with empirical climate data, we can represent the **stochastic nature and variability** inherent in solar radiation and wind speed.

$$\gamma_k = var[\underline{x}_j^{(k)}] = \gamma_1 / k^{2-2H}$$

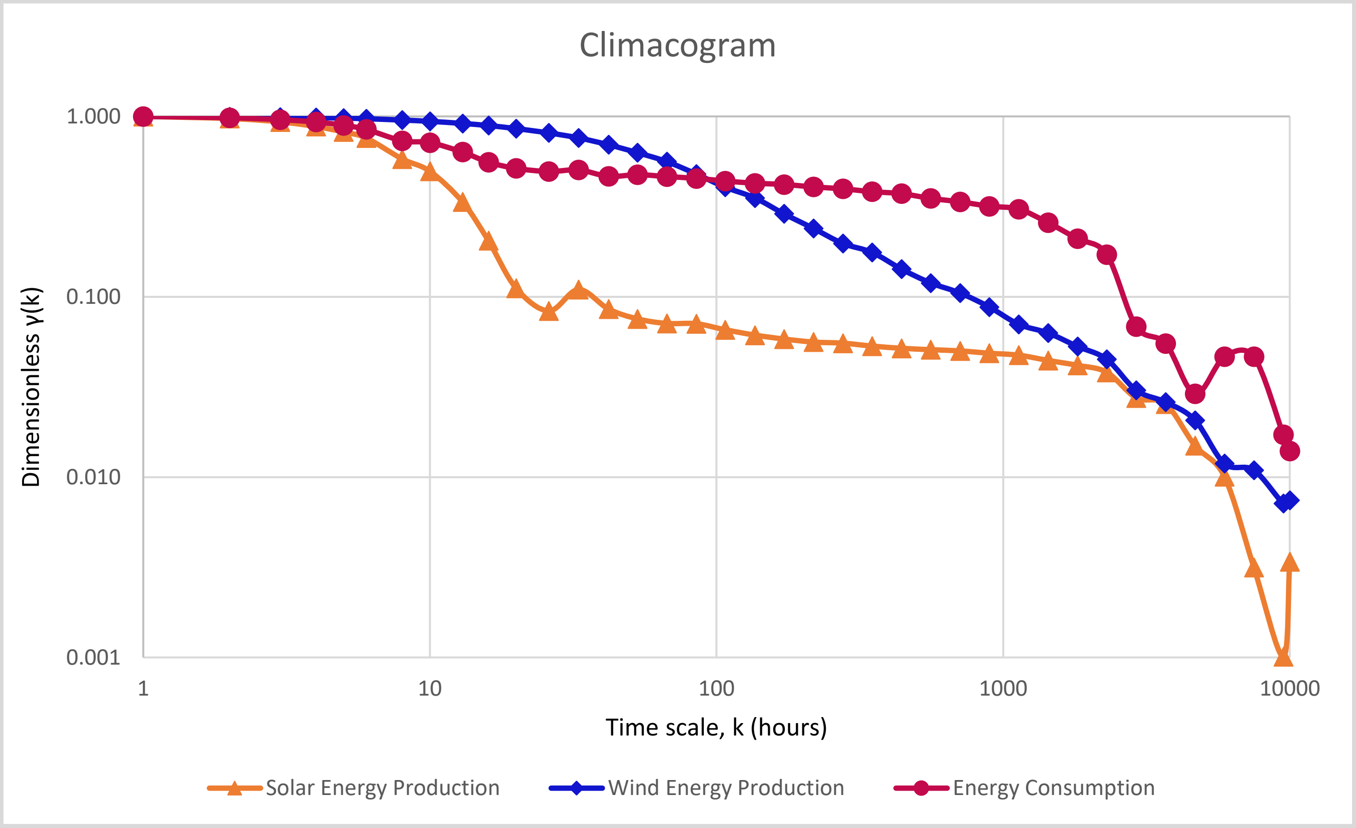
	Hurst
Solar Radiation	0.90
Wind Speed	0.69

Energy Production & Consumption





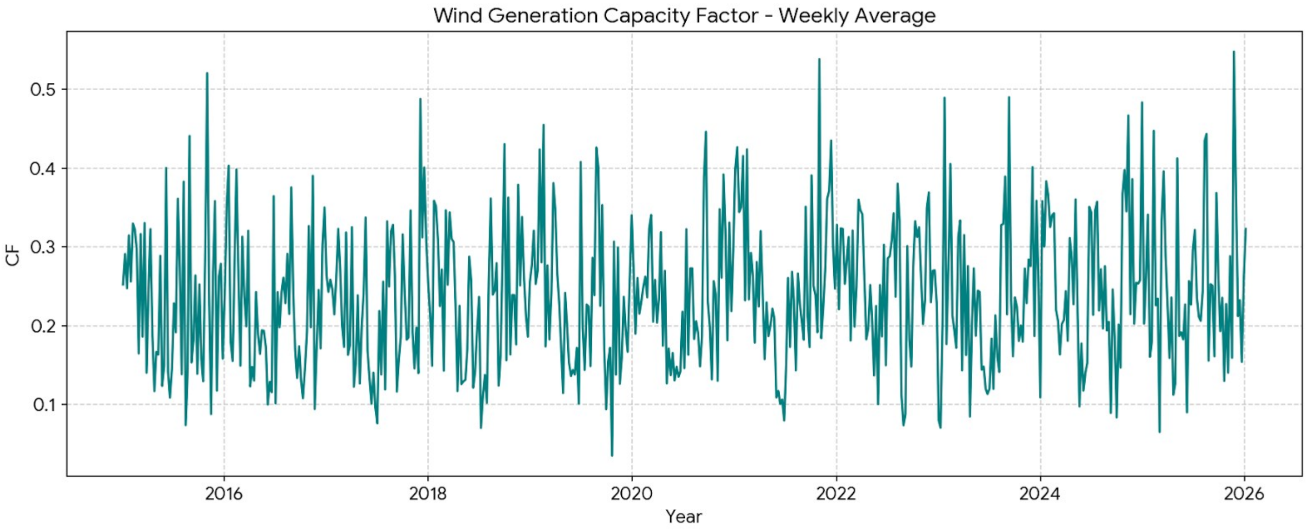
Energy Production and Energy Consumption: Hurst-Kolmogorov process

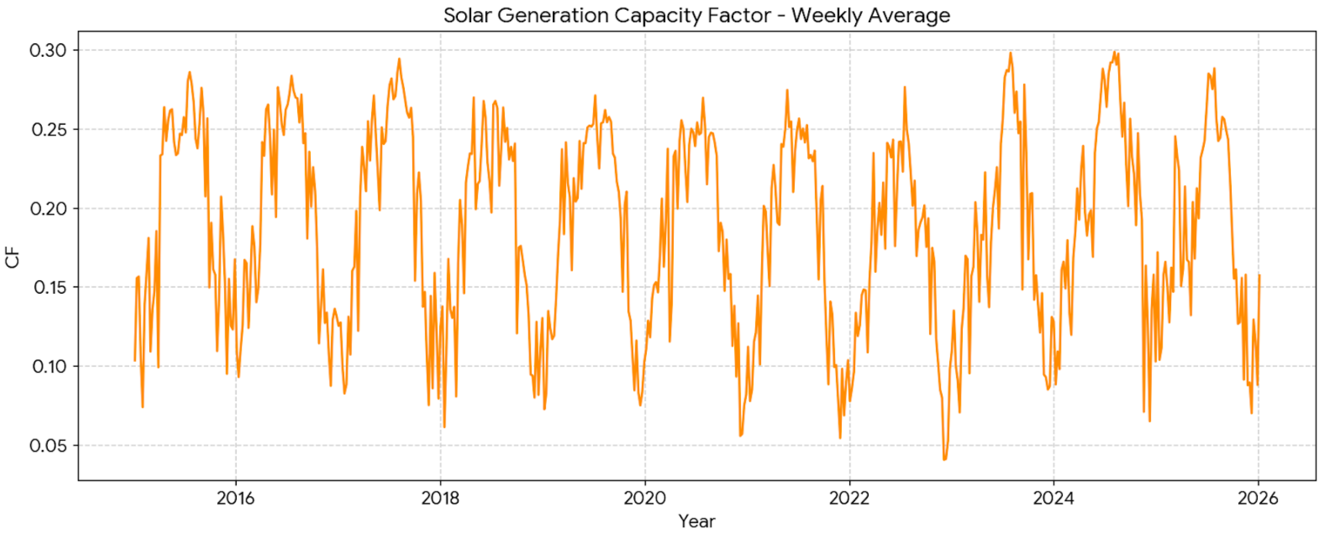


The climacograms are influenced by periodicity

	Hurst
Solar Energy	0.72
Wind Energy	0.71
Energy Consumption	0.81

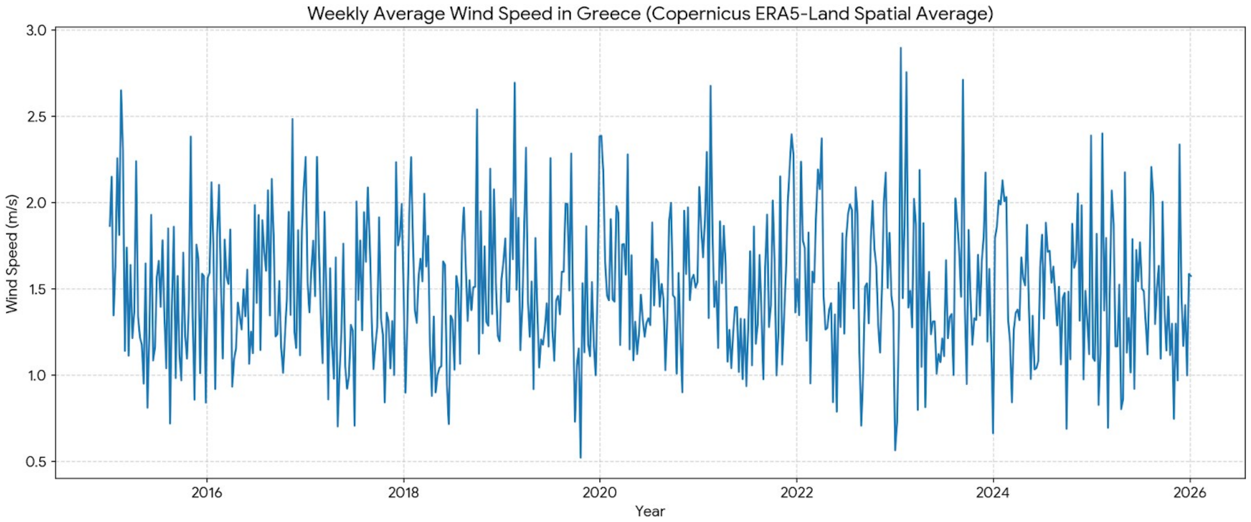
Solar & Wind Generation Capacity

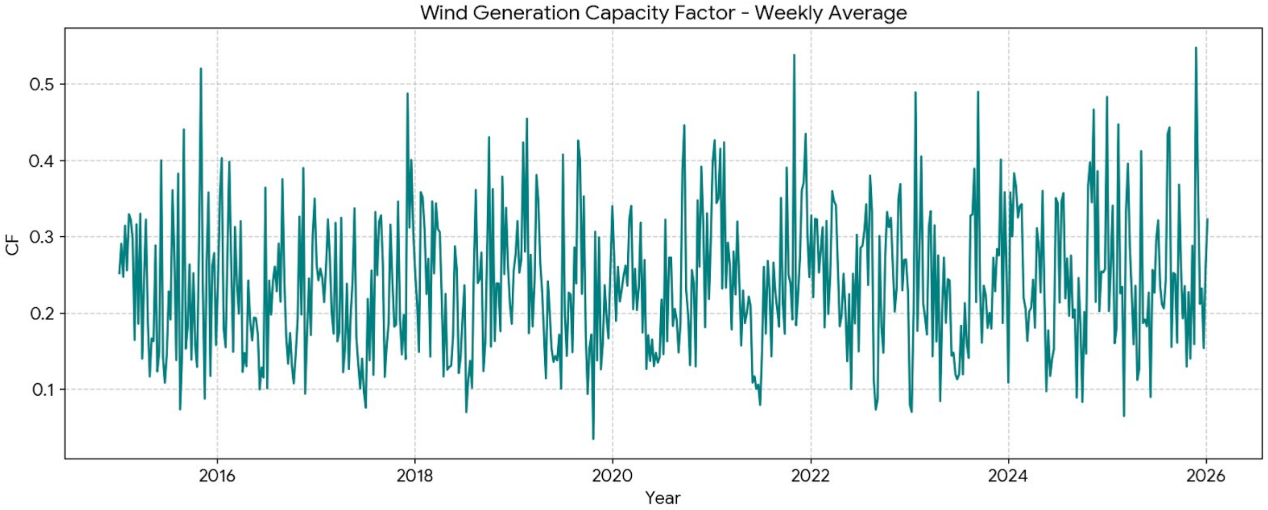




$$\text{Generation CF} = \frac{\text{Energy Production}}{\text{Installed Capacity}}$$

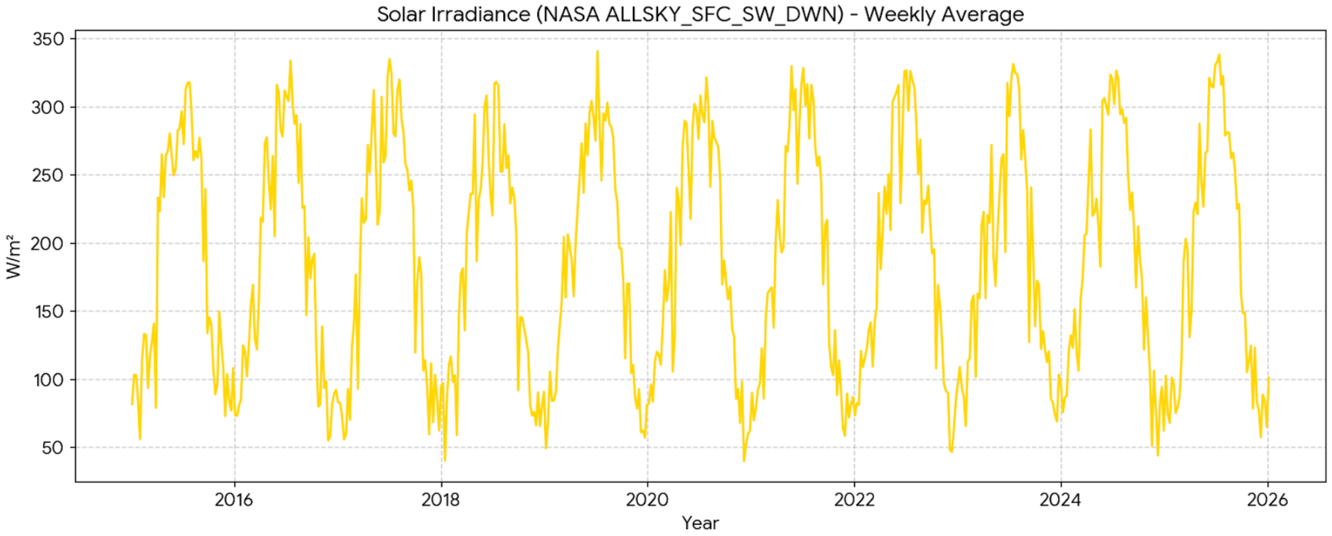
Correlation between Wind Speed and Wind Generation CF

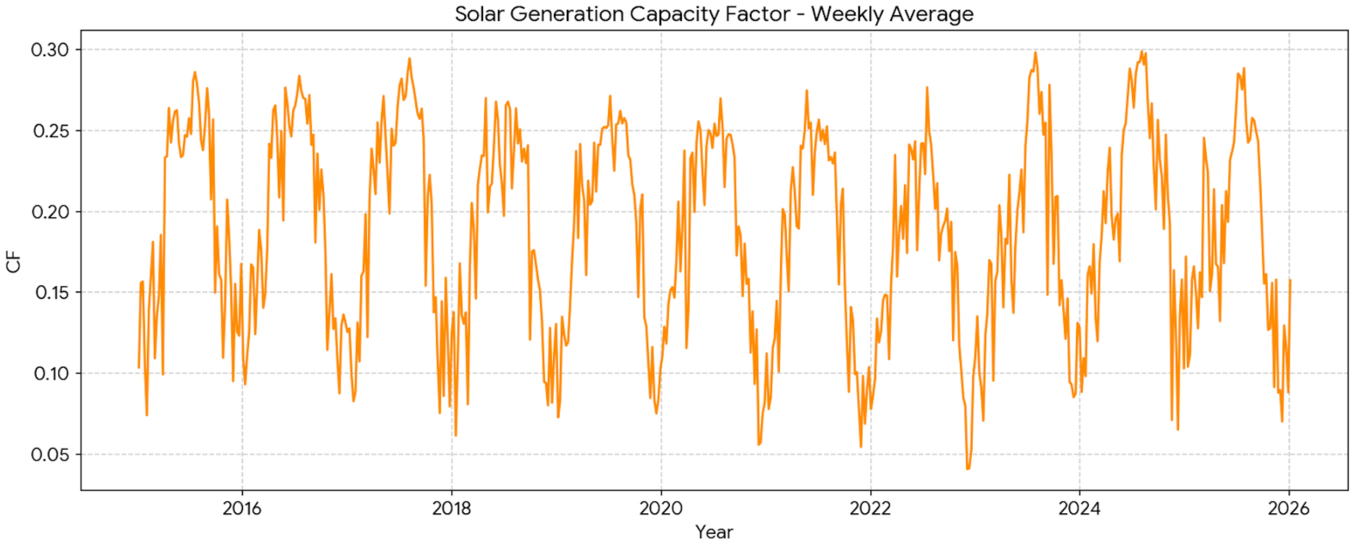




Correlation r=0.74

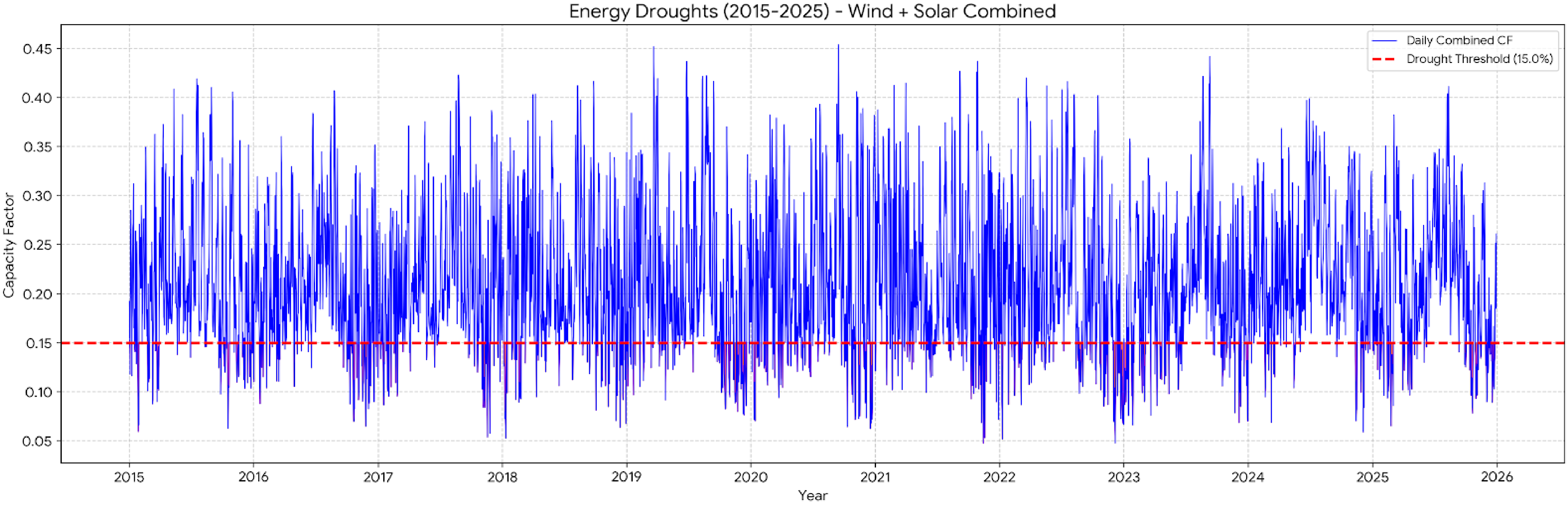
Correlation between Solar Irradiance and Solar Generation CF





Correlation: r=0.91

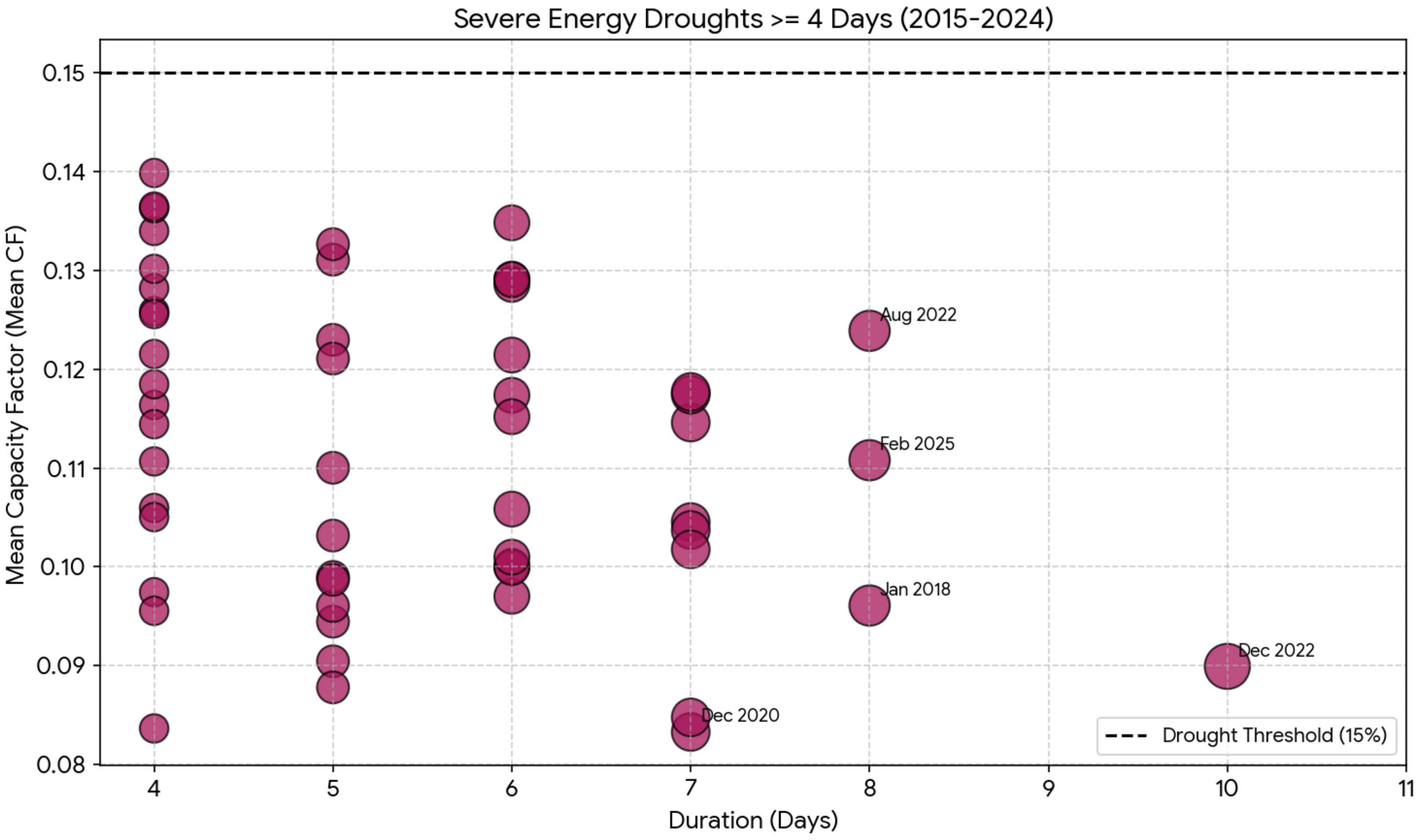
Energy Droughts



$$\text{CF\_combined} = \frac{\text{E\_solar} + \text{E\_wind}}{\text{C\_solar} + \text{C\_wind}}$$

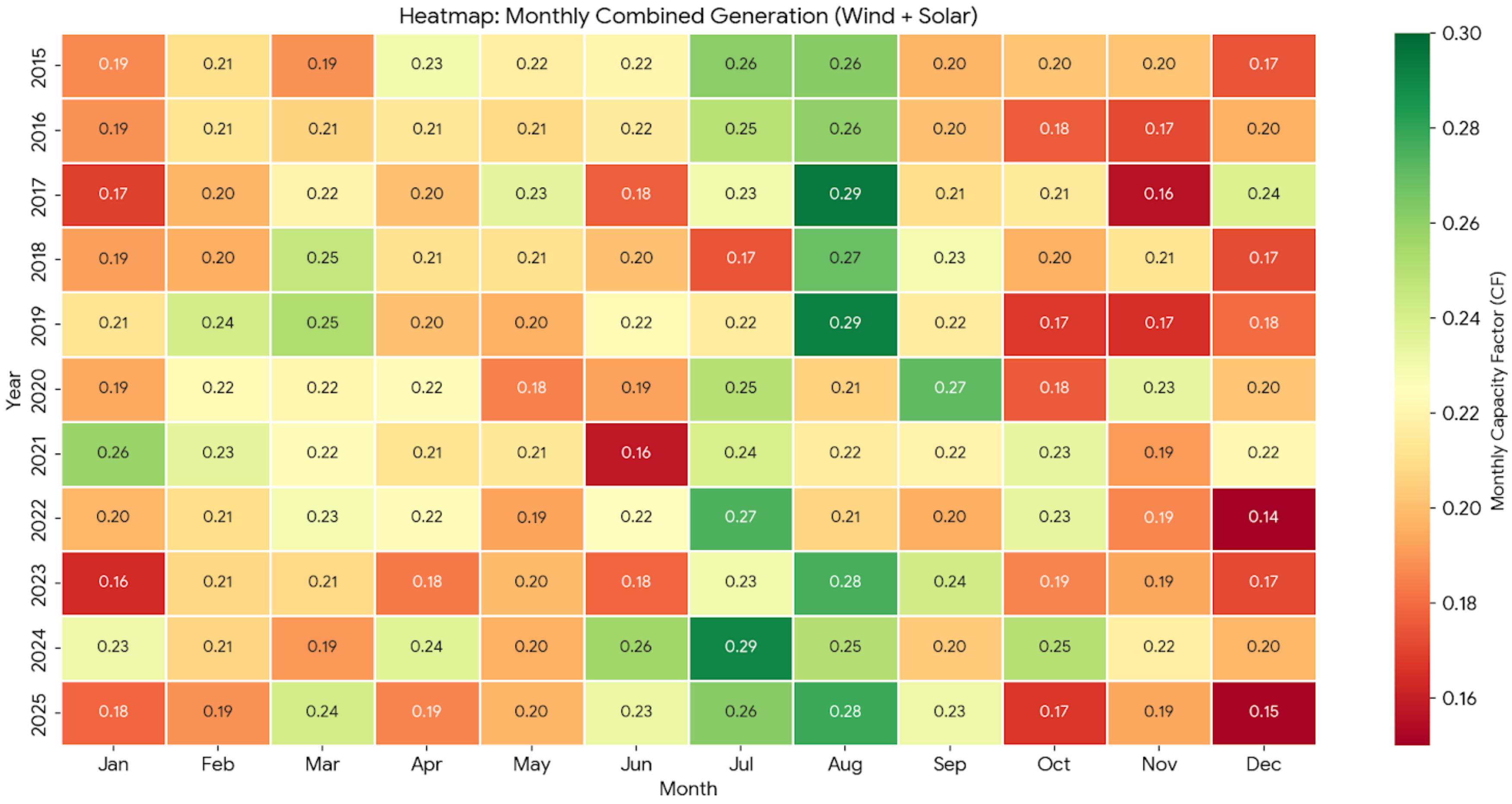
Drought Threshold: CF_combined = 0.15

Energy Droughts



The longest energy drought occurred in December 2022 and lasted for 10 days, with a mean CF of 0.09.

Energy Droughts

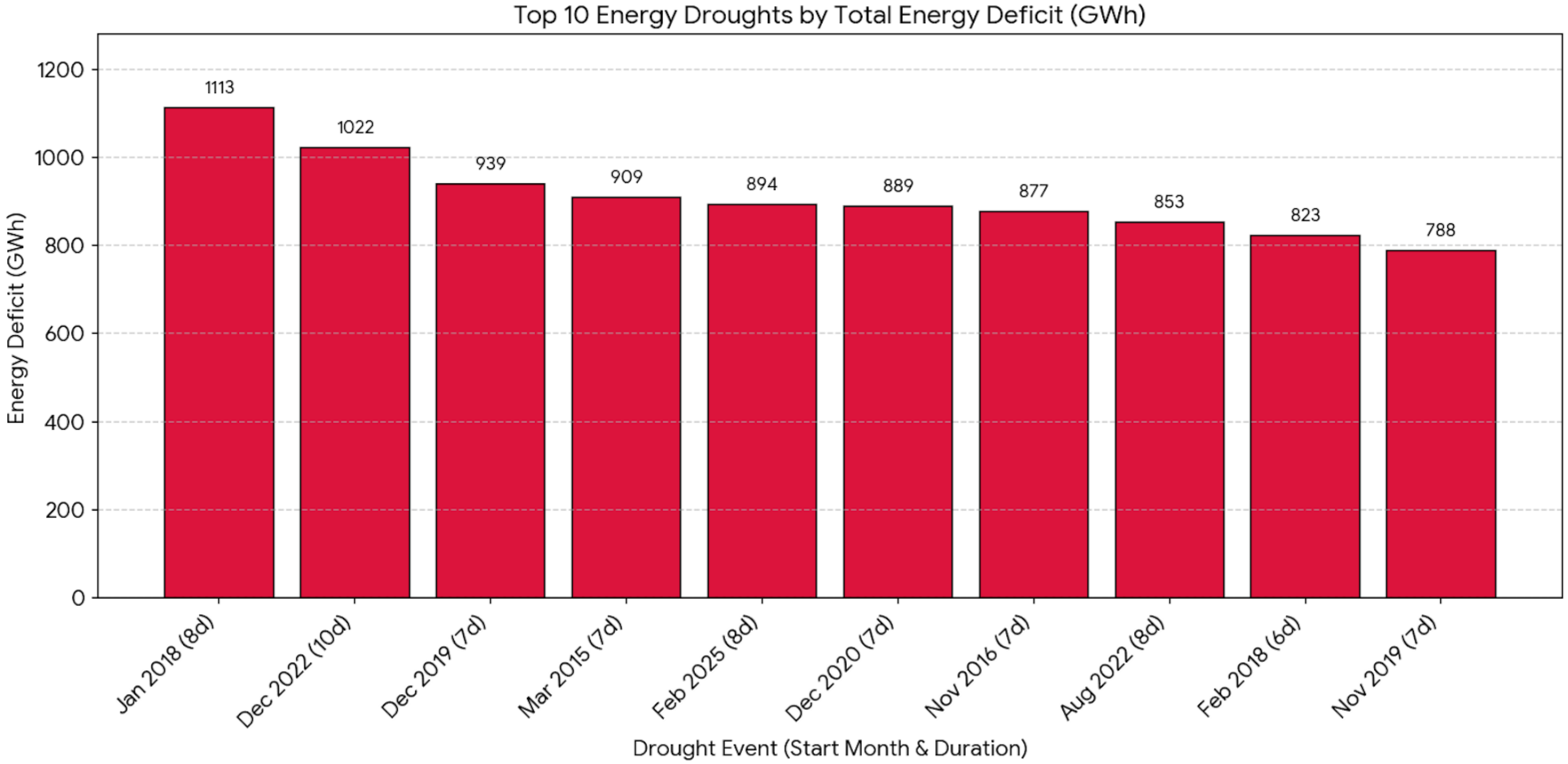


Heatmap: Monthly Combined Generation (Wind + Solar)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2015	0.19	0.21	0.19	0.23	0.22	0.22	0.26	0.26	0.20	0.20	0.20	0.17
2016	0.19	0.21	0.21	0.21	0.21	0.22	0.25	0.26	0.20	0.18	0.17	0.20
2017	0.17	0.20	0.22	0.20	0.23	0.18	0.23	0.29	0.21	0.21	0.16	0.24
2018	0.19	0.20	0.25	0.21	0.21	0.20	0.17	0.27	0.23	0.20	0.21	0.17
2019	0.21	0.24	0.25	0.20	0.20	0.22	0.22	0.29	0.22	0.17	0.17	0.18
2020	0.19	0.22	0.22	0.22	0.18	0.19	0.25	0.21	0.27	0.18	0.23	0.20
2021	0.26	0.23	0.22	0.21	0.21	0.16	0.24	0.22	0.22	0.23	0.19	0.22
2022	0.20	0.21	0.23	0.22	0.19	0.22	0.27	0.21	0.20	0.23	0.19	0.14
2023	0.16	0.21	0.21	0.18	0.20	0.18	0.23	0.28	0.24	0.19	0.19	0.17
2024	0.23	0.21	0.19	0.24	0.20	0.26	0.29	0.25	0.20	0.25	0.22	0.20
2025	0.18	0.19	0.24	0.19	0.20	0.23	0.26	0.28	0.23	0.17	0.19	0.15

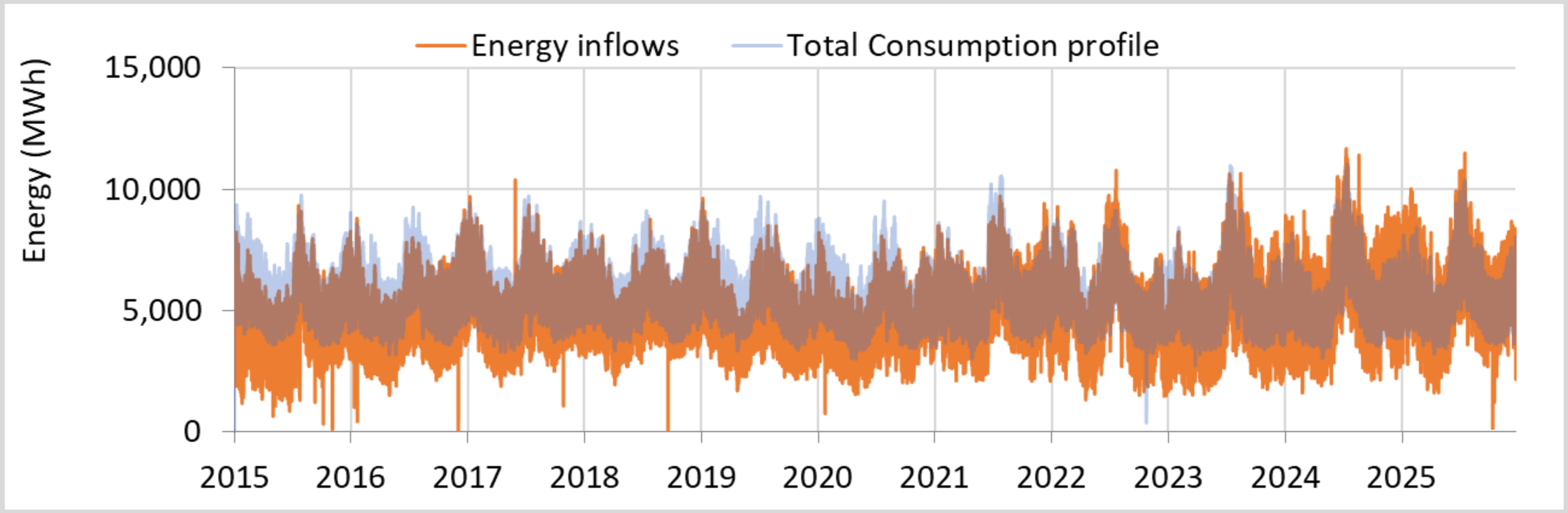
The most critical month regarding energy droughts appears to be December.

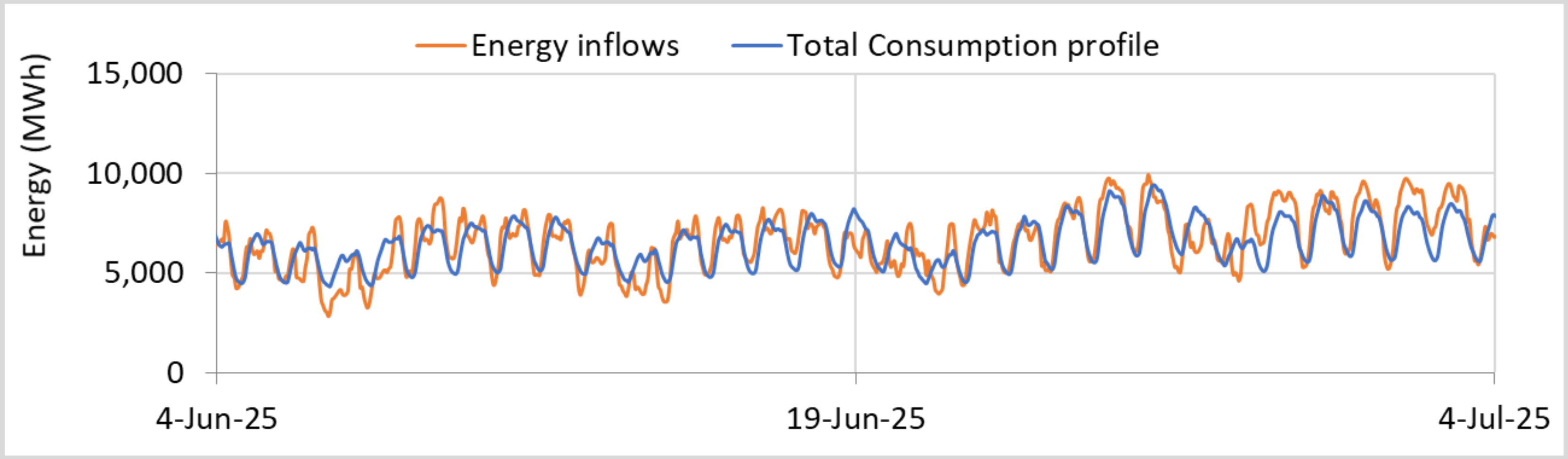
Energy Deficits



Incorporating the Energy Consumption Data, the 10 most critical Energy Droughts are being quantified, determining Storage Demand.

Profiles of Energy Consumption and Production (2015–2025)





- **In 2025, with a storage capacity of ≈1 GWh, the energy demand was met ≈64% of the time, meaning that ≈36% of the time Greece had to import energy.**
- **The big view is that post-2025, energy production matched overall consumption.**
- **In 2025, the system lacks the capacity to store all the produced energy. The energy surplus amounts to 3.62 TWh.**
- **However, we can see that in a smaller scale, energy demand remains unmet during certain periods as it did not align with the timeline of energy needs.**

Model for the Estimation of Storage Demand

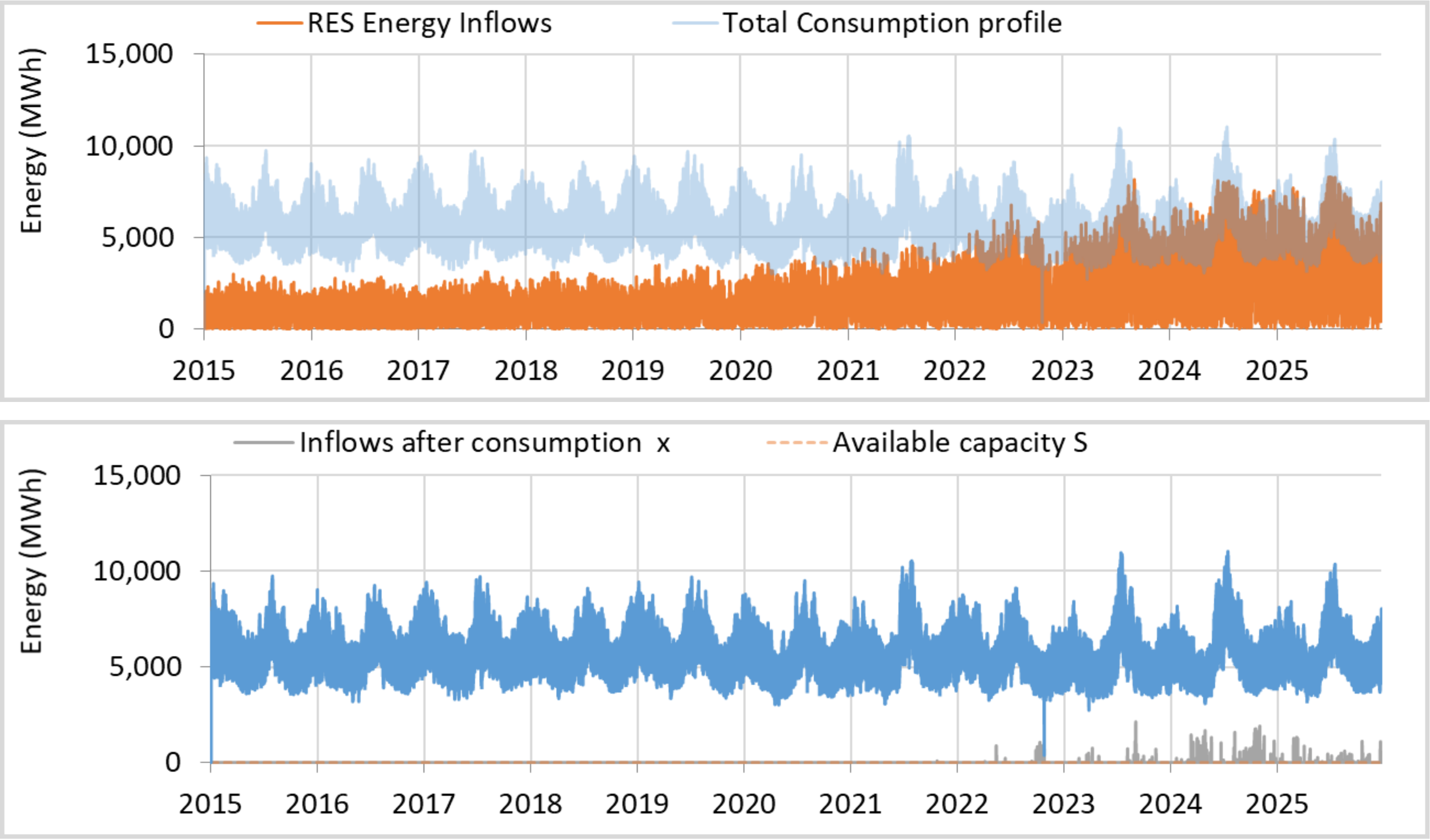
To describe the operation of the energy storage system, we employ a model described by the processes defined in Equations:

$$\underline{\boldsymbol{S}}_{\boldsymbol{T}} = \mathbf{max}\left(\mathbf{0}, \boldsymbol{min}(\underline{\boldsymbol{S}}_{\boldsymbol{T}-\mathbf{1}} + \underline{\boldsymbol{x}}_{\boldsymbol{T}} - \underline{\boldsymbol{\delta}}_{\boldsymbol{T}}, \boldsymbol{K}\right)$$

$$\underline{\boldsymbol{R}}_{\boldsymbol{T}} = \mathbf{min}(\underline{\boldsymbol{S}}_{\boldsymbol{T}-\mathbf{1}} + \underline{\boldsymbol{x}}_{\boldsymbol{T}}, \underline{\boldsymbol{\delta}}_{\boldsymbol{T}})$$

where T is time; K is the storage capacity of the system; S_T *is the stock in the storage energy system;* x_T *is the inflow to the energy storage system after consumption;* δ_T *is the energy demand and* R_T *is the actual amount of taken energy in an attempt to satisfy energy demand during the time period (t-1, t). When the storage energy system has sufficient energy,* R_T *equals demand* δ_T*; otherwise,* $R_T < \delta_T$*.*

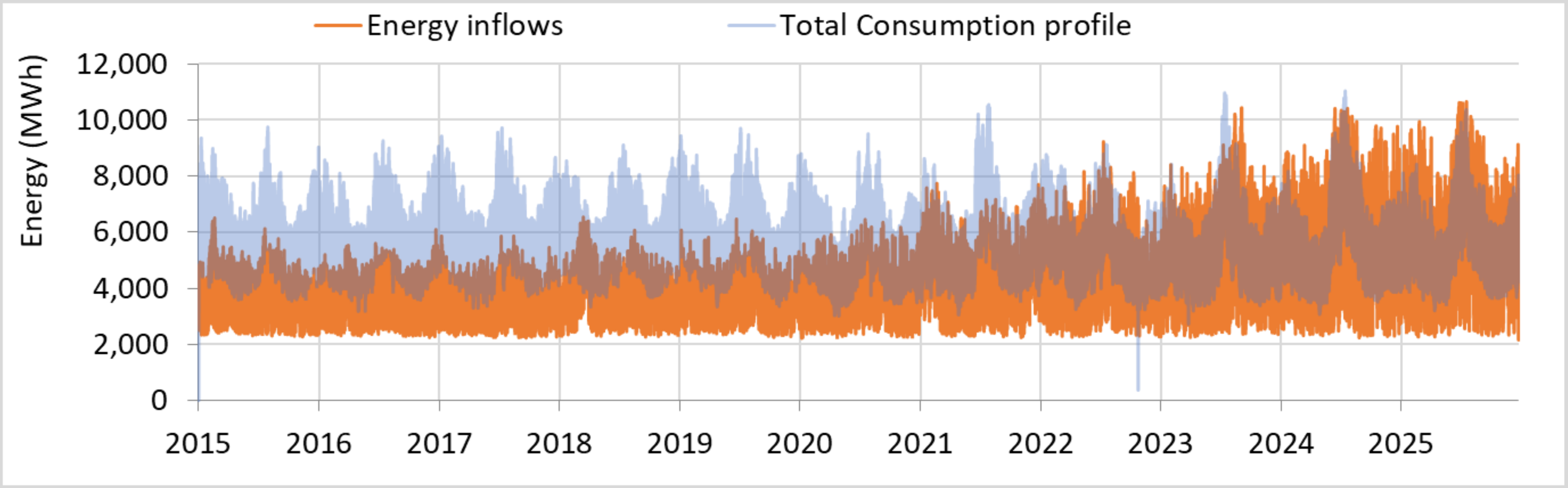
Toy model (1)– Only Renewable Energy Sources



- **The big view is that post-2021 RES production began to reach the energy consumption profile.**

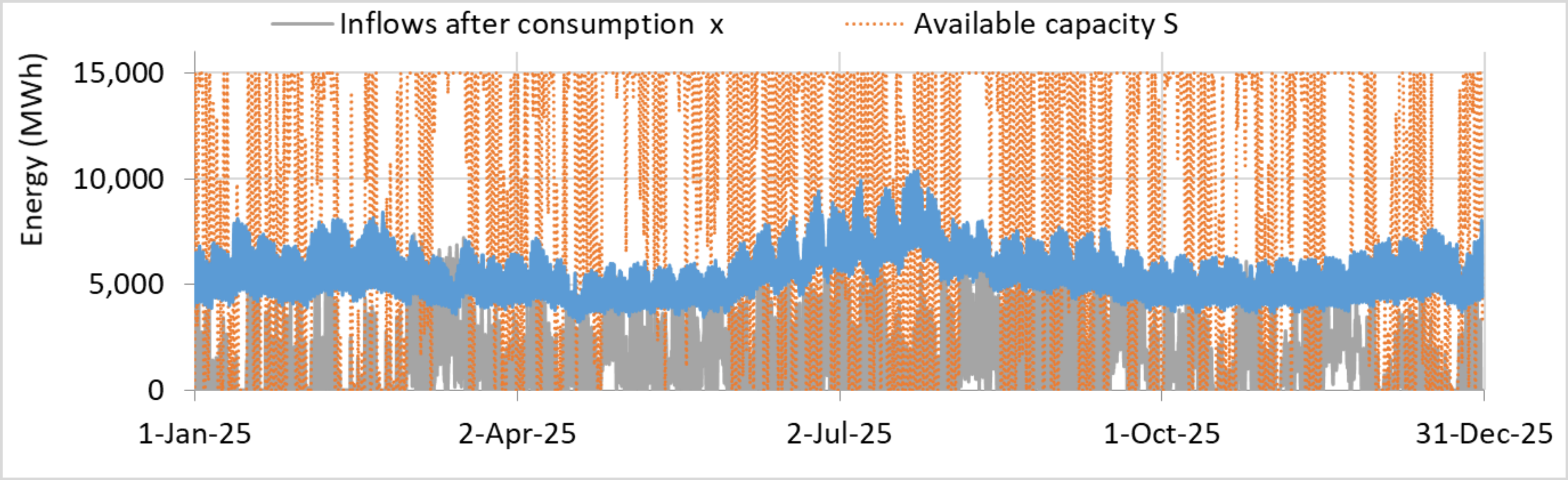
- **Excess energy is insufficient for storage, proving that adding storage capacity alone is not enough.**
- **Increased RES penetration is required to generate the necessary surplus for storage.**

Toy model (2)— System stability via domestic energy sources



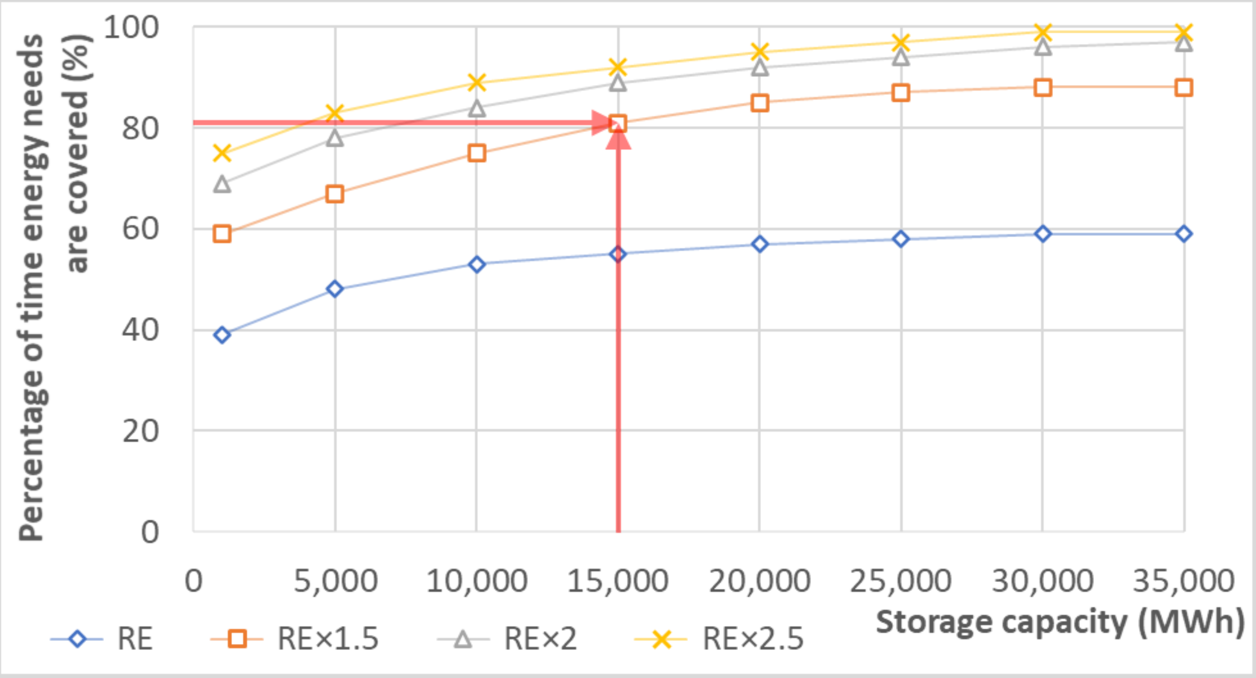
We are aiming at system stability and independence by optimizing domestic energy resources:

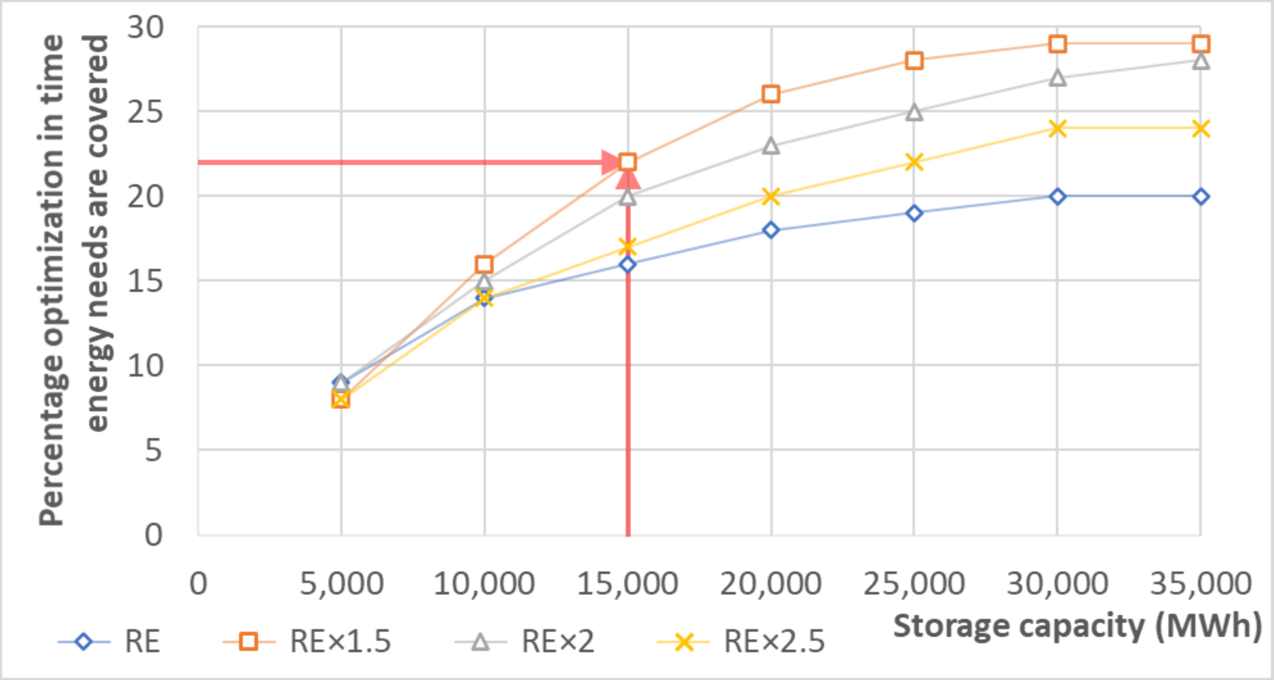
- **hydroelectric power**
- **Lignite**
- **Renewables (wind +solar)**



- **In 2025, the energy demand would be covered 33% of the time if we relied solely on domestic energy sources**
- **A ×1.5 increase in RES and installation of 15,000 GWh storage capacity results in ≈80% system reliability.**

Storage Demand – System Optimization





- **Alternative scenarios explored for storage capacity and RES penetration.**
- **System reliability plateaus after 20 GWh of storage capacity.**

- **System reliability growth was analyzed across different RES and storage capacity scenarios.**
- **It is shown that a ×1.5 increase in RES capacity provides the most significant boost to system reliability.**

Conclusions

Regarding Energy Droughts:

- The Most critical month regarding energy droughts in Greece appears to be December.
- The Longest Energy Drought of the last decade in Greece lasted 10 days, in December 2022 with a Mean Capacity Factor = 0.09.
- The worst energy drought of the last decade occurred in January 2018, lasting 8 days and resulting in an energy deficit of approximately 1100 GWh.

Regarding Energy Storage:

- Post-2021 RES production began to reach the energy consumption profile. In 2025, the energy surplus amounts to 3.62 TWh. However, since it did not align with the timeline of the needs, it was either exported or discarded.
- Expanding storage capacity alone is insufficient without a corresponding increase in RES generation to provide the necessary surplus.
- System Reliability Analysis & Scenarios with domestic sources
  a) Current Infrastructure Performance
    - Lignite, Hydro, RES: 40% reliability.
    - RES-only (Current Levels): Only 5% reliability.
    - Conventional-only (Lignite & Hydro): 0% reliability (insufficient capacity).
  b) Future Scenarios
    - ×1.5 RES + Hydro + 15 GWh Storage: ≈ 42% reliability.
    - ×1.5 RES + Lignite + Hydro + 15 GWh Storage: ≈ 80% reliability.

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