PHY408 Final Project: Analysis of Alternative Energy Trends in The United States

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Introduction

Understanding the evolving landscape of renewable energy is critical in a world increasingly focused on sustainability and energy independence. This report investigates historical patterns and growth trends in U.S. renewable energy consumption using monthly data compiled by the U.S. Energy Information Administration (EIA). As global efforts have shifted toward de-carbonisation and clean energy transitions, it is essential to examine not just the total rise in renewable energy use, but the specific behaviour of individual sources such as solar, wind, and hydroelectric, among others, over time to be able to make informed decisions about policies regarding their usage in the future.

Renewable energy technologies differ significantly in how they are adopted and consumed. Solar and wind power have experienced rapid expansion in recent years due to falling technology costs and supportive policies but are subject to variability based on weather and season. Hydroelectric power, a more mature source, provides reliable baseline generation but is geographically constrained. Biomass and geothermal energy sources offer relatively steady output, with applications in both electricity generation and direct heating. Given these varied characteristics, it is important to study each source individually to identify patterns, opportunities, and barriers to growth.

The primary objective of this report is to assess how each renewable energy source has evolved in terms of monthly U.S. consumption. This includes detecting long-term trends and exploring seasonal behaviours. A secondary objective is to determine which sources are growing most rapidly and making predictions on future usage. These insights aim to support energy policy development by providing a data-driven understanding of how the U.S. is progressing toward a renewable energy future.

Based on the plot of available data (Figure 1), I believe solar and wind will show the highest level of growth and seasonality, while biofuels and geothermal energy will show stable progression. I also predict that hydroelectric will remain stable while wood will show a decline.

By conducting time series analysis, this report provides a comprehensive view of renewable energy trends over time, I hope to contribute to the broader conversation on clean energy transitions by grounding observations in historical data and enabling forward-looking perspectives based on empirical evidence.

Data and Methods

The data used for this analysis can be found via this link. The dataset was sourced from the U.S. Energy Information Administration's (EIA) Monthly Energy Review (Table 10.1), which provides monthly consumption values for renewable energy sources (solar, wind, hydroelectric, geothermal, biofuels, and wood) in Trillion British Thermal Units (BTU) in columns 5 to 11. 1 BTU is approximately 1055 Joules. Raw data were preprocessed by converting YYYYMM timestamps to DateTimeIndex and filtering invalid entries (e.g., months outside 1–12). Missing values were addressed via time-based linear interpolation (method='time'), and each series was centered by subtracting its mean. The processed data were pivoted into a time series format for analysis.

Seasonal decomposition was performed using an additive model to isolate trend, seasonal, and residual components:

$$Y(t) = \text{Trend}(t) + \text{Seasonal}(t) + \text{Residual}(t), \tag{1}$$

where Y(t) represents the observed value at time t. The decomposition leveraged a fixed 12-month period to capture annual cycles.

For forecasting, Seasonal AutoRegressive Integrated Moving Average (SARIMA) models were employed, defined as:

$$\text{SARIMA}(1, 1, 1)(1, 1, 1)_{12}. \tag{2}$$

This assumes first-order differencing (d=1) and seasonal differencing (D=1) without explicit stationarity validation (e.g., ADF/KPSS tests). Model fitting used the SARIMAX implementation in statsmodels, with stationarity and invertibility checks disabled to accommodate potential nonconvergence. Forecasts for 2025–2030 were generated with 95 percent confidence intervals, though residual diagnostics (e.g., Ljung-Box test) and error metrics (e.g., RMSE) were omitted.

Spectral analysis employed the Fast Fourier Transform (FFT) to identify cyclical patterns:

$$Y_k = \sum_{n=0}^{N-1} y_n \cdot w_n \cdot e^{-2\pi ikn/N}, \tag{3}$$

where w_n represents a Hanning window applied to reduce spectral leakage. Power spectra were plotted on a logarithmic scale against period lengths (months), with key cycles (1y, 2y, 3y, 5y) annotated. Cross-spectral plots can be found in appendix B, as cross-spectral analysis falls outside the scope of PHY408.

Results and Discussion

We start with two plots of some of the raw data. One annual and one monthly plot of renewable energy consumption by source. The sources available are biofuels, geothermal, hydroelectric, solar, waste, wind, and wood. Waste energy analysis has been omitted from the main report but can be found in appendix A

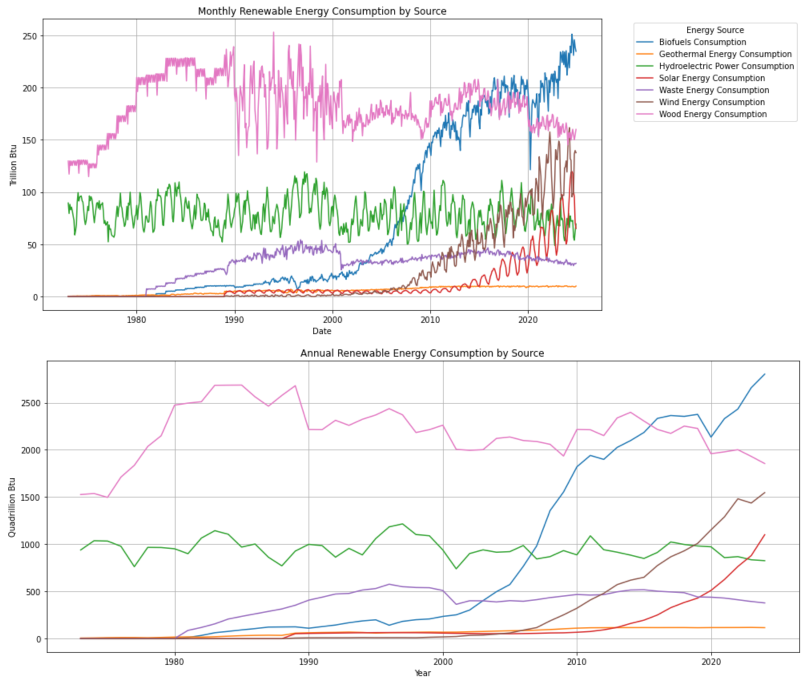
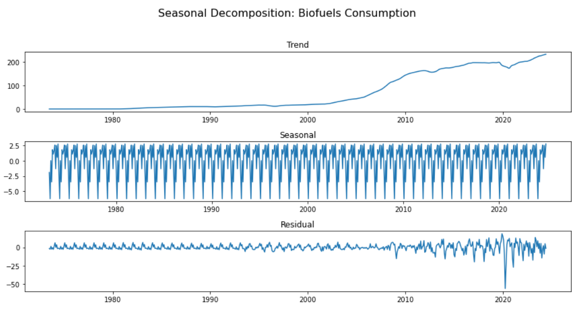
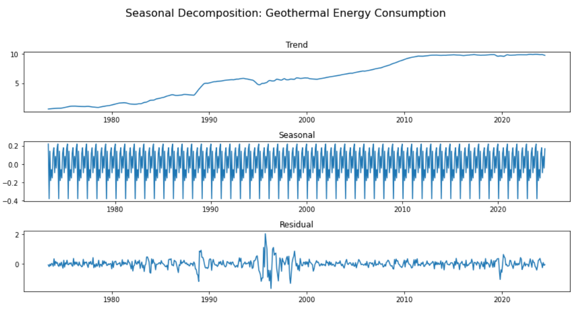


Figure 1: Monthly (top), annual (bottom) consumption by renewable source. Note the different units for clarity of plot

Now, to analyse the seasonal decompositions of each energy source; please note the different axes for each plot. We start with biofuels, which display accelerated growth post-2000, fuelled by biofuel mandates and transportation decarbonization. Weak seasonality implies stable demand year-round. Small residuals confirm policy-driven, predictable growth. Biofuels are critical for decarbonizing sectors like aviation but face feedstock sustainability challenges. In geothermal energy, we see a small, steady increase throughout the years and a recent flattening. The seasonal component is relatively stable with minor fluctuations, indicating no significant seasonal patterns in geothermal energy consumption. The residuals are also small, indicating that trend and seasonal analysis explains most variation.



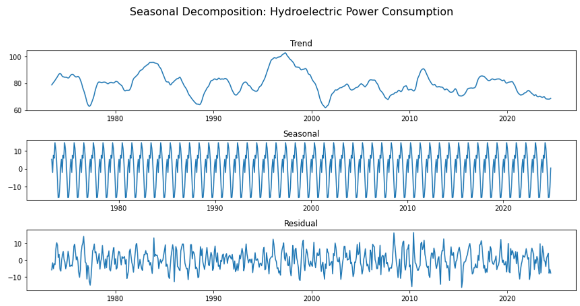
(a) Biofuels



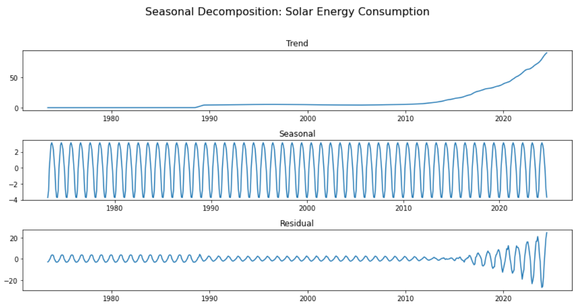
(b) Geothermal Energy

Figure 2: Seasonal decompositions of (a) Biofuels and (b) Geothermal

Hydroelectric consumption exhibits growth, despite a few dips, until 2000, then plateaus. This is possibly due to maxed-out dam capacity or environmental concerns. Pronounced seasonal fluctuations align with rainfall/snow melt cycles, causing variability in output. Residuals are moderate, which may imply external influences like droughts or policy shifts. Seasonal mismatches may require grid-scale storage or complementary energy sources. Solar trend reveals exponential growth post-2010, driven by falling costs and policy support. Clear seasonality peaks in sunnier months, reflecting sunlight dependency. Residuals are negligible, indicating predictable adoption patterns. The rapid expansion underscores its dominance in renewables, though seasonal peaks demand storage solutions for grid stability.



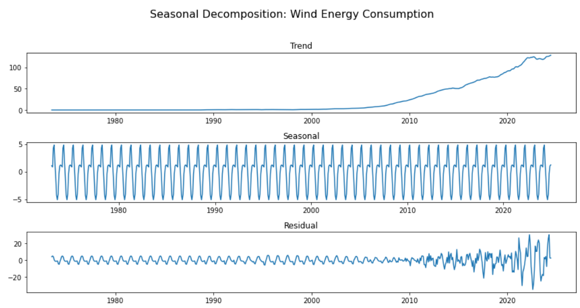
(a) Hydro



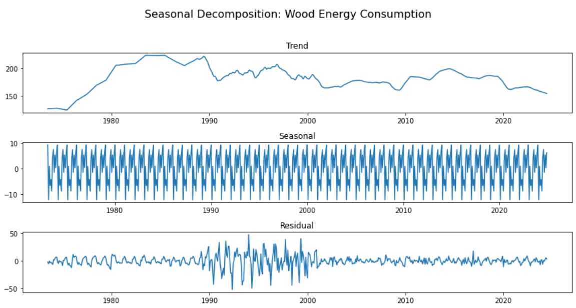
(b) Solar

Figure 3: Seasonal decompositions of (a) Hydro and (b) Solar

Wind energy shows rapid growth starting in 1990, mirroring global wind farm expansion. Seasonality is moderate, with fluctuations tied to regional wind patterns. Residuals are larger than solar's, suggesting noise from irregular wind variability or grid integration challenges. Wind's scalability is evident, but it also may require back up systems. The wood trend is flat or declining, signalling reduced reliance. Strong seasonality (e.g., winter heating demand) persists. Residuals are small in recent years suggesting a recent predictable adoption pattern.



(a) Wind

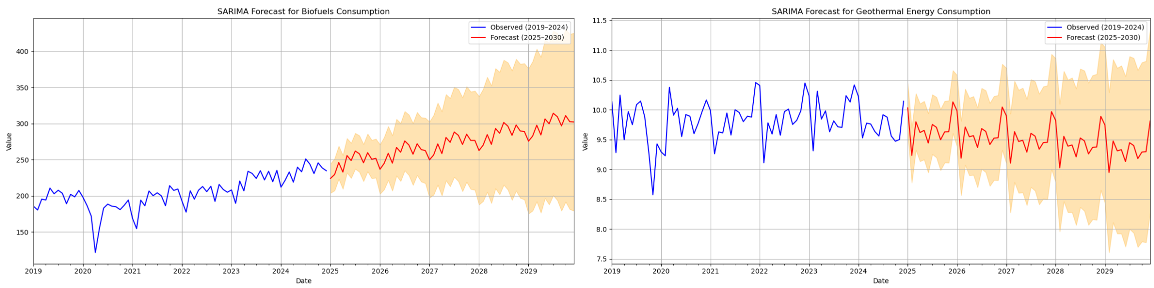


(b) Wood

Figure 4: Seasonal decompositions of (a) Wind and (b) Wood

To summarise the current trends, solar, wind, and biofuels dominate in terms of growth, likely due to policy pushes in recent decades. Solar, hydro, and wind exhibit the strongest seasonal trends, implying that reliance on them would need supplementation or methods of storage when demand/production are lower in winter months. Wood is declining, particularly in contrast to waste energy, which shows a switch to more modern forms of partial-renewables.

Next, to look at the predicted trends, starting with biofuels again. We can see below that biofuels exhibit steady, moderate growth in the forecast, indicating their continued importance for decarbonizing transportation. Policy measures should include gradually increasing biofuel blend mandates while funding research into advanced biofuels from non-food sources to improve sustainability and avoid competition with agricultural production. Geothermal shows minimal growth, remaining flat. Thus highlights the technology's current limitations in scalability. Policy should focus on targeted tax credits for exploratory drilling in high-potential regions and funding for research to unlock broader deployment potential.

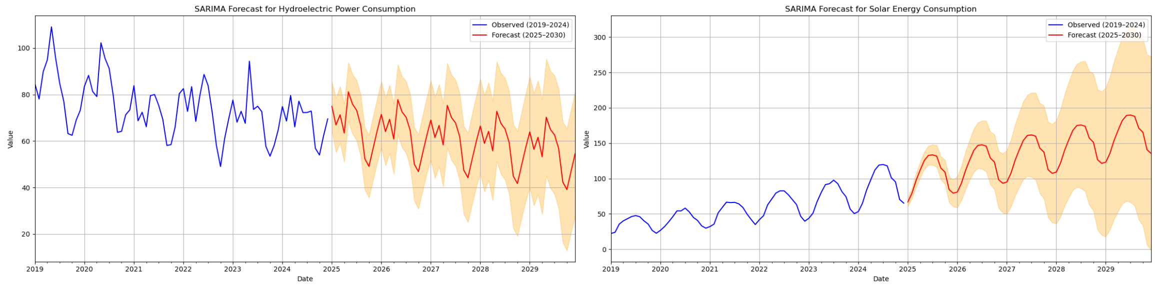


(a) Biofuels

(b) Geothermal

Figure 5: SARIMA 5 year forecast of (a) Biofuels and (b) Geothermal

The hydroelectric forecast shows slightly declining stable yet variable consumption, reflecting its nature as a geographically constrained mature form of energy production. Policies should emphasize optimising existing dam operations and improving drought resilience rather than new dam construction, along with exploring pumped storage solutions to complement variable renewables like solar and wind. The SARIMA forecast shows solar energy consumption growing rapidly, reinforcing solar's dominance in the renewable sector. The steep forecasted rise aligns with global trends favouring solar due to its scalability and cost-efficiency. Policymakers should prioritize expanding solar farm capacity through incentives and streamline permitting for utility-scale projects, while also investing in grid-scale battery storage to manage solar's intermittent generation patterns and ensure reliable evening power supply.

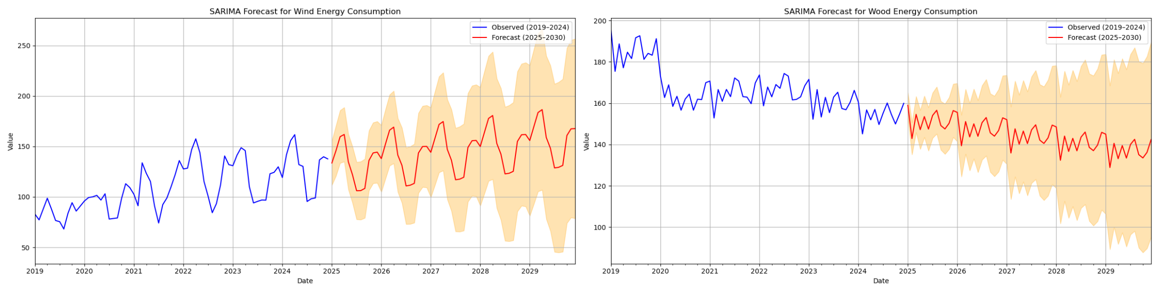


(a) Hydro

(b) Solar

Figure 6: SARIMA 5 year forecast of (a) Hydro and (b) Solar

Wind energy demonstrates strong growth in the forecast, though slightly less exponential than solar. This suggests wind remains a crucial pillar of renewable energy portfolios. Policy focus should be on developing offshore wind potential and upgrading transmission infrastructure to deliver wind power from coastal areas to population centres, while maintaining production tax credits to sustain growth momentum. Wood energy consumption is forecast to decline significantly. Thus, policy should focus on managed phase-out programs, including subsidies for replacing wood stoves with electric alternatives in rural areas and stricter emissions regulations on remaining wood energy use to mitigate air quality impacts.



(a) Wind

(b) Wood

Figure 7: SARIMA 5 year forecast of (a) Wind and (b) Wood

Now, for the spectral analysis, we have the following plot:

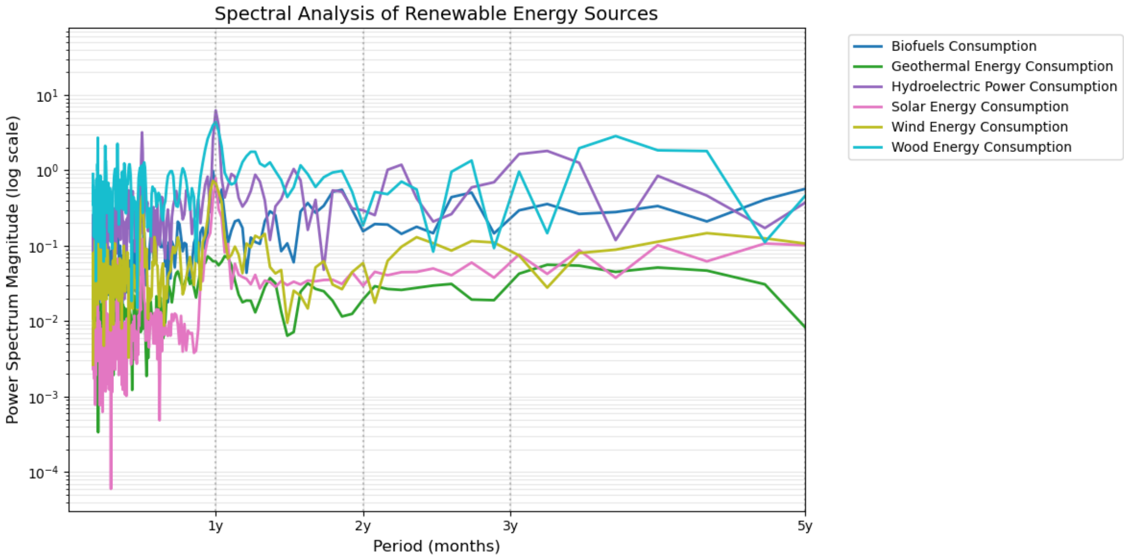


Figure 8

The FFT plot reveals distinct cyclical behaviours across energy sources. Solar and hydro exhibit strong annual (12-month) peaks, reflecting seasonal weather dependence, while hydro also shows a 3-year (36-month) cycle, likely tied to climate phenomena like El-Niño Southern Oscillation. Wind displays broadband variability, suggesting irregular weather-driven patterns. Geothermal's flat spectrum confirms its stable, non-cyclical nature, whereas wood energy's sharp annual peak and harmonic (6-month) indicate predictable winter seasonal demand. Finally, biofuels show primary annual and quarterly cycles that match agricultural practices but lacks significant multiyear cycles. The absence of significant cycles beyond 3 years for all sources implies that long-term trends manifest as gradual shifts rather than periodic oscillations. These findings underscore the need for seasonally adjusted grid planning (e.g., storage for solar's summer peaks) and climate-aware infrastructure investments, particularly for hydro and wind, where multi-year cycles significantly influence output.

Conclusion

The analysis confirmed the hypothesis that solar and wind energy exhibit the highest growth and seasonal variability, driven by falling costs and weather-dependent generation, while biofuels and geothermal energy show stable, policy-correlated trends. Solar consumption demonstrated exponential growth (tripling by 2030) with pronounced summer peaks, and wind energy displayed complementary winter peaks, underscoring their synergistic potential for grid balancing. Biofuels progressed steadily, aligned with agricultural cycles, while geothermal energy stagnated due to technological limitations. Hydroelectric output remained stable but revealed climate-sensitive, multi-year cycles tied to phenomena like ENSO, necessitating adaptive reservoir management. Wood energy consumption declined sharply, reflecting successful phase-out policies, though residual winter demand persists, most likely in rural regions.

However, the reliance on fixed SARIMA parameters (1,1,1)(1,1,1,12) for all sources limited model precision. For instance, hydroelectricity's 3-year ENSO-linked cycles and wind's irregular volatility were inadequately captured by uniform parameters, which oversimplified their unique dynamics. To address this, future analyses should adopt source-specific parameterization using automated tools like auto-ARIMA or grid searches to identify optimal (p,d,q)(P,D,Q,S) orders. For example, wind's sudden weather shifts might require higher moving average terms (q=2), while hydro's multi-year cycles could benefit from additional seasonal autoregressive components (P=2). Stationarity should be validated individually via ADF/KPSS tests, as geothermal's flat trend (d=0) and solar's exponential growth (d=2) demand differing differencing approaches.

Future work could leverage machine learning hybrids (e.g., LSTM networks to model non-linear solar-wind interactions, Prophet to handle abrupt policy changes) and Bayesian structural models to quantify forecast uncertainty. These advancements would enable granular policy simulations, such as optimizing storage deployment timing or stress-testing carbon pricing impacts. By transitioning from rigid to adaptive modeling frameworks, policymakers can design resilient, data-driven strategies to accelerate the renewable transition while ensuring grid reliability and equity.

Appendix A: Waste Energy

The waste energy trend shows moderate growth, supported by waste-to-energy infrastructure and landfill diversion policies. Strong seasonality links to waste generation cycles (e.g., holiday peaks). High residual variability points to irregular waste streams or policy impacts. Waste energy's potential hinges on circular economy adoption but requires handling seasonal supply fluctuations.

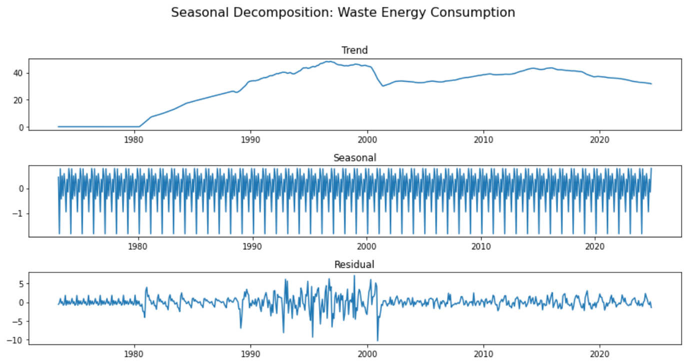


Figure 9: Waste seasonal decomposition

There is a clear decline in waste energy consumption. This downward trend reflects both improved waste reduction/recycling efforts and policy shifts away from incineration. Policymakers should accelerate this transition by implementing stronger recycling mandates and landfill diversion programs, while redirecting investments from waste incineration infrastructure toward circular economy solutions that prevent waste generation altogether. The decline suggests waste-to-energy is becoming a less viable renewable strategy and should be phased out in favour of zero-waste approaches.

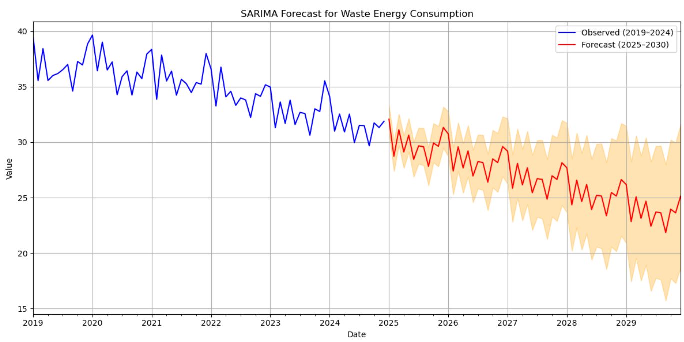


Figure 10: SARIMA Predictions for Waste

Appendix B: Cross Spectral Analysis

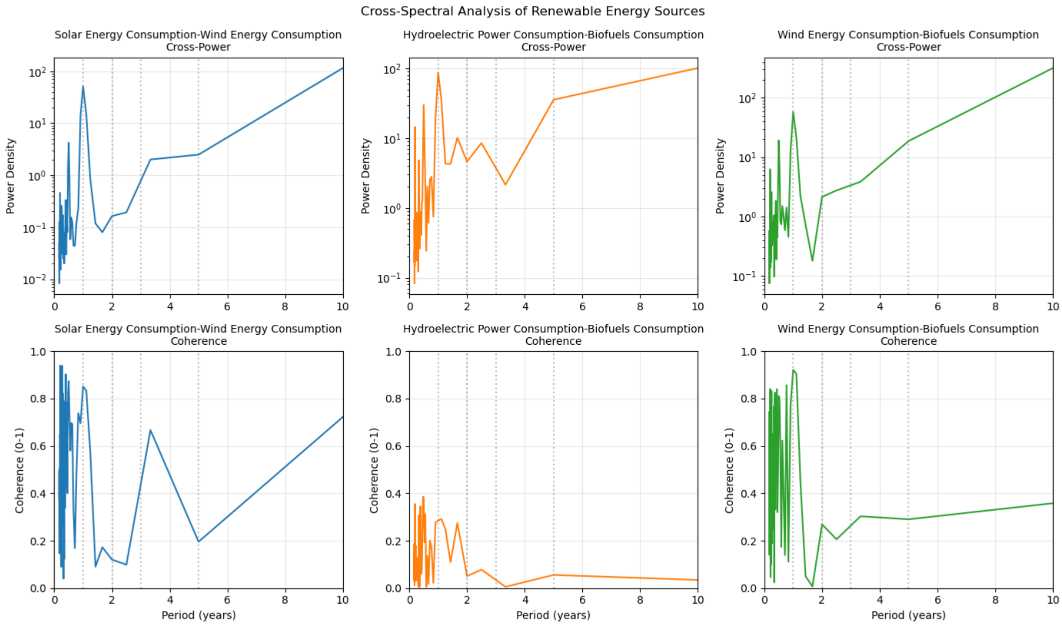


Figure 11: Cross spectral analysis unused in main body