

Identifying (volatility-)regimes in the EUR/USD spot exchange rate using clustering algorithms: An Oil and Gas Perspective on Parity Conditions.

Seminar in Applied Financial Economics: Applied Econometrics of FX Markets - Professor Reitz

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GitHub: <https://github.com/RobertHennings/Seminar>

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Outline

1 Research Hypothesis

Energy Commodity Price Shocks: The Pass-Through Effect and implications for Monetary Policy
Formulated Research Hypothesis

2 Literature Review

Systematic Literature Overview: Main Approaches

3 Theoretical Framework

Impact of Inflation on Measurements: What are prices and how are they measured?
A simple model of exchange rates and commodity prices
Theoretical Framework

4 Model Results

Regime identification - Model comparison and selection

5 Conclusion and Discussion

Seminar Project Summary
Seminar Project Limitations
Future Research

6 Appendix

Figures and Tables
Data and Definitions

7 References

Literature
Data
Software

Intro: Energy Commodities and Exchange Rates

This has led some to suggest that an unidentified real factor may be causing persistent shifts in real equilibrium exchange rates.

— R.A. Amano, S. van Norden¹

This may in fact be the case or it is also possible that the relationship between exchange rates and oil shocks is non-linear and not being detected by a linear regression framework.

— S. A. Basher, A. A. Haug, P. Sadorsky²

The long-run real exchange rate of these ‘commodity currencies’ is not constant but is time varying, being dependent on movements in the real price of commodity exports.

— P. Cashin, L. F. Cespedes, R. Sahay³

¹[AN98], p.301

²[BHS16a], p.17

³[CCS04], p.239

Intro: The PPP puzzle⁵ and Commodity Currencies

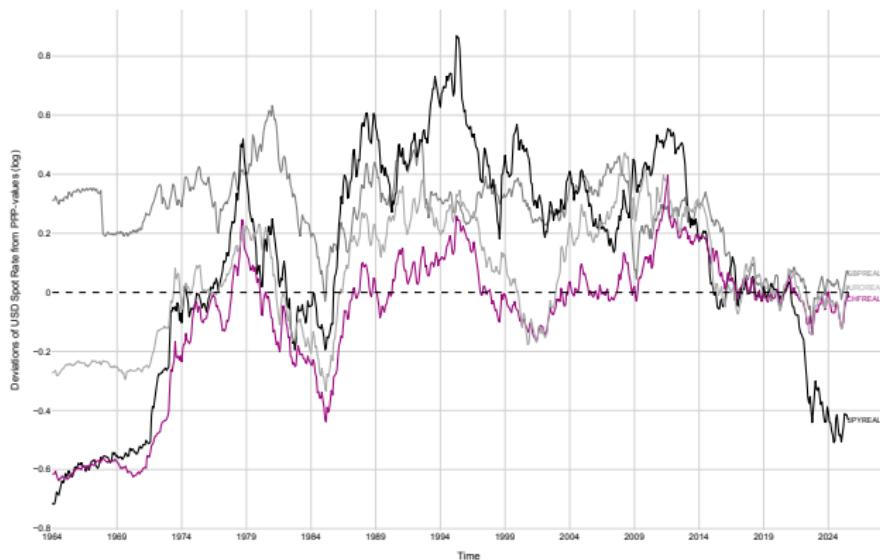


Figure: Monthly deviations of USD Spot Rate from PPP-values (in log terms) over the time: 1964 - 2025.⁴

⁴ Own Illustration based on [Rei25], section "Modeling Trends: Unit Roots in Time Series", page 18/18 and data taken from [IS25], last accessed 24.10.25, own calculations.

⁵This puzzle concerns the finding of many researchers that the speed of mean reversion of real exchange rates is too slow to be consistent with PPP, which is the proposition that exchange rates are determined by movements in relative prices.

Chapter 1)

Research Hypothesis

Energy Price Contributions to Inflation - USA

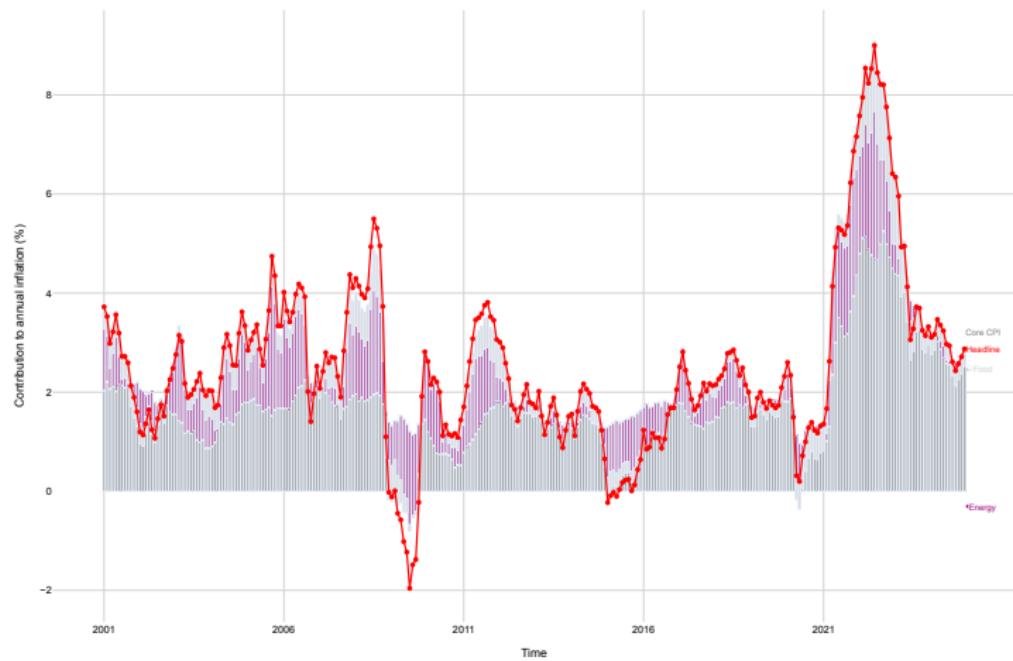


Figure: Monthly US CPI: Headline and component contributions over the time: 2001 - 2024.⁶

⁶Own Illustration based on [Ban22], Chart A and data taken from [SL25a], last accessed 24.10.25, own calculations.

Energy Price Contributions to Inflation - EU area

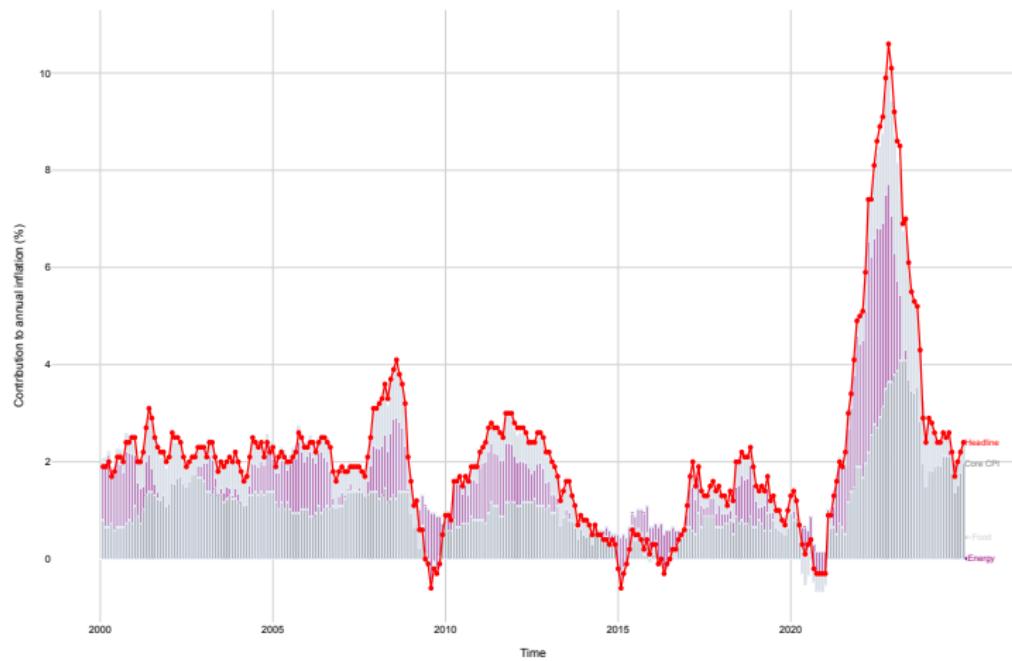


Figure: Monthly EU Area CPI: Headline and component contributions over the time: 2000 - 2024.⁷

⁷ Own Illustration based on [Ban22], Chart A and data taken from [Ban25], last accessed 24.10.25, own calculations.

Rolling Volatility of Exchange Rates and Energy Commodity Prices

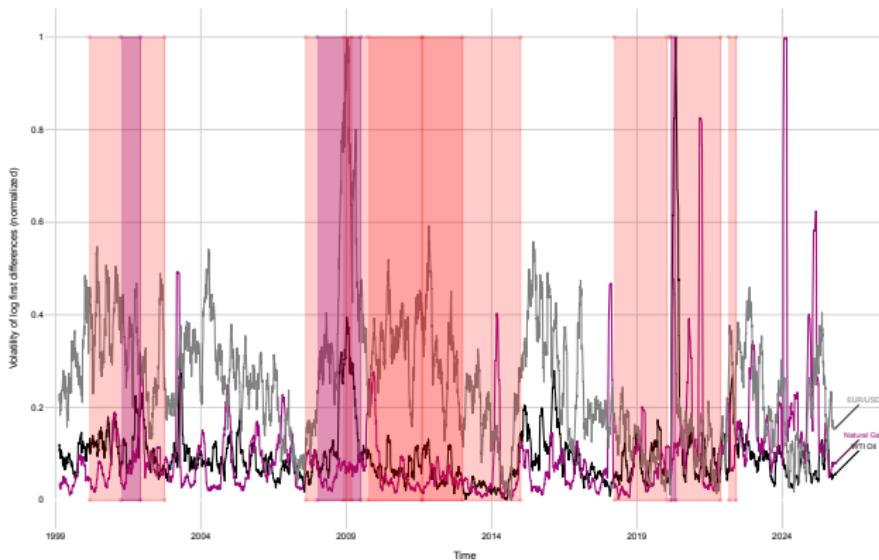


Figure: Daily normalized EUR/USD spot exchange rate, oil and gas log first differences volatility with highlighted crisis periods over the time: 2000 - 2024.⁸

⁸Own Illustration based on [Zub+21], page 7 and data taken from [SL25a], last accessed 24.10.25, own calculations.

Formulated Research Hypothesis

Main Research Hypothesis

"The standard UIP-equilibrium condition is time-dependent and primarily controlled by two main regimes, characterised by either high or low (market-) volatility."

Additional Research Hypothesis I

"Monetary policy, i.e. interest rates are, partly driven by energy commodity prices that induce volatility through the inflationary pass-through channel, especially during phases of market distress in economies heavily relying on import/export of energy commodities."

Additional Research Hypothesis II

"Factoring in variables related to energy commodity prices in combination with using alternative clustering techniques improves the identification of the regimes to better pinpoint the time-dependent testing of the standard UIP relation, compared to Markov-Switching benchmark models."

Chapter 2)

Literature Review

Systematic Literature Overview: Main Approaches

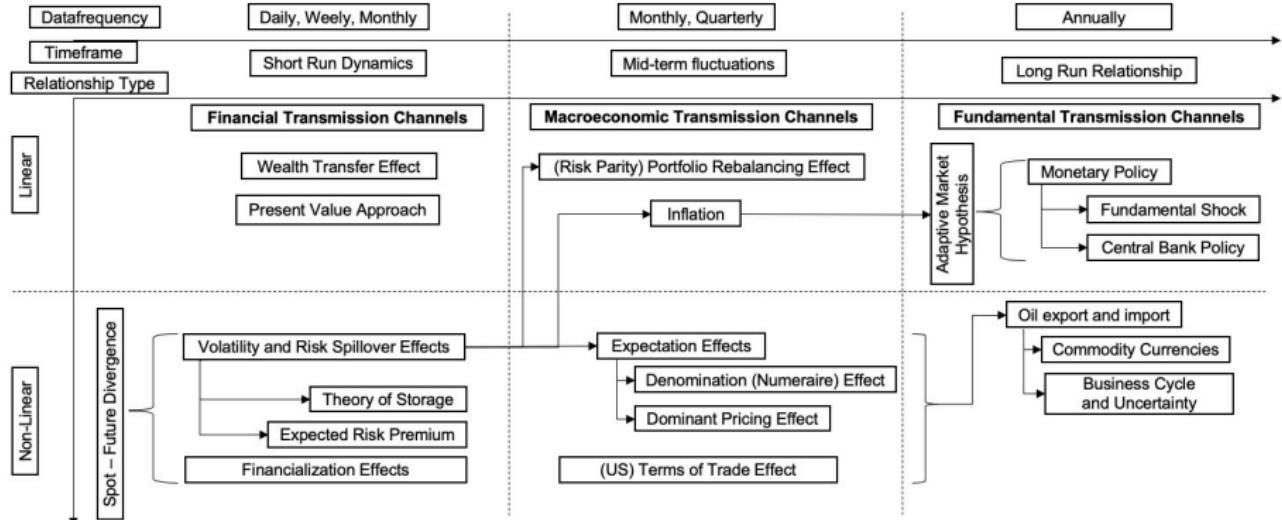


Figure: Systematic Overview about main theoretical approaches.⁹

⁹ Own Illustration based on [OUS20], Figure 5, page 5, full list provided in the References section.

Theoretical Framework

Definitions - prices and measurements

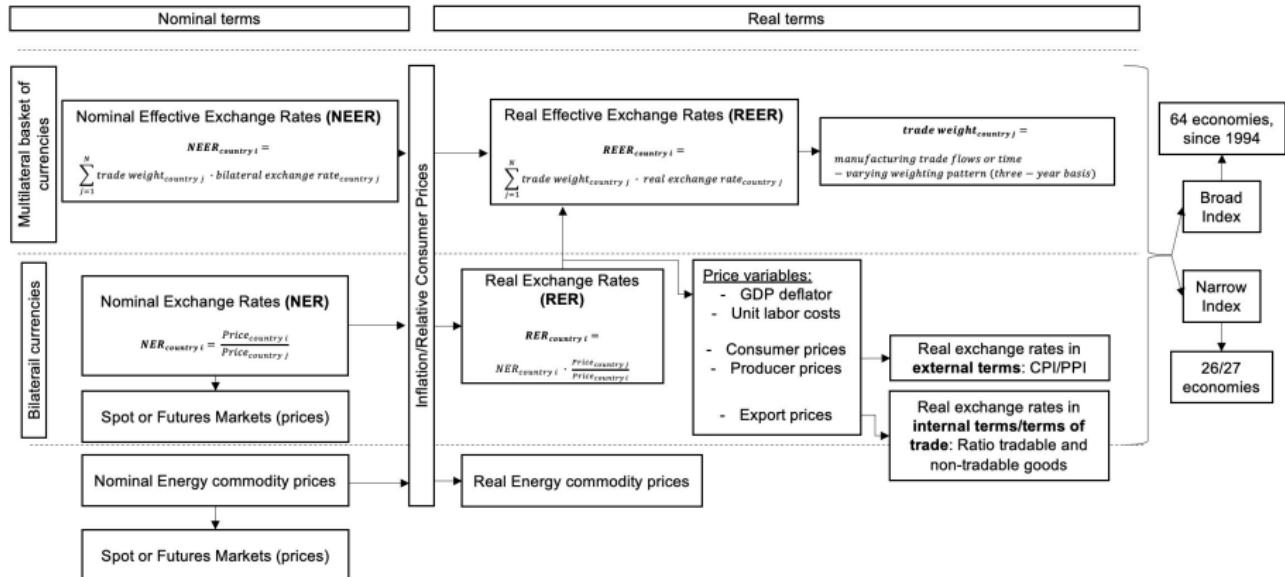


Figure: Schematic overview of prices and measurements of various exchange rate types.¹⁰

¹⁰ Own Illustration based on [Ros03], page 8, exchange rates in natural logarithm (geometric averages) and data definitions from [IS25].

A simple model of exchange rates and commodity prices

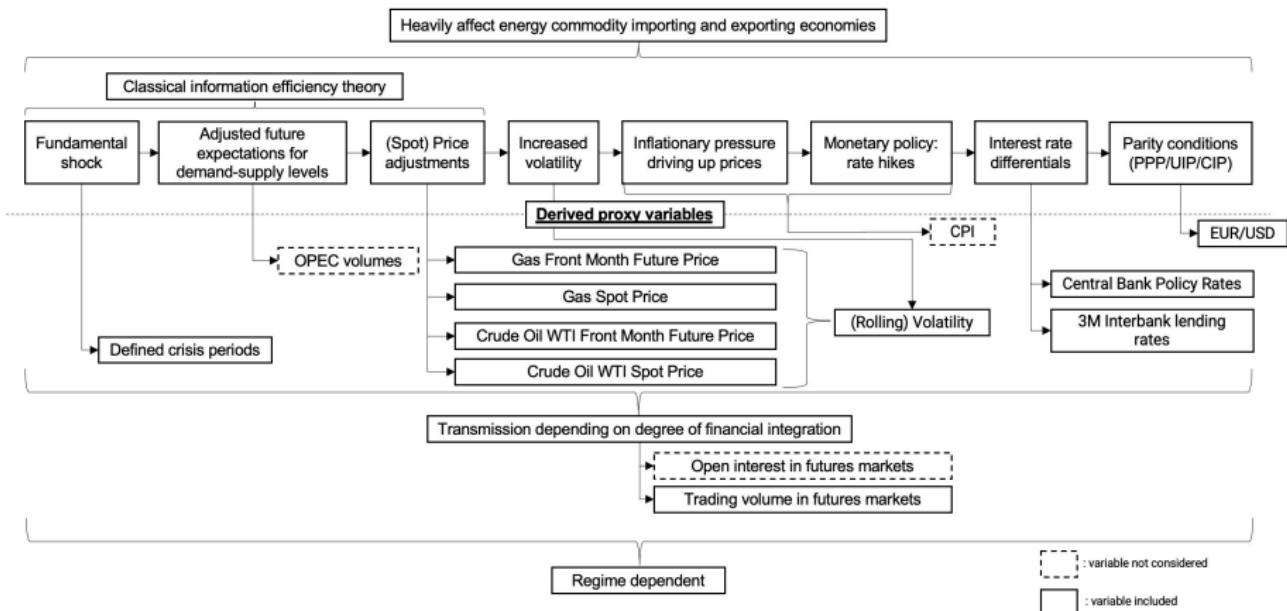


Figure: Main theoretical framework for the seminar project analysis, inflation pass-through effect of energy commodity prices.¹¹

¹¹ Own Illustration based on [OUS20], Figure 3, page 3.

Theoretical Framework (I)

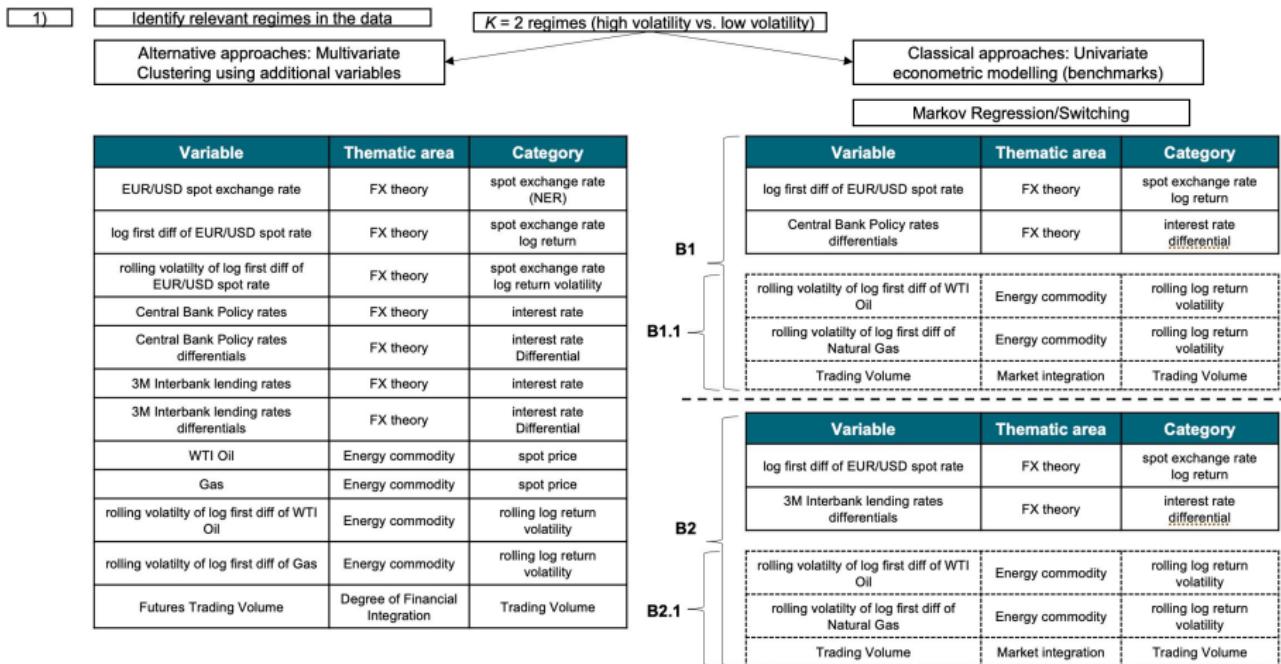


Figure: Main theoretical framework for the seminar project analysis, main variables and benchmark models used.¹²

¹²Own Illustration.

Theoretical Framework (II)

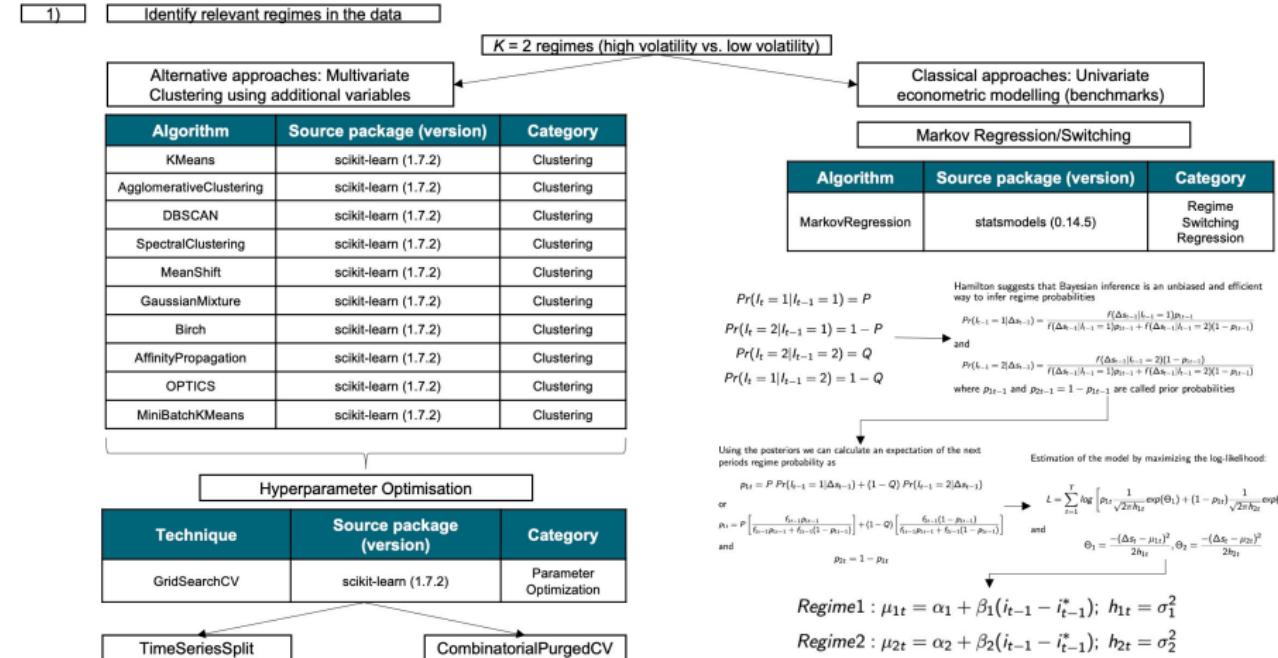


Figure: Main theoretical framework for the seminar project analysis, main algorithms used.¹³

¹³Own Illustration based on formulas taken from [Rei25], section "Modeling Nonlinearities I: Markov-Switching", page 7-15 and algorithms from [dev24a] and implemented in [Fou24].

Theoretical Framework (III)

2)

Analyze and compare the regimes

Model evaluation and selection

Evaluation metric	Source package (version)	Category	Value range	Interpretation
Silhouette Score	scikit-learn (1.7.2)	Clustering Scores	[-1, 1]	1 being best, -1 being worst, values near 0 indicate overlapping clusters.
RCM	[AB98]	MSM-Score	[0, 100]	0 (perfect regime classification), 100 (failure to detect any regime classification)
Crisis overlap percentage	Own calculations	Combined	[0, 100]	Percentage overlap ranging from 0% - 100%

Theoretically affecting crisis periods - major global shocks and US recessions

No.	Start-date	End-date	Event-Type	Event	Source
1	1970-01-01	1970-12-01	US-Recession	US Recession 1970-1970	[St 25b]
2	1971-08-15	1973-03-19	Major Global Crisis	Bretton Woods Breakdown	[Cor+25]
3	1971-08-15	1973-03-19	Major Global Crisis	Nixon Shock	[EF04]
4	1973-10-17	1974-03-01	Major Global Crisis	Oil Crisis I	[T T23]
5	1973-12-01	1975-04-01	US-Recession	US Recession 1973-1975	[St 25b]
6	1979-01-01	1981-03-01	Major Global Crisis	Oil Crisis II	[T T23]
7	1980-02-01	1980-08-01	US-Recession	US Recession 1980-1980	[St 25b]
8	1981-08-01	1982-12-01	US-Recession	US Recession 1981-1982	[St 25b]
9	1987-10-19	1987-10-19	Major Global Crisis	Black Monday Crash	[EF04]
10	1990-08-01	1991-04-01	US-Recession	US Recession 1990-1991	[St 25b]
11	1997-07-02	1998-12-31	Major Global Crisis	Asian Financial Crisis	[ML23]
12	1998-08-17	1998-09-01	Major Global Crisis	Russian Crisis	[ML23]
13	2000-03-01	2002-10-01	Major Global Crisis	Dot-com Bubble	[MNR25]
14	2001-04-01	2001-12-01	US-Recession	US Recession 2001-2001	[St 25b]
15	2007-08-09	2009-03-09	Major Global Crisis	Global Financial Crisis	[MNR25]
16	2008-01-01	2009-07-01	US-Recession	US Recession 2008-2009	[St 25b]
17	2008-11-25	2014-12-31	Major Global Crisis	US QE	[MNR25]
18	2009-10-01	2012-12-31	Major Global Crisis	European Debt Crisis	[MNR25]
19	2011-08-20	2011-08-05	Major Global Crisis	US Debt Ceiling Crisis	[MNR25]
20	2018-03-22	2020-01-15	Major Global Crisis	US-China Trade War	Various
21	2020-02-20	2021-11-16	Major Global Crisis	COVID-19 Pandemic	[ML23]
22	2020-03-01	2020-05-01	US-Recession	US Recession 2020-2020	[St 25b]
23	2022-02-24	2022-06-01	Major Global Crisis	Russia-Ukraine War	[Cha25]

Figure: Main theoretical framework for the seminar project analysis, main evaluation metrics and crisis periods used.¹⁴¹⁴ Own Illustration based on data taken from [SL25a], last accessed 24.10.25.

Theoretical Framework (IV)

3)

Test for UIP conditional on regimes

Model comparison – UIP Testing

We may suggest that UIP holds in 'normal' times, but is violated in 'non-normal' times

The sequences of switching between the two states may help us learning what drives the UIP puzzle

Therefore we need two separate mean equations to be estimated

$$\text{Regime1 : } \mu_{1t} = \alpha_1 + \beta_1(i_{t-1} - i_{t-1}^*); h_{1t} = \sigma_1^2$$

$$\text{Regime2 : } \mu_{2t} = \alpha_2 + \beta_2(i_{t-1} - i_{t-1}^*); h_{2t} = \sigma_2^2$$

Figure: Main theoretical framework for the seminar project analysis, testing the regime dependent UIP-relationship.¹⁵

¹⁵ Own Illustration based on formulas taken from [Rei25], section "Modeling Nonlinearities I: Markov-Switching", page 7-15.

Model Results

Model comparison and selection

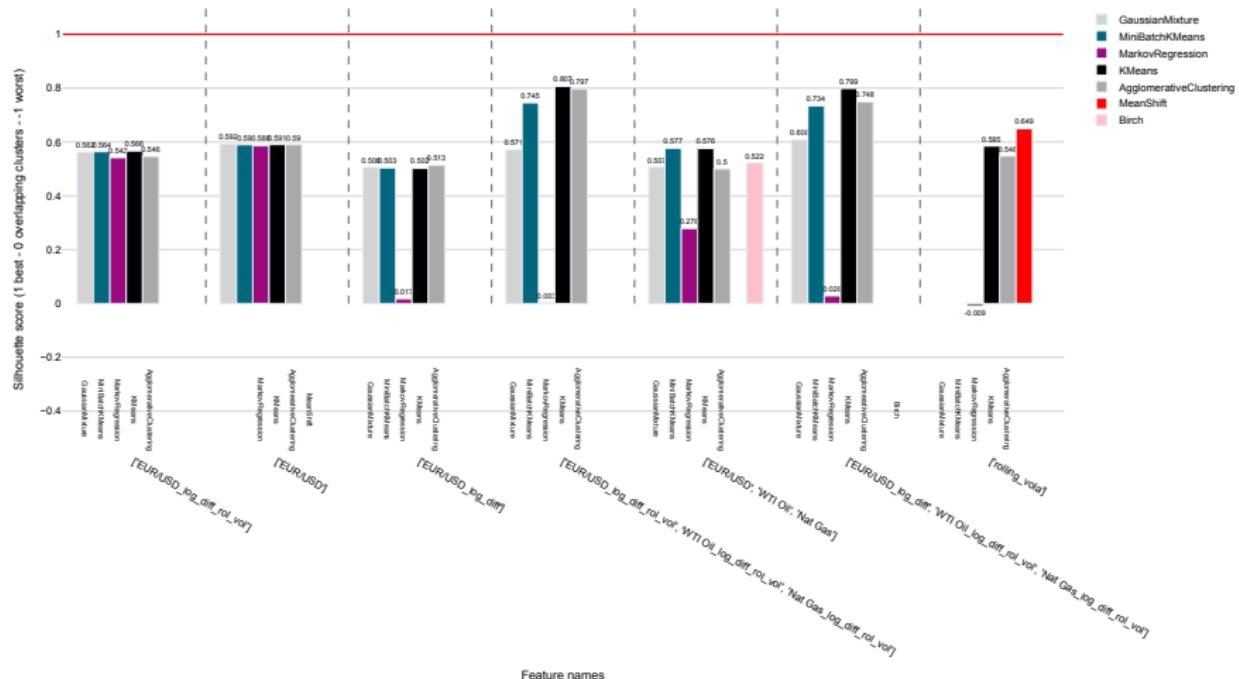


Figure: Model comparison using the silhouette score for various regime identification model configurations.¹⁶

¹⁶ Own illustration based on [Jah+24], page 9 and data taken from [SL25a], last accessed 24.10.25, own calculations.

Predicted Regimes - Evolution over time with highlighted Crisis Periods

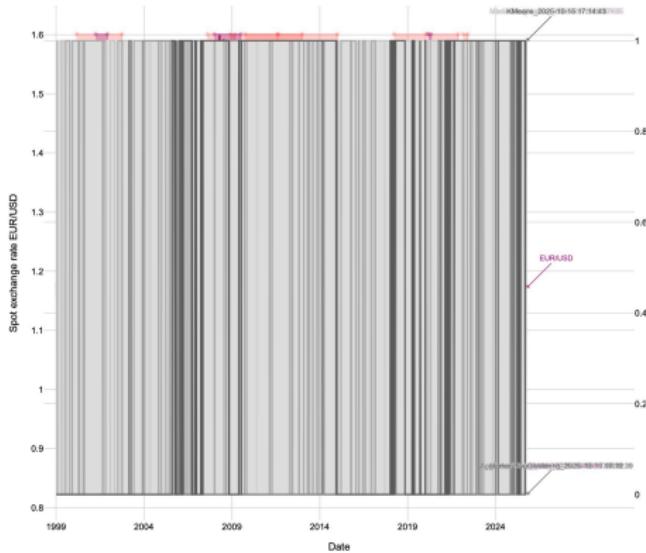


Figure: Predicted regimes over time with highlighted crisis periods.¹⁷

¹⁷ Own Illustration based on [Ayo16], page 5 and data taken from [SL25a], last accessed 24.10.25, own calculations.

Predicted Regimes - Some excerpts (I)

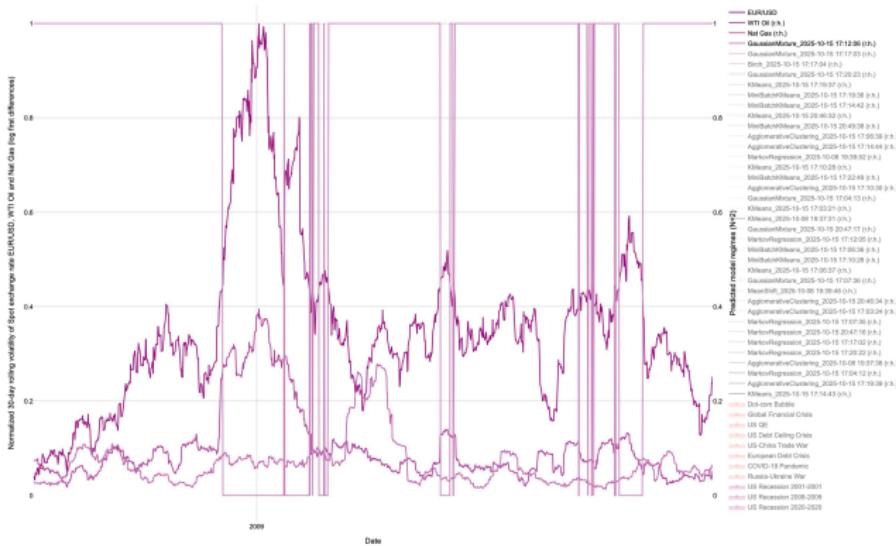


Figure: Predicted regimes over time with highlighted crisis periods, exemplary algorithm: GaussianMixture.¹⁸

¹⁸Own Illustration based on [Ayo16], page 5 and data taken from [SL25a], last accessed 24.10.25, own calculations.

Predicted Regimes - Some excerpts (II)

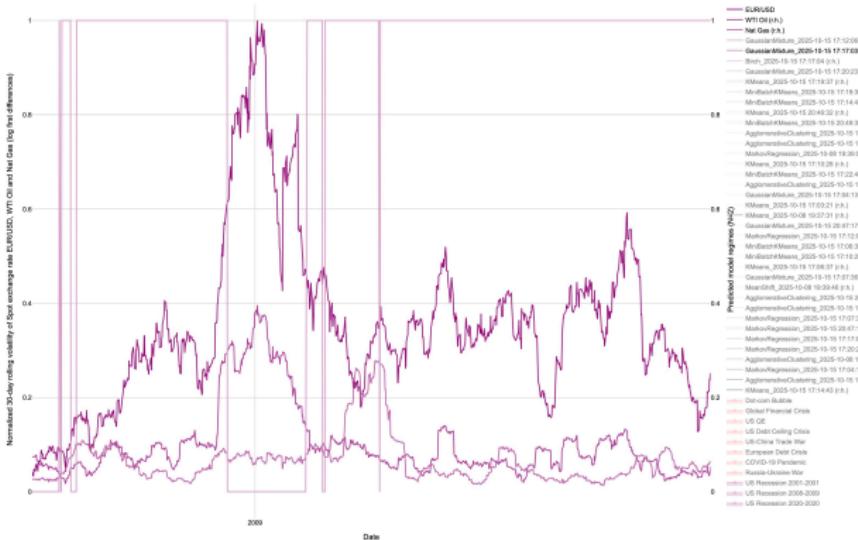


Figure: Predicted regimes over time with highlighted crisis periods, exemplary algorithm: GaussianMixture.¹⁹

¹⁹ Own Illustration based on [Ayo16], page 5 and data taken from [SL25a], last accessed 24.10.25, own calculations.

Predicted Regimes - Some excerpts (III)

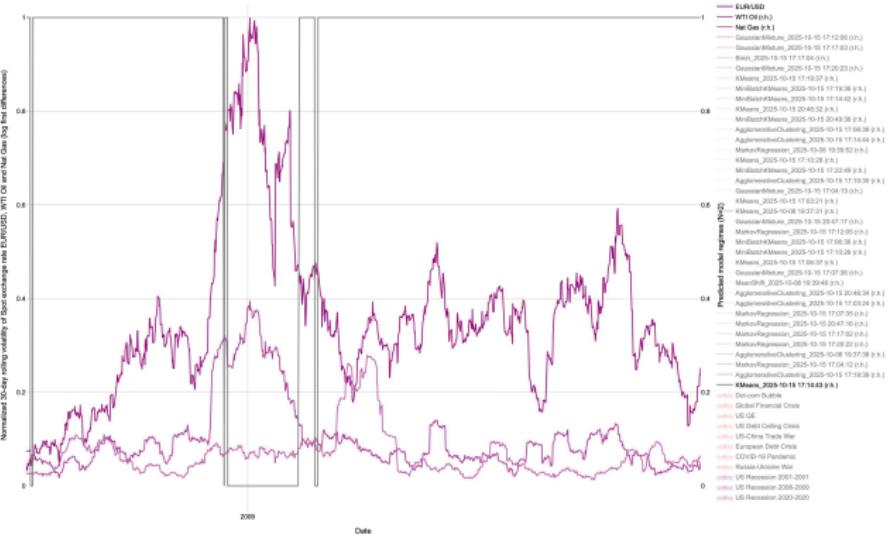


Figure: Predicted regimes over time with highlighted crisis periods, exemplary algorithm: KMeans.²⁰

²⁰Own illustration based on [Ayo16], page 5 and data taken from [SL25a], last accessed 24.10.25, own calculations.

Predicted Regimes - Some excerpts (IV)

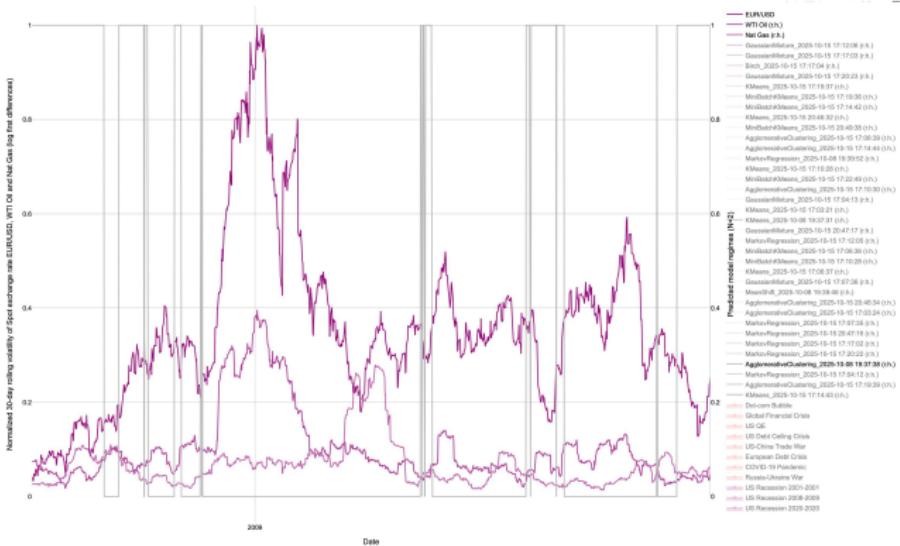


Figure: Predicted regimes over time with highlighted crisis periods, exemplary algorithm: AgglomerativeClustering.²¹

²¹ Own Illustration based on [Ayo16], page 5 and data taken from [SL25a], last accessed 24.10.25, own calculations.

Predicted Regimes - Some excerpts (V)

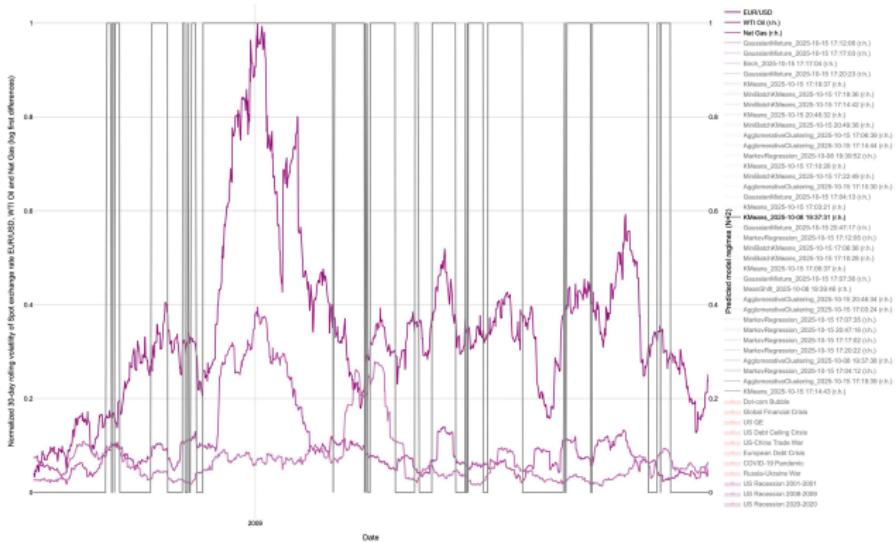


Figure: Predicted regimes over time with highlighted crisis periods, exemplary algorithm: KMeans.²²

²²Own illustration based on [Ayo16], page 5 and data taken from [SL25a], last accessed 24.10.25, own calculations.

Predicted Regimes - Overlapping Comparison

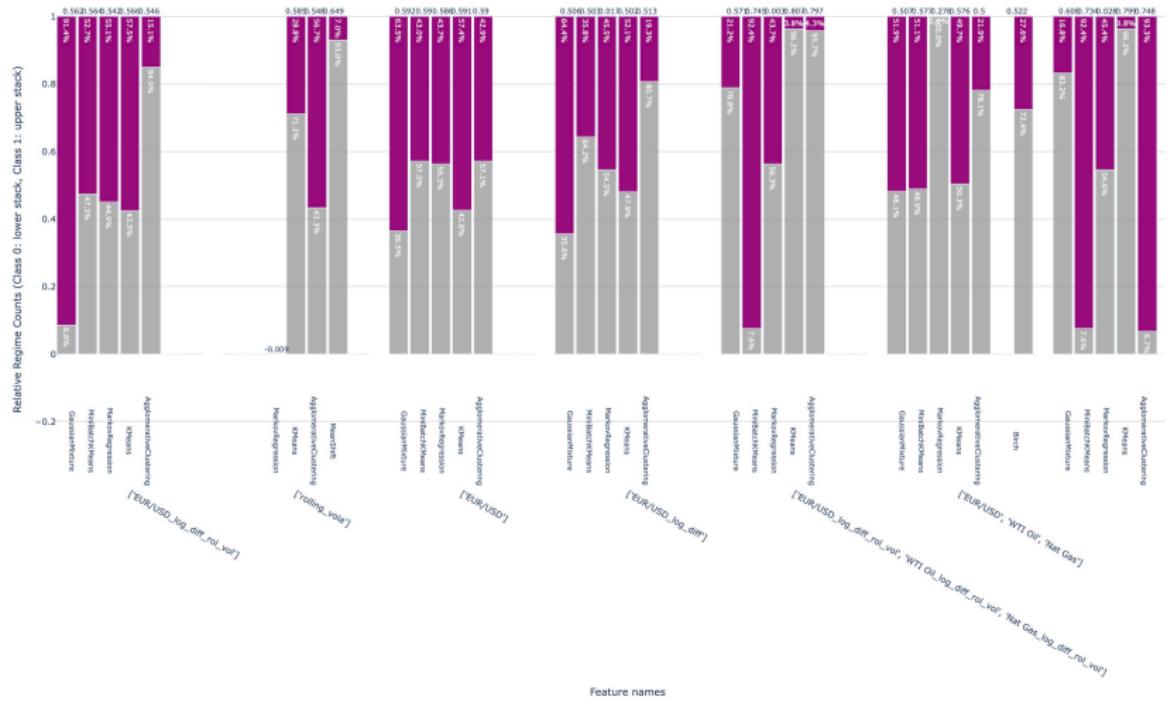


Figure: Relative share of regime classification per features per clustering algorithm.²³

²³ Own illustration based on [MB21], page 764 and data taken from [SL25a], last accessed 24.10.25, own calculations.

Predicted Regimes - Overlapping Comparison with theoretical crisis periods

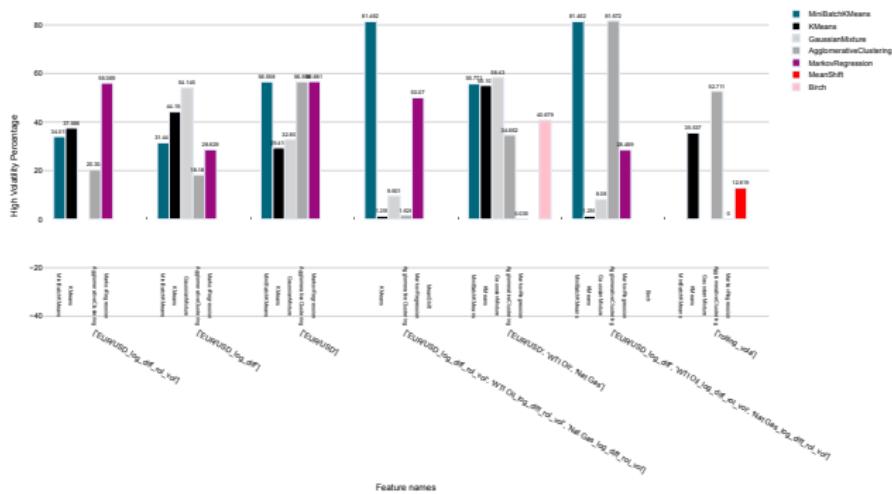


Figure: Relative share of observations classified into class 1 and falling into a defined theoretical crisis period per features per clustering algorithm.²⁴

²⁴Own Illustration based on [MB21], page 764 and data taken from [SL25a], last accessed 24.10.25, own calculations.

UIP estimation - benchmark models

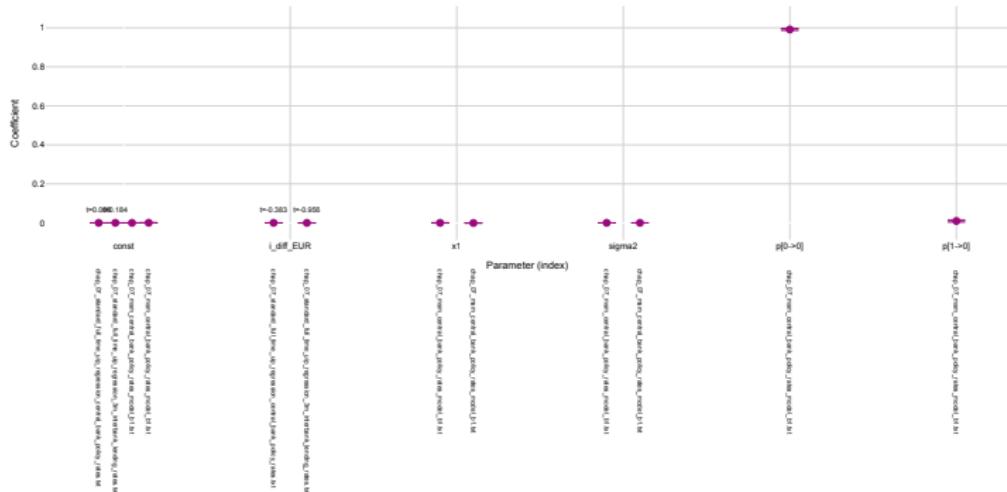


Figure: UIP estimation results for benchmark models - standard linear regression and markov-switching models.²⁵

²⁵ Own illustration based on data taken from [SL25a], last accessed 24.10.25, own calculations (used MacKinnon and White's (1985) HC1 heteroscedasticity robust standard errors).

UIP estimation - identified regimes

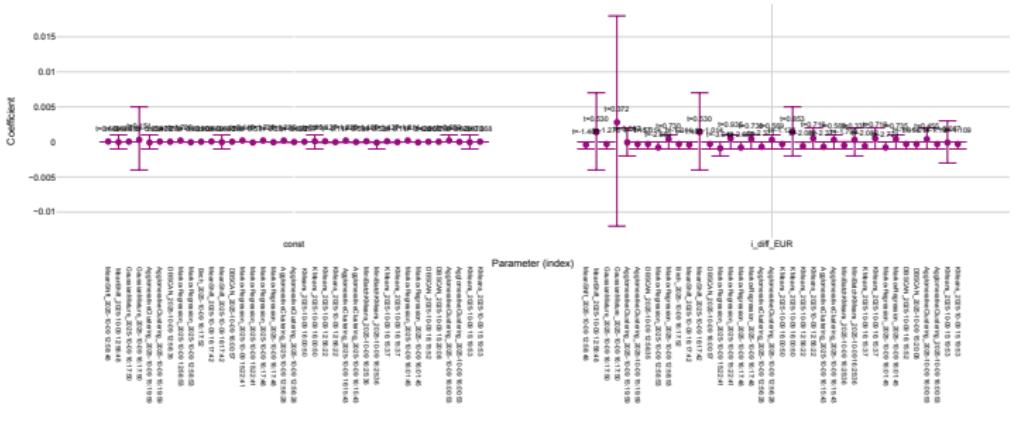


Figure: UIP estimation results for identified regimes using clustering algorithms.²⁶

²⁶ Own Illustration based on data taken from [SL25a], last accessed 24.10.25, own calculations (used MacKinnon and White's (1985) HC1 heteroscedasticity robust standard errors).

Conclusion and Discussion

Seminar Project Summary

Main Research Hypothesis

Comparing different (configurations of) optimised clustering algorithms to identify (volatility driven) exchange rate regimes in the EUR/USD spot exchange rate yields promising results.

Additional Research Hypothesis I

Incorporating commodity prices (WTI Crude Oil Prices and Natural Gas Prices/ their rolling volatilities) as an external variable improves the regime identification results.

Additional Research Hypothesis II

In comparison with the benchmark models, the clustering techniques seemed to be able to identify regimes more granular, but despite that were not able to yield more reliable/robust results for the standard UIP-relationship.

Seminar Project Limitations

Evaluation Metrics

Only used one metric for clustering (Silhouette Score).

Crisis Periods

May include more periods/find a suitable solution for overlapping crisis periods.

Hyperparameter Tuning

Hyperparameter tuning did not finish in time for all model configurations.

Future Research - Possible Extensions

Other Spot rate pairs

Extend the Analysis to other Spot Exchange Rate Pairs (focus on the Commodity Currencies with a strong Commodity Linkage).

Other commodities

Extend the Analysis to also include other Commodities (e.g. Natural Gas, Brent Oil, Gold, etc.).

Other macroeconomic/external variables

Extend the Analysis by incorporating other Macroeconomic Variables (e.g. Interest Rates, Inflation Rates, etc.).

Other data frequencies

Extend the Analysis by using intraday data to capture more granular dynamics.

Appendix

Appendix - Figures and Tables

Appendix - Figures and Tables

Modern Energy Commodity Markets The current state

Oil: Global Production and Consumption over time

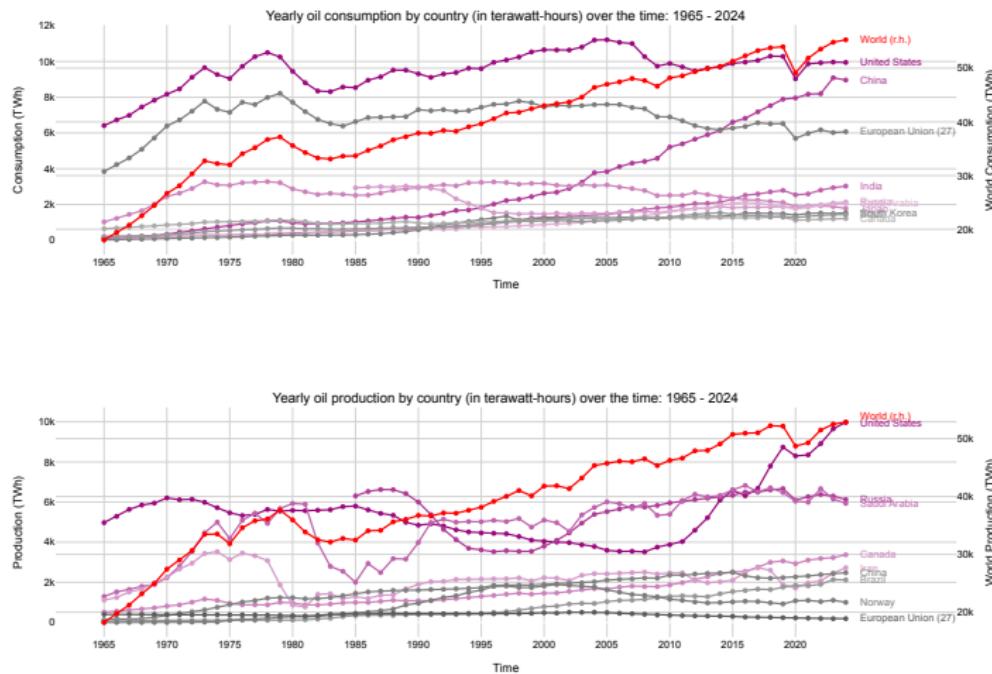


Figure: Yearly oil consumption and production by country over the time: 1965 - 2024 (in terawatt-hours).²⁷

²⁷ Own Illustration based on [Haa+09], page 5 and data taken from [Ins25b], last accessed 24.10.25.

Gas: Global Production and Consumption over time

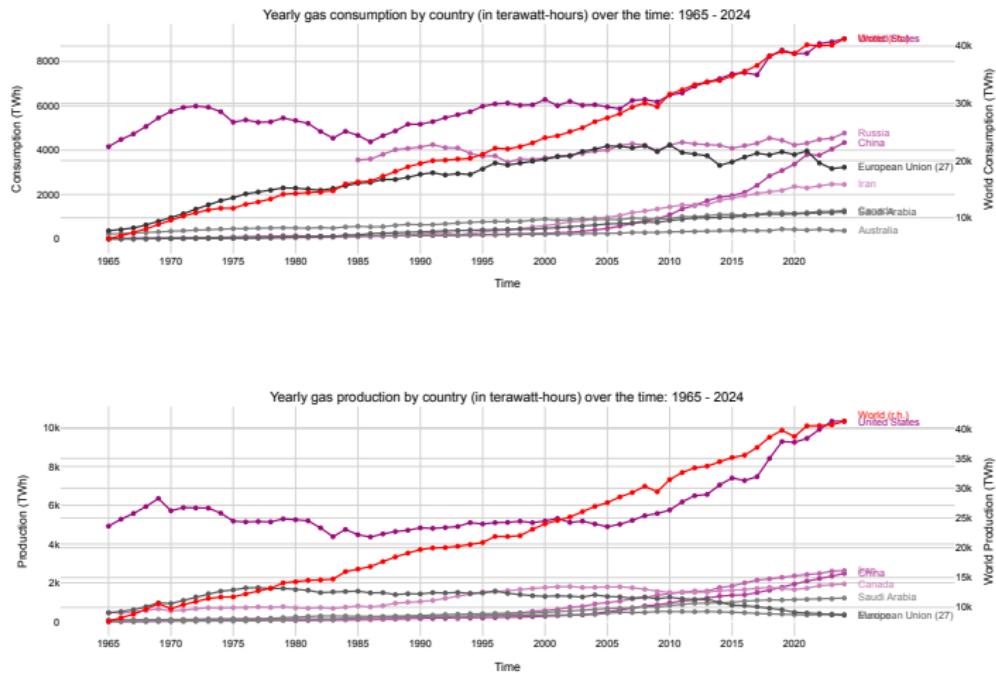


Figure: Yearly gas consumption and production by country over the time: 1965 - 2024 (in terawatt-hours).²⁸

²⁸Own Illustration based on [Haa+09], page 5 and data taken from [Ins25a], last accessed 24.10.25.

Financial Markets: Oil and Gas OI over time

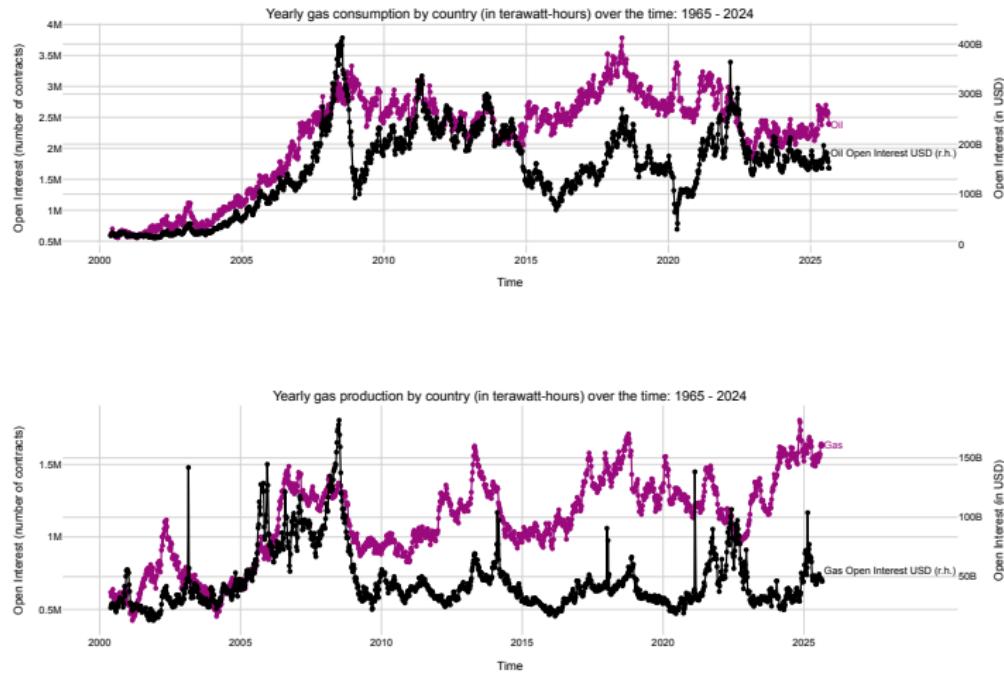


Figure: Weekly open interest of oil and gas products over the time: 2000 - 2024²⁹

²⁹ Own Illustration based on [Aus11], page 53 and data taken from [Com25], last accessed 24.10.25.

Appendix - Figures and Tables

Data Characteristics and Stylized Facts

Interest Rate Benchmarks - Absolute Levels

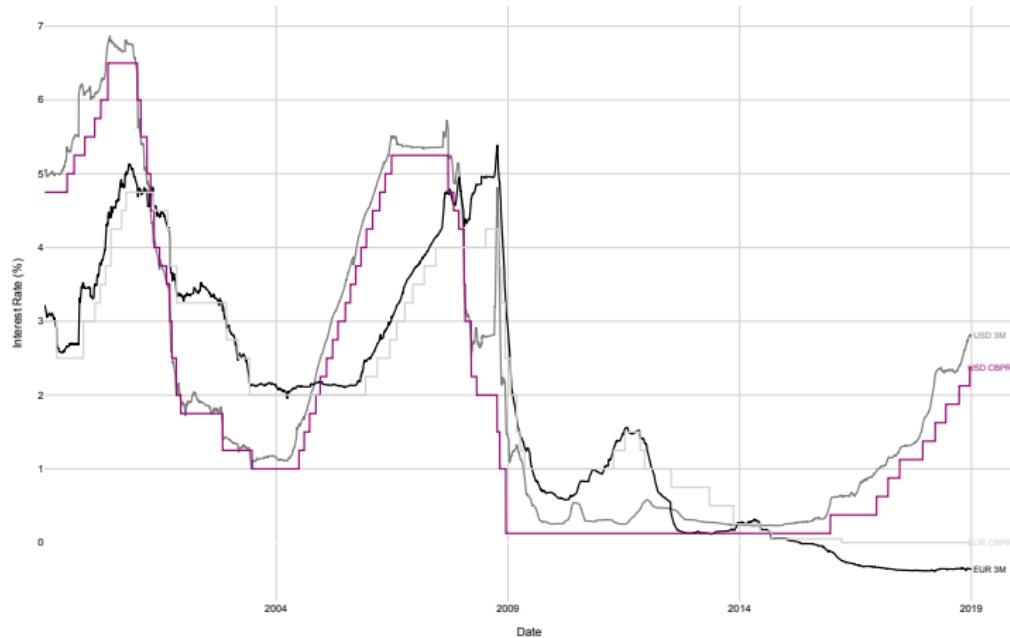


Figure: Daily BIS Central Bank Policy Rate and 3M Interbank Rates over the time: 1999 - 2019.³⁰

³⁰ Own Illustration based on [ANT24], Figure 1, page 2 and data taken from [IS25] and [Rei25]. Last accessed 24.10.25.

Interest Rate Benchmarks - Relative Levels

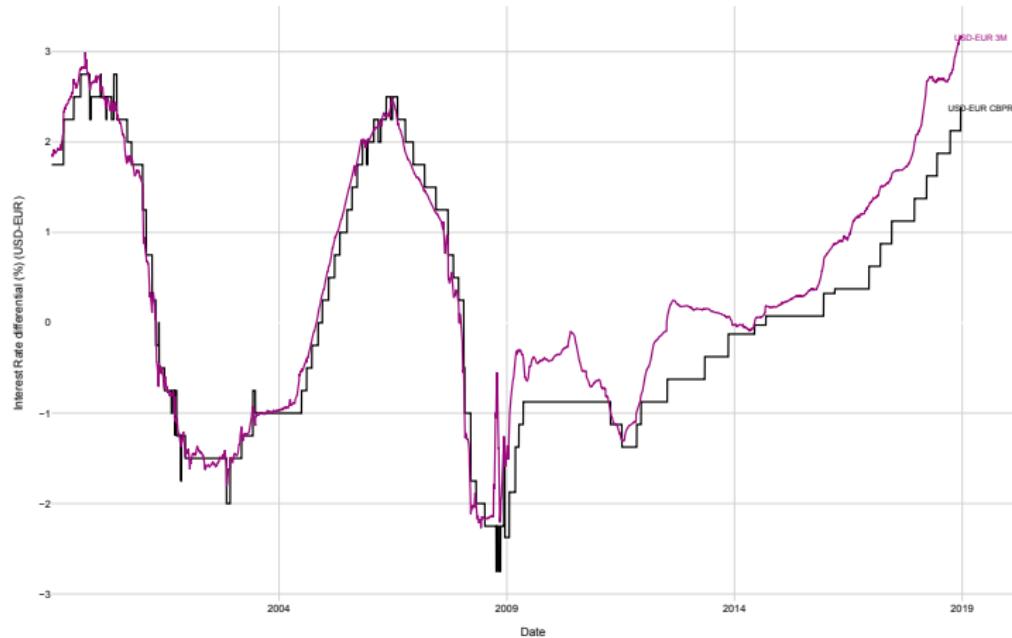


Figure: Daily BIS Central Bank Policy Rate and 3M Interbank Rates differentials (USD-EUR) over the time: 1999 - 2019.³¹

³¹ Own Illustration based on [ANT24], Figure 1, page 2 and data taken from [IS25] and [Rei25]. last accessed 24.10.25

Main variables distributions (raw data - normalized)

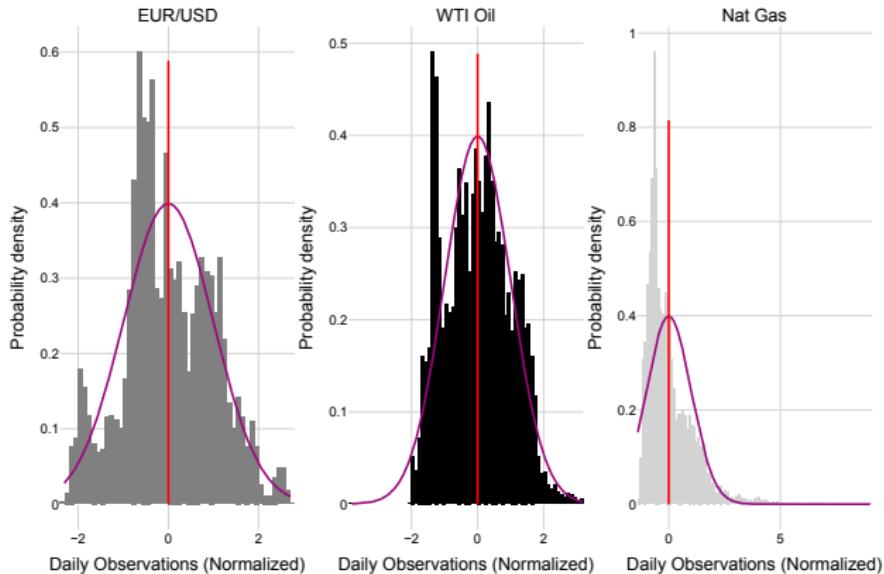


Figure: Normalized daily EUR/USD spot exchange rate, oil and gas over the time range: 1999 - 2025.³²

³²Own Illustration based on [DLS11], page 5 and data taken from [SL25a], last accessed 24.10.25.

Main variables distributions (log first differences)

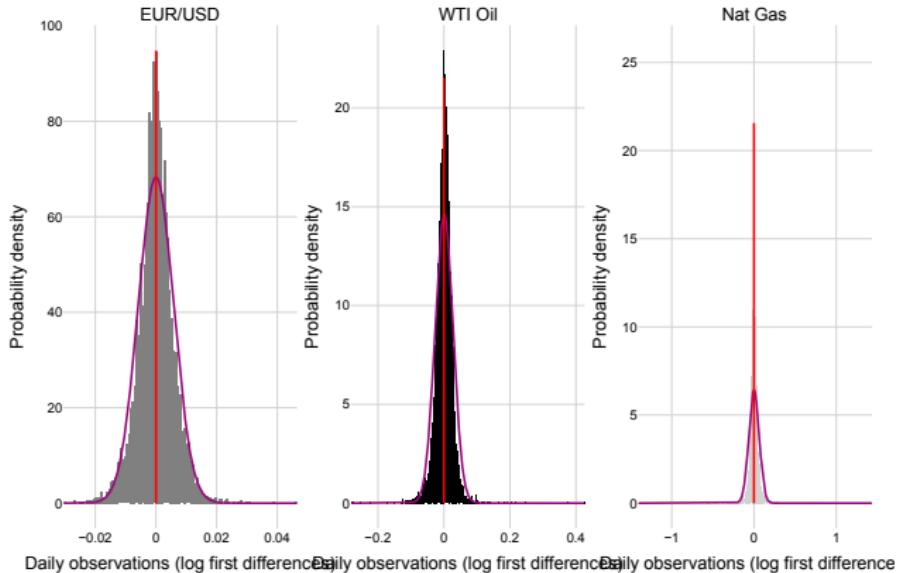


Figure: Log first differences of daily EUR/USD spot exchange rate, oil and gas over the time range: 1999 - 2025.³³

³³ Own Illustration based on [DLS11], page 5 and data taken from [SL25a], last accessed 24.10.25.

Tests for Normality (raw data)

Variable	Test	Statistic	p-value	Significance-level	p-value < 0.05	Result
EUR/USD	Shapiro-Wilk	0.989	0.000	0.050	True	Not-Normal
EUR/USD	Kolmogorov-Smirnov	0.799	0.000	0.050	True	Not-Normal
EUR/USD	D'Agostino's K^2	55.280	0.000	0.050	True	Not-Normal
WTI Oil	Shapiro-Wilk	0.981	0.000	0.050	True	Not-Normal
WTI Oil	Kolmogorov-Smirnov	1.000	0.000	0.050	True	Not-Normal
WTI Oil	D'Agostino's K^2	340.085	0.000	0.050	True	Not-Normal
Nat Gas	Shapiro-Wilk	0.8640	0.000	0.050	True	Not-Normal
Nat Gas	Kolmogorov-Smirnov	0.938	0.000	0.050	True	Not-Normal
Nat Gas	D'Agostino's K^2	2130.008	0.000	0.050	True	Not-Normal

Table: Shapiro-Wilks, Kolmogorov-Smirnov, D'Agostino's K^2 test for normality for the EUR/USD spot exchange rate, WTI Oil and Natural Gas daily observations over the time 1999 - 2025.³⁴

³⁴ Own Illustration based on [Küh07], page 24, tests used from: [Vir+25] and data taken from [SL25a], last accessed 24.10.25.

Tests for Normality (log first differences)

Variable	Test	Statistic	p-value	Significance-level	p-value < 0.05	Result
EUR/USD	Shapiro-Wilk	0.978	0.000	0.050	True	Not-Normal
EUR/USD	Kolmogorov-Smirnov	0.490	0.000	0.050	True	Not-Normal
EUR/USD	D'Agostino's K^2	406.730	0.000	0.050	True	Not-Normal
WTI Oil	Shapiro-Wilk	0.870	0.000	0.050	True	Not-Normal
WTI Oil	Kolmogorov-Smirnov	0.464	0.000	0.050	True	Not-Normal
WTI Oil	D'Agostino's K^2	2040.190	0.000	0.050	True	Not-Normal
Nat Gas	Shapiro-Wilk	0.677	0.000	0.050	True	Not-Normal
Nat Gas	Kolmogorov-Smirnov	0.439	0.000	0.050	True	Not-Normal
Nat Gas	D'Agostino's K^2	2698.020	0.000	0.050	True	Not-Normal

Table: Shapiro-Wilks, Kolmogorov-Smirnov, D'Agostino's K^2 test for normality for the EUR/USD spot exchange rate, WTI Oil and Natural Gas daily observations over the time 1999 - 2025.³⁵

³⁵ Own Illustration based on [Küh07], page 24, tests used from: [Vir+25] and data taken from [SL25a], last accessed 24.10.25.

Tests for Stationarity - ADF Tests (raw data)

ADF Statistic	p-value	Start Time	End Time	Regression Type	Observations	Variable	Result
-1.847	0.357	04-01-1999	04-01-1999	c	6640	EUR/USD	Non-Stationary
-1.846	0.682	04-01-1999	04-01-1999	ct	6640	EUR/USD	Non-Stationary
-2.655	0.480	04-01-1999	04-01-1999	ctt	6640	EUR/USD	Non-Stationary
-0.254	0.594	04-01-1999	04-01-1999	n	6640	EUR/USD	Non-Stationary
-2.789	0.059	04-01-1999	04-01-1999	c	6624	WTI Oil	Non-Stationary
-2.770	0.208	04-01-1999	04-01-1999	ct	6624	WTI Oil	Non-Stationary
-3.060	0.267	04-01-1999	04-01-1999	ctt	6624	WTI Oil	Non-Stationary
-0.697	0.413	04-01-1999	04-01-1999	n	6624	WTI Oil	Non-Stationary
-4.341	0.000	04-01-1999	04-01-1999	c	6633	Nat Gas	Stationary
-4.743	0.001	04-01-1999	04-01-1999	ct	6633	Nat Gas	Stationary
-4.742	0.003	04-01-1999	04-01-1999	ctt	6633	Nat Gas	Stationary
-1.897	0.055	04-01-1999	04-01-1999	n	6633	Nat Gas	Non-Stationary

Table: Augmented-Dickey-Fuller (ADF) test for stationarity in various variants for the EUR/USD spot exchange rate, WTI Oil and Natural Gas daily observations over the time 1999 - 2025.³⁶

³⁶ Own Illustration based on [Küh07], page 24, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Tests for Stationarity - ADF Tests (log first differences)

ADF Statistic	p-value	Start Time	End Time	Regression Type	Observations	Variable	Result
-80.613	0.000	05-01-1999	05-01-1999	c	6637	EUR/USD	Stationary
-80.607	0.000	05-01-1999	05-01-1999	ct	6637	EUR/USD	Stationary
-80.601	0.000	05-01-1999	05-01-1999	ctt	6637	EUR/USD	Stationary
-80.619	0.000	05-01-1999	05-01-1999	n	6637	EUR/USD	Stationary
-14.504	0.000	05-01-1999	05-01-1999	c	6603	WTI Oil	Stationary
-14.525	0.000	05-01-1999	05-01-1999	ct	6603	WTI Oil	Stationary
-14.547	0.000	05-01-1999	05-01-1999	ctt	6603	WTI Oil	Stationary
-14.463	0.000	05-01-1999	05-01-1999	n	6603	WTI Oil	Stationary
-20.094	0.000	05-01-1999	05-01-1999	c	6616	Nat Gas	Stationary
-20.102	0.000	05-01-1999	05-01-1999	ct	6616	Nat Gas	Stationary
-20.121	0.000	05-01-1999	05-01-1999	ctt	6616	Nat Gas	Stationary
-20.095	0.000	05-01-1999	05-01-1999	n	6616	Nat Gas	Stationary

Table: Augmented-Dickey-Fuller (ADF) test for stationarity in various variants for the EUR/USD spot exchange rate, WTI Oil and Natural Gas daily observations (log first differences) over the time 1999 - 2025.³⁷

³⁷ Own Illustration based on [Küh07], page 24, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Tests for Cointegration (raw data)

Cointegration Score	p-value	Start Time	End Time	Observations	Trend	Variable X	Variable Y	Result
-2.967	0.118	04-01-1999	01-10-2025	6641	c	EUR/USD	WTI Oil	Not Cointegrated
-3.364	0.134	04-01-1999	01-10-2025	6641	ct	EUR/USD	WTI Oil	Not Cointegrated
-3.635	0.167	04-01-1999	01-10-2025	6641	ctt	EUR/USD	WTI Oil	Not Cointegrated
-3.268	0.013	04-01-1999	01-10-2025	6641	n	EUR/USD	WTI Oil	Cointegrated
-2.416	0.317	04-01-1999	01-10-2025	6641	c	EUR/USD	Nat Gas	Not Cointegrated
-2.634	0.446	04-01-1999	01-10-2025	6641	ct	EUR/USD	Nat Gas	Not Cointegrated
-3.530	0.204	04-01-1999	01-10-2025	6641	ctt	EUR/USD	Nat Gas	Not Cointegrated
-4.182	0.001	04-01-1999	01-10-2025	6641	n	EUR/USD	Nat Gas	Cointegrated

Table: Engle and Granger Cointegration test for the EUR/USD spot exchange rate, WTI Oil and Natural Gas daily observations over the time 1999 - 2025.³⁸

³⁸ Own Illustration based on [Küh07], page 24, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Tests for Cointegration (log differences)

Cointegration Score	p-value	Start Time	End Time	Observations	Trend	Variable X	Variable Y	Result
-4.293	0.003	17-02-1999	01-10-2025	6609	c	EUR/USD	WTI Oil	Cointegrated
-4.805	0.002	17-02-1999	01-10-2025	6609	ct	EUR/USD	WTI Oil	Cointegrated
-4.830	0.006	17-02-1999	01-10-2025	6609	ctt	EUR/USD	WTI Oil	Cointegrated
-5.724	0.000	17-02-1999	01-10-2025	6609	n	EUR/USD	WTI Oil	Cointegrated
-4.001	0.007	17-02-1999	01-10-2025	6609	c	EUR/USD	Nat Gas	Cointegrated
-4.348	0.009	17-02-1999	01-10-2025	6609	ct	EUR/USD	Nat Gas	Cointegrated
-4.341	0.030	17-02-1999	01-10-2025	6609	ctt	EUR/USD	Nat Gas	Cointegrated
-4.246	0.000	17-02-1999	01-10-2025	6609	n	EUR/USD	Nat Gas	Cointegrated

Table: Engle and Granger Cointegration test for the EUR/USD spot exchange rate, WTI Oil and Natural Gas daily observations (log first differences) over the time 1999 - 2025.³⁹

³⁹ Own Illustration based on [Küh07], page 24, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Tests for Autocorrelation (raw data)

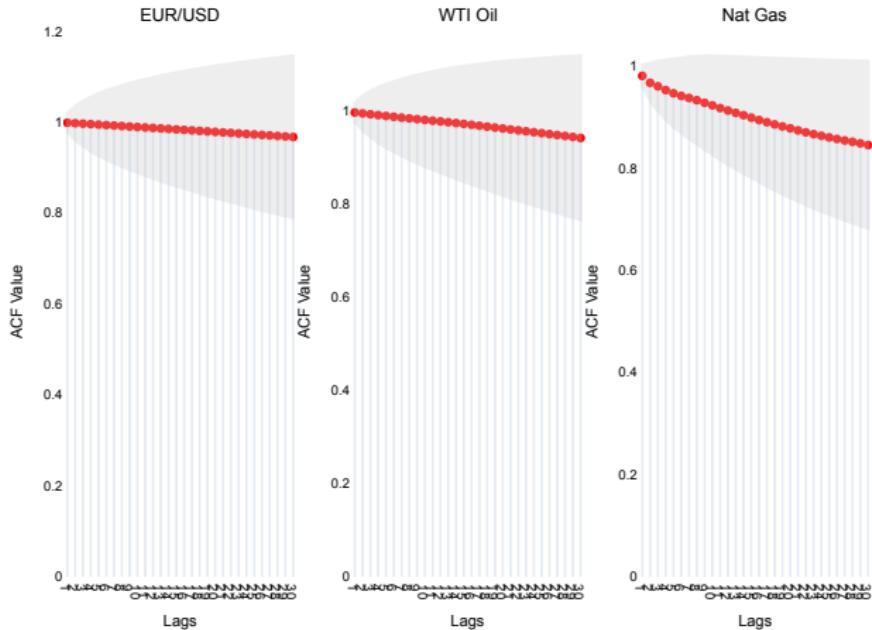


Figure: ACF values for daily observations of the EUR/USD spot exchange rate, oil and gas over the time: 1999 - 2025.⁴⁰

⁴⁰ Own Illustration based on [SSN19], page 10, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Tests for Autocorrelation (log first differences)

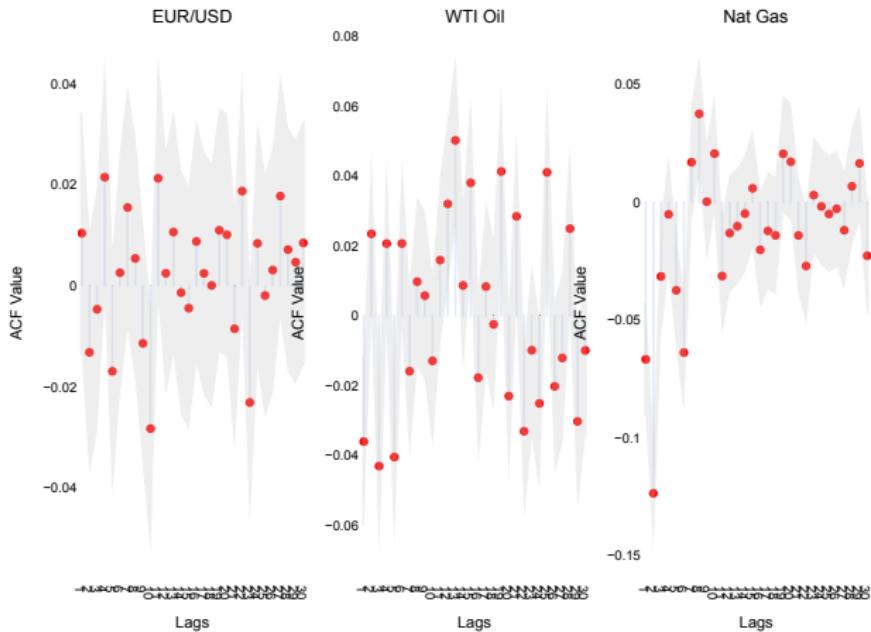


Figure: ACF values for daily observations (log first differences) of the EUR/USD spot exchange rate, WTI Oil and Natural Gas over the time: 1999 - 2025.⁴¹

⁴¹ Own Illustration based on [SSN19], page 10, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Tests for Partial Autocorrelation (raw data)

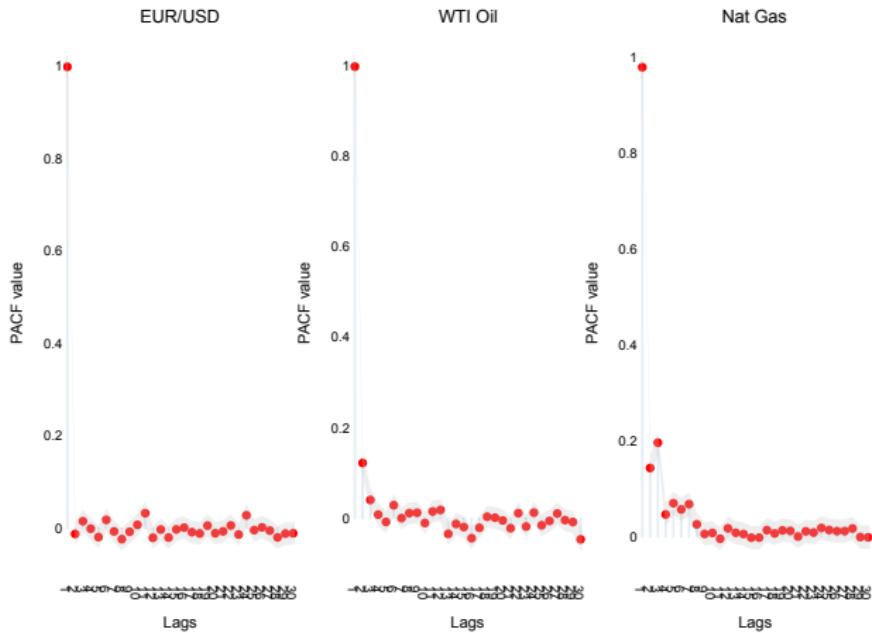


Figure: PACF values for daily observations of the EUR/USD spot exchange rate, WTI Oil and Natural Gas over the time: 1999 - 2025.⁴²

⁴² Own Illustration based on [SSN19], page 10, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Tests for Partial Autocorrelation (log first differences)

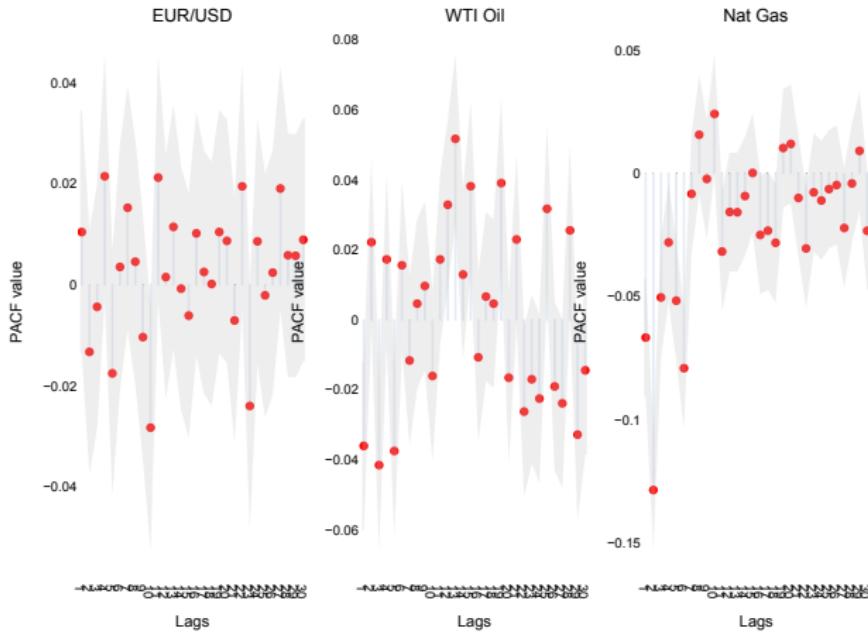


Figure: PACF values for daily observations (log first differences) of the EUR/USD spot exchange rate, WTI Oil and Natural Gas over the time: 1999 - 2025.⁴³

⁴³ Own Illustration based on [SSN19], page 10, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Granger Causality Tests - EUR/USD and oil (raw data)

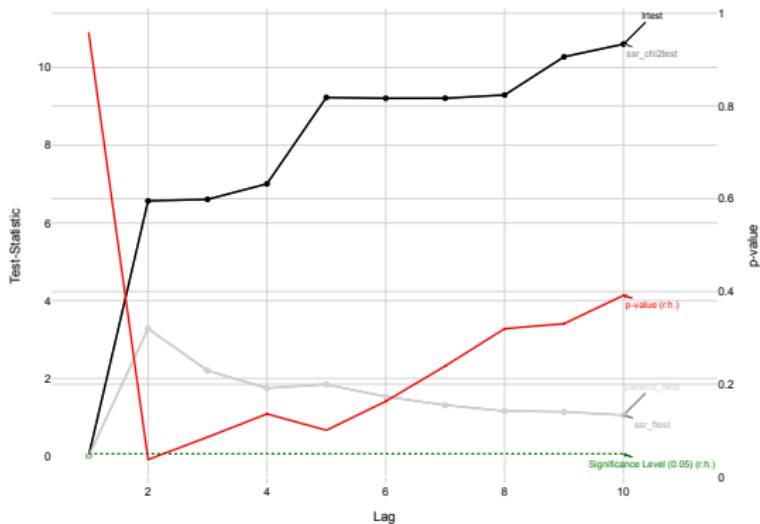


Figure: Granger causality test results testing granger causality of daily observations of oil for EUR/USD spot exchange rate over the time: 1999 - 2025.⁴⁴

⁴⁴ Own Illustration, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Granger Causality Tests - EUR/USD and gas (raw data)

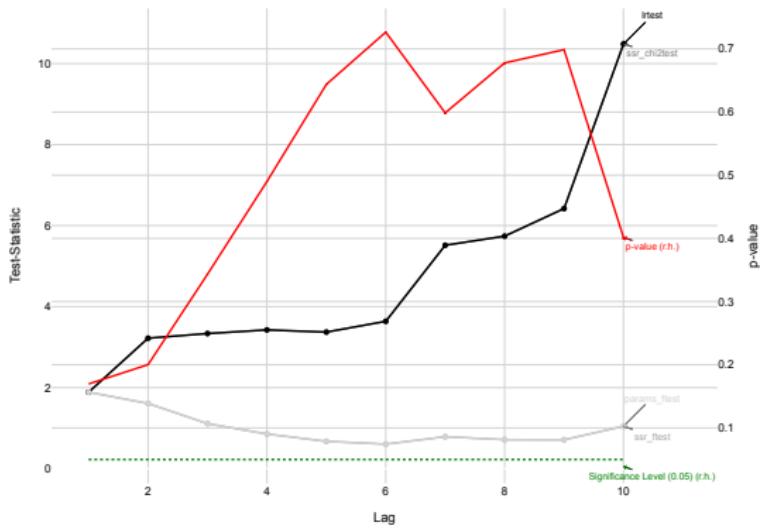


Figure: Granger causality test results testing granger causality of daily observations of gas for EUR/USD over the time: 1999 - 2025.⁴⁵

⁴⁵ Own Illustration, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Granger Causality Tests - EUR/USD and oil (log first differences)

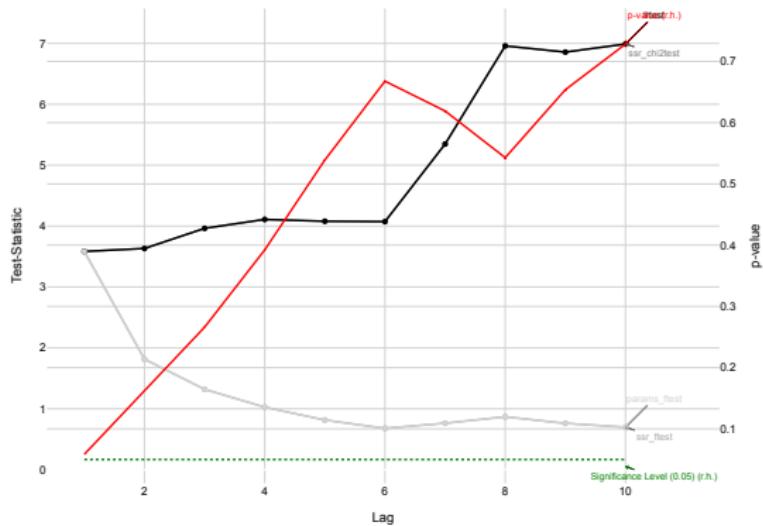


Figure: Granger causality test results testing granger causality of daily observations (log first differences) of WTI Oil for EUR/USD over the time: 1999 - 2025.⁴⁶

⁴⁶ Own Illustration, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Granger Causality Tests - EUR/USD and gas (log first differences)

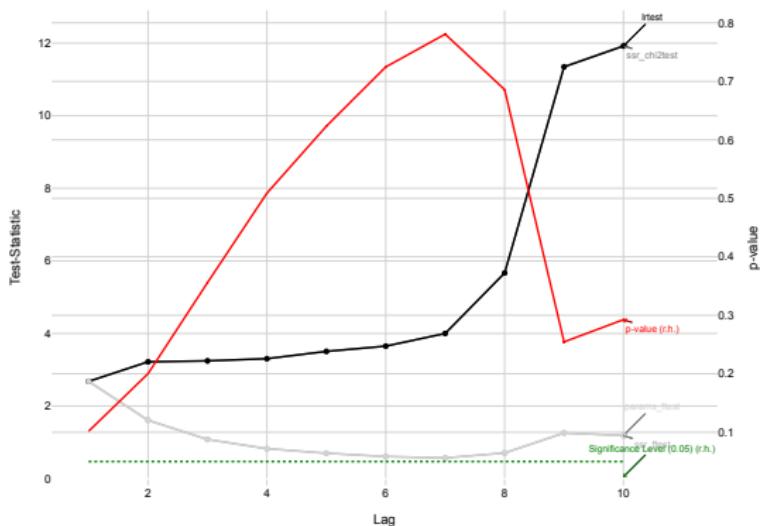


Figure: Granger causality test results testing granger causality of daily observations (log first differences) of Natural Gas for EUR/USD over the time: 1999 - 2025.⁴⁷

⁴⁷ Own Illustration, tests used from: [SP10] and data taken from [SL25a], last accessed 24.10.25.

Appendix - Figures and Tables

No.	Exchange Rate	Basket	Data Frequency	Data Availability	Exchange Rate Type	Bilateral/Multilateral	Source	Data ID	Link
1	Real effective exchange rate	broad	monthly	1994-01	REER	Multilateral	[IS25]	M.R.B.US	Link
2	Real effective exchange rate	narrow	monthly	1964-01	REER	Multilateral	[IS25]	M.R.N.US	Link
3	Nominal effective exchange rate	broad	monthly	1994-01	NEER	Multilateral	[IS25]	M.N.B.US	Link
4	Nominal effective exchange rate	narrow	monthly	1964-01	NEER	Multilateral	[IS25]	M.N.N.US	Link
5	Nominal effective exchange rate	narrow	daily	1983-10-03	NEER	Multilateral	[IS25]	D.N.N.US	Link
6	Nominal effective exchange rate	broad	daily	1995-04-11	NEER	Multilateral	[IS25]	D.N.B.US	Link
7	USD-EUR Spot Rate	-	daily	1999-01-04	NER	Bilateral	[SL25a]	DEXUSEU	Link
8	Nominal Broad U.S. Dollar Index	broad	daily	2006-01-02	NEER	Multilateral	[SL25a]	DTWEXBGS	Link
9	Real Broad Dollar Index	broad	monthly	2006-01-01	REER	Multilateral	[SL25a]	RTWEXBGS	Link

Table: Various exemplary exchange rate data sources for the USD.⁴⁸

⁴⁸ Own illustration based on [Ban21], page 3, Table 1, last accessed 24.10.2025.

Appendix - Data and Definitions

Appendix - Definitions

Appendix - Definitions

PPP Deviation Calculation

$$\text{PPP Deviation} = \log(REER_{country} - REER_{USD}) \quad (1)$$

Source: [ECoD25], data taken from [SL25a], last accessed 24.10.25.

CPI Component Distribution Calculation

$$\text{CPI Component Distribution} = \frac{\text{CPI}_{component}}{\text{CPI}_{total}} \times 100 \quad (2)$$

Source: Data taken from [SL25a] and [Ban25], last accessed 24.10.25.

Appendix - Definitions

Rolling Volatility Calculation

$$\text{Rolling Volatility} = \sqrt{\frac{1}{N} \sum_{t=1}^N (x_t - \bar{x})^2} \quad (3)$$

Source: Data taken from [SL25a], last accessed 24.10.25.

Appendix - Definitions

	Event	Start-date	End-date	Event-Type	Source
1	US Recession 1970-1970	1970-01-01	1970-12-01	US-Recession	[SL25b]
2	Bretton Woods Breakdown	1971-08-15	1973-03-19	Major Global Crisis	[Cor+25]
3	Nixon Shock	1971-08-15	1973-03-19	Major Global Crisis	[EF04]
4	Oil Crisis I	1973-10-17	1974-03-01	Major Global Crisis	[Tra23]
5	US Recession 1973-1975	1973-12-01	1975-04-01	US-Recession	[SL25b]
6	Oil Crisis II	1979-01-01	1981-03-01	Major Global Crisis	[Tra23]
7	US Recession 1980-1980	1980-02-01	1980-08-01	US-Recession	[SL25b]
8	US Recession 1981-1982	1981-08-01	1982-12-01	US-Recession	[SL25b]
9	Black Monday Crash	1987-10-19	1987-10-19	Major Global Crisis	[EF04]
10	US Recession 1990-1991	1990-08-01	1991-04-01	US-Recession	[SL25b]
11	Asian Financial Crisis	1997-07-02	1998-12-31	Major Global Crisis	[ML23]
12	Russian Crisis	1998-08-17	1998-09-01	Major Global Crisis	[ML23]
13	Dot-com Bubble	2000-03-01	2002-10-01	Major Global Crisis	[MNR25]
14	US Recession 2001-2001	2001-04-01	2001-12-01	US-Recession	[SL25b]
15	Global Financial Crisis	2007-08-09	2009-03-09	Major Global Crisis	[MNR25]
16	US Recession 2008-2009	2008-01-01	2009-07-01	US-Recession	[SL25b]
17	US QE	2008-11-25	2014-12-31	Major Global Crisis	[MNR25]
18	European Debt Crisis	2009-10-01	2012-12-31	Major Global Crisis	[MNR25]
19	US Debt Ceiling Crisis	2011-08-20	2011-08-05	Major Global Crisis	[MNR25]
20	US-China Trade War	2018-03-22	2020-01-15	Major Global Crisis	[HR25]
21	COVID-19 Pandemic	2020-02-20	2021-11-16	Major Global Crisis	[ML23]
22	US Recession 2020-2020	2020-03-01	2020-05-01	US-Recession	[SL25b]
23	Russia-Ukraine War	2022-02-24	2022-06-01	Major Global Crisis	[Cha25]

Table: Major global crisis periods (theoretical regimes).⁴⁹

⁴⁹ Own illustration based on [Löy23], Table 1, and data taken from [SL25b], last accessed 24.10.25.

Appendix - Definitions

Nominal effective exchange rate (NEER) (Slide 13):

$$\text{NEER} = \frac{1}{N} \sum_{i=1}^N \text{NER}_i \quad (4)$$

Source: Definition taken from [IS25].

Real effective exchange rate (REER) (Slide 13):

$$\text{REER} = \text{NEER} \times \frac{\text{CPI}_{\text{domestic}}}{\text{CPI}_{\text{foreign}}} \quad (5)$$

Source: Definition taken from [IS25].

Appendix - Definitions

Nominal exchange rate (NER) (Slide 13):

$$NER = \frac{\text{Units of Domestic Currency}}{\text{Units of Foreign Currency}} \quad (6)$$

Source: Definition taken from [CZR18], page 5.

Real exchange rate (RER) (Slide 13):

$$RER = NER \times \frac{CPI_{domestic}}{CPI_{foreign}} \quad (7)$$

Source: Definition taken from [CZR18], page 5.

Clustering Metrics: Silhouette Score (Slide 17):

$$\text{Silhouette Score} = \frac{b - a}{\max(a, b)} \quad (8)$$

Source: Definition taken from [dev24b].

Appendix - Definitions

Standard UIP relationship - log terms (Slide XX):

$$\Delta s_{t+1} = i_t^* + u_{t+1} \quad (9)$$

Source: Definition taken from [Rei25], section "Testing UIP conditions", page 7.

Calculation of the RCM (Slide 17):

$$RCM = 100 S^2 \left(1 - \frac{1}{N} \sum_{t=1}^N [g_t p_t + (1 - g_t)(1 - p_t)] \right) \quad (10)$$

with $g_t = \mathbf{1}\{p_t \geq \tau\}$, p_t the smoothed probability at time t , N the sample size, and τ the classification threshold (e.g. 0.5).

Source: Definition taken from [AB98].

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List of Figures

List of figures

- Figure 1: Monthly deviations of USD spot rates from PPP values (Slide 4)
- Figure 2: Monthly US CPI: Headline and component contributions over the time: 2001 - 2024 (Slide 6)
- Figure 3: Monthly EU Area CPI: Headline and component contributions over the time: 2000 - 2024 (Slide 7)
- Figure 4: Normalized oil price volatility and EUR/USD exchange rate with crisis periods highlighted (Slide 8)
- Figure 5: Systematic Literature Overview (Slide 11)
- Figure 6: Theoretical Framework: Price Measures (Slide 13)
- Figure 7: Theoretical Framework: Simple Model (Slide 14)
- Figure 8: Theoretical Framework: Model I (Slide 15)
- Figure 9: Theoretical Framework: Model II (Slide 16)
- Figure 10: Theoretical Framework: Model III (Slide 17)
- Figure 11: Theoretical Framework: Model IV (Slide 18)
- Figure 12: Model Comparison Bar Plot (Slide 20)
- Figure 13: Predicted Model Regimes with Crisis Periods Highlighted (Slide 21)
- Figure 14: Predicted Model Regimes with Crisis Periods Highlighted (I) (Slide 22)
- Figure 16: Predicted Model Regimes with Crisis Periods Highlighted (II) (Slide 24)
- Figure 17: Predicted Model Regimes with Crisis Periods Highlighted (III) (Slide 25)
- Figure 18: Predicted Model Regimes with Crisis Periods Highlighted (IV) (Slide 26)
- Figure 19: Predicted Model Regimes Relative Share Overlap (Slide 27)
- Figure 20: Predicted Model Regimes Relative Share Overlap with Theoretical Crisis Regimes (Slide 28)
- Figure 21: UIP Estimation Benchmark Models (Slide 29)
- Figure 22: UIP Estimation Identified Regimes (Slide 30)
- Figure 23: Yearly oil consumption and production by country (Slide 38)
- Figure 24: Yearly natural gas consumption and production by country (Slide 39)
- Figure 25: Weekly open interest in oil and natural gas futures contracts (Slide 40)
- Figure 26: Daily BIS Central Bank Policy Rate and 3M Interbank Rates over the time: 1999 - 2019 (Slide 42)
- Figure 27: Daily BIS Central Bank Policy Rate and 3M Interbank Rates differentials (USD-EUR) over the time: 1999 - 2019 (Slide 43)
- Figure 28: Normalized Histograms of Raw Data (Slide 44)
- Figure 29: Histograms of Log First Differences (Slide 45)
- Figure 30: ACF Plots of Raw Series (Slide 52)
- Figure 31: ACF Plots of Log First Differences (Slide 53)
- Figure 32: PACF Plots of Raw Series (Slide 54)
- Figure 33: PACF Plots of Log First Differences (Slide 55)

List of Tables

List of tables

- Table 1: Normality Tests for Raw Data (Slide 46)
- Table 2: Normality Tests for Log First Differences (Slide 47)
- Table 3: ADF Tests for Raw Data (Slide 48)
- Table 4: ADF Tests for Log First Differences (Slide 49)
- Table 5: Cointegration Tests for Raw Data (Slide 50)
- Table 6: Cointegration Tests for Log First Differences (Slide 51)
- Table 7: Exemplary Exchange Rate Types (Slide 60)
- Table 8: Major Global Crisis Periods (Slide 65)

Thank you for your attention!

We await your Questions and/or Comments.

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Discussion

- ① Have you expected this outcome?
- ② What do you think about the dynamics?
- ③ What other variables could be potentially included?



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Further Material for Illustrations - Questions

What is the silhouette score? What are other metrics?
Advantages-Disadvantages? Why exactly this data?