

European Carbon Market Connectedness and Risk Contagion: A Study of Return and Volatility Dynamics Between European Union Allowances (EUAs) and Financial Markets Post-Phase III and their Potential for Portfolio Diversification

Abstract

This paper uses Diebold-Yilmaz model to analyze the return and volatility connectedness between the European carbon market and the financial markets from the commencement of the 3rd phase of the EU emissions trading system in 2013 to the 4th phase until January 2025 in order to ascertain the impact of fixed income, equity, commodities, and energy markets, as well as exogenous shocks and the recent reforms introduced under the Fit for 55 package and RePowerEU Plan. We examine the static and dynamic characteristics of the connectedness network and find that the return and volatility behavior of the European carbon market are primarily driven by their own fundamental factors. Thus it is largely independent of other financial markets except for coal and natural gas, and except during periods of financial stress where a relatively short-lived increase in the connectedness with other financial markets is observed. With such characteristics, EUAs can offer diversification benefits, especially for non-energy portfolios.

Keywords: Carbon markets, emissions trading system, connectedness measures, risk diversification

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Appendix A. Static Return and Volatility Connectedness Matrix

Table A.1: Static Return and Volatility Connectedness Matrix (Jan 2013 - Jan 2025)

(a) Carbon returns connectedness matrix

	CARBON	EUROSTOXX	BRENT OIL	COAL API	NATGAS	EURSOVER	EURCORP	SPXINDEX	COMEXENG	METALS	DSF (FROM)
CARBON	60.06	4.00	3.80	7.85	10.21	2.48	2.26	3.47	2.76	3.11	39.94
EUROSTOXX	3.28	49.76	5.70	3.33	3.12	3.05	3.67	19.87	5.20	3.03	50.24
BRENT OIL	3.49	6.00	57.40	5.44	3.61	2.68	2.34	7.27	8.29	3.49	42.60
COAL API	6.34	3.77	5.80	56.02	13.78	1.85	2.04	3.84	3.96	2.62	43.98
NATGAS	9.93	3.03	3.88	13.58	58.73	1.80	1.76	2.48	2.56	2.24	41.27
EURSOVER	2.03	2.98	2.68	1.67	1.68	48.35	31.93	2.28	2.05	4.36	51.65
EURCORP	1.97	5.05	2.71	1.75	1.81	30.37	45.49	3.97	2.54	4.35	54.51
SPXINDEX	2.42	17.95	6.82	3.35	2.03	2.30	2.73	53.51	6.40	2.50	46.49
COMEXENG	2.48	5.08	7.44	3.49	2.40	2.16	2.37	6.59	53.07	14.91	46.93
METALS	2.37	3.15	3.10	2.28	2.47	4.83	5.59	2.96	16.14	57.11	42.89
DST (TO)	34.31	51.01	41.93	42.73	41.10	51.52	54.69	52.73	49.89	40.60	460.50
Inc.Own	94.37	100.77	99.33	98.75	99.83	99.87	100.18	106.24	102.96	97.70	TCI
NS (NET)	-5.63	0.77	-0.67	-1.25	-0.17	-0.13	0.18	6.24	2.96	-2.30	46.05

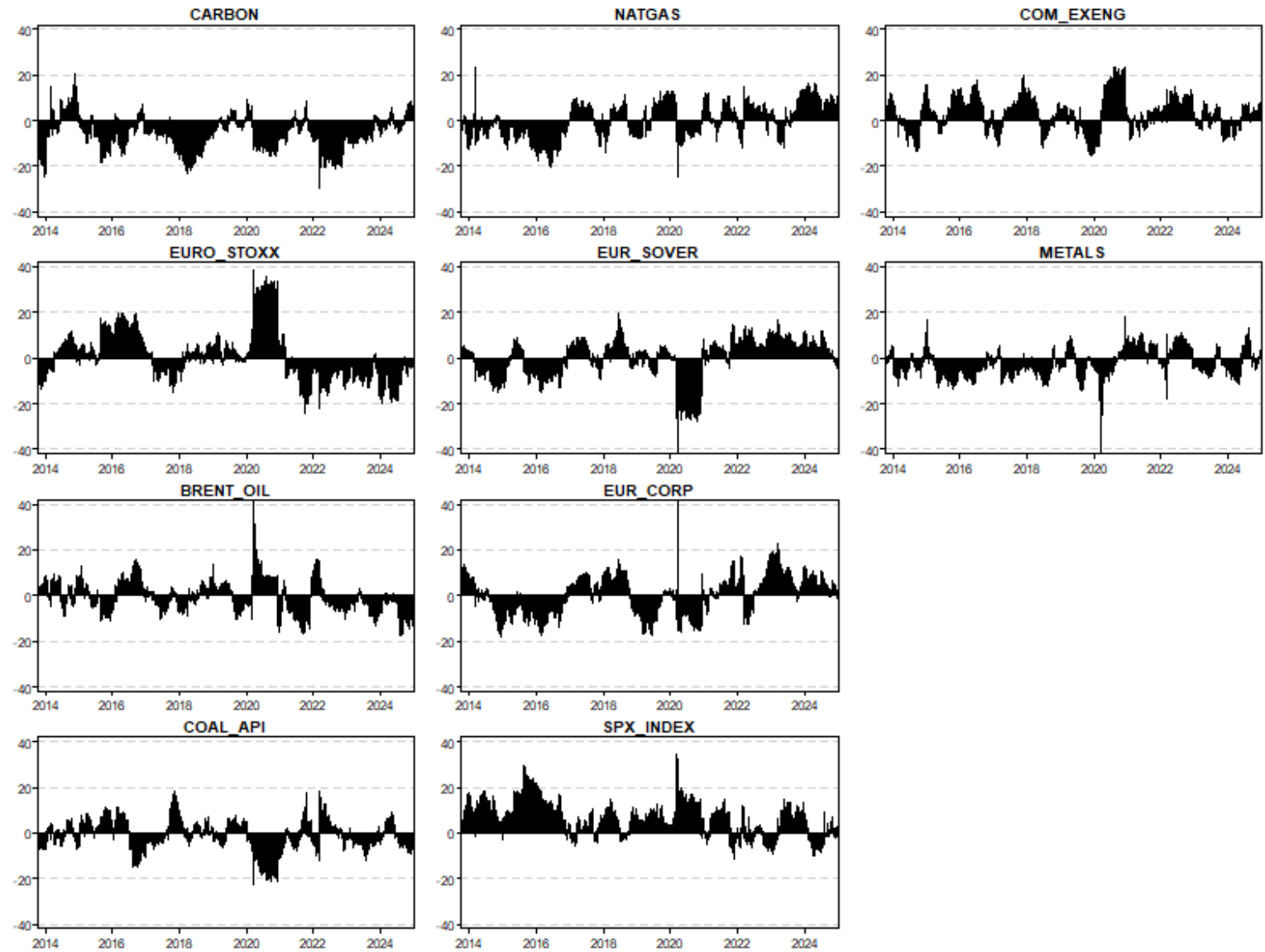
(b) Carbon volatility connectedness matrix

	CARBON	EUROSTOXX	BRENT OIL	COAL API	NATGAS	EURSOVER	EURCORP	SPXINDEX	COMEXENG	METALS	DSF (FROM)
CARBON	55.66	4.60	4.29	7.25	7.13	3.77	3.61	5.06	3.83	4.79	44.34
EUROSTOXX	3.63	47.09	5.17	3.59	3.45	5.12	4.14	16.60	5.25	5.95	52.91
BRENT OIL	4.20	6.54	52.55	4.93	3.59	3.85	4.54	6.49	7.10	6.20	47.45
COAL API	4.67	5.83	4.19	57.95	7.85	3.80	2.71	4.59	3.14	5.26	42.05
NATGAS	4.51	4.64	3.43	8.36	59.40	3.52	3.79	4.82	3.56	3.96	40.60
EURSOVER	2.17	6.27	3.30	2.43	1.86	44.69	25.39	5.60	3.86	4.44	55.31
EURCORP	2.81	5.70	2.52	2.34	2.40	28.32	41.90	5.97	4.70	3.33	58.10
SPXINDEX	3.29	15.44	5.03	3.08	1.71	4.71	3.98	53.15	4.44	5.17	46.85
COMEXENG	2.62	7.96	4.69	3.94	4.00	5.32	5.39	6.71	49.30	10.07	50.70
METALS	3.91	8.31	4.44	3.90	3.85	5.08	6.31	6.26	10.05	47.90	52.10
DST (TO)	31.83	65.30	37.07	39.82	35.85	63.47	59.86	62.11	45.92	49.18	490.40
Inc.Own	87.49	112.39	89.62	97.77	95.25	108.16	101.76	115.27	95.22	97.08	TCI
NS (NET)	-12.51	12.39	-10.38	-2.23	-4.75	8.16	1.76	15.27	-4.78	-2.92	49.04

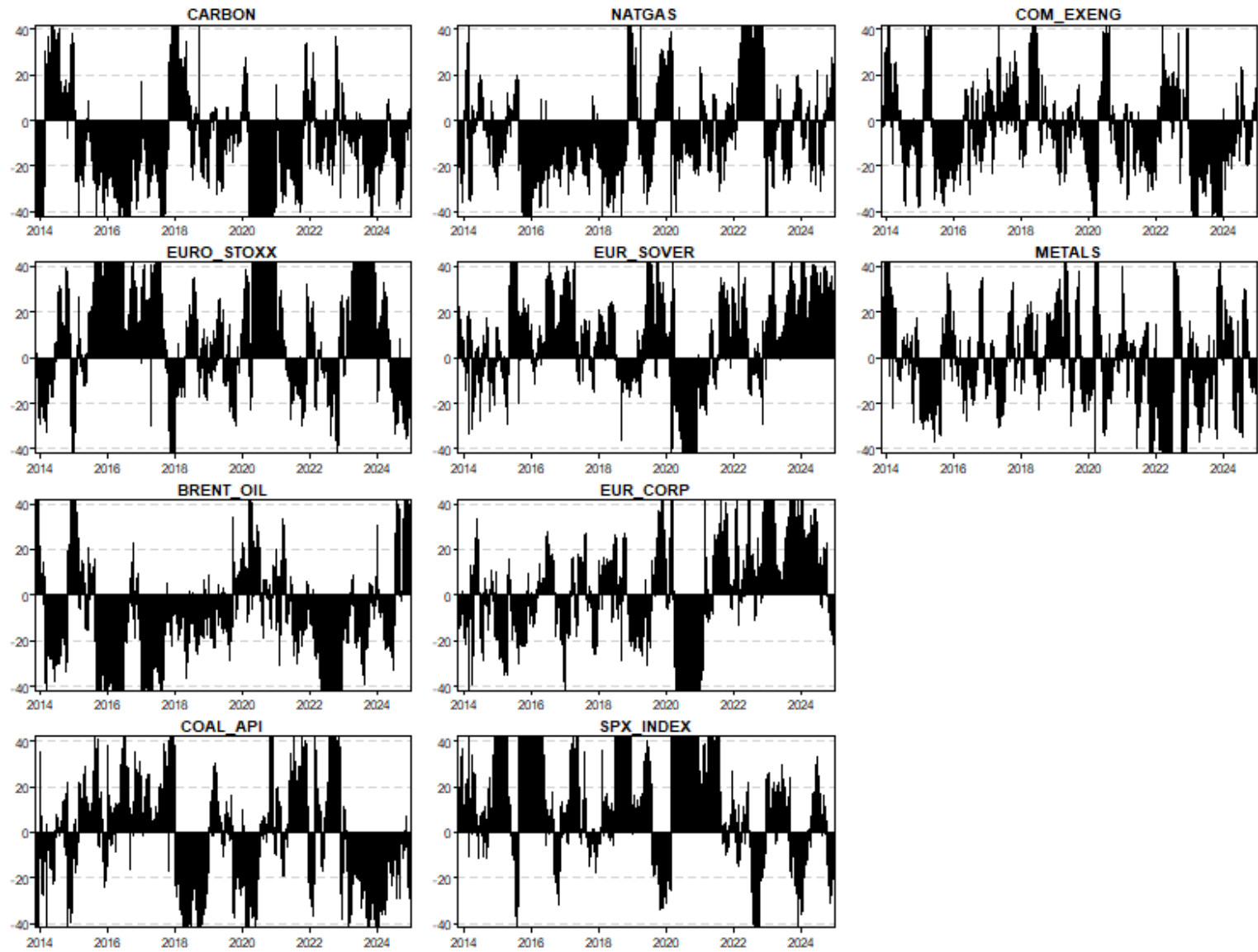
Appendix B. Dynamic Return and Volatility Net Directional Connectedness

Figure B.1: Dynamic Net Directional Connectedness (Jan 2013 – Jan 2025)

(a) Dynamic return net directional connectedness



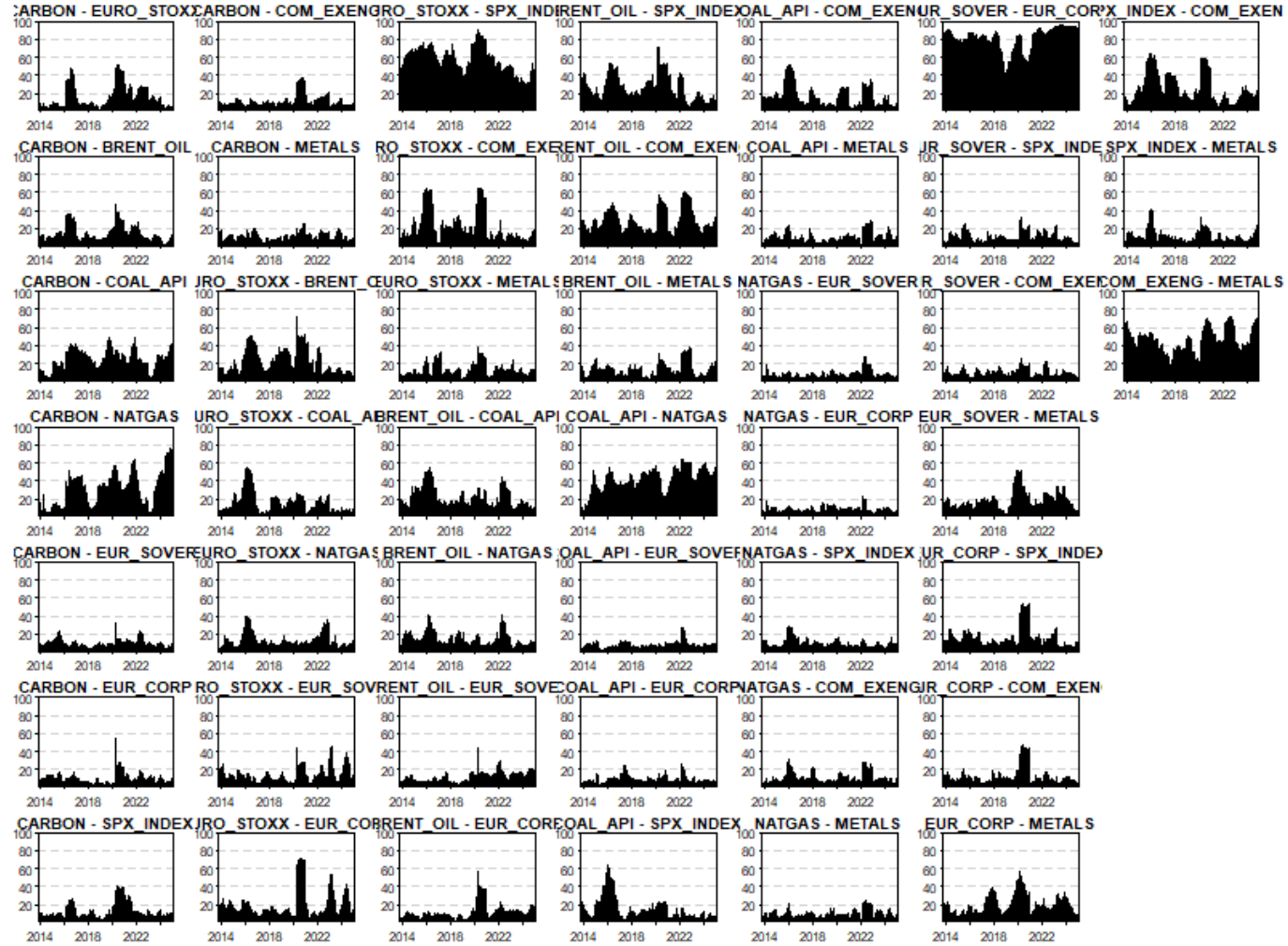
(b) Dynamic volatility net directional connectedness



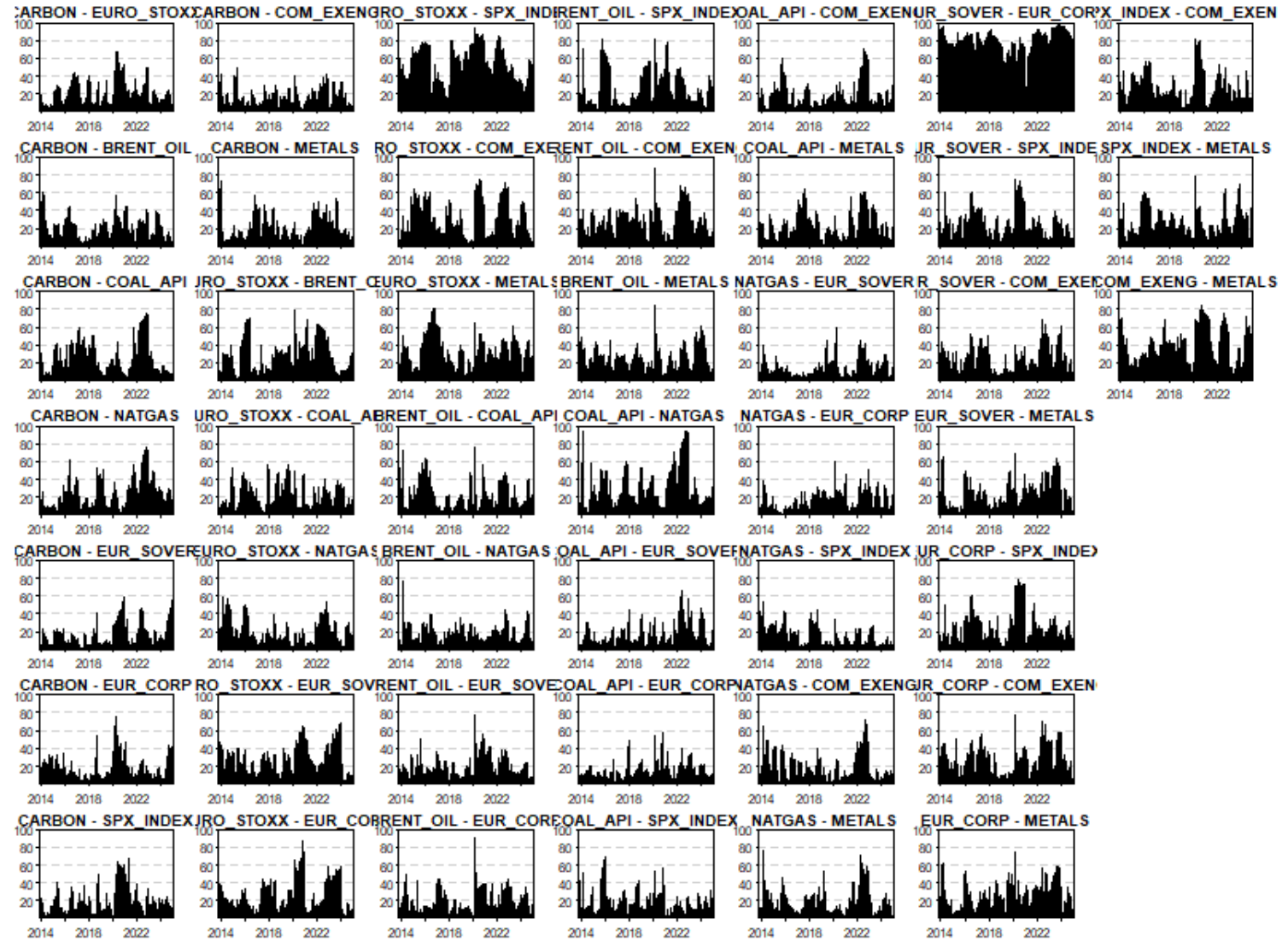
Appendix C. Dynamic Return and Volatility Pairwise Connectedness Index

Figure C.2: Dynamic Return and Volatility Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Dynamic return PCI



(b) Dynamic volatility PCI



Appendix D. Robustness Testing of Connectedness Model Parameters

Appendix D.1. 10-period forecast horizon and a rolling window of 180 observations

Appendix D.1.1. Static Return and Volatility Connectedness Matrix

Table D.2: Static Return and Volatility Connectedness Matrix (Jan 2013 - Jan 2025)

(a) Carbon returns connectedness matrix

	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	58.42	4.13	3.95	7.9	10.32	2.75	2.49	3.71	2.96	3.37	41.58
EUROSTOXX	3.42	48.5	5.77	3.45	3.35	3.4	3.94	19.55	5.3	3.32	51.5
BRENTOIL	3.73	6.14	56.08	5.53	3.75	2.88	2.51	7.34	8.26	3.78	43.92
COALAPI	6.47	3.92	5.88	54.74	13.63	2.07	2.25	4.02	4.11	2.91	45.26
NATGAS	10.05	3.24	4.05	13.36	57.16	2.07	1.99	2.76	2.82	2.49	42.84
EUROVER	2.25	3.24	2.94	1.89	1.94	47.16	31.34	2.45	2.3	4.48	52.84
EURCORP	2.18	5.15	2.89	1.98	2.05	29.92	44.6	4.04	2.7	4.48	55.4
SPXINDEX	2.62	17.77	6.93	3.49	2.29	2.53	2.92	52.31	6.39	2.75	47.69
COMEXENG	2.68	5.17	7.47	3.64	2.68	2.41	2.56	6.59	51.98	14.82	48.02
METALS	2.58	3.42	3.38	2.51	2.73	4.92	5.67	3.2	15.94	55.65	44.35
DST(TO)	35.98	52.19	43.28	43.75	42.74	52.95	55.68	53.66	50.79	42.39	473.4
Inc. Own	94.41	100.69	99.36	98.49	99.9	100.11	100.28	105.96	102.76	98.04	cTCI/TCI
NS (NET)	-5.59	0.69	-0.64	-1.51	-0.1	0.11	0.28	5.96	2.76	-1.96	52.60/47.34

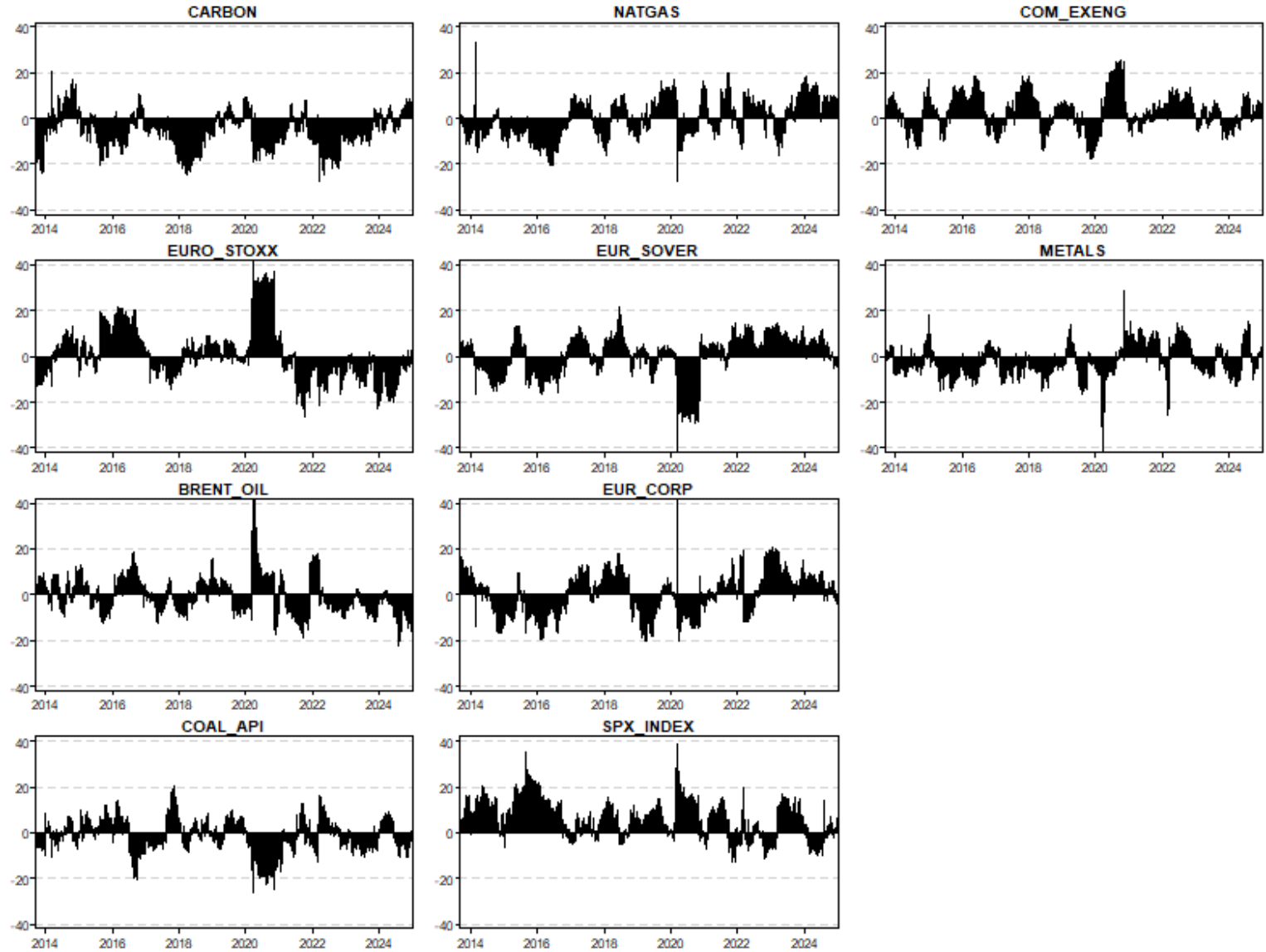
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(b) Carbon volatility connectedness matrix

	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	52.95	4.7	4.74	7.16	7.63	4.19	3.79	5.42	4.13	5.3	47.05
EUROSTOXX	4.01	45.08	5.34	4.25	3.87	5.52	4.38	15.91	5.33	6.3	54.92
BRENTOIL	4.76	6.68	49.8	5.09	3.85	4.3	4.99	6.78	7.12	6.64	50.2
COALAPI	4.88	6.1	4.69	54.65	8.24	4.24	3.12	5.11	3.45	5.52	45.35
NATGAS	4.74	4.99	3.73	8.42	56.56	3.94	3.96	5.28	4.05	4.33	43.44
EUROVER	2.49	6.48	3.6	2.86	2.38	42.69	24.76	5.84	4.43	4.47	57.31
EURCORP	3.24	5.76	2.65	2.84	3	27.52	39.98	6.12	5.26	3.63	60.02
SPXINDEX	3.54	15.08	5.4	3.42	2.05	5.22	4.41	50.56	4.69	5.63	49.44
COMEXENG	3.18	7.91	4.75	4.33	4.51	6.08	5.78	7.11	46.34	10	53.66
METALS	4.27	8.4	4.76	4.29	4.33	5.28	6.78	6.91	9.64	45.33	54.67
DST(TO)	35.11	66.11	39.64	42.67	39.87	66.29	61.97	64.48	48.1	51.81	516.05
Inc. Own	88.06	111.19	89.44	97.33	96.43	108.98	101.96	115.04	94.45	97.14	cTCI/TCI
NS (NET)	-11.94	11.19	-10.56	-2.67	-3.57	8.98	1.96	15.04	-5.55	-2.86	57.34/51.60

Figure D.3: Dynamic Net Directional Connectedness (Jan 2013 – Jan 2025)

(a) Dynamic return net directional connectedness



(b) Dynamic volatility net directional connectedness

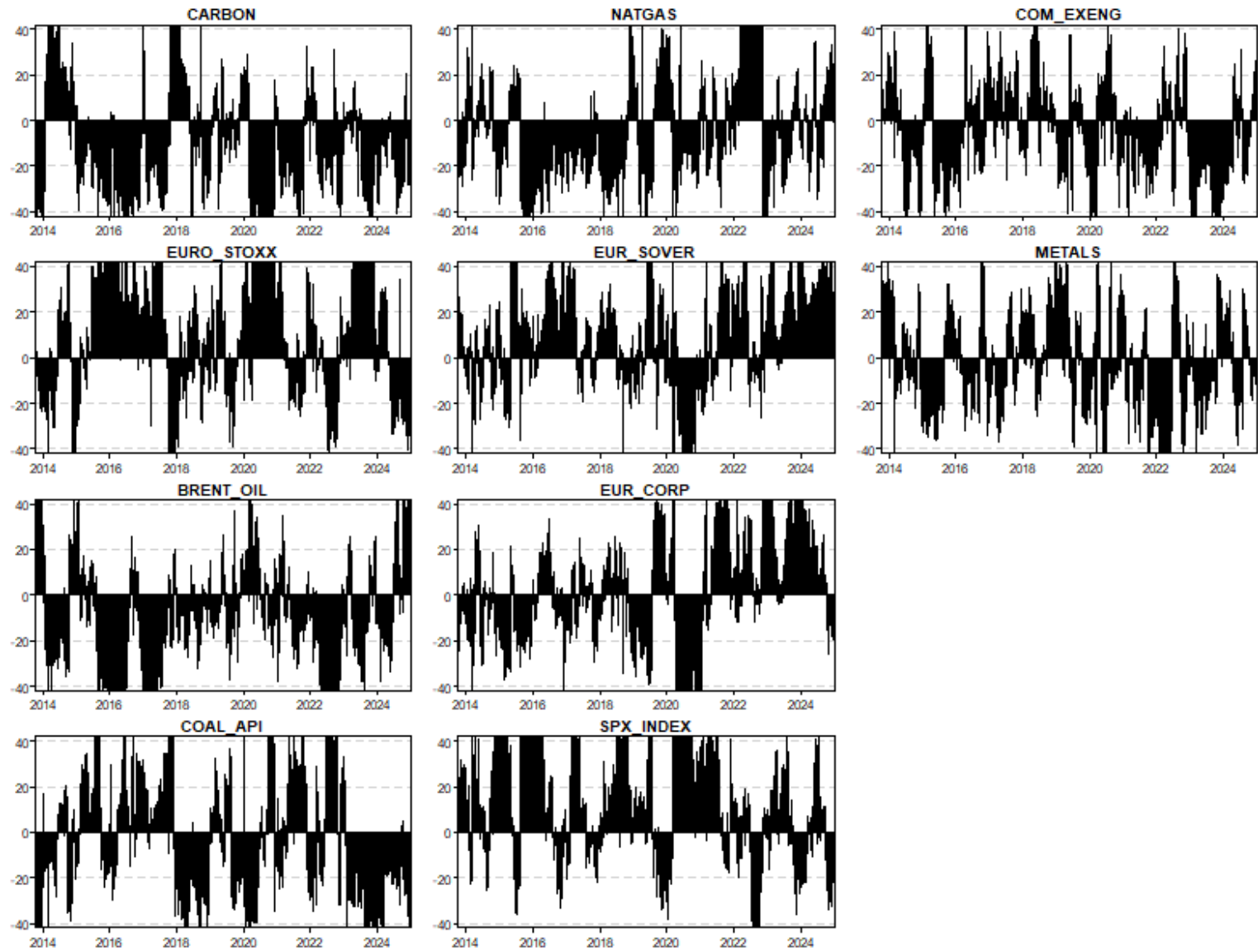
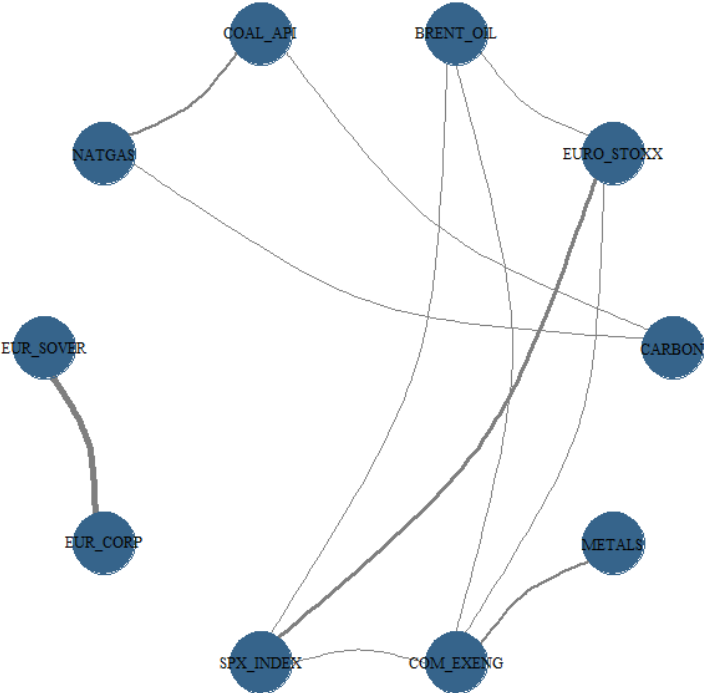
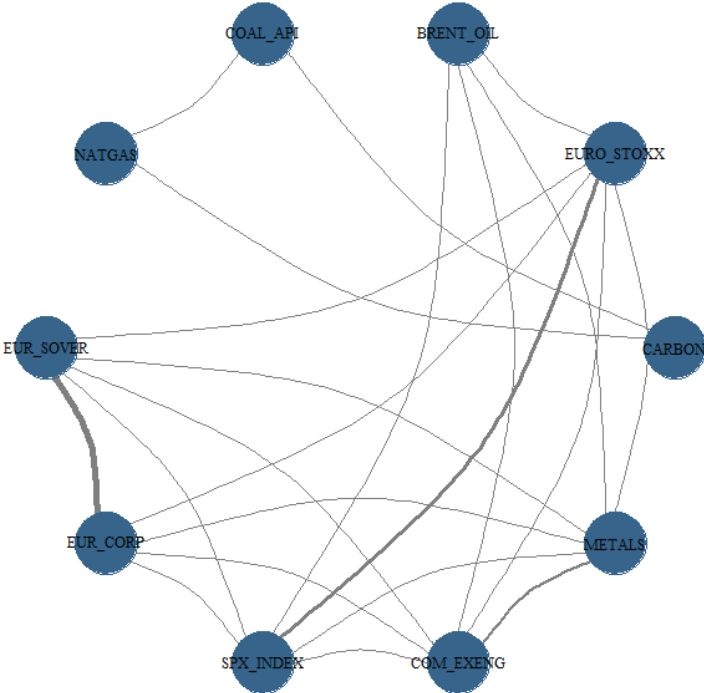


Figure D.4: Network Representation of Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Static Return PCI network



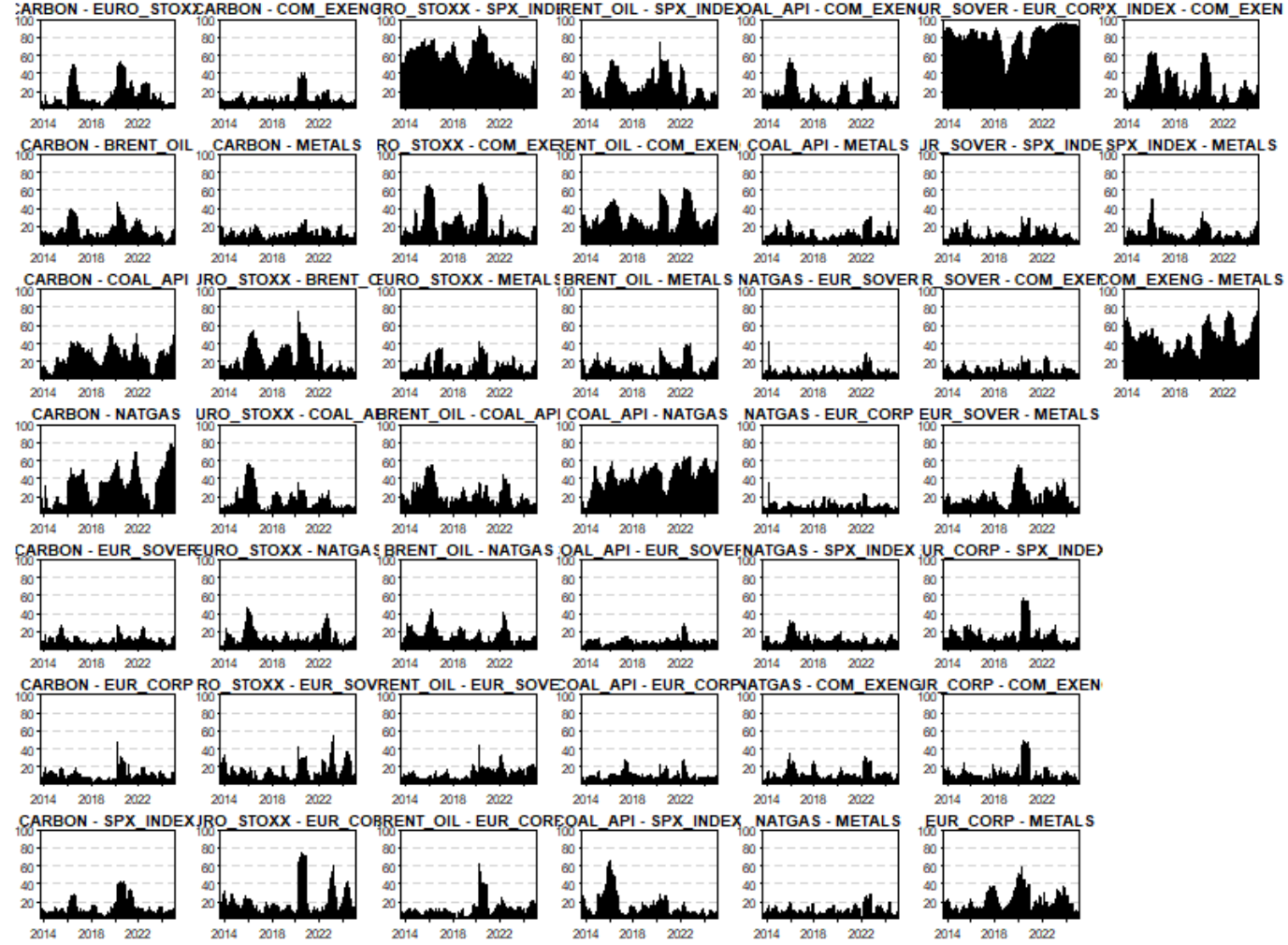
(b) Static Volatility PCI network



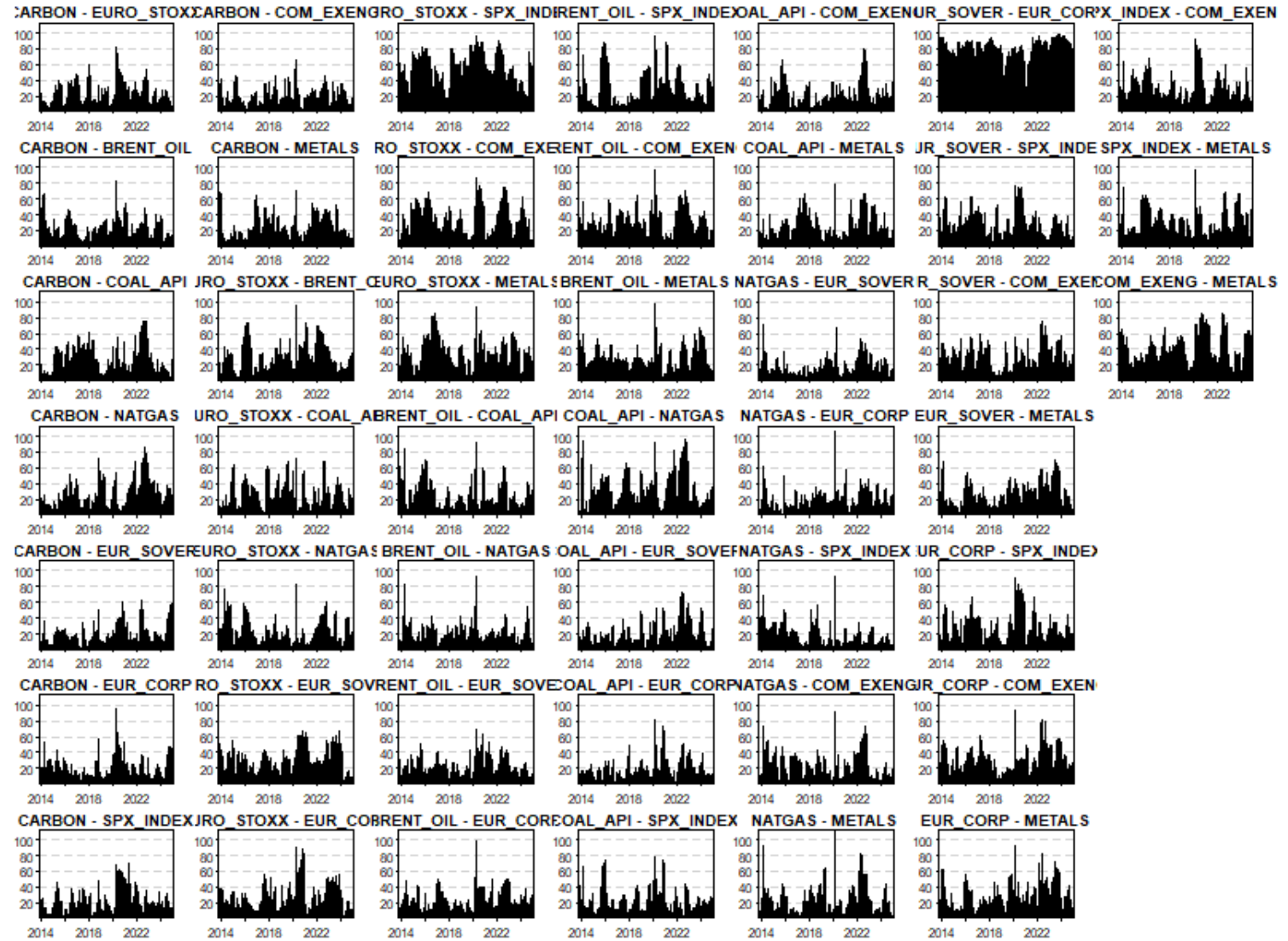
Appendix D.1.4. Dynamic Return and Volatility Pairwise Directional Connectedness

Figure D.5: Dynamic Return and Volatility Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Dynamic return PCI



(b) Dynamic volatility PCI



Appendix D.2. 10-period forecast horizon and a rolling window of 220 observations

Appendix D.2.1. Static Return and Volatility Connectedness Matrix

Table D.3: Static Return and Volatility Connectedness Matrix (Jan 2013 - Jan 2025)

(a) Carbon returns connectedness matrix

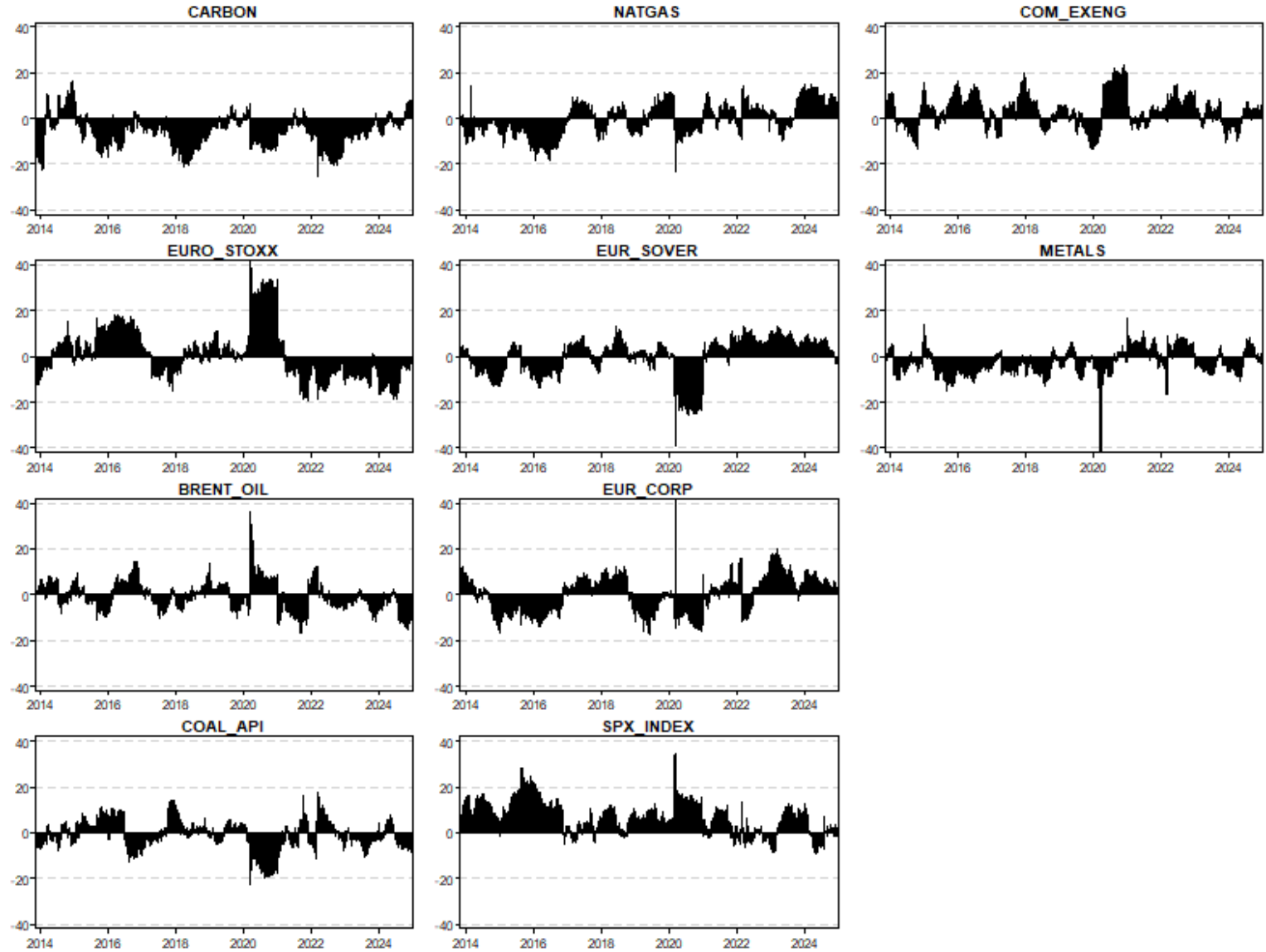
	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	61.35	3.93	3.67	7.77	10.07	2.29	2.12	3.28	2.6	2.91	38.65
EUROSTOXX	3.17	50.79	5.67	3.23	2.94	2.75	3.43	20.12	5.14	2.77	49.21
BRENTOIL	3.31	5.91	58.43	5.38	3.49	2.5	2.22	7.19	8.32	3.25	41.57
COALAPI	6.21	3.65	5.74	57.04	13.87	1.71	1.88	3.69	3.82	2.38	42.96
NATGAS	9.8	2.86	3.74	13.76	59.97	1.62	1.6	2.23	2.37	2.05	40.03
EUROVER	1.86	2.78	2.47	1.5	1.47	49.32	32.36	2.14	1.84	4.25	50.68
EURCORP	1.83	5	2.6	1.56	1.6	30.68	46.15	3.92	2.43	4.22	53.85
SPXINDEX	2.25	18.12	6.71	3.21	1.8	2.12	2.58	54.48	6.44	2.29	45.52
COMEXENG	2.32	5.03	7.42	3.34	2.17	1.96	2.21	6.63	53.93	14.98	46.07
METALS	2.21	2.9	2.88	2.07	2.24	4.77	5.5	2.76	16.3	58.36	41.64
DST(TO)	32.96	50.19	40.89	41.83	39.66	50.41	53.92	51.95	49.25	39.11	450.17
Inc. Own	94.31	100.98	99.31	98.87	99.63	99.74	100.08	106.43	103.18	97.48	cTCI/TCI
NS (NET)	-5.69	0.98	-0.69	-1.13	-0.37	-0.26	0.08	6.43	3.18	-2.52	50.02/45.02

(b) Carbon volatility connectedness matrix

	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	57.82	4.6	3.99	7.25	6.77	3.43	3.28	4.71	3.77	4.37	42.18
EUROSTOXX	3.26	48.44	4.96	3.2	3.12	4.95	4.06	17.08	5.26	5.68	51.56
BRENTOIL	3.71	6.49	54.56	4.78	3.39	3.48	4.09	6.32	7.29	5.9	45.44
COALAPI	4.61	5.41	3.49	60.67	7.47	3.55	2.54	4.17	3	5.09	39.33
NATGAS	4.33	4.33	3.04	8.15	62.01	3.2	3.63	4.47	3.24	3.6	37.99
EUROVER	1.88	6.07	3.1	2.09	1.59	46.2	25.84	5.5	3.43	4.3	53.8
EURCORP	2.48	5.69	2.46	1.93	1.95	28.91	43.34	5.93	4.14	3.17	56.66
SPXINDEX	3.03	15.53	4.64	2.83	1.51	4.32	3.72	55.36	4.18	4.88	44.64
COMEXENG	2.16	7.92	4.69	3.69	3.6	4.81	4.93	6.45	51.6	10.15	48.4
METALS	3.68	8.12	4.08	3.63	3.45	4.91	5.83	5.71	10.35	50.22	49.78
DST(TO)	29.15	64.17	34.46	37.57	32.84	61.55	57.91	60.35	44.66	47.14	469.8
Inc. Own	86.97	112.61	89.02	98.23	94.85	107.74	101.25	115.71	96.26	97.36	cTCI/TCI
NS (NET)	-13.03	12.61	-10.98	-1.77	-5.15	7.74	1.25	15.71	-3.74	-2.64	52.20/46.98

Figure D.6: Dynamic Net Directional Connectedness (Jan 2013 – Jan 2025)

(a) Dynamic return net directional connectedness



(b) Dynamic volatility net directional connectedness

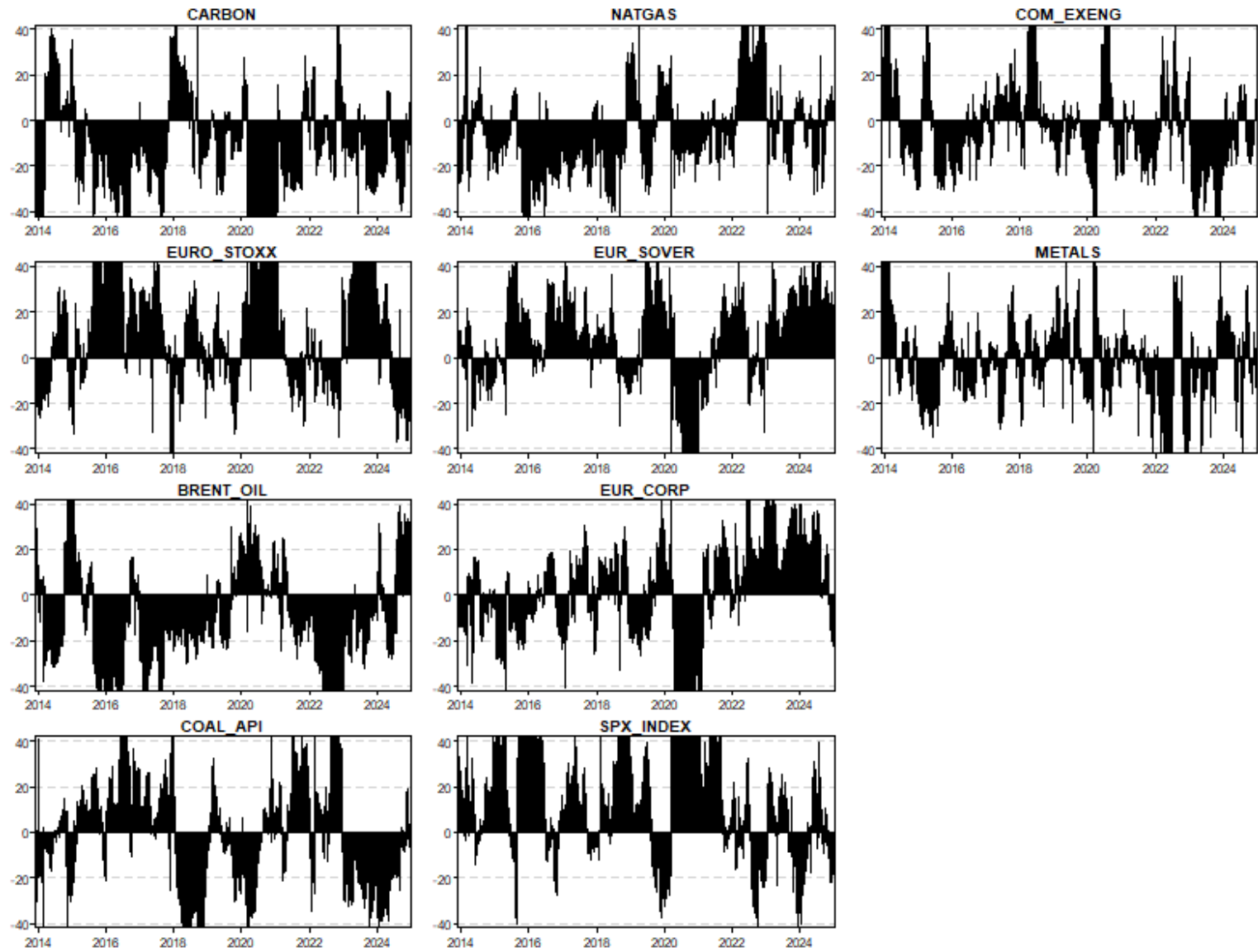
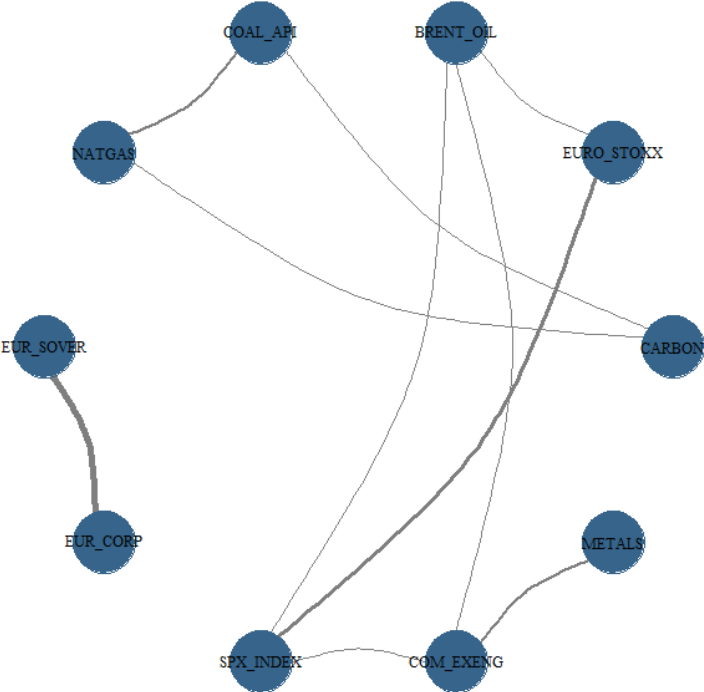
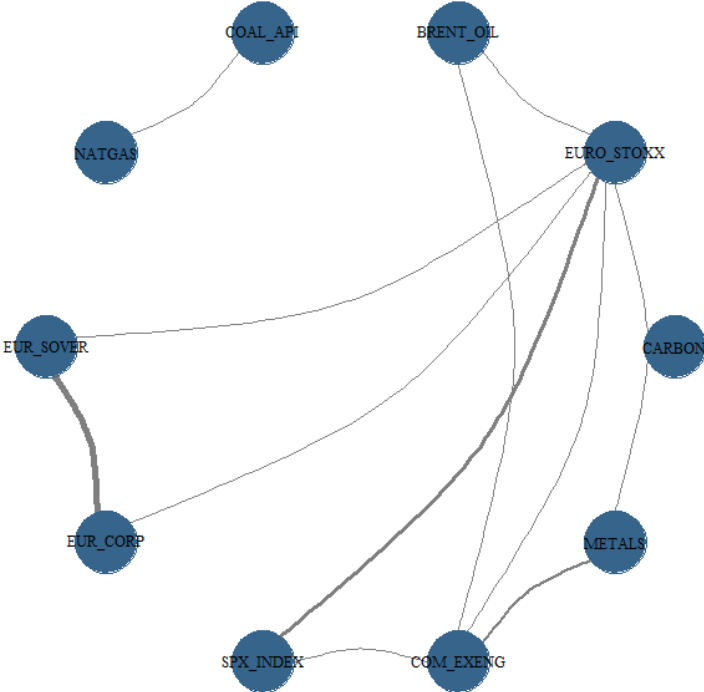


Figure D.7: Network Representation of Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Static Return PCI network



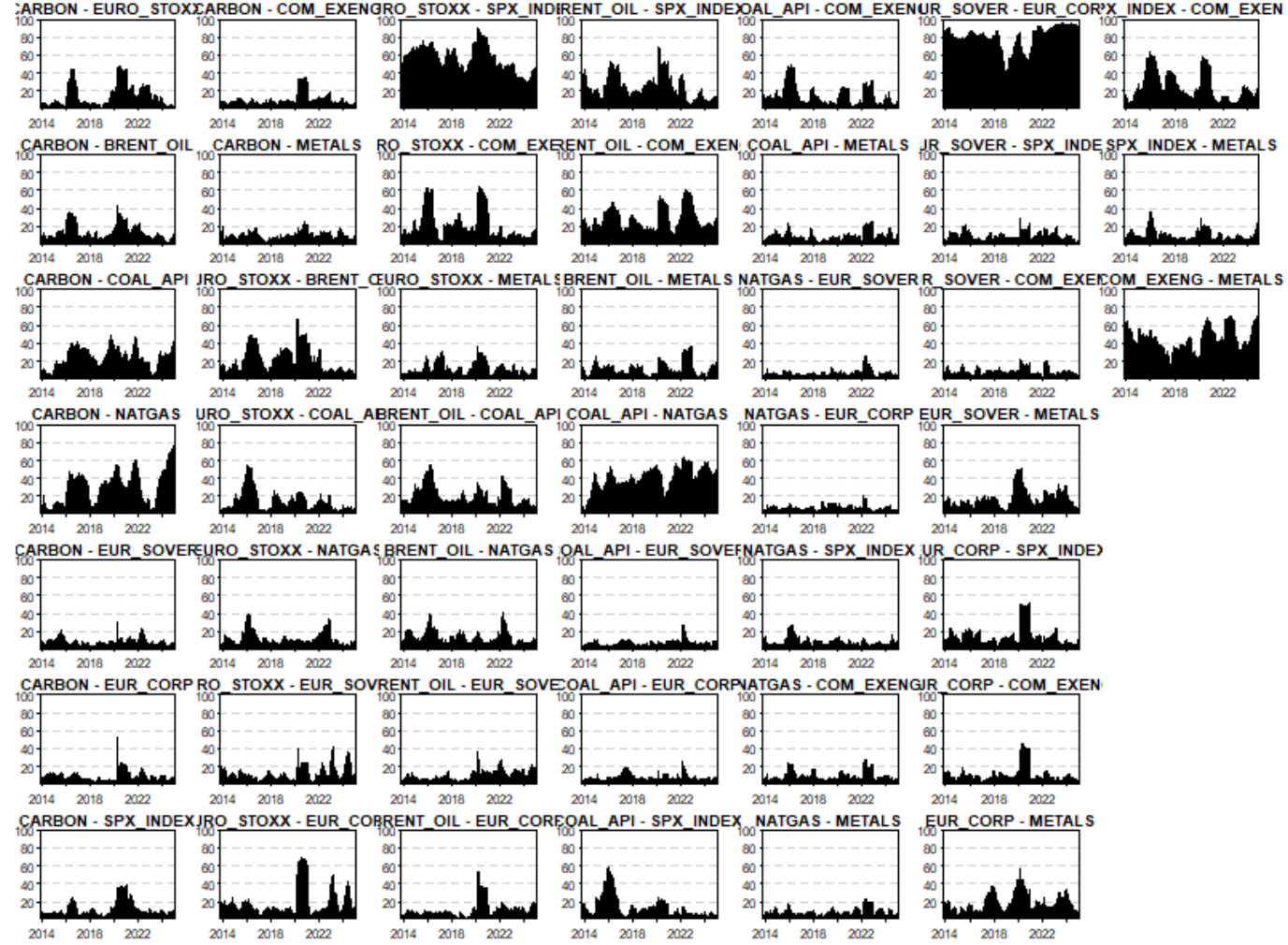
(b) Static Volatility PCI network



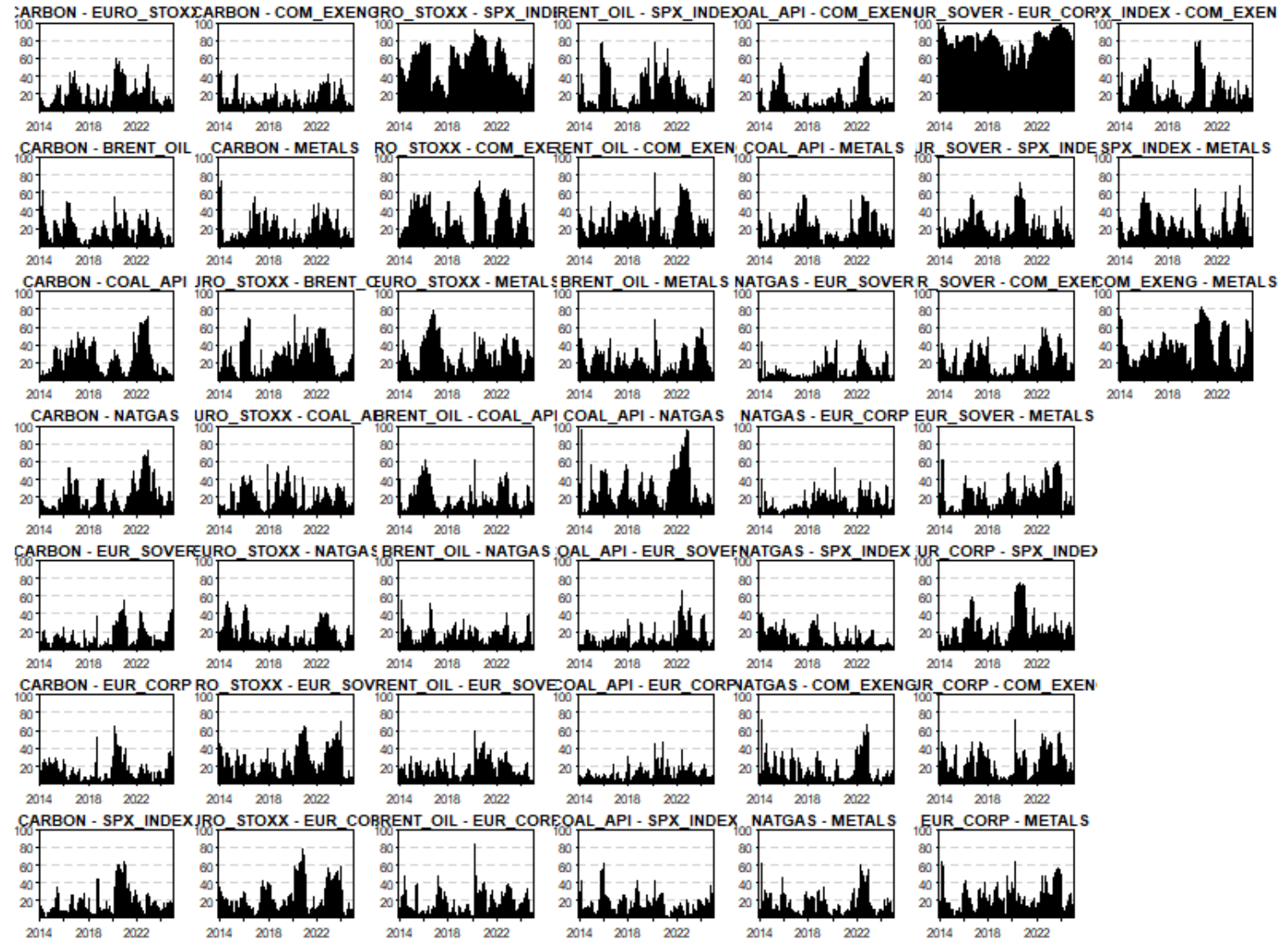
Appendix D.2.4. Dynamic Return and Volatility Pairwise Directional Connectedness

Figure D.8: Dynamic Return and Volatility Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Dynamic return PCI



(b) Dynamic volatility PCI



Appendix D.3. 8-period forecast horizon and a rolling window of 180 observations

Appendix D.3.1. Static Return and Volatility Connectedness Matrix

Table D.4: Static Return and Volatility Connectedness Matrix (Jan 2013 - Jan 2025)

(a) Carbon returns connectedness matrix

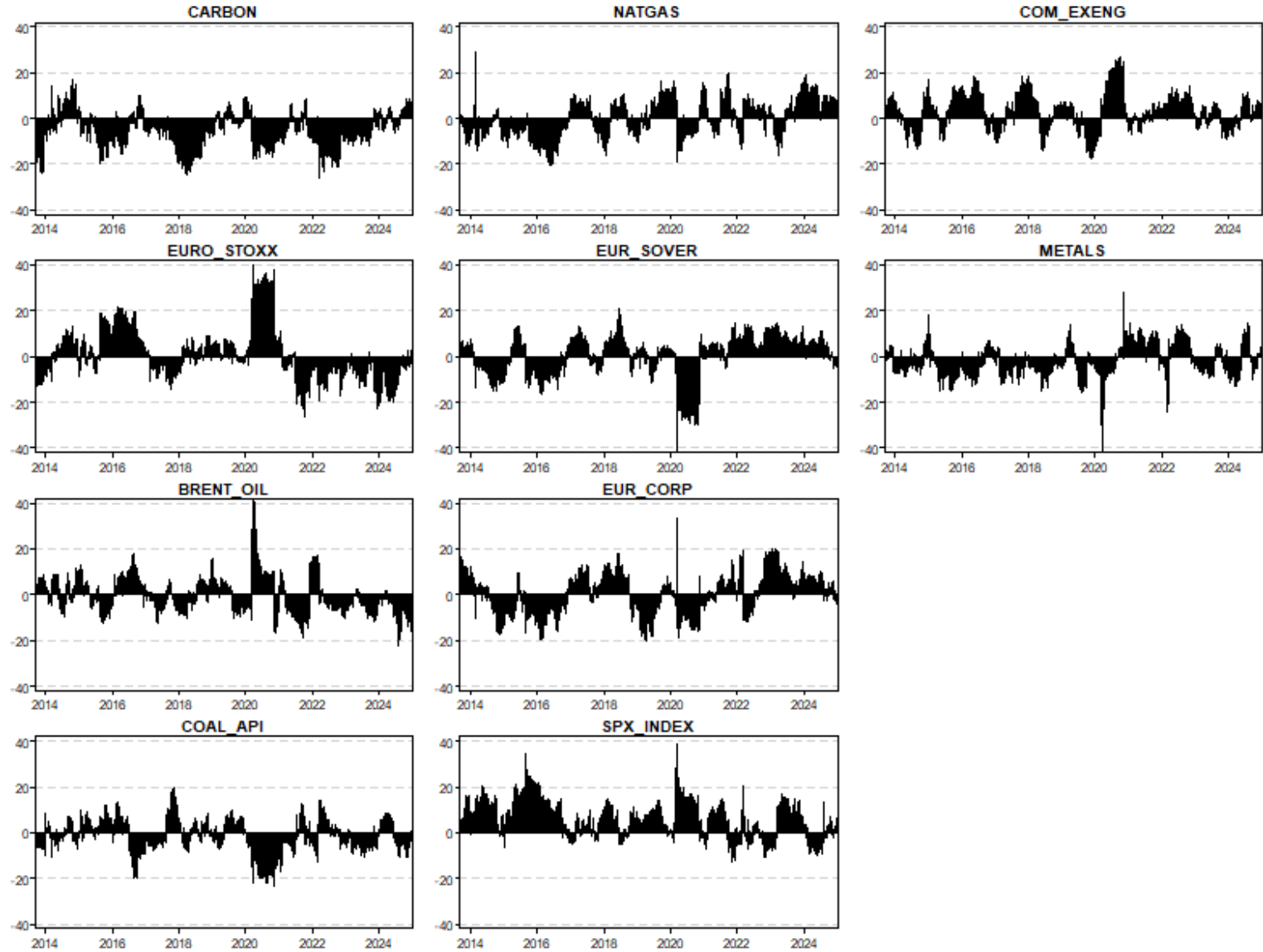
	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	58.73	4.12	3.91	7.88	10.34	2.69	2.43	3.68	2.92	3.3	41.27
EUROSTOXX	3.39	48.68	5.76	3.42	3.3	3.36	3.91	19.61	5.29	3.28	51.32
BRENTOIL	3.7	6.12	56.35	5.5	3.71	2.85	2.46	7.32	8.25	3.74	43.65
COALAPI	6.46	3.9	5.87	54.95	13.64	2.04	2.22	3.99	4.08	2.87	45.05
NATGAS	10.06	3.2	4.03	13.38	57.41	2.03	1.95	2.71	2.77	2.45	42.59
EUROVER	2.21	3.22	2.9	1.85	1.87	47.39	31.45	2.41	2.25	4.43	52.61
EURCORP	2.16	5.13	2.86	1.94	1.99	30.01	44.76	4.01	2.69	4.47	55.24
SPXINDEX	2.58	17.81	6.93	3.46	2.26	2.47	2.89	52.51	6.38	2.71	47.49
COMEXENG	2.66	5.13	7.45	3.6	2.65	2.37	2.51	6.56	52.2	14.86	47.8
METALS	2.55	3.37	3.34	2.48	2.67	4.89	5.64	3.13	15.99	55.95	44.05
DST(TO)	35.76	51.99	43.06	43.51	42.42	52.71	55.46	53.43	50.61	42.12	471.08
Inc. Own	94.5	100.68	99.41	98.45	99.83	100.1	100.22	105.94	102.81	98.07	cTCI/TCI
NS (NET)	-5.5	0.68	-0.59	-1.55	-0.17	0.1	0.22	5.94	2.81	-1.93	52.34/47.11

(b) Carbon volatility connectedness matrix

	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	57.54	4.29	4.24	6.61	7.04	3.68	3.29	4.63	3.58	5.1	42.46
EUROSTOXX	3.64	47.92	5.2	3.73	3.31	5.24	4.1	16.18	4.86	5.81	52.08
BRENTOIL	4.54	6.27	54.13	4.66	3.32	3.65	4.43	6.37	6.68	5.96	45.87
COALAPI	4.31	5.16	4.37	59.14	7.71	3.82	2.8	4.58	3.16	4.95	40.86
NATGAS	4.37	4.61	3.24	7.83	61.1	3.29	3.43	4.7	3.63	3.81	38.9
EUROVER	2.2	5.98	3.36	2.47	2.19	44.51	25.76	5.33	3.96	4.24	55.49
EURCORP	2.95	5.35	2.3	2.49	2.54	28.14	42.31	5.81	4.68	3.43	57.69
SPXINDEX	3.08	15.12	5.25	2.88	1.77	4.81	4.19	53.9	4.15	4.85	46.1
COMEXENG	2.82	7.63	4.56	4.09	4.03	5.57	5.32	6.51	49.19	10.29	50.81
METALS	3.96	7.74	4.37	3.92	3.82	5.1	6.4	6.17	9.52	49.01	50.99
DST(TO)	31.86	62.14	36.9	38.68	35.72	63.29	59.73	60.27	44.22	48.44	481.25
Inc. Own	89.41	110.06	91.03	97.82	96.83	107.8	102.03	114.17	93.41	97.45	cTCI/TCI
NS (NET)	-10.59	10.06	-8.97	-2.18	-3.17	7.8	2.03	14.17	-6.59	-2.55	53.47/48.12

Figure D.9: Dynamic Net Directional Connectedness (Jan 2013 – Jan 2025)

(a) Dynamic return net directional connectedness



(b) Dynamic volatility net directional connectedness

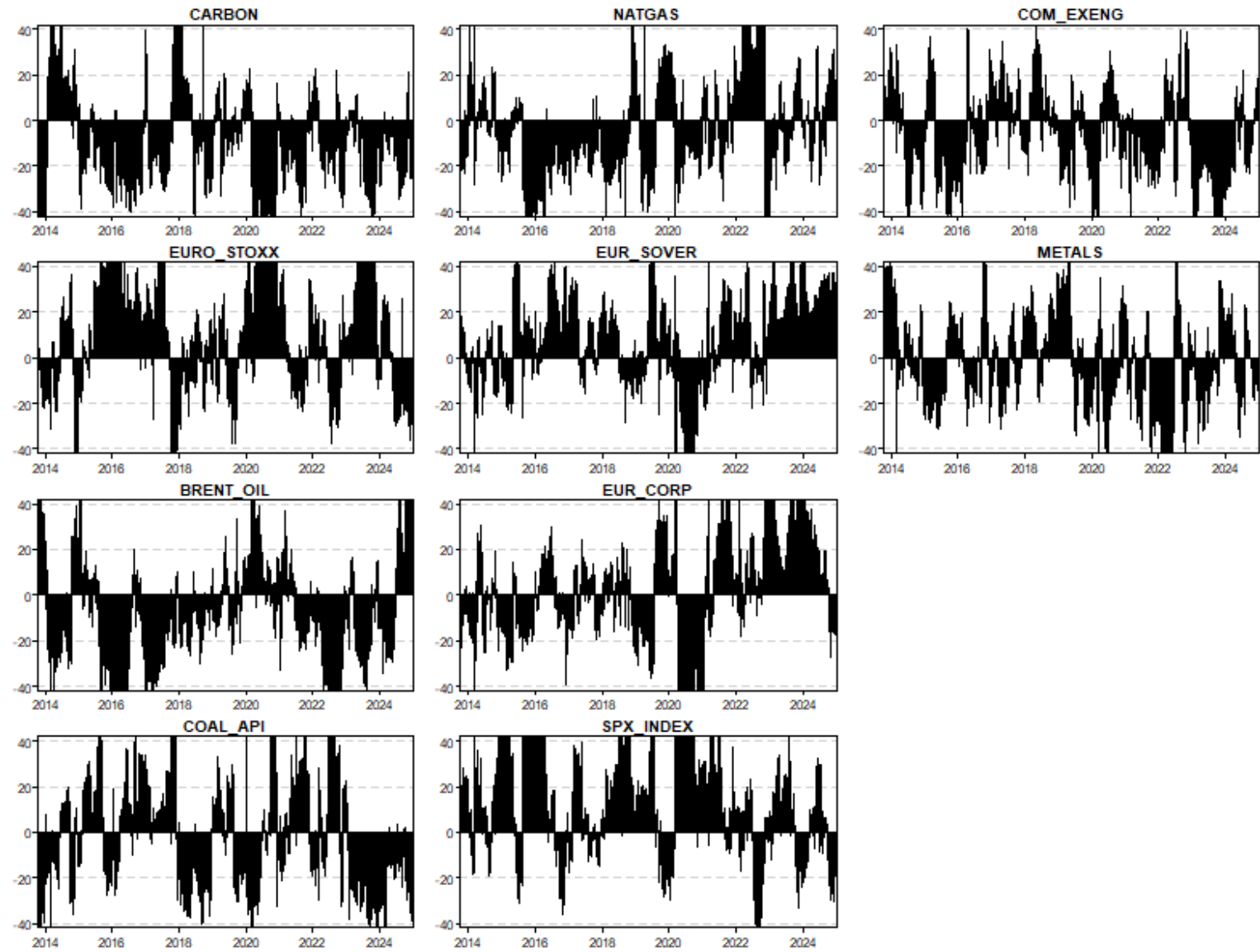
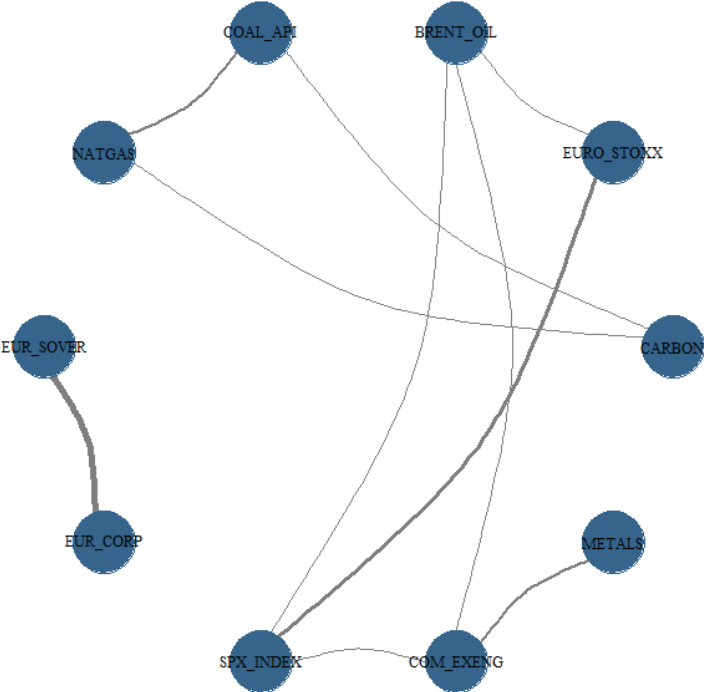
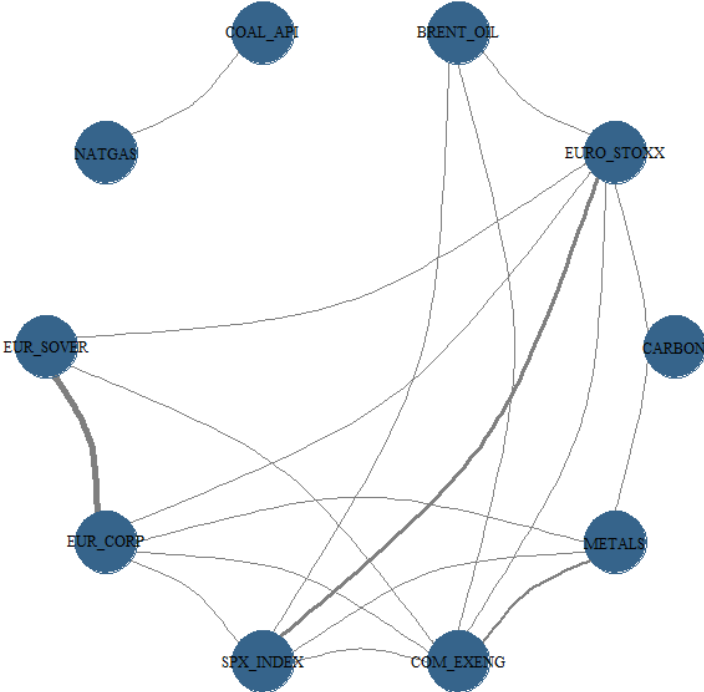


Figure D.10: Network Representation of Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Static Return PCI network



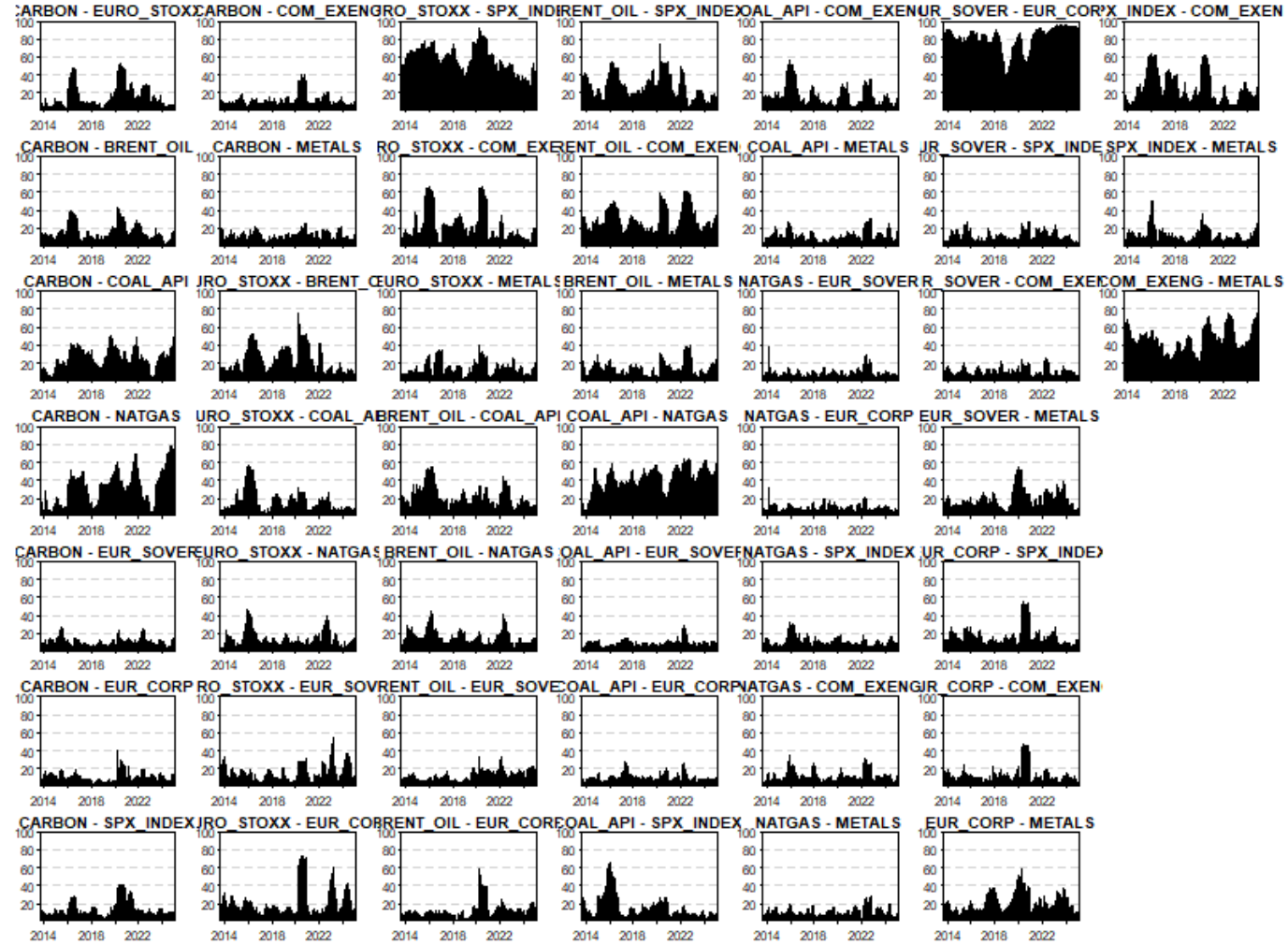
(b) Static Volatility PCI network



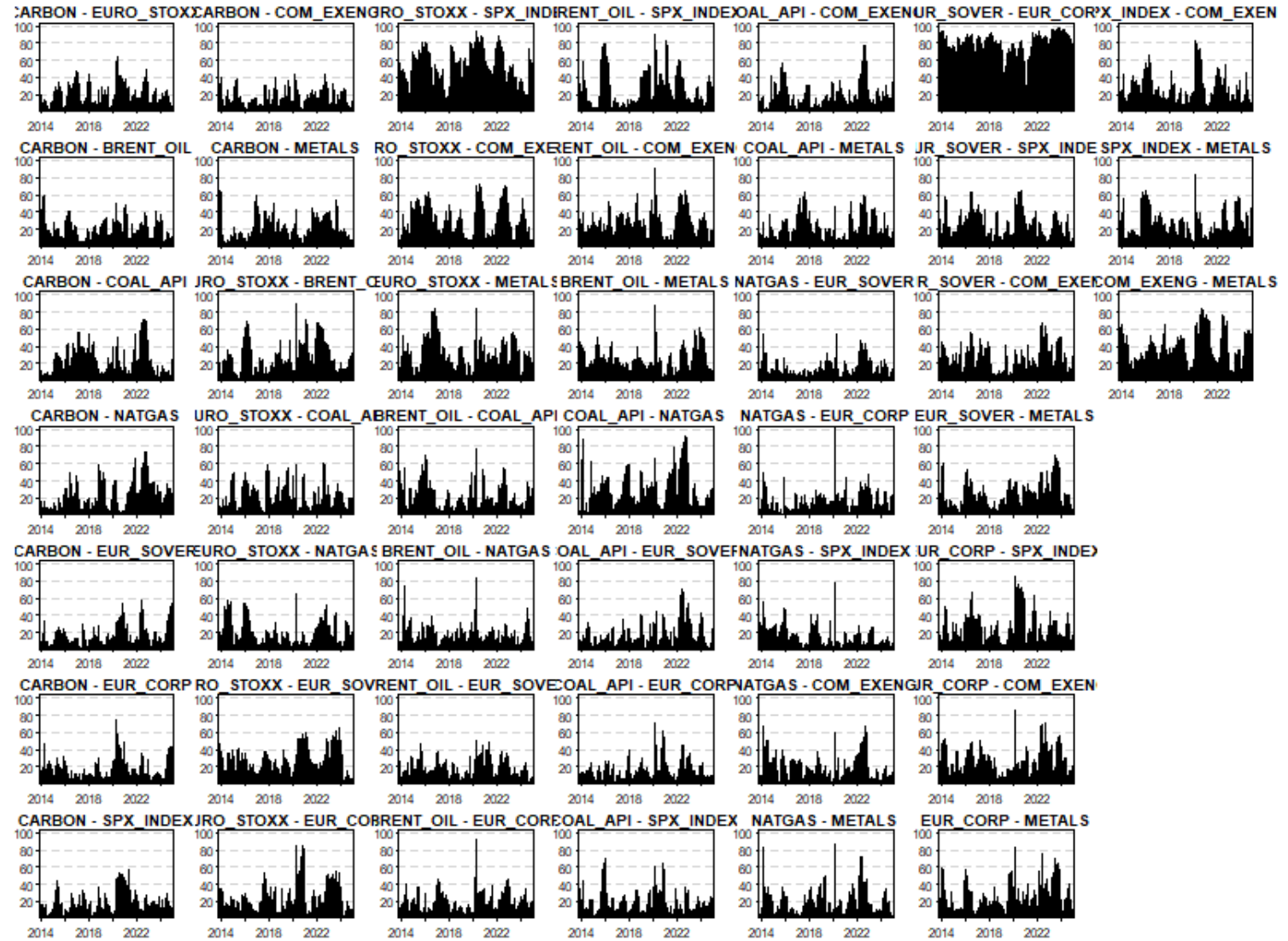
Appendix D.3.4. Dynamic Return and Volatility Pairwise Directional Connectedness

Figure D.11: Dynamic Return and Volatility Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Dynamic return PCI



(b) Dynamic volatility PCI



Appendix D.4. 8-period forecast horizon and a rolling window of 200 observations

Appendix D.4.1. Static Return and Volatility Connectedness Matrix

Table D.5: Static Return and Volatility Connectedness Matrix (Jan 2013 - Jan 2025)

(a) Carbon returns connectedness matrix

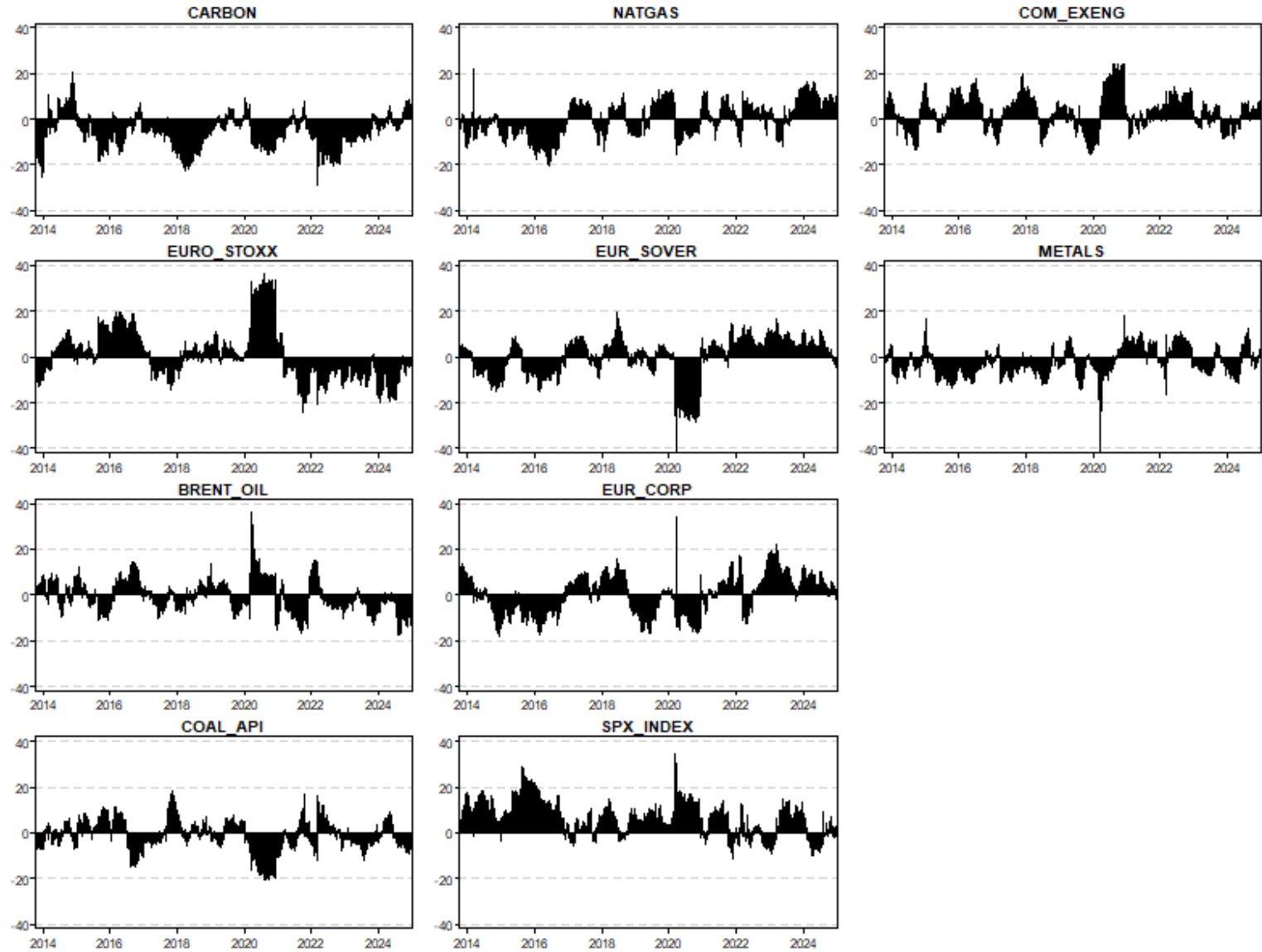
	CARBON	EUROSTOXX	BRENTOL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	60.33	3.99	3.77	7.83	10.23	2.42	2.21	3.44	2.72	3.05	39.67
EUROSTOXX	3.26	49.92	5.7	3.3	3.08	3.01	3.64	19.93	5.19	2.98	50.08
BRENTOL	3.47	5.98	57.62	5.41	3.57	2.65	2.3	7.25	8.28	3.46	42.38
COALAPI	6.33	3.75	5.78	56.18	13.78	1.83	2.01	3.82	3.94	2.59	43.82
NATGAS	9.94	3	3.86	13.6	58.93	1.78	1.72	2.44	2.52	2.21	41.07
EUROVER	1.99	2.97	2.64	1.64	1.63	48.54	32.01	2.25	2	4.33	51.46
EURCORP	1.94	5.03	2.68	1.71	1.75	30.44	45.63	3.94	2.53	4.33	54.37
SPXINDEX	2.38	17.98	6.82	3.32	2	2.25	2.7	53.68	6.39	2.47	46.32
COMEXENG	2.47	5.04	7.42	3.46	2.38	2.12	2.33	6.56	53.26	14.96	46.74
METALS	2.34	3.1	3.07	2.25	2.42	4.81	5.56	2.9	16.18	57.37	42.63
DST(TO)	34.12	50.84	41.75	42.53	40.82	51.31	54.49	52.53	49.76	40.39	458.54
Inc. Own	94.45	100.75	99.37	98.71	99.76	99.85	100.12	106.21	103.02	97.76	cTCI/TCI
NS (NET)	-5.55	0.75	-0.63	-1.29	-0.24	-0.15	0.12	6.21	3.02	-2.24	50.95/45.85

(b) Carbon volatility connectedness matrix

	CARBON	EUROSTOXX	BRENTOL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	60.17	4.17	3.78	6.68	6.57	3.32	3.11	4.33	3.26	4.61	39.83
EUROSTOXX	3.29	49.69	5.1	3.09	2.94	4.86	3.93	16.76	4.8	5.55	50.31
BRENTOL	4.03	6.12	56.72	4.48	3.04	3.25	4.01	6.11	6.72	5.54	43.28
COALAPI	4.14	4.95	3.92	62.24	7.35	3.39	2.39	4.07	2.83	4.7	37.76
NATGAS	4.18	4.25	2.96	7.77	63.79	2.87	3.22	4.26	3.21	3.49	36.21
EUROVER	1.94	5.82	3.08	2.1	1.74	46.3	26.28	5.1	3.44	4.21	53.7
EURCORP	2.58	5.27	2.19	2.05	2.04	28.8	44.04	5.7	4.16	3.17	55.96
SPXINDEX	2.84	15.41	4.97	2.56	1.49	4.35	3.82	56.19	3.92	4.45	43.81
COMEXENG	2.32	7.68	4.52	3.73	3.57	4.87	4.97	6.12	51.84	10.37	48.16
METALS	3.62	7.62	4.07	3.51	3.33	4.94	5.95	5.62	9.94	51.42	48.58
DST(TO)	28.93	61.29	34.59	35.97	32.07	60.65	57.69	58.07	42.27	46.09	457.61
Inc. Own	89.1	110.98	91.3	98.21	95.85	106.95	101.73	114.26	94.11	97.51	cTCI/TCI
NS (NET)	-10.9	10.98	-8.7	-1.79	-4.15	6.95	1.73	14.26	-5.89	-2.49	50.85/45.76

Figure D.12: Dynamic Net Directional Connectedness (Jan 2013 – Jan 2025)

(a) Dynamic return net directional connectedness



(b) Dynamic volatility net directional connectedness

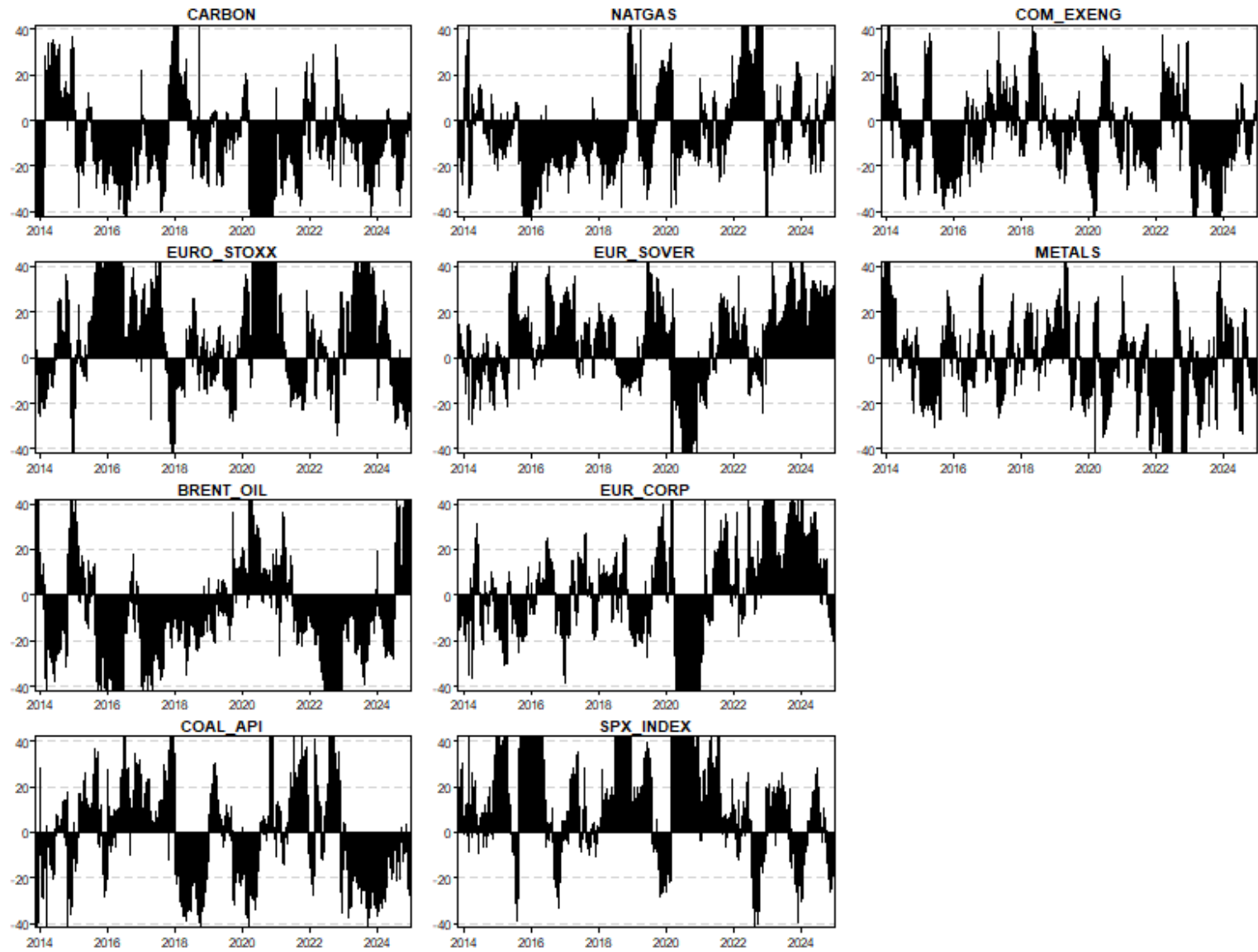
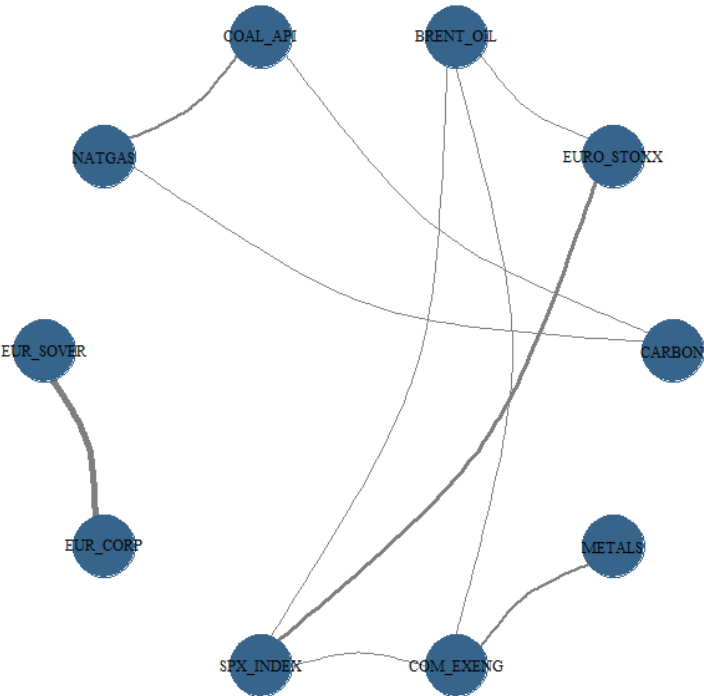
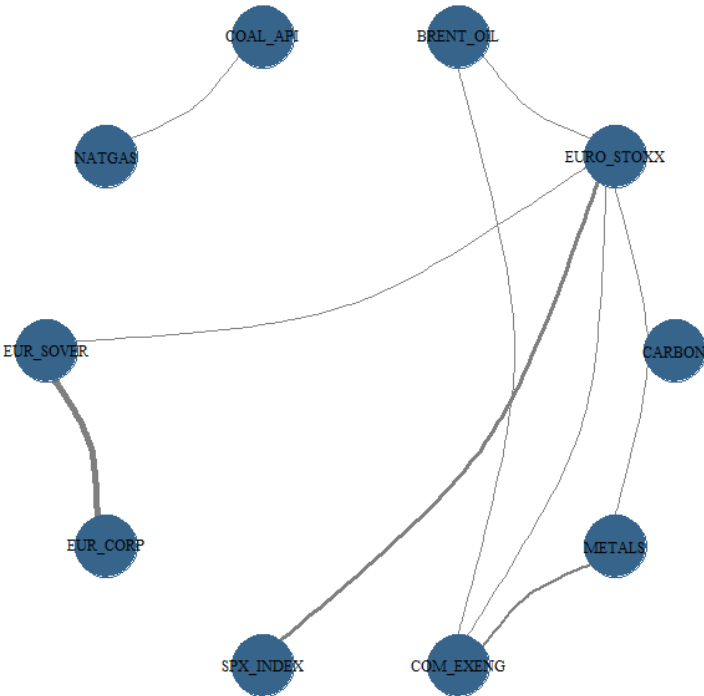


Figure D.13: Network Representation of Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Static Return PCI network



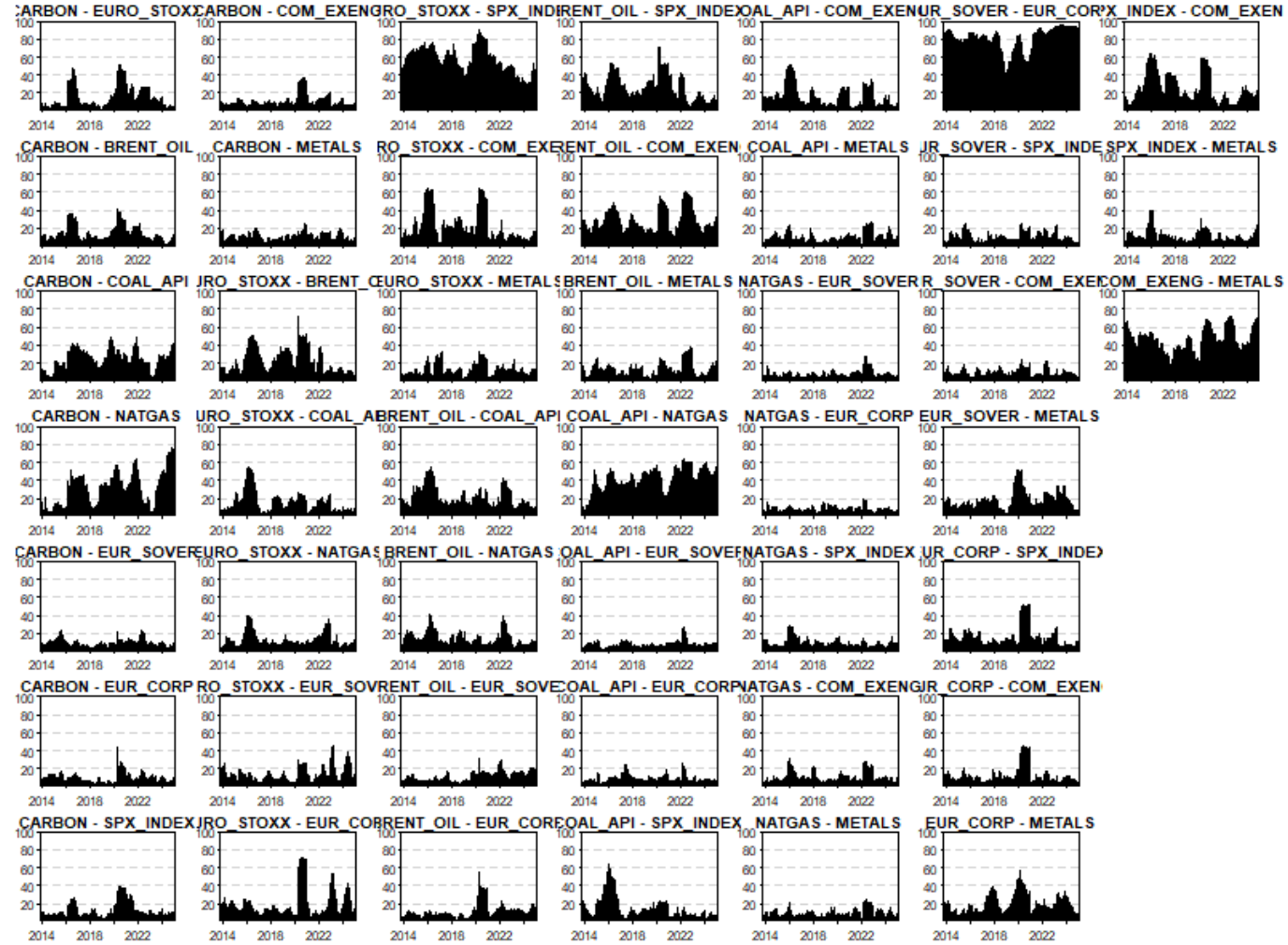
(b) Static Volatility PCI network



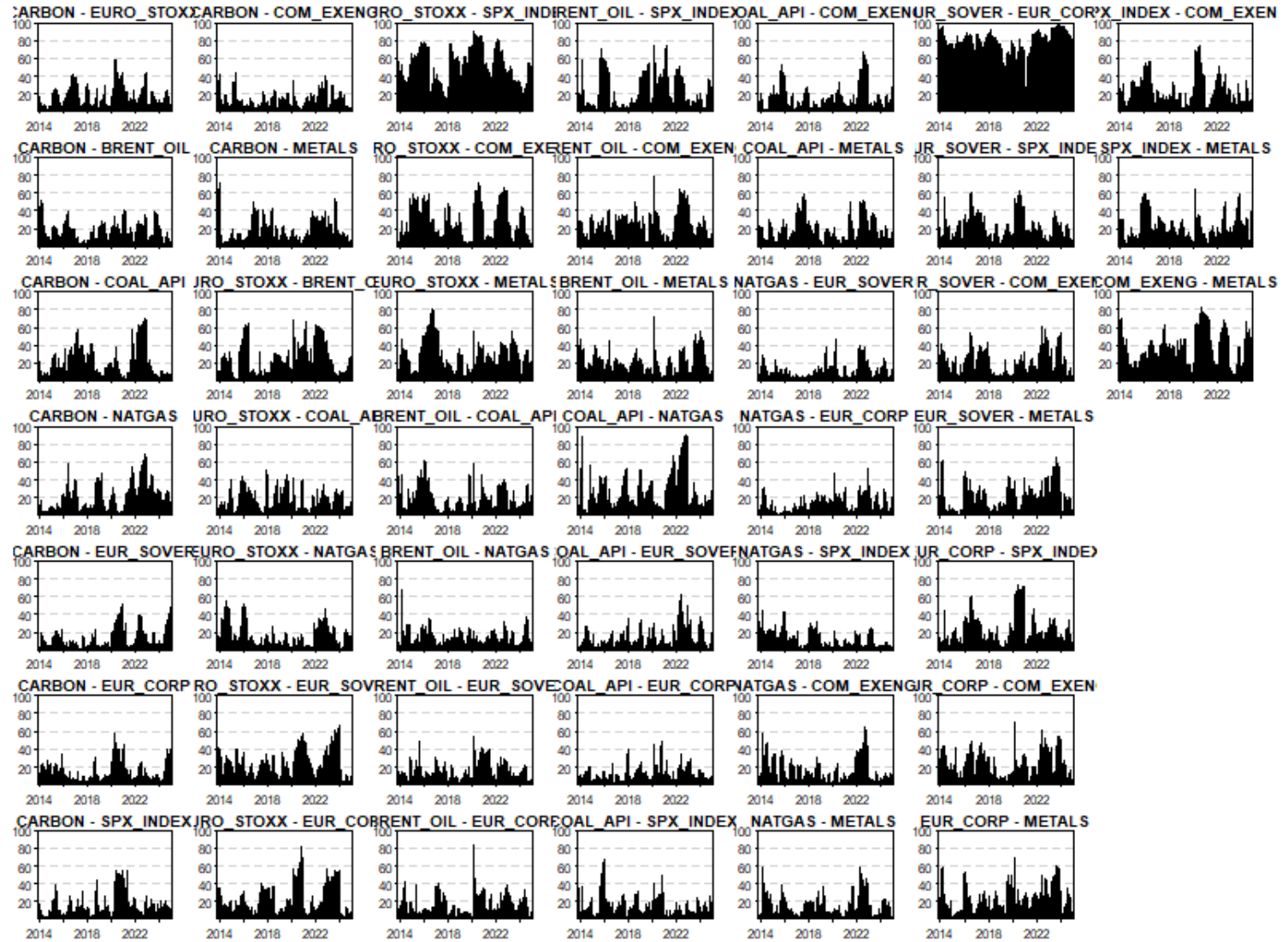
Appendix D.4.4. Dynamic Return and Volatility Pairwise Directional Connectedness

Figure D.14: Dynamic Return and Volatility Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Dynamic return PCI



(b) Dynamic volatility PCI



Appendix D.5. 8-period forecast horizon and a rolling window of 220 observations

Appendix D.5.1. Static Return and Volatility Connectedness Matrix

Table D.6: Static Return and Volatility Connectedness Matrix (Jan 2013 - Jan 2025)

(a) Carbon returns connectedness matrix

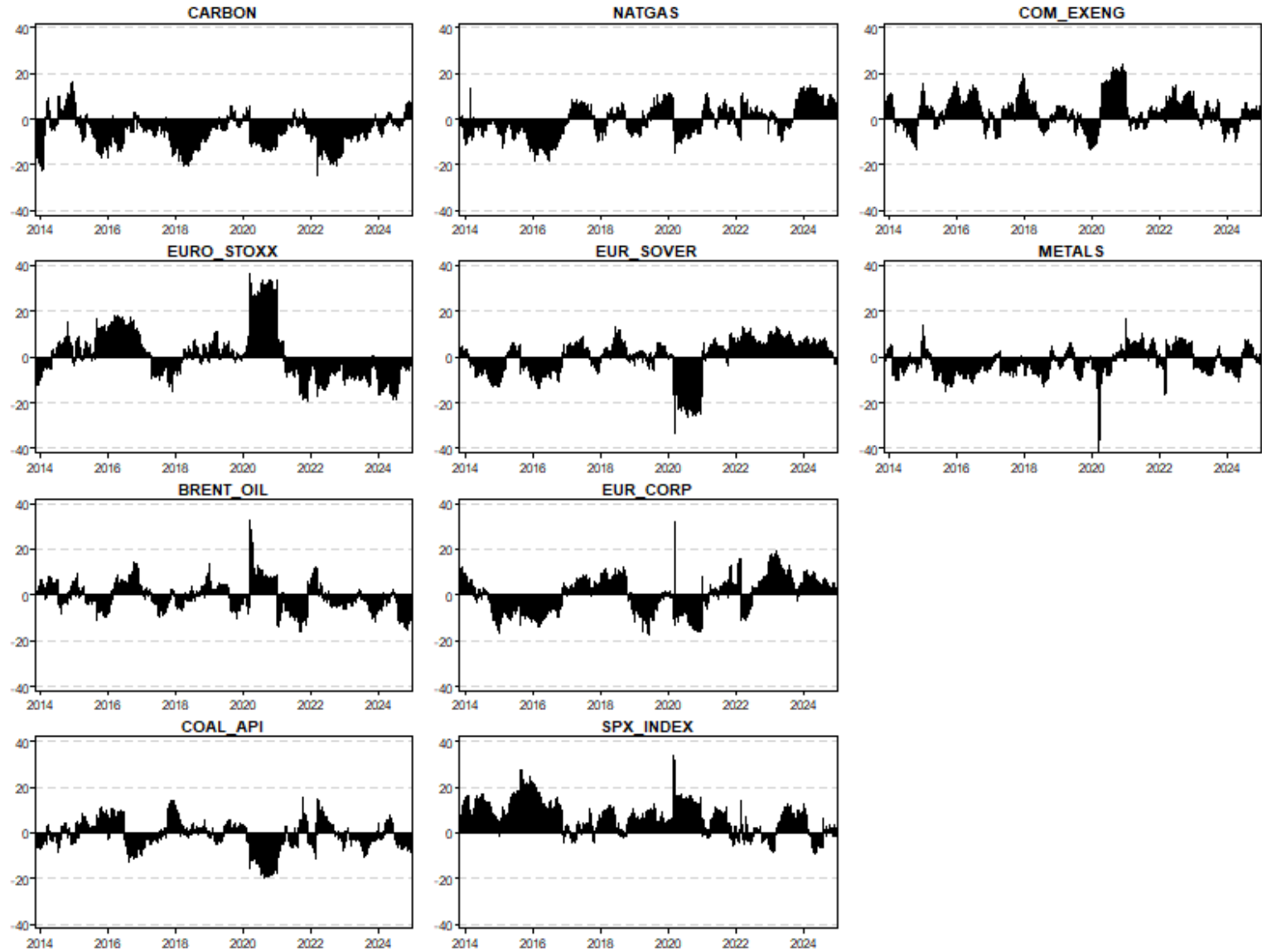
	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	61.59	3.93	3.64	7.76	10.08	2.24	2.07	3.26	2.57	2.86	38.41
EUROSTOXX	3.15	50.93	5.67	3.2	2.9	2.71	3.41	20.17	5.13	2.73	49.07
BRENTOIL	3.3	5.9	58.62	5.37	3.45	2.48	2.19	7.17	8.31	3.22	41.38
COALAPI	6.2	3.63	5.73	57.17	13.87	1.69	1.86	3.68	3.8	2.36	42.83
NATGAS	9.8	2.83	3.73	13.77	60.14	1.6	1.57	2.19	2.34	2.03	39.86
EUROVER	1.83	2.76	2.44	1.47	1.43	49.48	32.44	2.12	1.8	4.23	50.52
EURCORP	1.81	4.98	2.57	1.53	1.55	30.74	46.27	3.9	2.43	4.21	53.73
SPXINDEX	2.22	18.15	6.71	3.18	1.78	2.07	2.56	54.62	6.44	2.26	45.38
COMEXENG	2.31	4.99	7.41	3.32	2.15	1.93	2.17	6.6	54.09	15.02	45.91
METALS	2.19	2.85	2.84	2.05	2.2	4.76	5.48	2.69	16.34	58.6	41.4
DST(TO)	32.81	50.03	40.74	41.65	39.42	50.23	53.75	51.77	49.15	38.94	448.48
Inc. Own	94.4	100.96	99.36	98.83	99.56	99.71	100.02	106.39	103.24	97.54	cTCI/TCI
NS (NET)	-5.6	0.96	-0.64	-1.17	-0.44	-0.29	0.02	6.39	3.24	-2.46	49.83/44.85

(b) Carbon volatility connectedness matrix

	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	62.2	4.14	3.49	6.68	6.23	3.06	2.83	4.04	3.14	4.2	37.8
EUROSTOXX	2.95	50.86	4.93	2.73	2.66	4.69	3.87	17.15	4.84	5.33	49.14
BRENTOIL	3.56	6.04	58.65	4.31	2.84	2.92	3.59	5.91	6.93	5.24	41.35
COALAPI	4.12	4.62	3.28	64.8	7	3.13	2.22	3.66	2.66	4.52	35.2
NATGAS	4.07	3.96	2.61	7.59	66.13	2.57	3.05	3.93	2.92	3.16	33.87
EUROVER	1.71	5.66	2.88	1.82	1.5	47.64	26.63	4.99	3.08	4.09	52.36
EURCORP	2.3	5.25	2.14	1.71	1.66	29.27	45.3	5.68	3.66	3.02	54.7
SPXINDEX	2.61	15.47	4.61	2.36	1.32	4.01	3.62	58.11	3.72	4.17	41.89
COMEXENG	1.91	7.65	4.54	3.52	3.19	4.42	4.56	5.92	53.86	10.43	46.14
METALS	3.41	7.37	3.76	3.24	2.95	4.79	5.5	5.17	10.24	53.57	46.43
DST(TO)	26.64	60.17	32.23	33.96	29.35	58.88	55.87	56.45	41.18	44.17	438.89
Inc. Own	88.84	111.02	90.88	98.75	95.49	106.52	101.17	114.56	95.04	97.73	cTCI/TCI
NS (NET)	-11.16	11.02	-9.12	-1.25	-4.51	6.52	1.17	14.56	-4.96	-2.27	48.77/43.89

Figure D.15: Dynamic Net Directional Connectedness (Jan 2013 – Jan 2025)

(a) Dynamic return net directional connectedness



(b) Dynamic volatility net directional connectedness

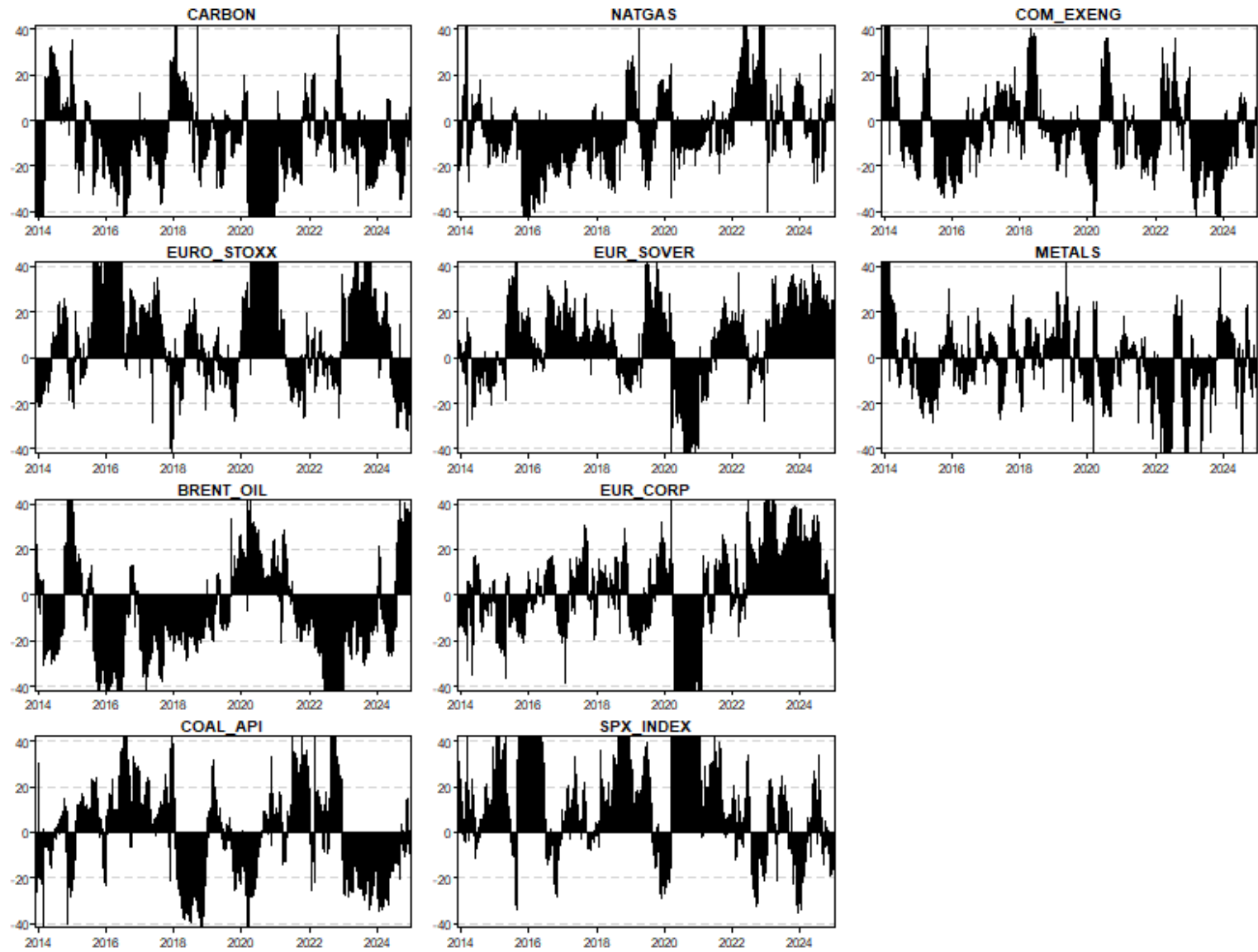
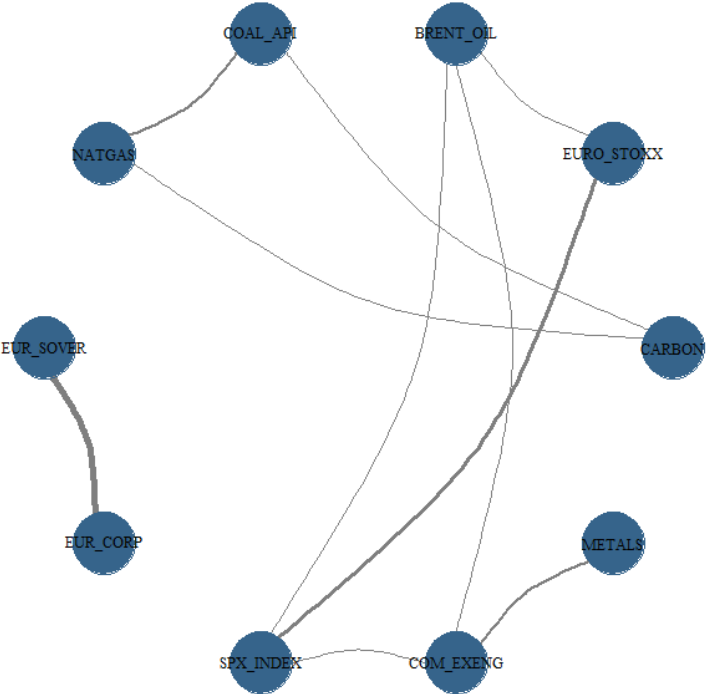
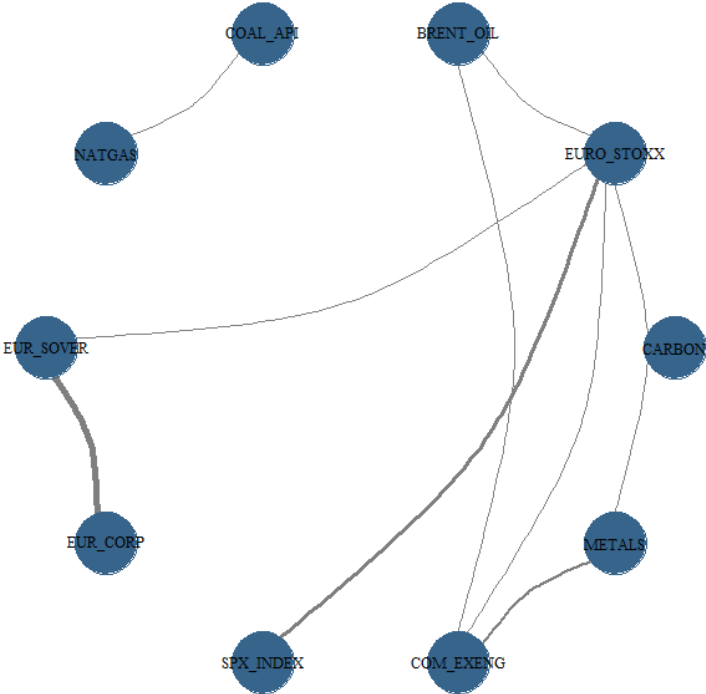


Figure D.16: Network Representation of Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Static Return PCI network



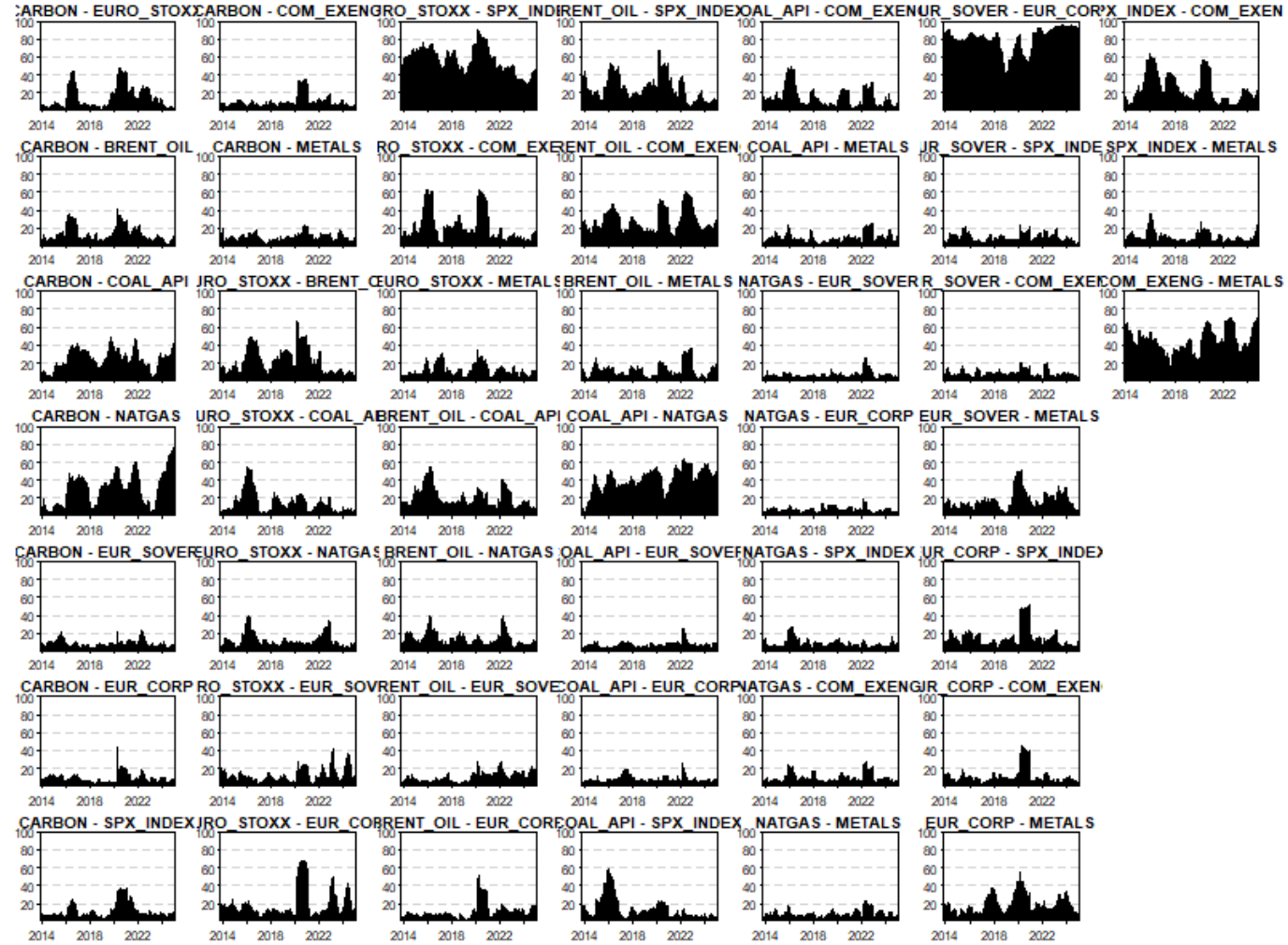
(b) Static Volatility PCI network



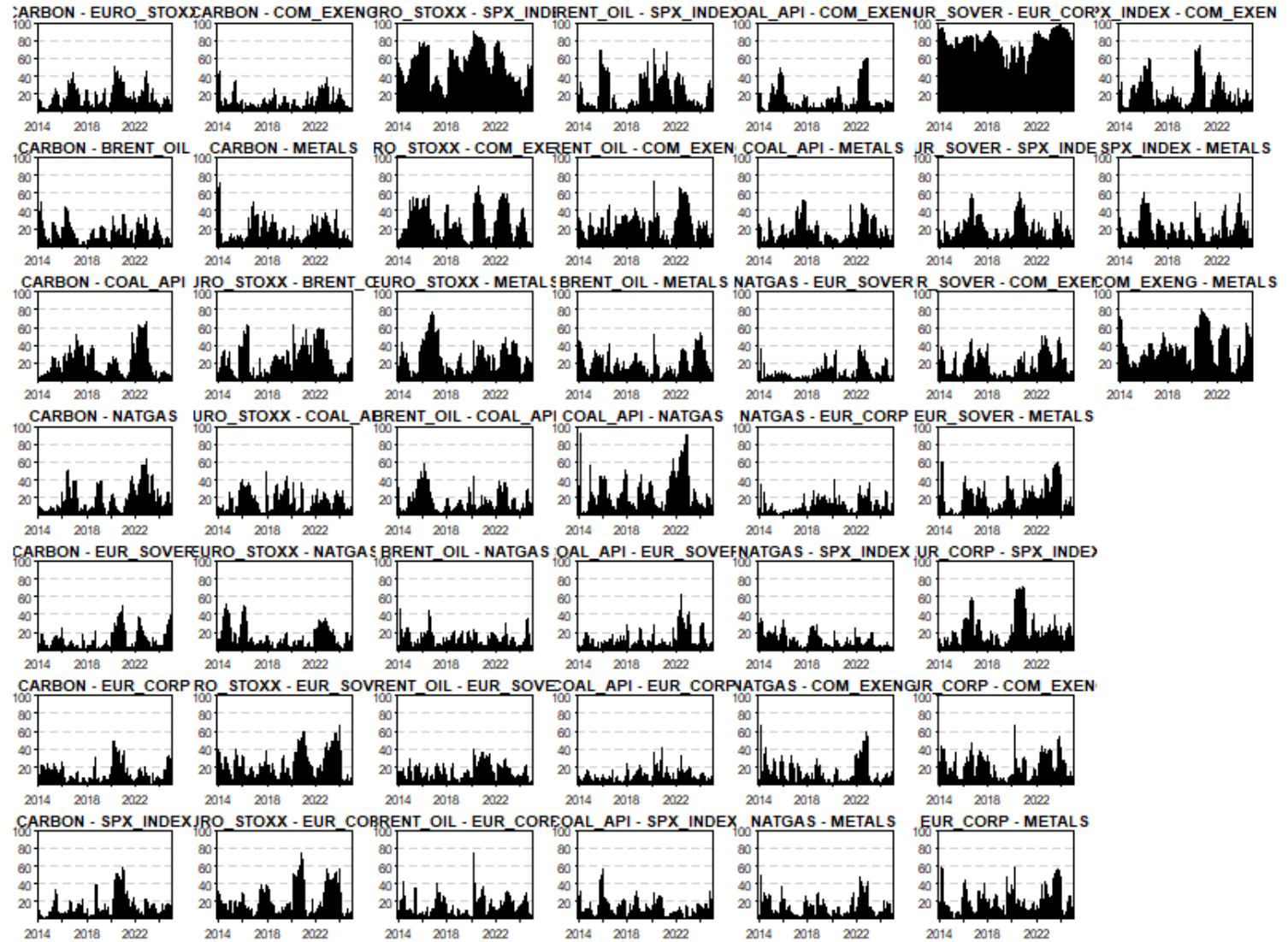
Appendix D.5.4. Dynamic Return and Volatility Pairwise Directional Connectedness

Figure D.17: Dynamic Return and Volatility Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Dynamic return PCI



(b) Dynamic volatility PCI



Appendix D.6. 12-period forecast horizon and a rolling window of 180 observations

Appendix D.6.1. Static Return and Volatility Connectedness Matrix

Table D.7: Static Return and Volatility Connectedness Matrix (Jan 2013 - Jan 2025)

(a) Carbon returns connectedness matrix

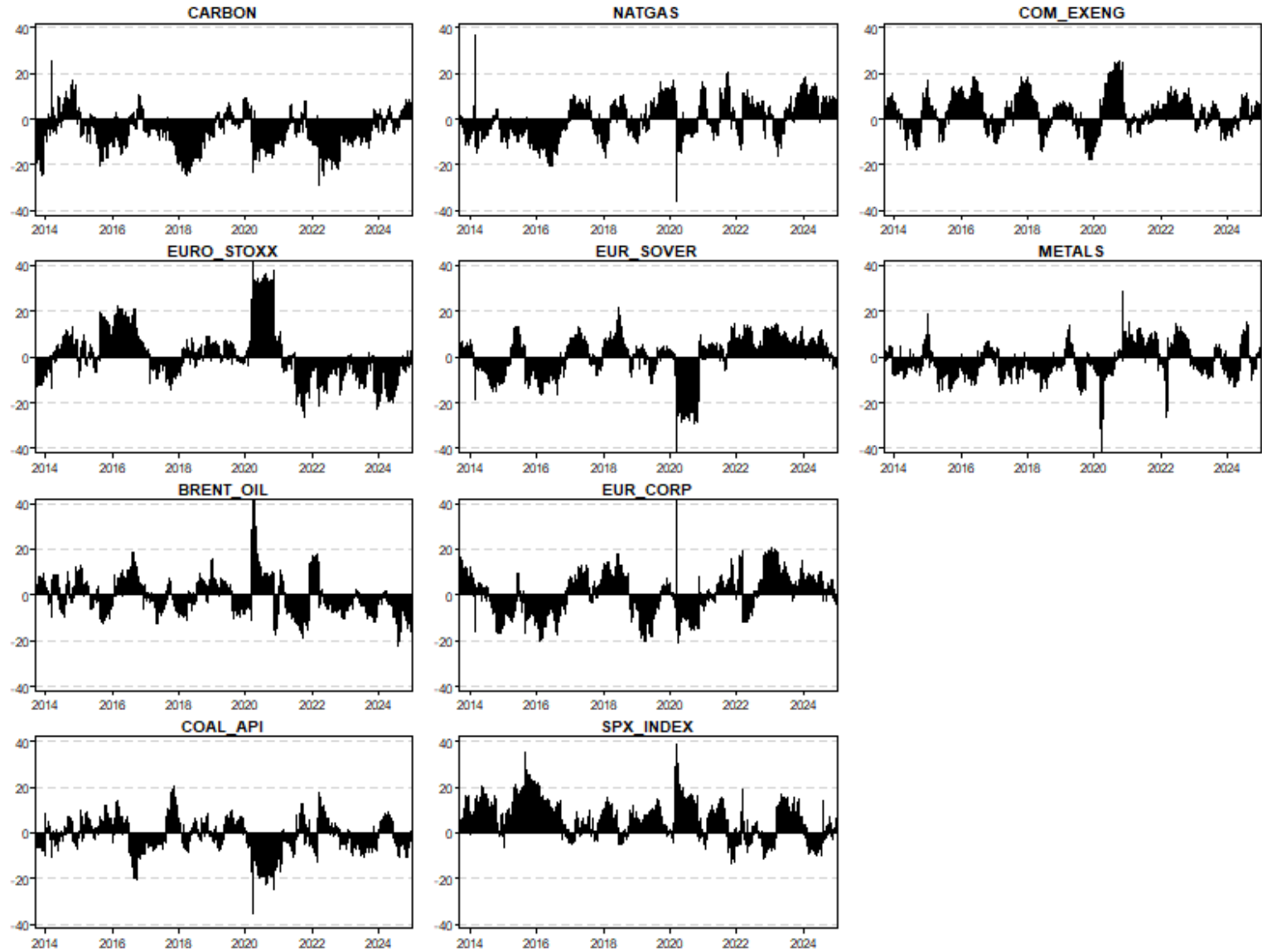
	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	58.33	4.13	3.97	7.9	10.32	2.77	2.5	3.72	2.98	3.39	41.67
EUROSTOXX	3.43	48.44	5.78	3.45	3.36	3.41	3.95	19.53	5.31	3.33	51.56
BRENTOIL	3.74	6.15	55.99	5.54	3.77	2.9	2.52	7.35	8.26	3.79	44.01
COALAPI	6.48	3.93	5.89	54.66	13.62	2.09	2.26	4.03	4.12	2.93	45.34
NATGAS	10.05	3.25	4.07	13.36	57.07	2.08	2.01	2.78	2.84	2.5	42.93
EUROVER	2.27	3.27	2.96	1.9	1.95	47.08	31.3	2.47	2.32	4.48	52.92
EURCORP	2.19	5.15	2.91	1.99	2.07	29.9	44.54	4.04	2.71	4.5	55.46
SPXINDEX	2.63	17.76	6.94	3.51	2.3	2.54	2.93	52.24	6.4	2.76	47.76
COMEXENG	2.69	5.18	7.48	3.64	2.69	2.43	2.57	6.6	51.91	14.81	48.09
METALS	2.58	3.45	3.41	2.53	2.74	4.92	5.68	3.22	15.92	55.54	44.46
DST(TO)	36.06	52.28	43.39	43.82	42.82	53.03	55.73	53.74	50.85	42.49	474.2
Inc. Own	94.39	100.72	99.38	98.47	99.89	100.11	100.27	105.98	102.76	98.03	cTCI/TCI
NS (NET)	-5.61	0.72	-0.62	-1.53	-0.11	0.11	0.27	5.98	2.76	-1.97	52.69/47.42

(b) Carbon volatility connectedness matrix

	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	49.07	5.05	5.04	7.53	8.1	4.71	4.25	6.24	4.55	5.47	50.93
EUROSTOXX	4.34	42.48	5.5	4.66	4.47	5.91	4.68	15.49	5.76	6.72	57.52
BRENTOIL	4.91	7.05	46.16	5.52	4.3	4.89	5.5	7.04	7.5	7.13	53.84
COALAPI	5.42	6.83	4.96	50.79	8.67	4.61	3.48	5.51	3.82	5.91	49.21
NATGAS	5.12	5.38	4.23	8.78	52.69	4.47	4.44	5.78	4.38	4.72	47.31
EUROVER	2.74	6.84	3.83	3.16	2.59	41.18	23.89	6.2	4.83	4.75	58.82
EURCORP	3.51	6.06	2.89	3.07	3.37	26.97	38.08	6.43	5.71	3.9	61.92
SPXINDEX	4	14.79	5.55	3.89	2.41	5.65	4.67	47.45	5.22	6.37	52.55
COMEXENG	3.54	8.03	4.9	4.53	4.92	6.48	6.13	7.47	44.23	9.77	55.77
METALS	4.45	8.84	5.11	4.64	4.75	5.52	7.13	7.41	9.82	42.32	57.68
DST(TO)	38.03	68.87	42.02	45.78	43.58	69.22	64.17	67.57	51.57	54.74	545.55
Inc. Own	87.1	111.35	88.18	96.57	96.27	110.4	102.26	115.01	95.8	97.06	cTCI/TCI
NS (NET)	-12.9	11.35	-11.82	-3.43	-3.73	10.4	2.26	15.01	-4.2	-2.94	60.62/54.55

Figure D.18: Dynamic Net Directional Connectedness (Jan 2013 – Jan 2025)

(a) Dynamic return net directional connectedness



(b) Dynamic volatility net directional connectedness

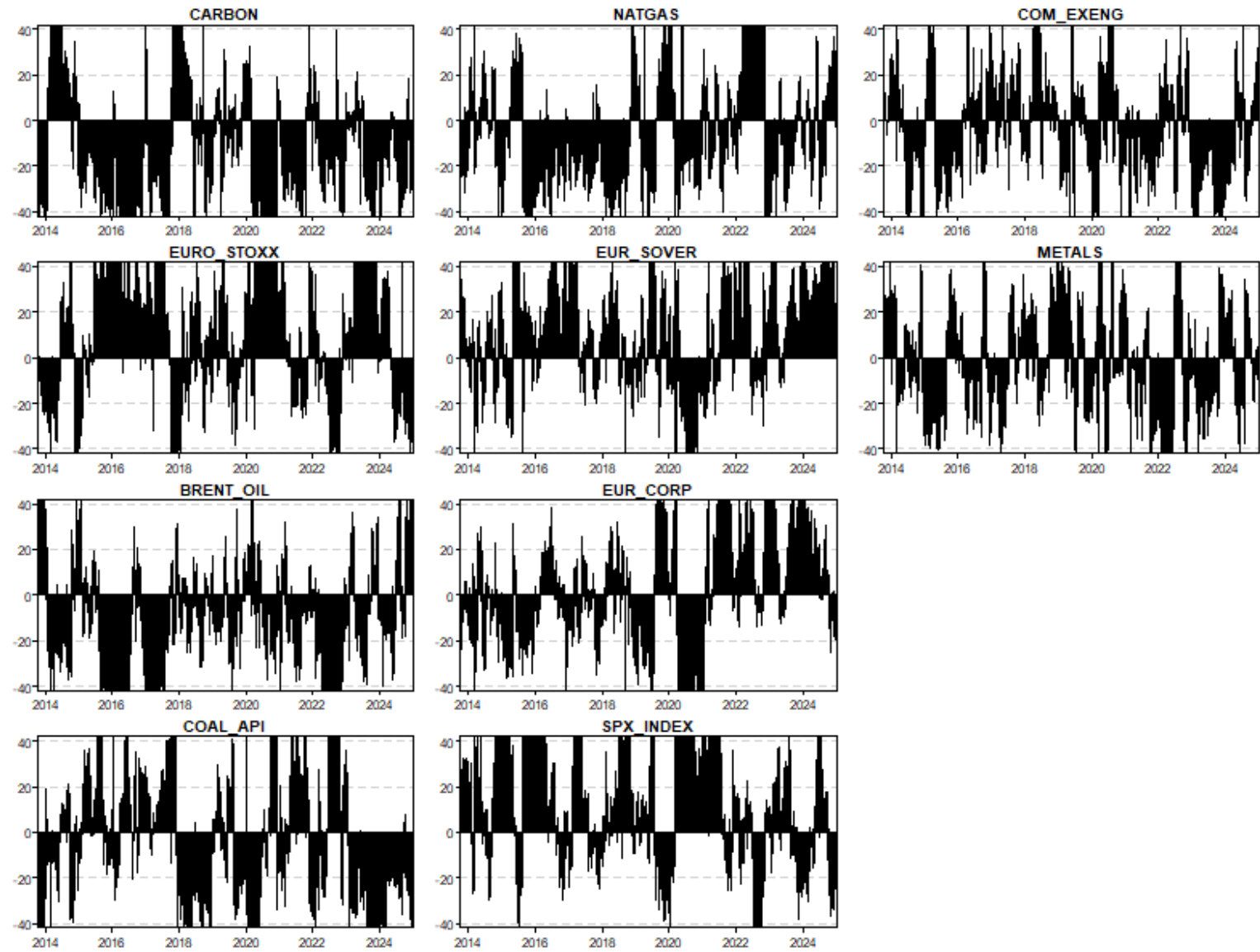
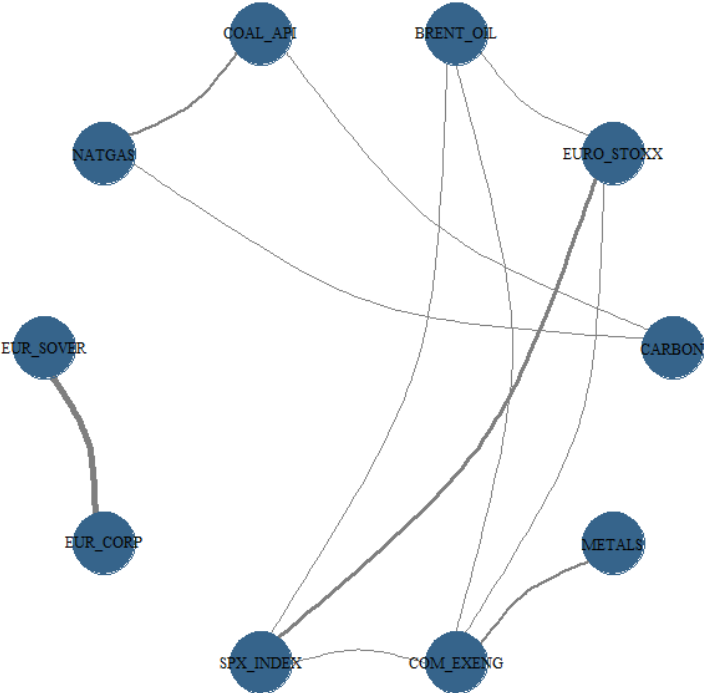
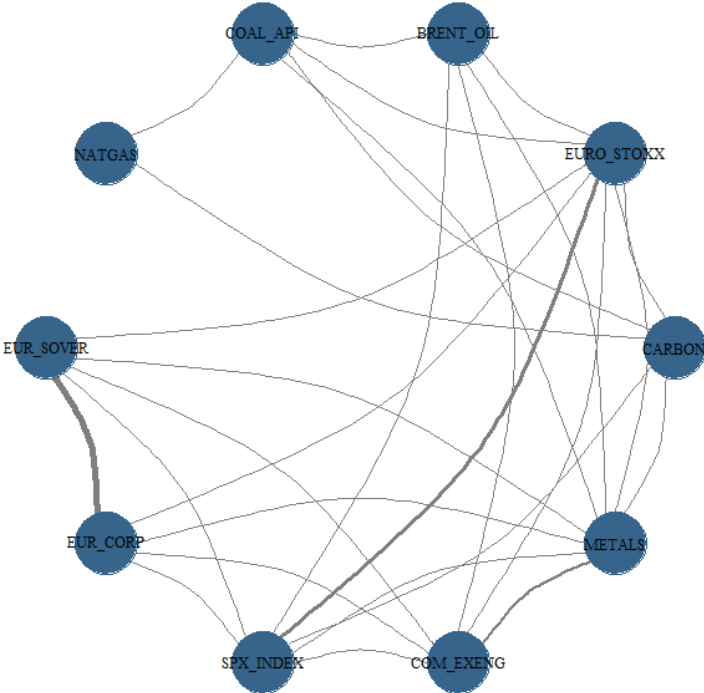


Figure D.19: Network Representation of Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Static Return PCI network



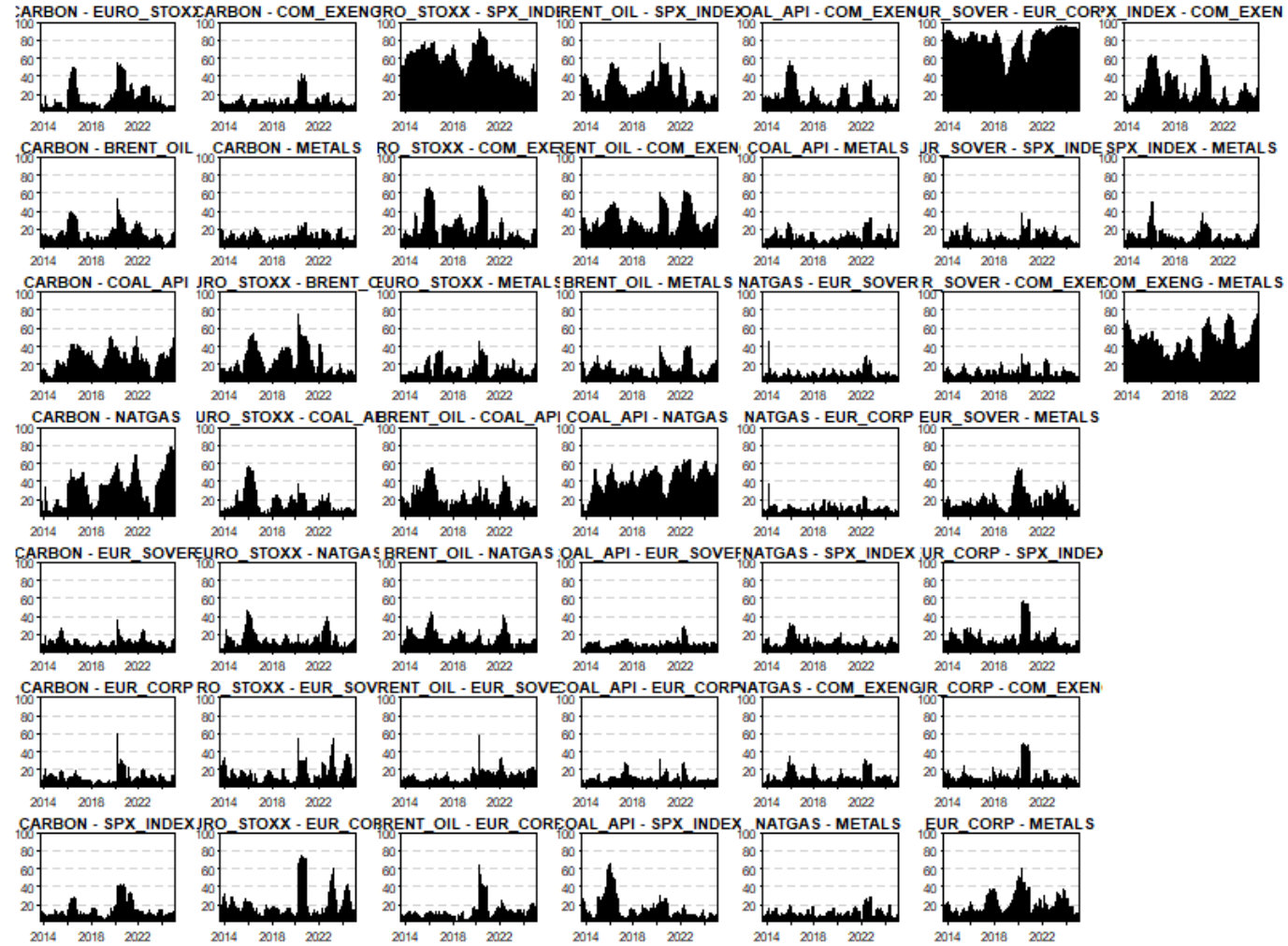
(b) Static Volatility PCI network



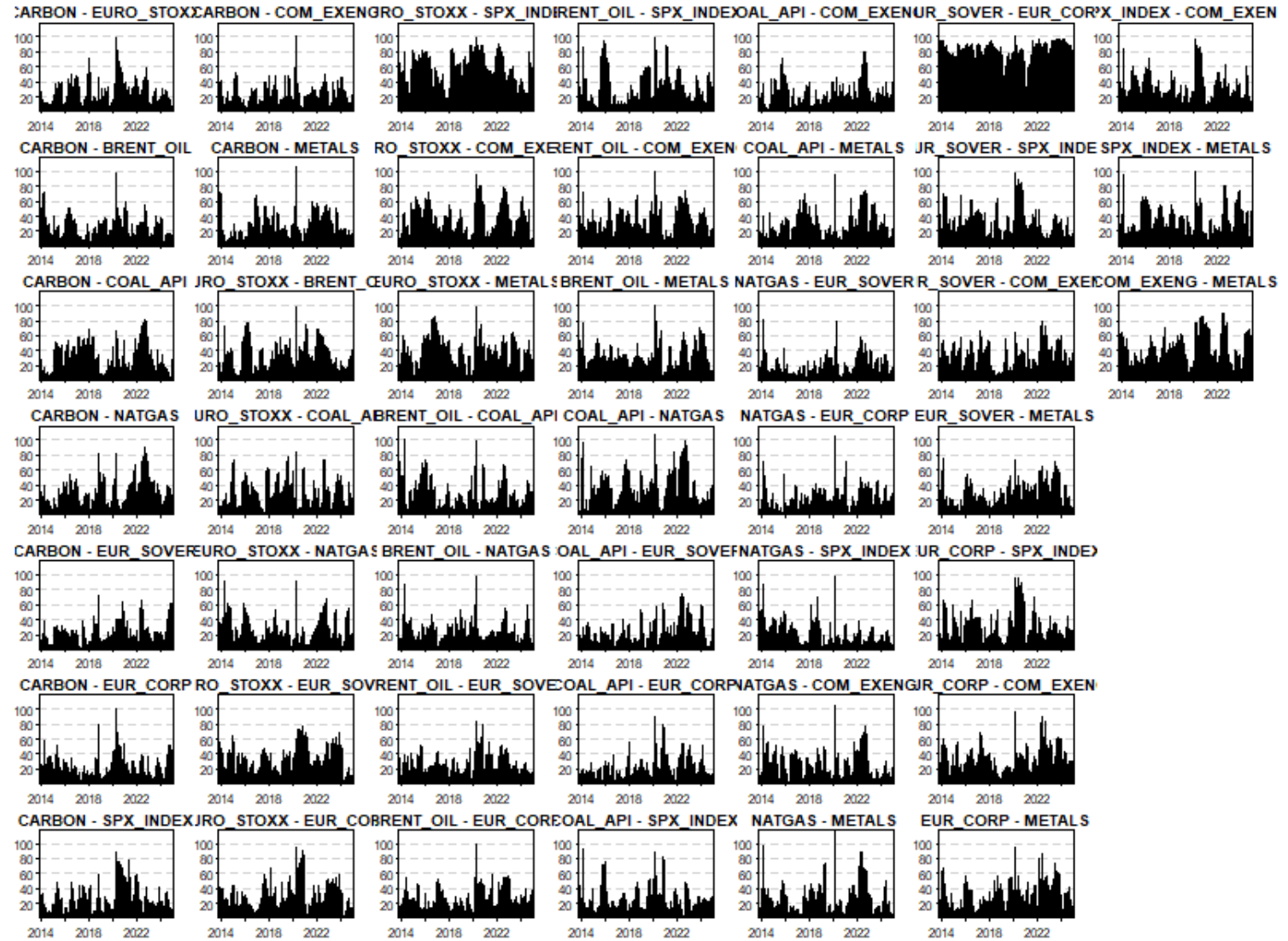
Appendix D.6.4. Dynamic Return and Volatility Pairwise Directional Connectedness

Figure D.20: Dynamic Return and Volatility Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Dynamic return PCI



(b) Dynamic volatility PCI



Appendix D.7. 12-period forecast horizon and a rolling window of 200 observations

Appendix D.7.1. Static Return and Volatility Connectedness Matrix

Table D.8: Static Return and Volatility Connectedness Matrix (Jan 2013 - Jan 2025)

(a) Carbon returns connectedness matrix

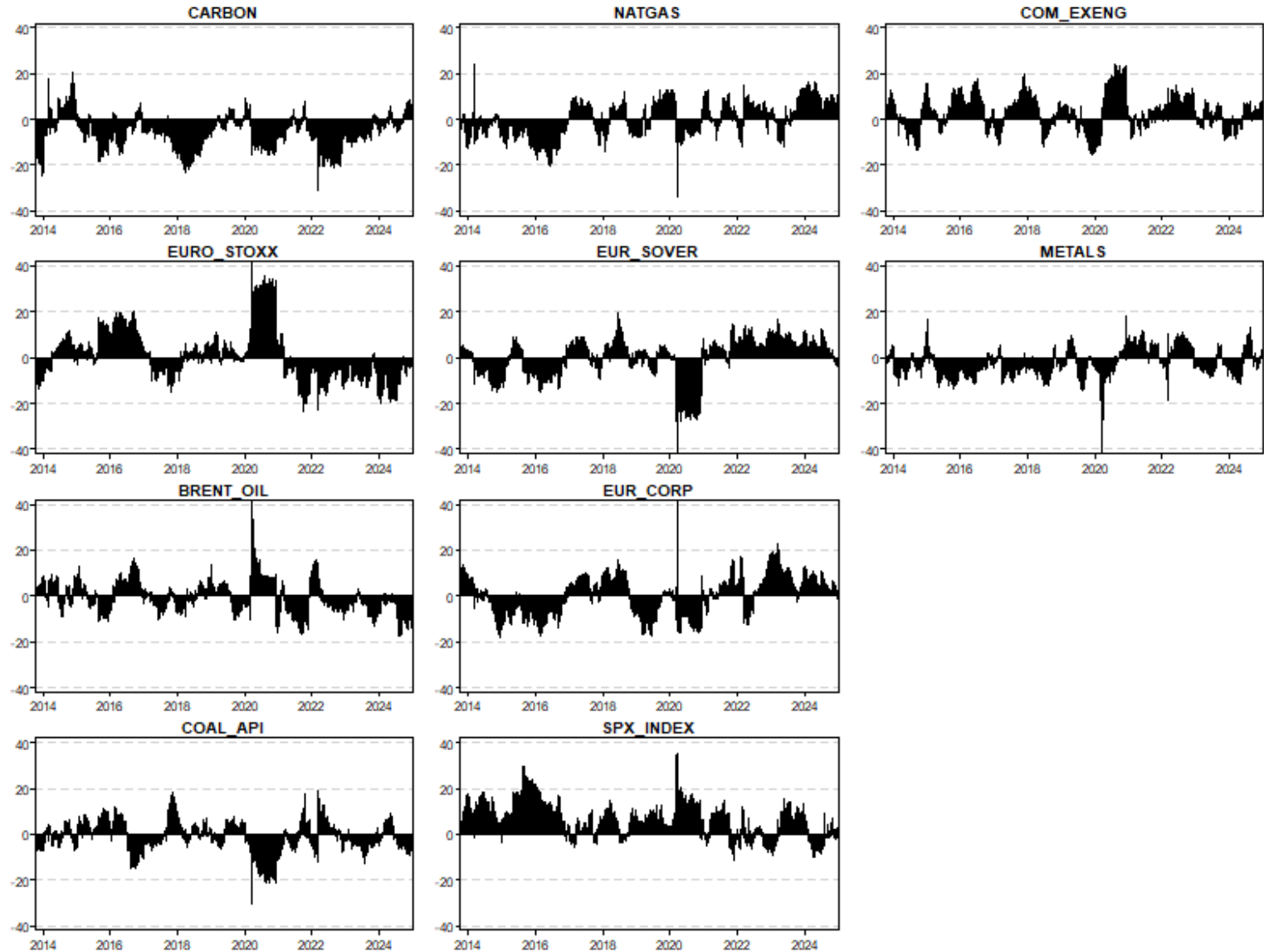
	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	59.98	4	3.81	7.85	10.21	2.49	2.28	3.48	2.77	3.13	40.02
EUROSTOXX	3.28	49.71	5.71	3.34	3.13	3.05	3.68	19.85	5.21	3.03	50.29
BRENTOIL	3.5	6.01	57.33	5.44	3.62	2.69	2.35	7.28	8.29	3.5	42.67
COALAPI	6.34	3.78	5.8	55.96	13.77	1.86	2.05	3.84	3.96	2.64	44.04
NATGAS	9.93	3.04	3.89	13.57	58.66	1.81	1.77	2.5	2.57	2.25	41.34
EUROVER	2.04	3.01	2.69	1.68	1.69	48.28	31.89	2.3	2.06	4.36	51.72
EURCORP	1.98	5.05	2.72	1.75	1.82	30.35	45.45	3.97	2.55	4.36	54.55
SPXINDEX	2.43	17.94	6.82	3.36	2.04	2.32	2.74	53.46	6.4	2.51	46.54
COMEXENG	2.49	5.09	7.45	3.49	2.41	2.17	2.38	6.6	53.02	14.9	46.98
METALS	2.38	3.18	3.13	2.29	2.47	4.84	5.59	2.98	16.13	57.02	42.98
DST(TO)	34.37	51.09	42.02	42.78	41.16	51.58	54.72	52.79	49.94	40.68	461.13
Inc. Own	94.35	100.8	99.35	98.74	99.82	99.86	100.17	106.25	102.96	97.69	cTCI/TCI
NS (NET)	-5.65	0.8	-0.65	-1.26	-0.18	-0.14	0.17	6.25	2.96	-2.31	51.24/46.11

(b) Carbon volatility connectedness matrix

	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	51.77	4.95	4.62	7.64	7.57	4.25	4.08	5.87	4.28	4.97	48.23
EUROSTOXX	3.95	44.7	5.26	4	4.01	5.47	4.39	16.25	5.63	6.33	55.3
BRENTOIL	4.33	6.94	48.98	5.34	4.07	4.39	5.01	6.77	7.45	6.73	51.02
COALAPI	5.18	6.48	4.42	54.18	8.27	4.19	3.09	5.01	3.51	5.67	45.82
NATGAS	4.87	5.04	3.94	8.7	55.58	4.08	4.28	5.31	3.85	4.35	44.42
EUROVER	2.39	6.61	3.52	2.68	2.03	43.31	24.59	5.95	4.24	4.68	56.69
EURCORP	3.04	6.01	2.75	2.55	2.71	27.87	40.08	6.26	5.14	3.58	59.92
SPXINDEX	3.75	15.2	5.1	3.55	2.01	5.11	4.18	50.28	4.96	5.87	49.72
COMEXENG	2.95	8.09	4.83	4.12	4.36	5.67	5.7	7.07	47.39	9.81	52.61
METALS	4.08	8.78	4.77	4.27	4.3	5.29	6.67	6.72	10.22	44.9	55.1
DST(TO)	34.53	68.1	39.22	42.85	39.32	66.32	61.99	65.21	49.29	51.99	518.82
Inc. Own	86.3	112.8	88.19	97.03	94.9	109.63	102.07	115.49	96.68	96.89	cTCI/TCI
NS (NET)	-13.7	12.8	-11.81	-2.97	-5.1	9.63	2.07	15.49	-3.32	-3.11	57.65/51.88

Figure D.21: Dynamic Net Directional Connectedness (Jan 2013 – Jan 2025)

(a) Dynamic return net directional connectedness



(b) Dynamic volatility net directional connectedness

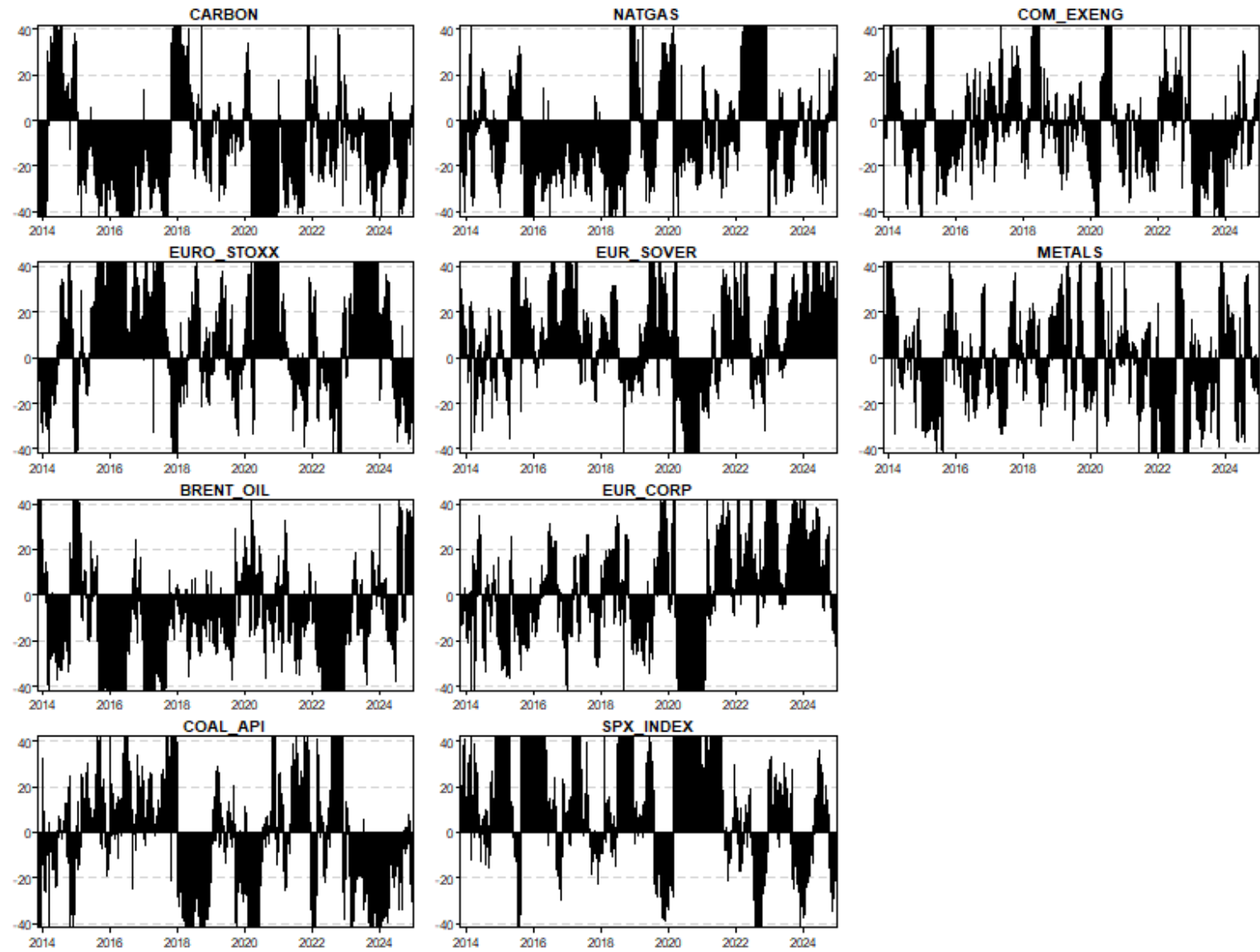
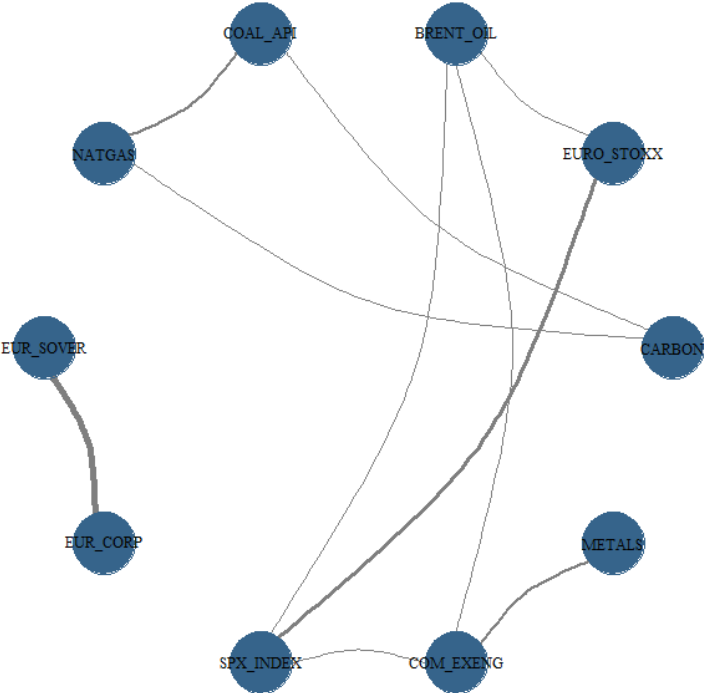
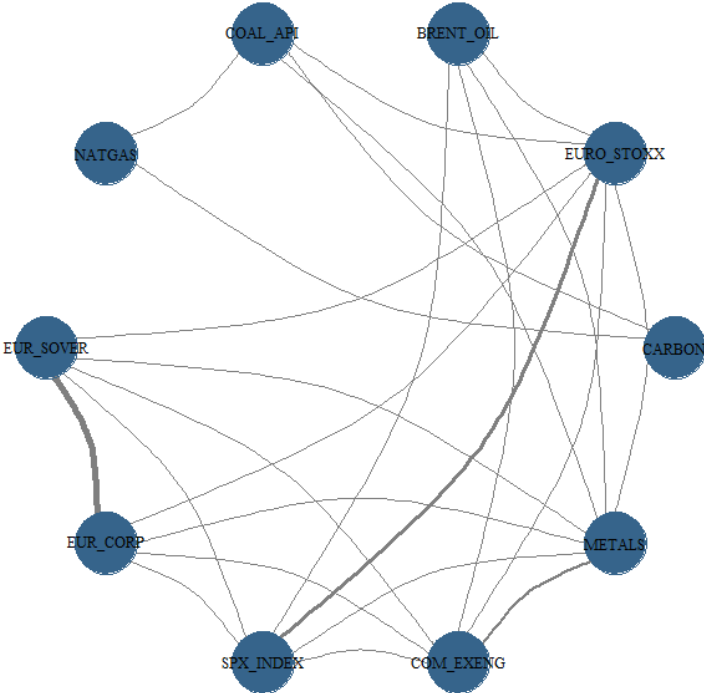


Figure D.22: Network Representation of Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Static Return PCI network



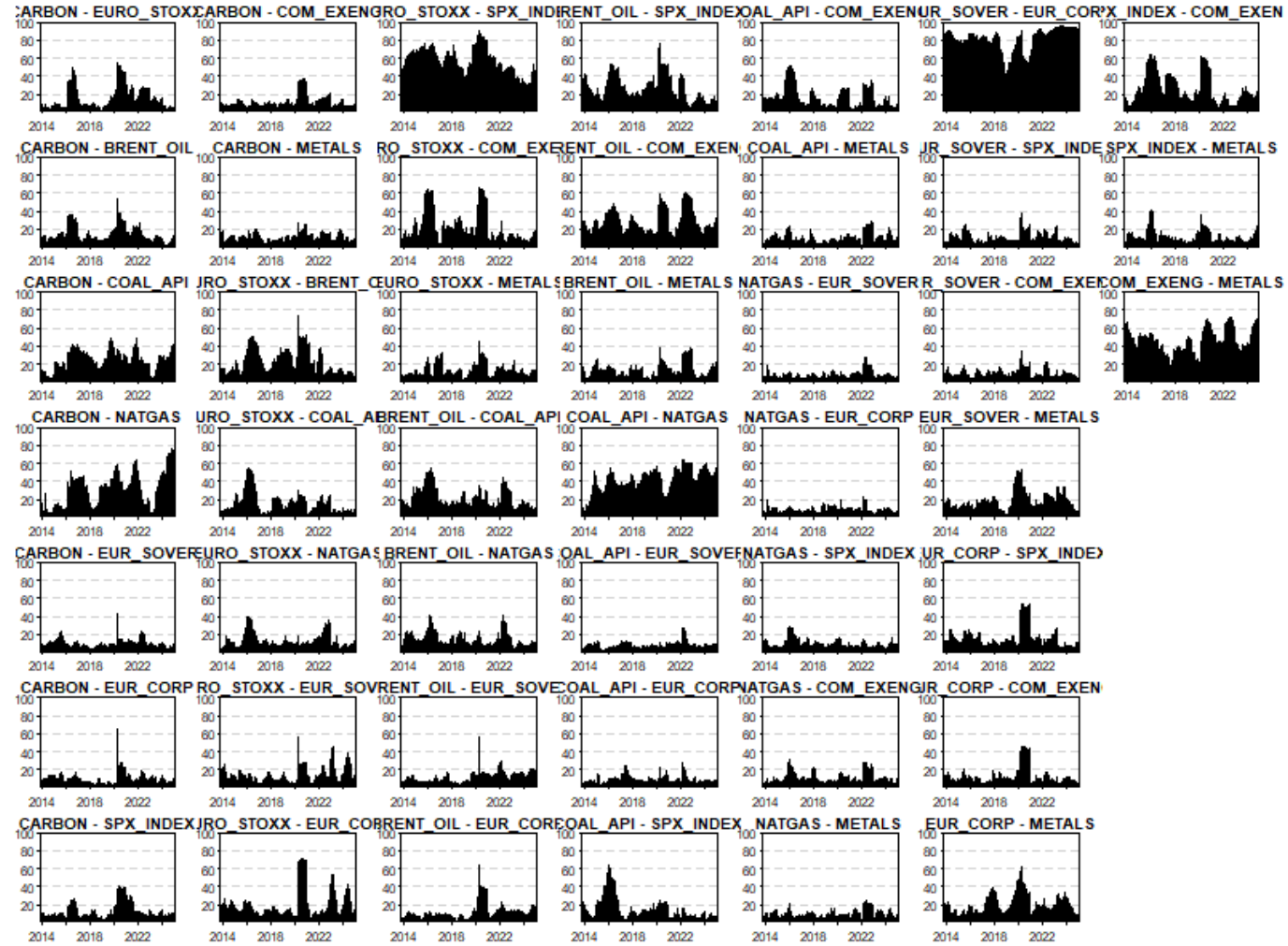
(b) Static Volatility PCI network



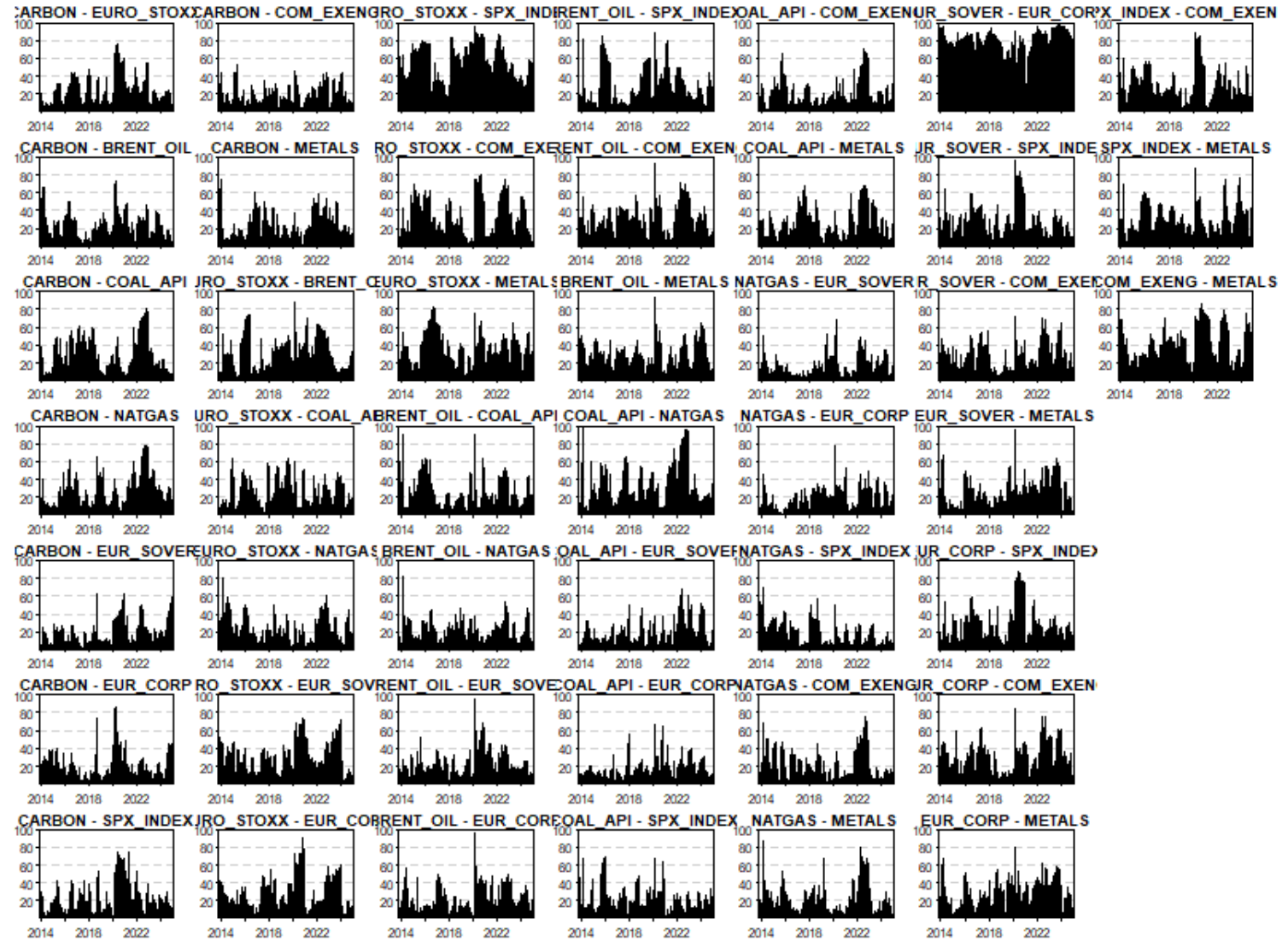
Appendix D.7.4. Dynamic Return and Volatility Pairwise Directional Connectedness

Figure D.23: Dynamic Return and Volatility Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Dynamic return PCI



(b) Dynamic volatility PCI



Appendix D.8. 12-period forecast horizon and a rolling window of 220 observations

Appendix D.8.1. Static Return and Volatility Connectedness Matrix

Table D.9: Static Return and Volatility Connectedness Matrix (Jan 2013 - Jan 2025)

(a) Carbon returns connectedness matrix

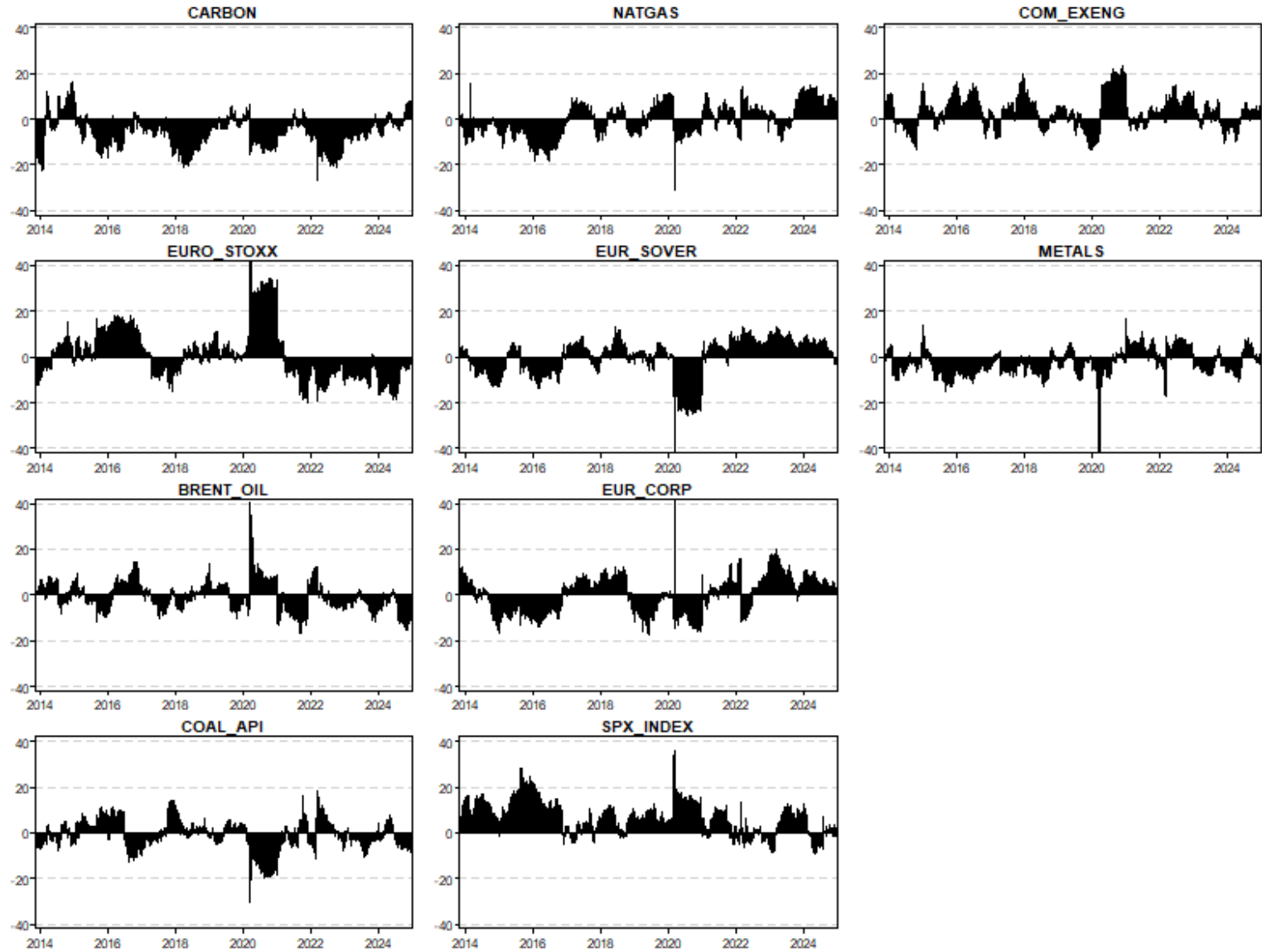
	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	61.29	3.94	3.67	7.78	10.07	2.3	2.13	3.29	2.61	2.93	38.71
EUROSTOXX	3.18	50.75	5.67	3.23	2.95	2.75	3.44	20.11	5.14	2.78	49.25
BRENTOIL	3.31	5.92	58.37	5.39	3.49	2.52	2.23	7.2	8.31	3.26	41.63
COALAPI	6.22	3.66	5.74	56.99	13.87	1.72	1.89	3.7	3.83	2.39	43.01
NATGAS	9.79	2.87	3.75	13.75	59.92	1.63	1.61	2.24	2.38	2.06	40.08
EUROVER	1.87	2.8	2.48	1.5	1.48	49.27	32.33	2.16	1.85	4.26	50.73
EURCORP	1.84	5	2.61	1.57	1.62	30.67	46.12	3.92	2.43	4.23	53.88
SPXINDEX	2.26	18.11	6.71	3.22	1.81	2.14	2.59	54.44	6.44	2.29	45.56
COMEXENG	2.33	5.03	7.43	3.35	2.18	1.97	2.22	6.63	53.89	14.98	46.11
METALS	2.22	2.93	2.91	2.08	2.25	4.77	5.51	2.77	16.29	58.28	41.72
DST(TO)	33.01	50.26	40.96	41.87	39.71	50.46	53.95	52	49.28	39.18	450.7
Inc. Own	94.3	101.01	99.33	98.86	99.62	99.73	100.06	106.44	103.17	97.47	cTCI/TCI
NS (NET)	-5.7	1.01	-0.67	-1.14	-0.38	-0.27	0.06	6.44	3.17	-2.53	50.08/45.07

(b) Carbon volatility connectedness matrix

	CARBON	EUROSTOXX	BRENTOIL	COALAPI	NATGAS	EUROVER	EURCORP	SPXINDEX	COMEXENG	METALS	FROM
CARBON	53.98	4.97	4.32	7.64	7.18	3.84	3.72	5.49	4.29	4.56	46.02
EUROSTOXX	3.55	46.21	4.99	3.61	3.61	5.32	4.27	16.81	5.63	6.01	53.79
BRENTOIL	3.82	6.9	51.01	5.18	3.86	3.98	4.53	6.63	7.62	6.47	48.99
COALAPI	5.06	5.98	3.68	57.01	7.87	3.96	2.92	4.6	3.39	5.53	42.99
NATGAS	4.63	4.71	3.52	8.47	58.3	3.77	4.15	4.94	3.53	3.99	41.7
EUROVER	2.06	6.39	3.31	2.32	1.72	44.95	25.12	5.85	3.77	4.53	55.05
EURCORP	2.67	6.01	2.68	2.1	2.2	28.56	41.62	6.19	4.53	3.42	58.38
SPXINDEX	3.46	15.35	4.67	3.27	1.77	4.68	3.85	52.71	4.66	5.58	47.29
COMEXENG	2.45	8.05	4.81	3.83	3.94	5.14	5.21	6.79	49.88	9.9	50.12
METALS	3.87	8.67	4.35	4	3.91	5.1	6.19	6.11	10.51	47.28	52.72
DST(TO)	31.56	67.03	36.35	40.42	36.07	64.35	59.96	63.39	47.93	49.97	497.04
Inc. Own	85.54	113.25	87.36	97.43	94.38	109.3	101.59	116.09	97.81	97.25	cTCI/TCI
NS (NET)	-14.46	13.25	-12.64	-2.57	-5.62	9.3	1.59	16.09	-2.19	-2.75	55.23/49.70

Figure D.24: Dynamic Net Directional Connectedness (Jan 2013 – Jan 2025)

(a) Dynamic return net directional connectedness



(b) Dynamic volatility net directional connectedness

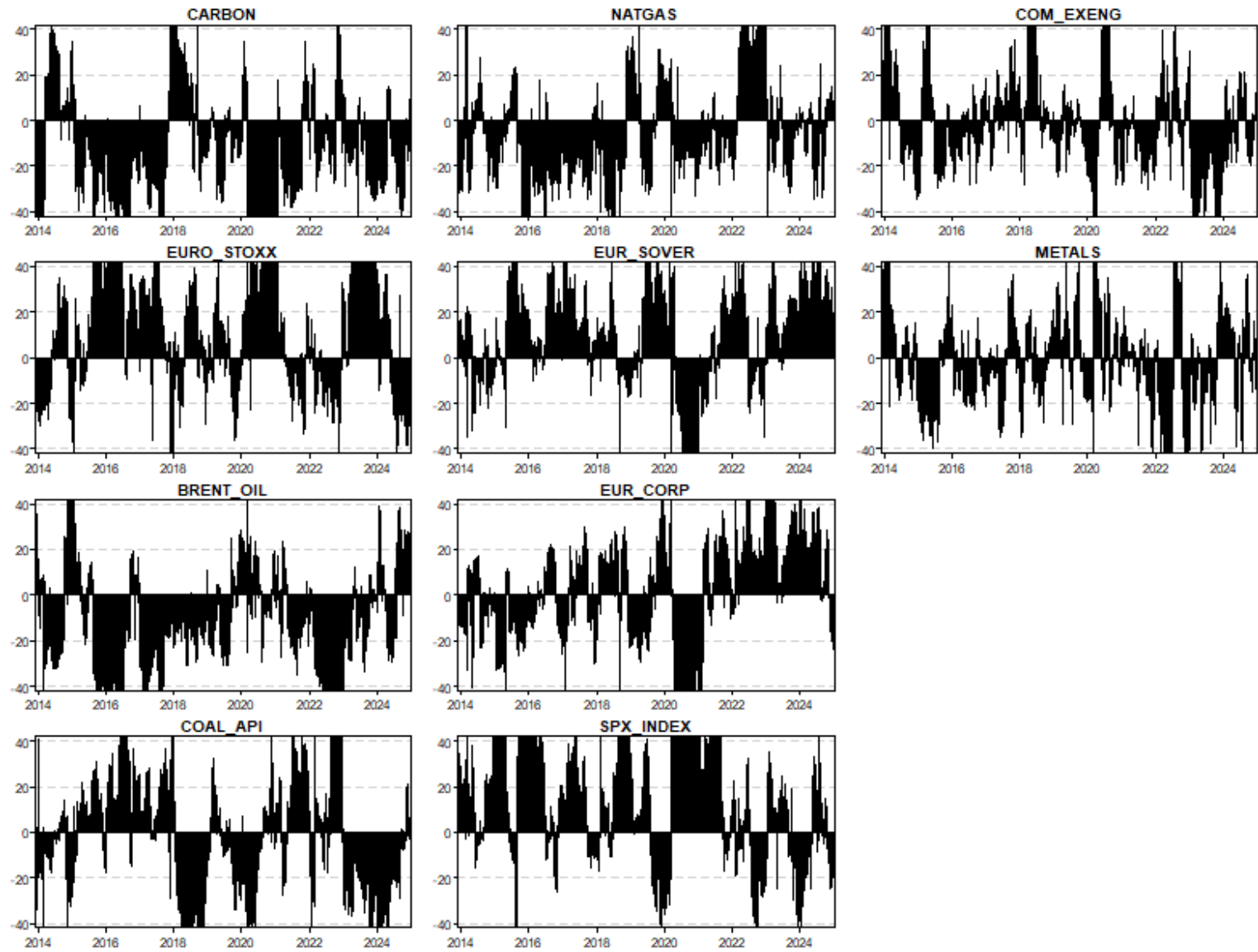
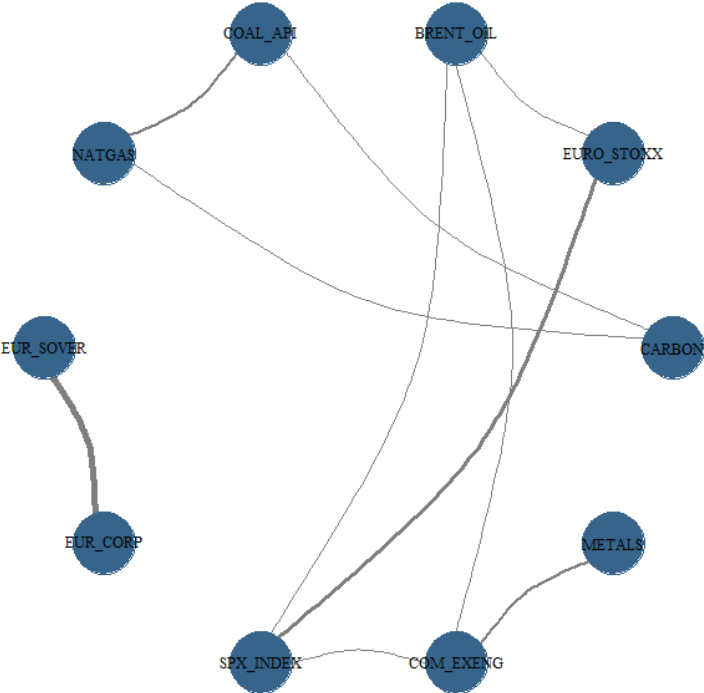
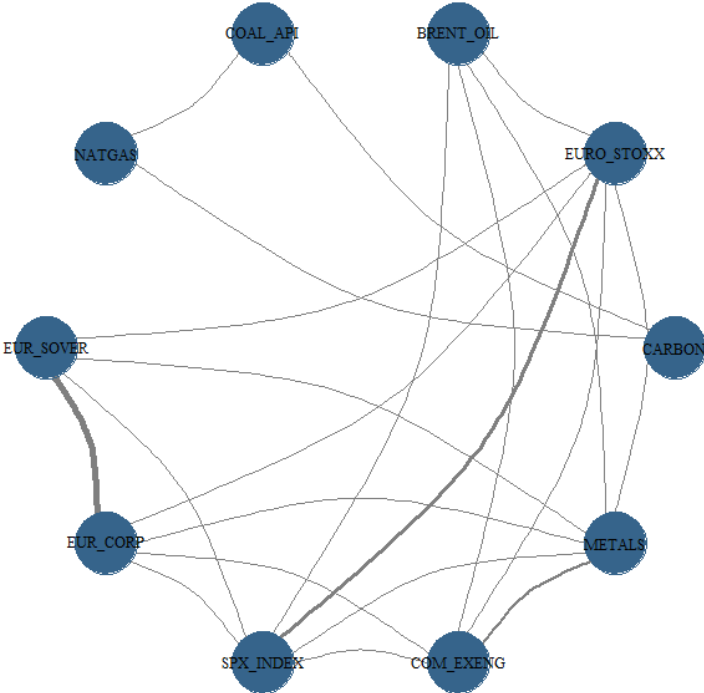


Figure D.25: Network Representation of Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Static Return PCI network



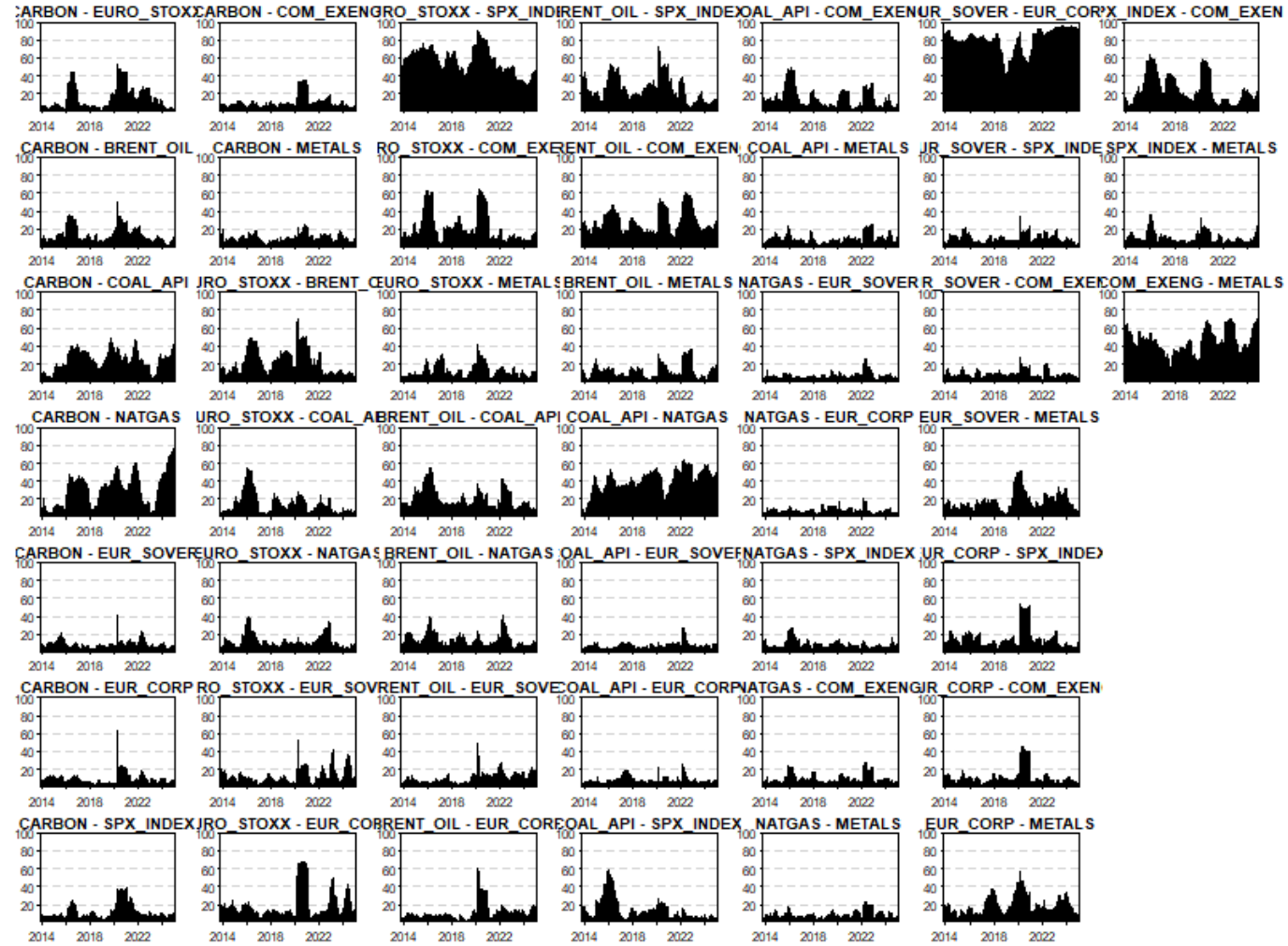
(b) Static Volatility PCI network



Appendix D.8.4. Dynamic Return and Volatility Pairwise Directional Connectedness

Figure D.26: Dynamic Return and Volatility Pairwise Connectedness Index (Jan 2013 – Jan 2025)

(a) Dynamic return PCI



(b) Dynamic volatility PCI

