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Go green or stay black: Bond market dynamics in Asia

Gazi Salah Uddin [a], Ranadeva Jayasekera [b,*], Donghyun Park [c], Tianqi Luo [d], Shu Tian [c]

[a] *Department of Management and Engineering, Linköping University, Linköping, Sweden*
[b] *Trinity Business School, Trinity College Dublin, Ireland*
[c] *Economic Research and Regional Cooperation Department, Asian Development Bank, Philippines*
[d] *Trinity Business School, Trinity College Dublin, Ireland*

A R T I C L E I N F O

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A B S T R A C T

This paper presents a picture of the risk spillover relationship of green & black bonds in Asia. In normal situations and the long-term horizon, green bonds and black bonds have similar impacts with each other, with a slight predominance of black bonds. Based on the dynamic connectedness results, we classify the sample period into three stages. The first stage is a period with equal role of green and black bonds from Jan 2018 to Feb 2020, which is regarded as a normal situation of the bond market. The second stage is an unbalanced period with a pivotal point of the Covid-19, demonstrating an increased gap of the connectedness exported by green and black bonds. The third stage is the recovery period after Oct 2020, where we see a correction with the role of green and black bonds recovering gradually to the equal status. In addition, the green-to-black connectedness in longer term witnesses faster and stronger recovery, which suggests that the long-term influences of green bonds are relatively stable than the short-term influences. Moreover, the paper tests the effects of the same issuer. Our analysis shows that there are strong connections among bonds in the Philippines that are issued by the same institution. However, the same issuer is not a sufficient condition for a strong connectedness. Furthermore, our analysis in China Mainland, reveals that the green policy will firstly cause the change of green bonds price and then spillover the impact to conventional markets. Through the study of the drivers of connectedness dynamics in four directions (green-to-green, black-to-black, green-to-black, black-to-green), we present empirical findings that are crucial for investors and policymakers in risk management, hedging strategy, and green investment acceleration.

1. Introduction

Rapid developments in the Asian region have led to serious challenges in carbon dioxide emissions, pollutants, and catastrophic ecological changes.[1] Perhaps a possible capital market correction, as response to these environmental issues may be seen as an explanation for the sharply increasing Green bond issuances observed in recent years in Asia.[2] Green bonds may come with tax incentives (Heine et al., 2019), environmental friendly preferences (Zerbib, 2019), good investment performance (Kanamura, 2020) and diversification of investment returns (Nanayakkara & Colombage, 2019). Investors in fixed income face a choice between black bonds (i.e., non-green or conventional bonds) and green bonds. Going Green or Black may be motivated by a wide variety of factors such as bond yields, reinvestment risk, credit risk,

* Corresponding author.
E-mail addresses: gazi.salah.uddin@liu.se (G.S. Uddin), jayasekr@tcd.ie (R. Jayasekera), dpark@adb.org (D. Park), luot@tcd.ie (T. Luo).

[1] Of the world's cities with the worst air pollution last year, the top 148 are all in the Asia-Pacific region, ranked by Swiss air quality technology company IQAir.

[2] China Mainland has the third largest volume of green bonds globally, with US$115 billion in outstanding bonds, and led emerging markets in 2020 issuance. Association of Southeast Asian Nations (ASEAN) countries issued a combined US$3. 8 billion in 2020, an 8. 6% increase from 2019. Renewable energy corporates based in Indonesia, Malaysia, the Philippines, and Thailand made up most of the rest of the region's issuance. India has the second largest volume of outstanding green bonds (US$10. 8 billion) and has consistently been the second largest issuer after China Mainland. This past year, however, India's green bond issuance dropped significantly, to US$916 million from US$3. 2 billion in 2019. Data on green loan issuance, which more than doubled from US$1. 5 billion in 2019 to US$3. 6 billion in 2020, according to Bloomberg, suggest that bank financing was more attractive than bonds ASEAN issuance almost doubled, reaching USD $ 8. 1 billion in 2019 from USD $4. 1 billion in 2018. Sales of China Mainland's green bonds reach record pace, reaching USD $ 6. 7 billion in 2020 from USD $23. 2 billion in 2021. (See, Climate Bonds Initiative, https://www. climatebonds. net/resources/reports/asean-green-finance-state-market-2019; Emerging Market Green Bonds Report 2020, https://research-center. amundi. com/files/nuxeo/dcb26585-de19-4e28-9f38-51dbe57d75b5).

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interest rate risk, tax incentives and sentiment. Hence a study that investigates the dynamic, complex interrelationship between Green vs Black investment would not only have far reaching implications for capital market participants but also for policy level decision makers and regulators to effectively design reform legislation to facilitate the flow of capital to environmentally sustainable green projects. Whilst there are some studies that examine the relationship between green investment and other asset classes, such as Pham (2021), Reboredo, Ugolini, and Aiube (2020) and Reboredo and Ugolini (2020), research in the Asian region in this aspect is virtually nonexistent expect perhaps Hanif, Aziz, and Chaudhry (2019). We are the first to investigate the dynamics of risk spillover among green bonds and black bonds, to understand the nature of investor decision making between green and black investments.

To capture the connectedness and risk spillover among Asian bonds, we build a high-dimensional network methodology implemented by two steps. Firstly, we use several GARCH models and distributions to fit the daily return, and select the best-fitting model based on Akaike information criteria (AIC) and the post ARCH effect test of standardized residual. The series of conditional volatility of bonds are estimated for further modelling. Second, the connectedness measures are based on the framework of Diebold and Yilmaz (2014, DY framework afterwards). The multivariate time series of zero-mean log conditional volatilities are considered as a VAR process. The generalized variance decomposition is utilized to analyze the connectedness between a pair of bonds, i. e., one source bond and one target bond. We provide the results of connectedness across green and black bonds in both static and time-varying horizons. By considering the country-specific foundation of important events and policies, the dynamics of domestic connectedness among green and black bonds are analyzed. We also study the cross-national connectedness among green and black bonds, to provide some suggestions on portfolio strategy in Asian or worldwide level.

Our dataset contains 42 bonds in six countries and territories in Asia, including China Mainland, Hong Kong, India, Japan, Philippines, and Singapore. We follow a paired sample design by including 21 green-black bond pairs. In order to minimise any omitted variable bias and to ensure that the effects we infer from the price discovery process is mainly attributable to the Green vs Black characteristics, we construct a green-black pair of bonds by a green bond and a black bond that have same borrower's country, same level of Moody's credit rating, similar issue date (within 1 year) and similar maturity period at issue. We utilize the daily mid-price of bond from Jan 1st 2018 to Sep 15th 2021 (968daily observations).

This paper makes contributions to the literature on five aspects. First, the paper presents a picture of the risk spillover relationship of green & black bonds in Asia. Empirical evidence shows that in normal periods (where the market is not very volatile) and in the long-term horizon, green bonds and black bonds have similar impact on each other, with a slight predominance of black bonds. This finding adds to the literature that focuses on the US and Europe market, such as Saeed, Bouri, and Alsulami (2021) that states black bonds have stronger impact than green bonds. The results suggest that despite green bonds being a special type of fixed-income asset, the risk of green bonds should be managed together with the conventional fixed-income market.

Second, using a time-varying horizon perspective, the paper examines the influences of Covid-19. We classify the sample period into three stages on the basis of the dynamic connectedness results. The first stage is a period with equal mutual impact to and from green and black bonds from Jan 2018 to Feb 2020, which is regarded as a normal situation of the bond market. The second stage is the unbalanced period, corresponding to the start of the Covid-19 pandemic. The most striking feature here is the increased gap of the connectedness exported by green and black bonds. The Covid-19 pandemic changes the pattern of green & black relationship, by eliciting enormously increased the spillover risk from the conventional financial market to green bonds. A possible reasoning for the heightened black-to-green spillover risk could be that the preferred fixed-income investment at the outset is the conventional financial markets as safe havens (in comparison to Green bonds), and this may have caused a jump in the price and volatility of black bonds. The higher demand for black bonds may be attributed to a lower risk profile and vulnerability. Then, with the near completion of subsequent price adjustment of the fixed-income assets in the conventional financial markets, the other investors turn to select green bonds as safe-haven investment. The significant lead-lag relationship between the black and green bonds forms a heightened black-to-green connectedness and weakens the connectedness in the reverse direction. The third stage is the recovery period after Oct 2020, sees the role of green and black bonds recovering slowly to equal status. It is worth highlighting that the green-to-black connectedness in longer term witnesses faster and stronger recovery. This result suggests that the long-term influences of green bonds are relatively stable than the short-term influences.

Third, we analyze features of six countries and territories and characterize them in terms of risk profile and connectedness. The results of risk profile of six countries and territories include: (1) In Hong Kong, Indian and Philippines, green bonds have higher levels of risk; In Singapore and Japan, green bonds have lower levels of risk; In China Mainland, there are similar levels of risks for green and black bonds; (2) Although The green bonds have lower risk for some countries, in certain instances of extreme financial risk (e.g., stock market crash), the green bonds always have higher volatility. The higher risk of green bonds is closely related to the minimal risk, safe-haven roles exhibited by the conventional financial markets. The results of connectedness of six countries and territories include: (1) Japan and Philippines are the major exporter of connectedness; (2) India, Philippines and Japan have similar dynamics as the Asia overall connectedness, including the disruption of the equal black & green equilibrium relationships in Covid-19 period and the recovery of green bonds' impact. (3) In Hong Kong, there was an unequal black & green relationship before Covid-19. (4) In China Mainland, there are several peaks of green-to-black connectedness after 2020 where these peaks are related to the green policy of China Mainland with the objective of achieving carbon neutrality before 2060. It suggests that the green policy will firstly cause the change of green bonds price and then spillover the impact to conventional markets. (5) Singapore shows good risk minimisation capability, with the lowest level of both input and output spillover risks with other countries with the Black-to-green spillover risk dominating the domestic connectedness perhaps because the green bonds have lower volatility, i.e., lower value of the source for spillover risk. In addition, Singapore is the country with best environmental performance except Japan, with low CO_2 Emissions (Huang & Xu, 2020) and a long history of green policy (Azhgaliyeva, Kapoor, & Liu, 2020; Chang, 2015). The limited risk exposure controls the spillover from the green bonds to black bonds at its source. Another finding is that the domestic green-to-green and black-to-black connectedness in Singapore is higher than other countries, indicating a well-developed financial market and high systemic relationship in Singapore.

Moreover, the paper tests the effects of the same issuer. Our analysis shows that there are strong connections among bonds in the Philippines that are issued by the same institution, i.e., Asian Development Bank. These black and green bonds share remarkable similarities in terms of investment credit ratings, default risk, coupon rates and maturity, which justifies the considerable connectedness between the green bond market and the conventional fixed-income markets. We find that the same issuer is not a sufficient condition for a strong connectedness. For example, in

Table 1
Sample of green bonds and black bonds.

NUMBER	BOND	SIN. CODE	NAME	BORROWER COUNTRY	CURRENCY	ISSUE. DATE	LIFE. AT ISSUE	AMOUNT ISSUED	MOODY'S RATING	MOODY'S RATING DATE	GREEN BOND	PAIR
1	G-CN1-P1	XS1711173218	CHINA DEV. BANK 2017 3/8% 16/11/21 REG. S	CN	E	2017/11/16	4	1,000,000	A1	2019/12/5	GREEN	1
2	G-CN2-P2	XS1711039591	CHINA DEV. BANK 2017 2 3/4% 16/11/22 REG. S	CN	U$	2017/11/16	5	500,000	A1	2019/12/5	GREEN	2
3	G-HK1-P3	XS1691346693	MTR CORP. LTD. 2017 3 3/8% 27/09/47 S	HK	U$	2017/9/27	30	100,000	Aa3	2017/9/27	GREEN	3
4	G-HK2-P4	XS1725553066	CGNPC INTL. LTD. 2017 1 5/8% 11/12/24	HK	E	2017/12/11	7	500,000	A2	2019/4/25	GREEN	4
5	G-HK3-P5	XS1690683211	MTR CORP. LTD. 2017 3 3/8% 27/09/47 REG. S	HK	U$	2017/9/27	30	100,000	Aa3	2017/9/27	GREEN	5
6	G-IN1-P6	XS1467374473	NTPC LIMITED 2016 7 3/8% 10/08/21 REG. S	IN	IR	2016/8/10	5	20,000,000	Baa3	2016/8/10	GREEN	6
7	G-IN2-P7	XS1733877762	INDIAN RAILWAY FIN. 2017 3.835% 13/12/27 REG. S	IN	U$	2017/12/13	10	500,000	Baa3	26 + 5020/6/2	GREEN	7
8	G-IN3-P8	XS1641477119	REC LIMITED 2017 3 7/8% 07/07/27 REG. S	IN	U$	2017/7/7	10	450,000	Baa3	2020/6/2	GREEN	8
9	G-IN4-P9	XS1692377945	INDIAN RENWEN. DEV. 2017 7 1/8% 10/10/22 REG. S	IN	IR	2017/10/10	5	19,500,000	Baa3	2019/1/14	GREEN	9
10	G-JP1-P10	JP354565BHB9	JAPAN RAILWAY CON. 2017 0.23% 26/11/27 ZAI 109	JP	Y	2017/11/28	9.9904	20,000,000	A1	2017/11/17	GREEN	10
11	G-JP2-P11	XS1691909920	MIZUHO FLGP. INCO. 2017 0. 956% 16/10/24 REG. S	JP	E	2017/10/16	7	500,000	A1	2019/8/28	GREEN	11
12	G-JP3-P12	XS1505655537	DEV. BK. OF JAPAN 2016 2% 19/10/21 REG. S	JP	U$	2016/10/19	5	500,000	A1	2019/5/27	GREEN	12
13	G-JP4-P13	US606822AH76	MITSUB. UFJ FLGP. 2016 2. 527% 13/09/23 S	JP	U$	2016/9/13	7	500,000	A1	2019/11/21	GREEN	13
14	G-JP5-P14	XS1694219780	SUMIT. MTI. FINL. GP. 2017 0. 934% 11/10/24 REG. S	JP	E	2017/10/11	7	500,000	A1	2019/8/28	GREEN	14
15	G-PH1-P15	XS1609444713	ASIAN DEV. BANK 2017 9. 55% 26/05/21920–00-	PH	TL	2017/5/25	4.0028	105,200	Aaa	2021/5/26	GREEN	15
16	G-PH2-P16	US045167CY77	ASIAN DEV. BANK 2015 2 1/8% 19/03/25806–00-	PH	U$	2015/3/19	10	500,000	Aaa	2021/8/2	GREEN	16

(*continued on next page*)

Table 1 (*continued*)

NUMBER	BOND	SIN. CODE	NAME	BORROWER COUNTRY	CURRENCY	ISSUE. DATE	LIFE. AT ISSUE	AMOUNT ISSUED	MOODY'S RATING	MOODY'S RATING DATE	GREEN BOND	PAIR
17	G-PH3-P17	US045167EC30	ASIAN DEV. BANK 2017 2 3/8% 10/08/27936–00-	PH	U$	2017/8/10	10	500,000	Aaa	2021/8/2	GREEN	17
18	G-PH4-P18	US045167EB56	ASIAN DEV. BANK 2017 1 7/8% 10/08/22935–00-	PH	U$	2017/8/10	5	750,000	Aaa	2021/8/2	GREEN	18
19	G-PH5-P19	US045167DR18	ASIAN DEV. BANK 2016 1 3/4% 14/08/26876–00-	PH	U$	2016/8/16	9.9944	500,000	Aaa	2021/8/2	GREEN	19
20	G-SG1-P20	US24023KAC27	DBS GROUP HLTD. 2017 F/R 07/22144A	SG	U$	2017/7/25	5.0021	500,000	Aa2	2020/11/18	GREEN	20
21	G-SG2-P21	US24023LAC00	DBS GROUP HLTD. 2017 F/R 07/22 REG. S	SG	U$	2017/7/25	5.0021	500,000	Aa2	2020/11/18	GREEN	21
22	NG-CN1-P1	XS1521637113	EXPORT-IMPORT BOC. 2016 5/8% 02/12/21 REG. S	CN	E	2016/12/2	5	850,000	A1	2019/12/3	BLACK	1
23	NG-CN2-P2	XS1575044364	EXPORT-IMPORT BOC. 2017 2 5/8% 14/03/22 REG. S	CN	U$	2017/3/14	5	1,150,000	A1	2019/12/3	BLACK	2
24	NG-HK1-P3	HK0000324977	HONG KONG MGE. CORP. 2017 2. 65% 26/01/32	HK	K$	2017/1/26	15	110,000	Aa3	2020/1/21	BLACK	3
25	NG-HK2-P4	HK0000346806	HKCG FINANCE LTD. 2017 2. 65% 03/07/27 Q	HK	K$	2017/7/3	10.0021	700,000	A1	2018/12/13	BLACK	4
26	NG-HK3-P5	XS1587900090	HONG KONG MGE. CORP. 2017 3. 675% 30/03/27 REG. S	HK	A$	2017/3/30	10	65,000	Aa3	2020/1/21	BLACK	5
27	NG-IN1-P6	JP535604AGQ0	ICICI BANK LTD. 2016 0. 678% 16/12/21 1	IN	Y	2016/12/16	4.9986	10,000,000	Baa3	2016/12/16	BLACK	6
28	NG-IN2-P7	US00652MAD48	ADANI PORTS &. SPC. 2017 4% 30/07/27144A	IN	U$	2017/6/30	10.0833	500,000	Baa3	2020/6/2	BLACK	7
29	NG-IN3-P8	XS1637846616	HINDUSTAN PETROLEUM 2017 4% 12/07/27 REG. S	IN	U$	2017/7/12	10	500,000	Baa3	2020/6/2	BLACK	8
30	NG-IN4-P9	XS1656195796	EXIM. BANK OF INDIA 2017 F/R 08/22 REG. S	IN	U$	2017/8/21	5.0021	400,000	Baa3	2020/6/2	BLACK	9
31	NG-JP1-P10	JP2150001HB3	NIIGATA 2017 0. 19% 30/11/27 H29–2	JP	Y	2017/11/30	9.9986	20,000,000	A1	2020/3/16	BLACK	10
32	NG-JP2-P11	JP363360BH79	TOYOTA FINANCE 2017 0. 145% 25/07/24 77	JP	Y	2017/7/25	7.0041	10,000,000	A1	2021/3/18	BLACK	11
33	NG-JP3-P12	JP379990BH40	EAST NPN. EXPWY. CO. 2017 0. 07% 20/06/22 42	JP	Y	2017/4/28	5.1466	50,000,000	A1	2017/4/19	BLACK	12

(*continued on next page*)

Table 1 (*continued*)

NUMBER	BOND	SIN. CODE	NAME	BORROWER COUNTRY	CURRENCY	ISSUE. DATE	LIFE. AT ISSUE	AMOUNT ISSUED	MOODY'S RATING	MOODY'S RATING DATE	GREEN BOND	PAIR
34	NG-JP4-P13	XS1506462784	JAPAN FIN. ORGSZ. 2016 2 1/8% 25/10/23 REG. S	JP	U$	2016/10/25	7	1,000,000	A1	2016/10/19	BLACK	13
35	NG-JP5-P14	XS1675764945	MITSUB. UFJ FLGP. 2017 0.872% 07/09/24 REG. S	JP	E	2017/9/7	7	750,000	A1	2019/11/21	BLACK	14
36	NG-PH1-P15	AU3CB0241883	ASIAN DEV. BANK 2017 2 3/4% 19/01/22 S	PH	A$	2017/1/19	5	1,050,000	Aaa	2021/8/2	BLACK	15
37	NG-PH2-P16	US045167CW12	ASIAN DEV. BANK 2015 2% 22/01/25 S	PH	U$	2015/1/22	10	1,500,000	Aaa	2021/8/2	BLACK	16
38	NG-PH3-P17	US045167DU47	ASIAN DEV. BANK 2017 2 5/8% 12/01/27896–00-	PH	U$	2017/1/12	10	1,300,000	Aaa	2021/8/2	BLACK	17
39	NG-PH4-P18	US045167ED13	ASIAN DEV. BANK 2017 1 3/4% 13/09/22 S	PH	U$	2017/9/13	5	4,000,000	Aaa	2021/8/2	BLACK	18
40	NG-PH5-P19	XS1496739464	ASIAN DEV. BANK 2016 6. 2% 06/10/26886–00-	PH	IR	2016/10/6	10	26,000,000	Aaa	2021/8/2	BLACK	19
41	NG-SG1-P20	XS1548844247	DBS GROUP HLTD. 2017 2. 8% 13/01/22 REG. S	SG	K$	2017/1/13	5	794,000	Aa2	2020/11/18	BLACK	20
42	NG-SG2-P21	XS1550132655	DBS GROUP HLTD. 2017 2. 78% 13/01/22 REG. S	SG	K$	2017/1/13	5	106,000	Aa2	2020/11/18	BLACK	21

Notes. Countries of China Mainland, Hong Kong, India, Japan, Philippines, and Singapore are abbreviated to CN, HK, IN, JP, PH, SG.

Singapore, strong connectedness only exists in black-to-black or green-to-green pairs.

Our findings are crucial for investors and policymakers, especially in relation to the pertinent question of whether to "go green or stay black" investment decisions, as well as the acceleration of sustainable development and green investments. Accordingly, it is not appropriate to consider the green and black bonds as unrelated assets, or ignore the impacts from green to black bonds, as this could result in the stronger safe-haven properties a associated with green bonds in crisis to be masked. For policy makers, our findings provide evidence that the green policy intensifies the dominant role and safe-haven of green bonds offering suggestions to stimulate green investment and setting bail-out mechanisms. As for investors, they can use our analyses while making decisions regarding risk management and return predictability in various market conditions. The drivers of the green & black connectedness, would be useful to predict the risk spillover directions and help investors to get hedging benefits. Furthermore, time-varying risk spillovers matter to traders and portfolio managers who can make adjustments to their trading and investment positions according to various market states.

The rest of the paper proceeds as follows. Section 2 describes the methodology; data and preliminary statistics are presented in section 3; empirical results and discussion are provided in section 4; section 5 concludes the paper by providing a summary of the paper.

2. Methodology

To capture the risk connectedness and spillover among bonds, our methodology implements two steps. Firstly, we use several GARCH models and distributions to fit the daily return, and select the best-fitting model based on Akaike information criteria (AIC) and the post ARCH effect test of standardized residual. The series of conditional volatility of bond is estimated for afterward modelling.

Second, the connectedness measures are based on the framework of Diebold and Yilmaz (2014). The multivariate time series of zero-mean log conditional volatilities are considered as VAR process. The generalized variance decomposition is utilized to analyze the connectedness between pair of bonds, i. e. one source bond and one target bond.

2.1. Conditional volatility

To capture the connectedness, we first estimate the conditional volatility for all the bonds. We model the daily return by different variations of ARMA(m, n) model with the standard residuals following Normal, Student-T, and Skewed-T distribution. To model the conditional variance, we utilize several GARCH types (GARCH, IGARCH, GJR-GARCH, and TGARCH) frameworks with different lag lengths (p, q). Based on AIC and posttest of standardized residual, we select the model with the best performance, which is the ARMA (2,2) - GJRGARCH (3,3) model with Gaussian distribution.

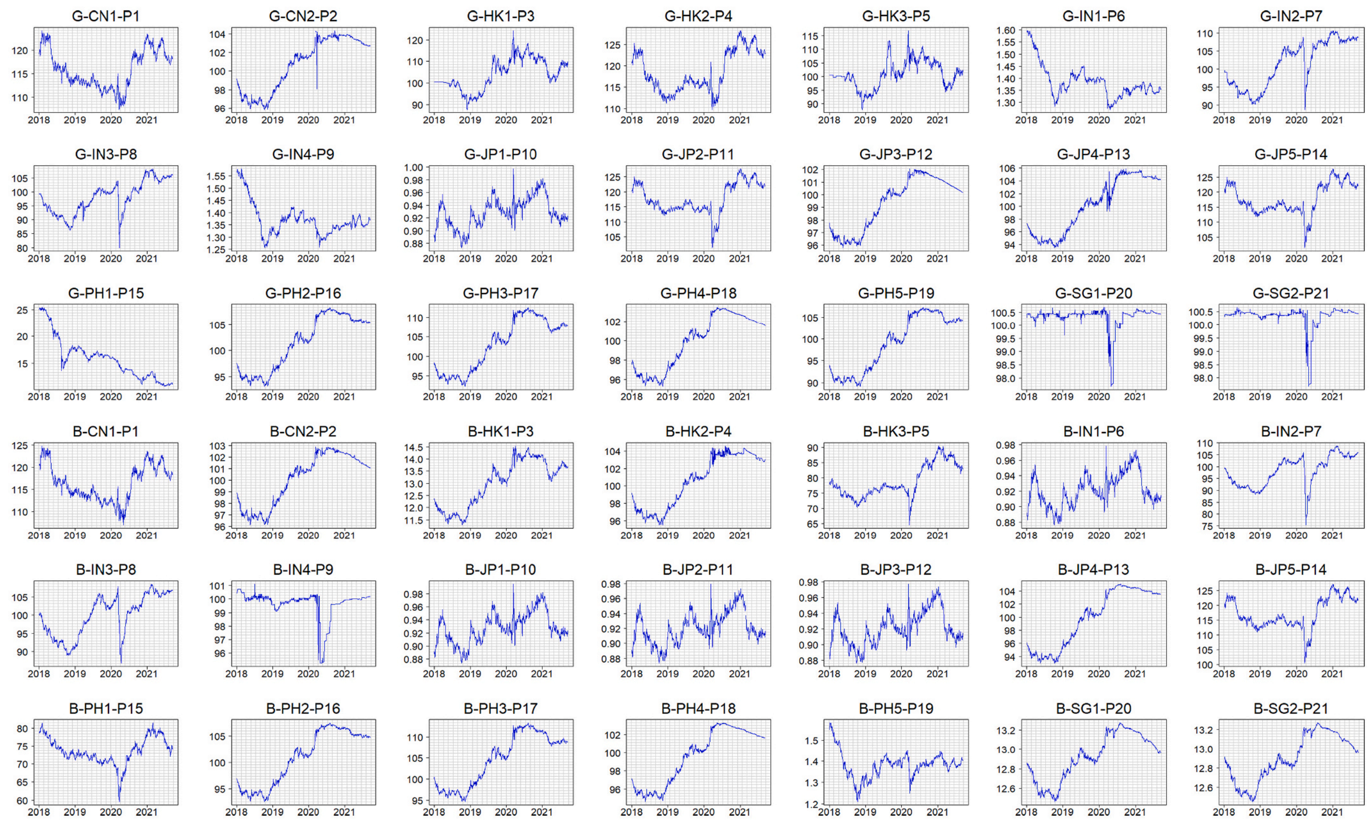

Fig. 1. Price of each bond.
Notes. We utilize daily data for the sample period from Jan 1st 2018 to Sep 15th 2021 (968 daily observations). The tile of each plot is the name of bond showed in the second column of Table 1. Countries of China Mainland, Hong Kong, India, Japan, Philippines, and Singapore are abbreviated to CN, HK, IN, JP, pH, SG.

The ARMA (2, 2) - GJRGARCH (3, 3) model with Gaussian distribution is formed as follows.

Let $r_{i,\,t}$ denote the stochastic process of return for the i_{th} series:

$$r_{i,t} = \mu_i + \sum_{m=1}^{2} \omega_m r_{i,t} + u_{i,t} + \sum_{n=1}^{2} \beta_n u_{i,t-\mathrm{n}} \tag{1}$$

where μ_i is the constant term, $u_{i,\,t} = \varepsilon_{i,\,t}\sigma_{i,\,t}$ is the residual term. The white noise process follows a standard Gaussian distribution, i.e., $\varepsilon_{i,\,t} \sim i.\,i.\,d\,N(0,1)$. We model the conditional volatility, $\sigma_{i,\,t}$, for each univariate series by utilizing the GJRGARCH(3, 3) specification as

$$\sigma_{i,t}^2 = \theta_0 + \sum_{p=1}^{3} \theta_p {u_{i,t-p}}^2 + \sum_{q=1}^{3} \eta_q \sigma_{i,t-q}^2 + \sum_{p=1}^{3} \gamma_q I_{t-q} u_{i,t-q}^2 \tag{2}$$

where $I_{t-q} = \left\{ \begin{matrix} 1, if\ u_{i,t-q} < 0 \\ 0, if\ u_{i,t-q} \geq 0 \end{matrix} \right\}$. With conditional volatility estimated by ARMA (2, 2) - GJRGARCH (3, 3) model with Gaussian distribution, we normalized the volatility into log value of volatility with zero mean value, to fit the following calculations.

2.2. Connectedness

The network representation in the energy sectors is analyzed by applying a vector autoregression (VAR) model and the generalized variance decomposition of the DY (2014) framework. With the N-dimensional multivariate time series of estimated conditional volatility $y_t = \{y_{1,\,t}, y_{2,\,t}, \ldots, y_{N,\,t}\}$, we estimate the VAR in p-order as:

$$y_t = \sum_{k=1}^{p} A_k y_{t-k} + \varepsilon_t, \varepsilon_t \sim i.i.d\left(0, C^{-1}\right) \tag{4}$$

where the autoregressive matrix A_k and the concentration matrix C are $N \times N$ matrices. To adopt the VAR model with no constant term, the volatility series that obtained from ARMA (2, 2) - GJRGARCH (3, 3) model with Gaussian distribution are standardized to have zero mean value. The mean values only affect the intercept term, so the results of connectedness will not be influenced by the standardization. Specifically, we take the log value of conditional volatility, and then minus the mean value for each bond which is zero-mean standardization.

After the VAR process, we apply H-step-ahead generalized variance decomposition that allows us to measure the pairwise directional connectedness from j_{th} node to i_{th} node by

$$\theta_{ij}^H = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} \left(e_i^{'} \Theta_h \Sigma e_j\right)^2}{\sum_{h=0}^{H-1} \left(e_i^{'} \Theta_h \Sigma \Theta_h^{'} e_i\right)} \tag{5}$$

where Σ is the variance matrix of the error vector ε_t, the σ_{jj} is the standard deviation of the error term for the j_{th} series, and e_i is the selection vector equal to 1 for the j_{th} element and 0 otherwise. For $h = 0, 1, 2, \ldots$, the $N \times N$ coefficient matrices Θ_h can be obtained using the following iteration

Table 2
Descriptive statistics.

	Green bond	Black Bond	All
Mean (%)	−0. 0010	0. 0030	0. 0010
Std. Dev. (%)	0. 4350	0. 3540	0. 3950
Sharpe Ratio	−3. 0740	−3. 6630	−3. 3680
Maximum (%)	3. 1570	2. 3200	2. 7390
Minimum (%)	−4. 1800	−2. 3750	−3. 2770
Skewness	−0. 8510	−0. 2150	−0. 5330
Kurtosis	38. 0930	13. 2470	25. 6700
Jarque-Bera	188,839. 7920***	25,155. 4600***	106,997. 6260***
Q (20)	83. 8050**	60. 7530**	72. 2790**
Q2 (20)	335. 8430**	422. 0700***	378. 9570***
ARCH-LM (20)	214. 4930***	202. 7840***	208. 6380***
ARCH-LM (standardized residual)	10. 3680	12. 3120	11. 3400

Notes. This table reports the average sector-wise descriptive statistics of the underlying bonds. Jarque-Bera test presents the test-statistics of the Jarque and Bera (1987) normality test. Q (20) and Q2(20) corresponds to the test-statistics from Ljung-Box test for autocorrelation in returns and squared returns, respectively. ARCH(20) presents the statistics from Engle (1982) test of ARCH effects in the underlying series. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% level respectively.

$$\Theta_h = A_1\Theta_{h-1} + A_2\Theta_{h-2} + \ldots + A_p\Theta_{h-p} \quad (6)$$

where Θ_0 is a $N \times N$ identity matrix and $\Theta_h = 0$ for $h < 0$. The direction and magnitude of each node are different based on the degree of connectedness across the time series.

The DY (2014) framework states that the variance shares do not necessarily add to 1, i.e., $\sum_{j=1}^{N}\theta_{ij}^{H} \neq 1$. Each entry of the generalized variance decomposition matrix is normalized by give unit row sum value, that is, $\sum_{j=1}^{N}\widetilde{\theta_{ij}^{H}} = 1$. And the normalized pairwise directional connectedness $\widetilde{\theta_{ij}^{H}} = \frac{\theta_{ij}^{H}}{\sum_{j=1}^{N}\theta_{ij}^{H}}$. The normalized pairwise directional connectedness is defined as the proportion of the H-step ahead forecast error variance of i_{th} node which is accounted for by the innovations in j_{th} node in the VAR. For each entry in the adjacency matrix, $\widetilde{\theta_{ij}^{H}} > 0$ indicates an influence of j_{th} node on i_{th} node. A higher value of $\widetilde{\theta_{ij}^{H}}$ implies that the corresponding connection between two nodes is stronger. With the normalized pairwise directional connectedness given as entries, we obtain the adjacency matrix $\widetilde{\theta^{H}} = \left[\widetilde{\theta_{ij}^{H}}\right]$.

3. Data

Our dataset contains 42 bonds in six Asian countries and territories, including China Mainland, Hong Kong, India, Japan, Philippines, and Singapore, collected from Thompson Reuters Datastream. To be specific, the sample include 21 green-black bond pairs. A green-black pair of bond is made up by a green bond and a black bond that have same borrower's country, same level of Moody's credit rating, similar issue date (within 1 year) and similar life at issue, listed in Table 1. As can be seen, the Moody's credit ratings of bonds range from the highest Aaa to the lowest Baa3. There are three developed countries and territories, i.e., Hong Kong, Japan, and Singapore and three developing countries and territories, i.e., China Mainland, India, and Philippines. Interestingly, in Philippines, all the selected bonds come from one issuer, i.e., the Asian Development Bank. The reasons include that (1) the Asian Development Bank is the earliest (before 2018) to issue green bond; (2) in the Thompson Reuters Datastream, around 90% of the recorded green bonds in Philippines are issued by Asian Development Bank; (3) it brings us a near perfect case study example to understand the connectedness of black and green bonds with a same issuer, since the issuer characteristics are the same one might rationally expect that the inherent differences of Green Vs. Black bonds would play more of a role in determining the differential bond price/yield characteristics.

We utilize the daily mid-price of bond from Jan 1st 2018 to Sep 15th 2021 (968 daily observations). Our empirical analysis is based on the daily stock returns of each company which is calculated as the 100 times of logarithmic difference of stock prices at time t and t-1.

The Figs. 1 plot the price of each bond. In the early stage of Covid-19, i.e., between Jan to Mar 2020, the price of most bonds gradually

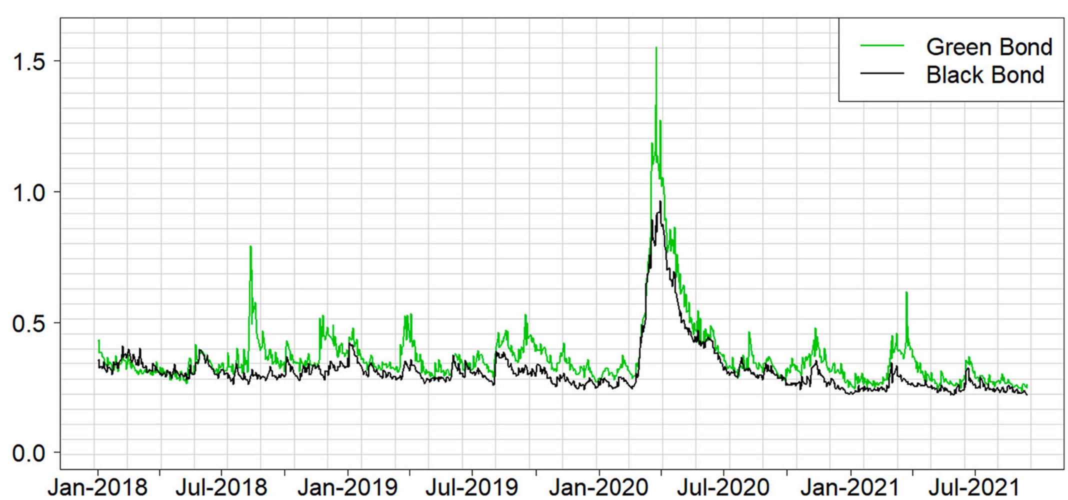

Fig. 2. Volatility of green and black bonds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Notes. Time series plots for daily volatilities. For each bond, the volatility, i.e., standard deviation of returns, is estimated by the ARMA (2, 2)-GJRGARCH (3, 3) model with Gaussian distribution which is selected based on AIC and post-test of standardized residual. The daily volatility for each bond is calculated firstly and then averaged by group.

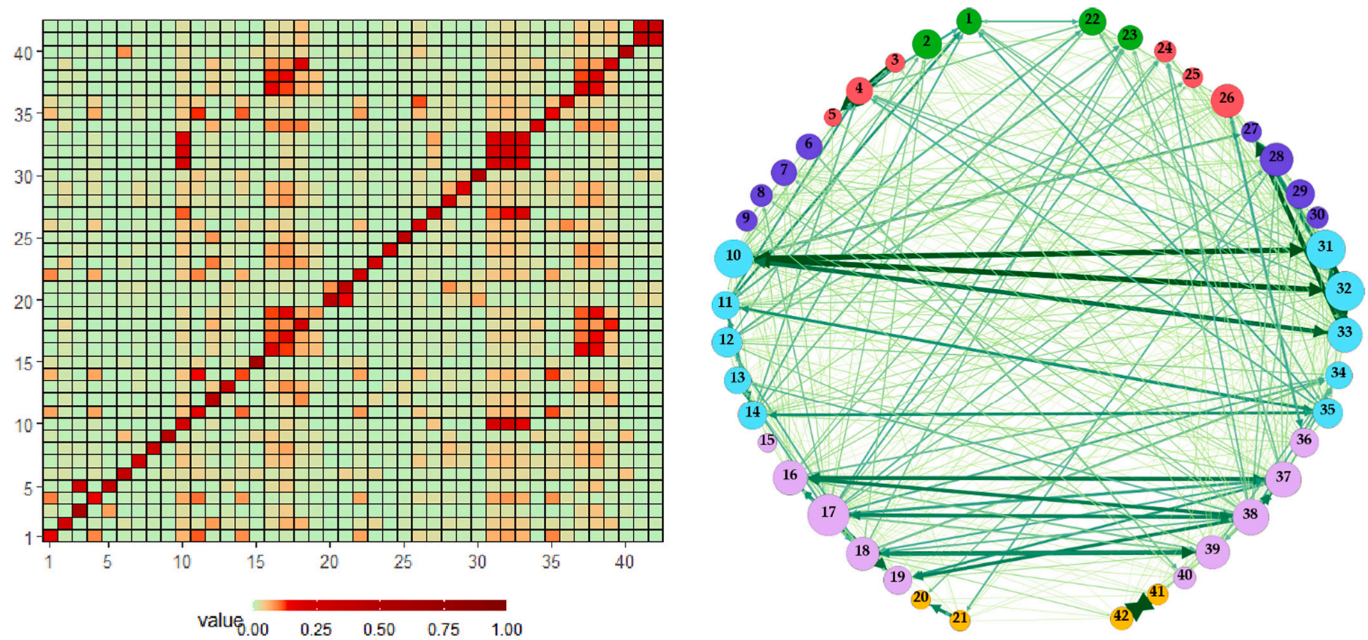

Fig. 3. Adjacency matrix and topological network in full period horizon.
Notes. The adjacency matrix in the left subfigure is derived based on eq. (5–6), where we consider the full-period panel of volatility of all bonds as a first-order zero-mean vector autoregression process. By applying 12-step generalized variance decomposition, we generate the adjacency matrix shown in this figure. For each entry in the adjacency matrix, a higher value indicates that a shock of the output bond increases the variance of the target bond, so the corresponding connection between two bonds is stronger. In the right subfigure, the corresponding network of the adjacency matrix is plotted. The China Mainland, Hong Kong, India, Japan, Philippines, and Singapore are respectively showed in color of green, red, blue, light blue, purple, and orange. The nodes with larger centrality are presented by bigger size while the connections with larger value are displayed by deeper color and bigger arrow size.

increased due to the reduced market expectation of the rate of investment return. However, Indian bond prices witnessed a sharp drop and then a rapid jump in the bond price associated with Covid-19. This rapid crash and jump can be also be witnessed in China Mainland, Japan, and Philippines. As the Covid-19 pandemic unfolds, the demands for liquidity by corporate bond investors increased dramatically, which put downward pressure on the prices of investment-grade corporate bonds. With the government actions that calmed the markets, the bonds became a safe-haven asset for investors. The safe-haven effects existed for the majority of bonds, as seen by the gradually increased price of all bonds. The expectation yield decreased due to the covid, and the investment demand of bonds increased. Compared with black bonds, some of the green bonds, e.g., No. 2 in China Mainland and No. 15 in Philippines showed a downward or flat trend of their prices during the Covid-19, perhaps because these countries are not considered as safe-haven choices for investors. It could also be due to the fact that green bonds are specifically destined for the funding or refunding of green projects, i.e., projects such as renewable energy, energy efficiency, clean transportation or responsible waste management, and these green projects could have a significant impact to the real economy, especially in the case of green bonds with short life to maturity. A downward trend of all bond prices can be noticed in 2021 perhaps reflecting the effects of economic resurgence and raised market rate of return.

Table 2 provides the descriptive statistics and stochastic properties of the bonds in our sample, averaged by bond type. The mean returns of black bond is positive (0. 0030%) while the green bond exhibit negative value (−0. 0010%). The standard deviation varies from 0. 3540% to 0. 4350% for black bond and green bond, respectively, indicating that the bonds related to climate or environmental projects exhibit significantly higher volatility than the black bonds in our sample. The return series are negatively skewed. The null hypothesis of normality, autocorrelation and homoscedasticity is respectively rejected by the Jarque-Bera test, the Ljung-Box test, and the ARCH test.

4. Empirical results and discussion

4.1. Connectedness in Asia

With the best-fitted GARCH model with marginal distribution model, i.e., ARMA (2, 2) - GJRGARCH (3, 3) model with Gaussian distribution, we estimate daily volatility, i.e., standard deviation of returns, shown in Fig. 2 by bond types. It can be noticed that the volatility of green bonds are higher than black bonds in the majority of the period. More transient extreme value can be witnessed for green bonds. The volatility of black bonds has only one significant peak in April 2020, mainly impacted by Covid-19. It is also noteworthy that green and black bonds have similar fluctuations throughout the sample period especially in the period without extreme risk events, revealing that the risk profiles of black and green bonds have long-term connectedness in Asia.

Fig. 3 displays the static results of connectedness calculated on the basis of the DY(2014) framework with VAR and generalized variance decomposition. The heatmap in the left figure shows the connectedness among bonds in Asia. The x-axis and y-axis respectively indicate source and target, while the number marked in the axis represent the corresponding bond shown in Table 1. The darker color of entry indicates a higher value of connectedness. The topological visualization of the connectedness matrix is shown in the right figure, where the nodes represent bonds while the linkages represent the connectedness. China Mainland, Hong Kong, India, Japan, Philippines, and Singapore are respectively shown in color of green, red, blue, light blue, purple, and

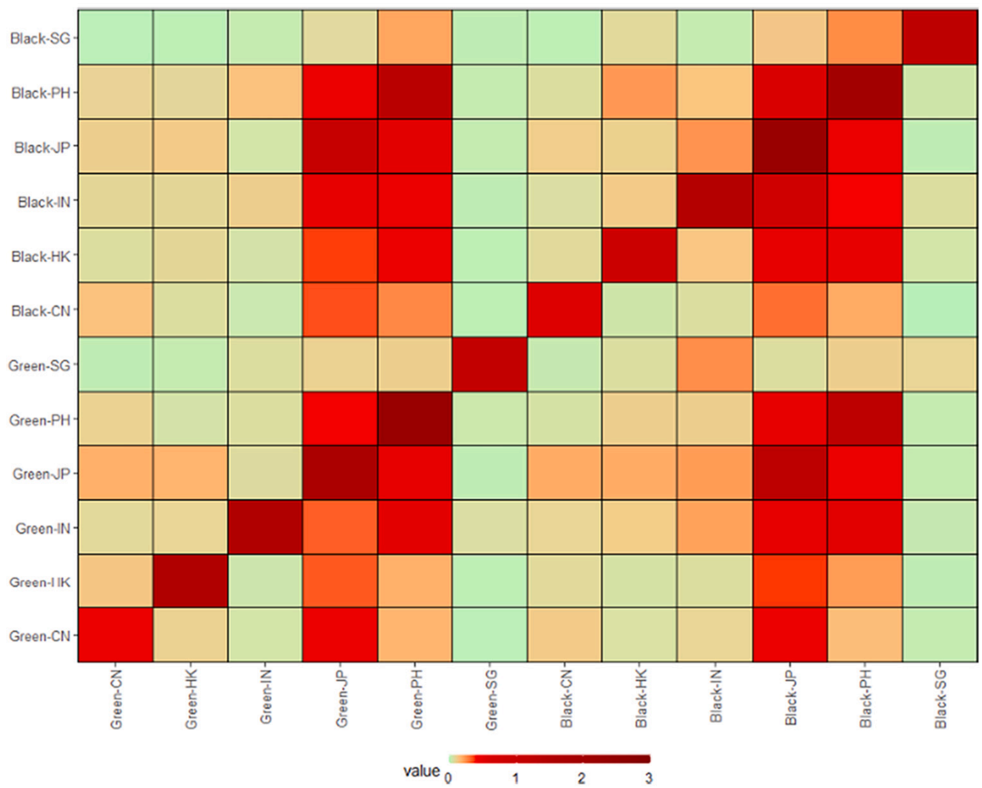

Fig. 4. Heatmap of cross-national connectedness.
Notes. The matrix entries in this figure represent the connectedness between two "Type-Country" groups. For example, to calculate the value of the entry noted by Green-HK in x-axis and Black-JP in y-axis, we extract a submatrix of connectedness that outputted from all black bonds of Japan in our sample and inputted by all green bonds of Hong Kong in our sample, and obtain the sum value. Countries of China Mainland, Hong Kong, India, Japan, Philippines, and Singapore are abbreviated to CN, HK, IN, JP, PH, SG.

orange. The bond with larger centrality is presented by bigger node size, and the connectedness with larger value is displayed by deeper color and bigger arrow size of edge.

The heatmap shows the long-term connectedness among Asian green and black bonds. It can be observed that green bonds and black bonds have similar impacts with each other, with a slight predominance of black bonds. The results suggest that despite green bonds being a special type of fixed-income asset, the risk of green bonds should be managed together with the conventional fixed-income market. This evidence is a supplement to Reboredo (2018), Reboredo et al. (2020) and Ferrer, Shahzad, and Soriano (2021) that document a close relationship between the conventional bond markets and the green bond market in both the European Union and the United States.

The national differences for green-black relationship are significant. As displayed the purple nodes in the topological network, there are strong connections among bonds in Philippines. The overall average value of connectedness between two bonds is 0. 02381, while in Philippines the average value of connectedness is 0. 09433. This result is not surprising in view of the fact that all the black and green bonds in the sample of Philippines are issued by the same institution, i.e., Asian Development Bank. These black and green bonds share remarkable similarities in terms of investment credit ratings, default risk, coupon rates and maturity, which justifies the considerable connectedness between the green bond market and the conventional fixed-income markets.

However, the same issuer is not a sufficient condition for a strong connectedness. For example, in Singapore, the green bonds No. 20 & 21 and the black bonds No. 41 & 42 are all issued by DBS Group Holdings, Ltd. But strong connectedness only exists in black-to-black or green-to-green pairs. It suggests the existence of diversification benefits by using green-black pairs from one issuer. In addition, in Hongkong, we notice another possibility for risk hedging by using green-green pairs from one issuer. As shown, the connection between the green bonds No. 3 & 5 issued by MTR Corporation Limited is relatively lower than the connection between the black bonds No. 24 and 26 issued by MGE Group.

The Japanese bonds presented by light blue nodes have witnessed a strong connectedness as well. The strong black-to-green connectedness in Japan reflects that the promotion of green investment by the financial sector of Japan It can be attributed to a well-developed financial service that encourages the investors to maintain their commitment to the fight against climate change without sacrificing a significant part of financial return. In addition, the transmission of shocks from green-to-green and black-to-black channels is not surprising, given that the conventional fixed-income market in Japan is highly self-connected (Ahmad, Mishra, & Daly, 2018), based on the grounds of credit quality, currency, risk-free rate of return, and market expectation, etc. Interestingly, there is a strong risk transmission from green bonds to black bonds in Japan. It may be attributed to the fact that a broad range of environmental issues in Japan cause potential concerns to the expected economic growth; for example, due to the small size of the tiny island nation of Japan, there is a lack of space that can accommodate trash production. Furthermore, Japanese are still in the process of dealing with the aftermath of the Fukushima Daiichi nuclear plant disaster, which caused deep environmental concerns of residents. The potential risk of green projects could result in a risk spillover to the economy and conventional financial markets. Another important reason is that the issuer of green bonds in Japan could be the top companies in Japan, such as Japan Railway Construction Public Corporation which is a public corporation responsible for the construction of railway lines in Japan. For the green bonds issued by companies with a good credit standing, the bond yield and price is highly tied to the risk-free rate of return in conventional financial markets.

Furthermore, from the topological network, it can be also noticed that the green-to-black and black-to-green spillover risk widely exists between different countries and territories in Asia. To gain a better insight into the intensity of cross-national connectedness among the green and black bonds, the matrix representing the connectedness between each two "Type-Country" groups is plotted as a heatmap in Fig. 4. Each tick on the x-axis or y-axis of the heatmap denotes a "Type-

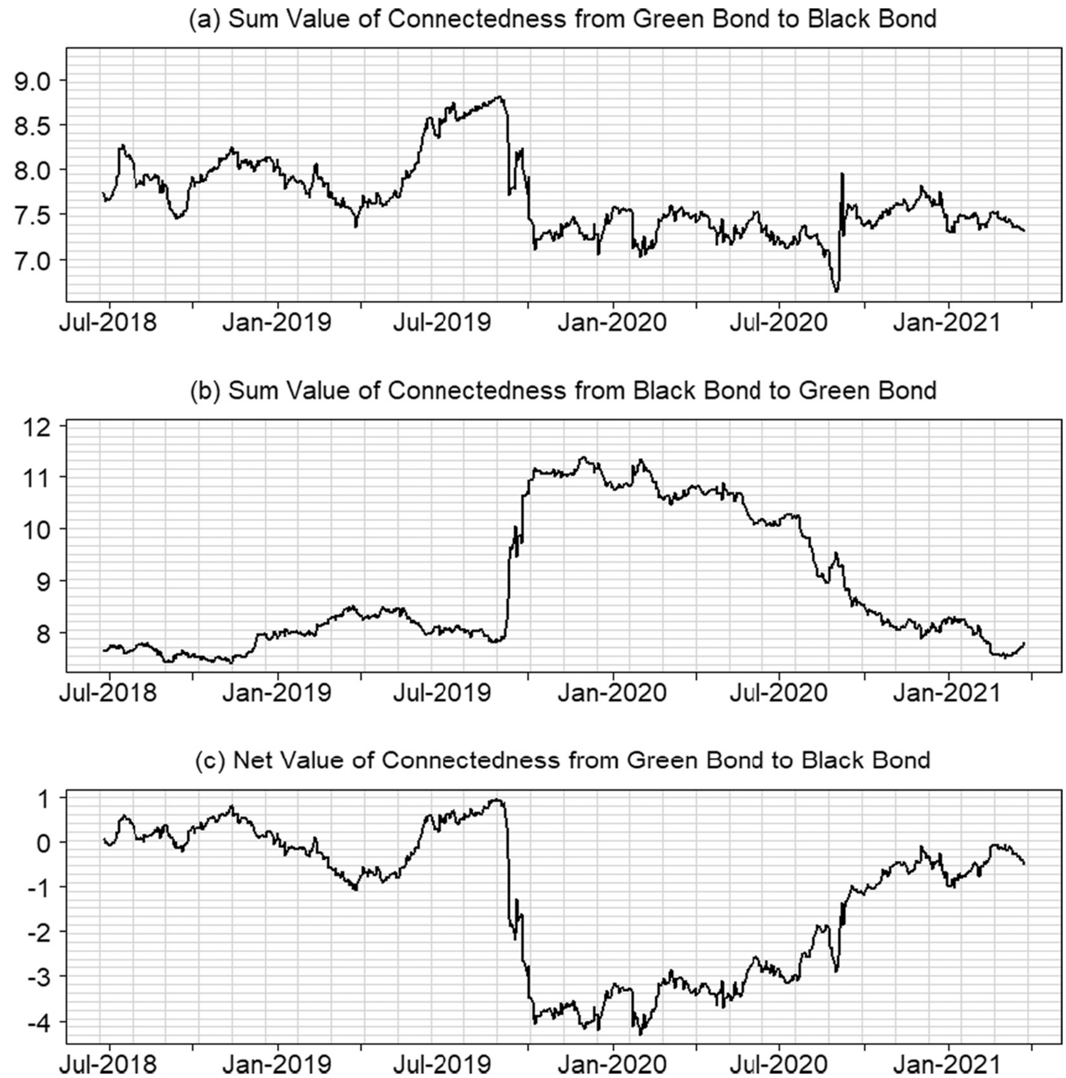

Fig. 5. Time-varying connectedness among green and black bonds. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Notes. The top figure shows the time-varying dynamics in the connectedness from all green bonds to all black bonds in our sample, while the second figure shows the connectedness in the opposite direction. The lowest figure shows the net value of the connectedness from green bonds to black bonds in our sample, which is obtained by taking the difference between the connectedness from green to black bonds and the connectedness from black to green bonds. The connectedness value is calculated by generalized variance decomposition in eq. (5–6), estimated by rolling window, with $T = 250$, $P = 1$, H = 12, and rolling step = 1. The x-ticks show the midpoint of each rolling window, e.g., the value ticked at "Jul-2019" shows the result of window from Jan 2019 to Jan 2020.

Country" group. For example, the entry noted by Green-HK in x-axis and Black-JP in y-axis indicates the sum value of all connectedness outputs from all black bonds of Japan in our sample and are subject to input connections by all green bonds of Hong Kong in our sample. Singapore shows good anti-risk capability and risk regulation, with both input and output spillover risks of Singapore having the lowest level of cross-national connectedness. It can be found that Japan and Philippines are the major exporter of connectedness, and the spillover effects from the black bonds are slightly stronger than green bonds. However the strong impacts of spillovers from Japan and Philippines to others, the imported volatility only explains a small fraction of the total variance (around 36%). This may be explained by the fact that the spillover risk starting from the bonds inside Japan and Philippines will cause second- and successive-round spillover effects to the other countries. This result suggests that the international investors should pay attention to not only the cross-national connectedness but also the internal connectedness of each country and its risk accumulation, because the internal connectedness can cause serious and continuous impacts to the international green and black bond market.

Fig. 5 displays the time-varying dynamics of connectedness in Asian green and black bonds. Specifically, we calculate the connectedness with green-to-black and black-to-green directions, by using generalized variance decomposition in eq. (5–6), with rolling window $T = 250$, $P = 1$, H = 12, and rolling step = 1. Then the net value from green bonds to black bonds is obtained by taking the difference of the two directional connectedness, to identify who played the role of predominance in a dynamic horizon. The x-ticks show the midpoint of each rolling window. It is observed that with the rolling window reaching the midpoint of Aug

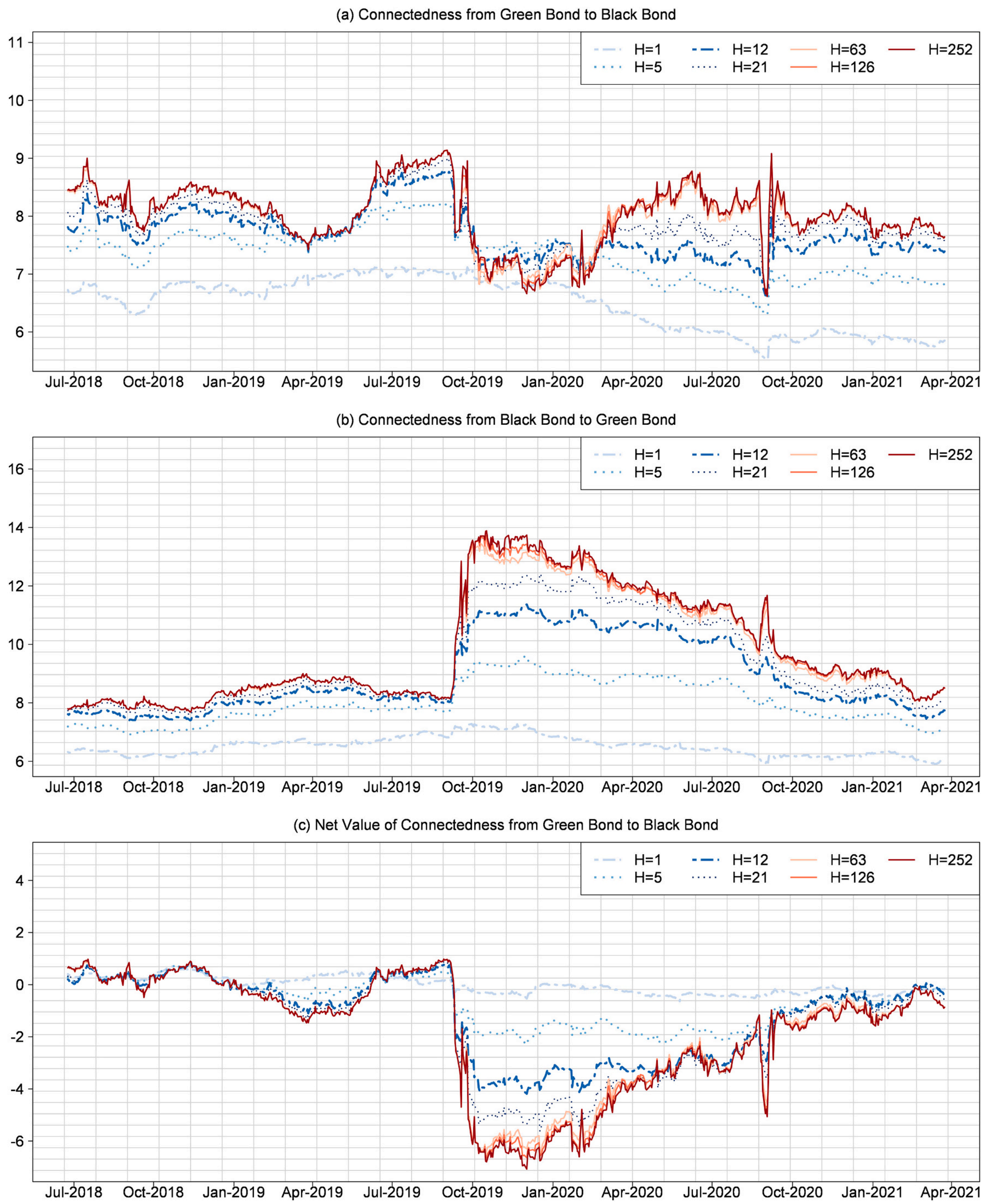

Fig. 6. Time-varying connectedness among green and black bonds with different horizons H. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Notes. The figures plot the dynamics of connectedness with different horizons, i.e., H = 1 day, 5 days (one week), 12 days (common-used horizon), 21 days (one month), 63 days (one season), 126 days (half a year), and 252 days (one year). The connectedness value is calculated by generalized variance decomposition in eq. (5–6), estimated by rolling window, with $T = 250$, $P = 1$, and rolling step = 1. The top figure shows the time-varying dynamics in the connectedness from all green bonds to all black bonds in our sample, while the second figure shows the connectedness in the opposite direction. The lowest figure shows the net value of the connectedness from green bonds to black bonds in our sample, which is obtained by taking the difference between the connectedness from green to black bonds and the connectedness from black to green bonds. The x-ticks show the midpoint of each rolling window, e.g., the value ticked at "Jul-2019" shows the result of window from Jan 2019 to Jan 2020.

2019, the green bonds suddenly took on the major role of deficit connectedness exporters. Meanwhile, the input connectedness of green bonds jumped dramatically, while the output connectedness weakened. Note that the x-ticks show the midpoint of each rolling window, e.g., the value ticked at Aug 2019 shows the estimation result of the window from Feb 2019 to Feb 2020. Since the rolling window means the inclusion of new date data and the exclusion of old date data, the time-varying changes of the connectedness always reflects the information around the start or end date of the rolling window. Therefore, with the newly involved date of Feb 2020 in the rolling window, the dramatic

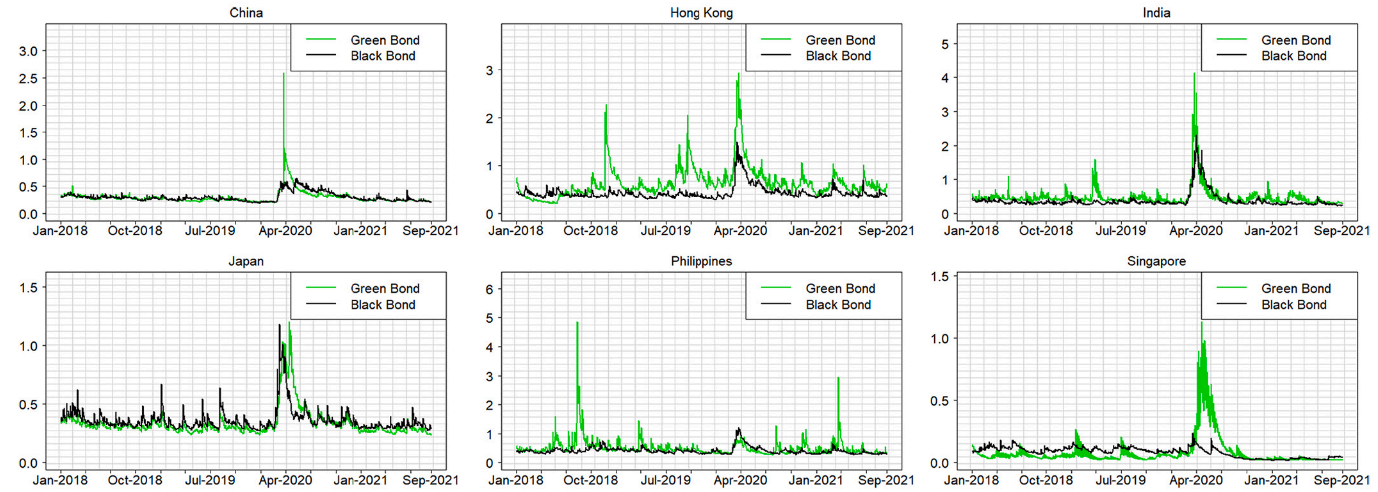

Fig. 7. Volatility for green and black bond in six countries and territories. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Notes. For each bond, the volatility, i.e., standard deviation of returns, is estimated by the ARMA (2, 2)-GJRGARCH (3, 3) model with Gaussian distribution which is selected based on AIC and post-test of standardized residual. The daily volatility for each bond is calculated first and then they are averaged by bond types in each country.

change of connectedness can be attributed to the data of the Covid-19 period.

From the dynamic connectedness presented in this figure, the sample period can be classified into three stages. The first stage is a period of small fluctuation from Jan 2018 to Feb 2020. Small fluctuation with policy changes and asset price adjustments is a normalcy of the financial markets. In this period, green and black bonds acted as the exporters of the net connectedness in turn. The net value of the connectedness from green bonds to black bonds is close to zero, indicating that green and black bondsplayed approximately equal role in term of connectedness exporter. This normalcy with equal role of green and black bonds is in line with Fig. 3 that shows the similar impacts of green and black bonds in the long term.

The second stage is the unbalanced period with a turning point of the Covid-19. The most striking feature is the increased gap of the connectedness exported by green and black bonds. It is observed that when the rolling window starts to involve the data of Covid-19, the magnitude of connectedness exported from black bonds to the green bonds jumped dramatically from approximately 7. 5 to 11. 4, while the magnitude of connectedness exported from green bonds to black bonds decreased from approximately 8. 8 to 7. 1. Comparing with Fig. A7 which shows the daily incremental covid cases, we see that the China's case number jumped in line with the hightened connectedness from green bond to black bonds in the whole of Asia. This evidence shows that the Covid-19 pandemic changes the pattern of green & black relationship, by enormously increasing the spillover risk from the conventional financial market to green bonds. The economic and business disruption caused by the pandemic rapidly reduced the market expectation of investors in all fixed-income assets. One possible explanation of the jumped connectedness exported from black bonds could be that the fixed-income assets in conventional financial markets will be the initial preferred investment as safe havens, and this may have caused the jumped price and volatility of black bonds. The higher priority of black bonds can be attributed to a lower risk profile and vulnerability as shown in Fig. 2. Then, with the price adjustment of the fixed-income assets in the conventional financial market almost complete, the other investors (possibly the impact investors) turn to select green bonds as safe-haven investment. The significant lead-lag relationship between the black and green bonds forms the jumped black-to-green connectedness and weakens the other direction.

The third stage is the recovery period after Oct 2020, with the role of green and black bonds recovered slowly to the equal status. As shown in Fig. 5 (c), the net value of connectedness from green to black bonds recovered from around −4 to zero. This result can be attributed to the fact that the price adjustment and correction caused by the reduced market expectation is now complete.[3] It means that the lead-lag relationship between the black and green bonds remitted, after the investors completed to seek safe-haven properties on a large scale. Furthermore, the significant disruptions caused by the dramatically increased demand for liquidity by corporate bond investors is likely to be alleviated by this time. In addition, there are frequent natural hazards and climate crises in 2020 and 2021, such as cyclones, landslides, heatwaves and volcanic eruptions. Because green bonds have higher environmental sensibility, it is plausible that the green bonds are being pencilled in to play the leading role of risk exporter to conventional financial market. During the new round of covid in April–June 2021 in India, there were short-term dramatic changes of connectedness inside all countries and regions. However, the impact of new round of covid in April–June 2021 on the green-black relationship is not as strong as the first round of Covid.

In line with by Diebold and Yilmaz (2014) and Demirer et al., (2018), the selection of connectedness horizon, H, should be in sync with the rebalancing period in portfolio management. The Fig. 6 plots the dynamics of connectedness with different horizons, i.e., H = 1 day, 5 days (one week), 12 days (common-used horizon), 21 days (one month), 63 days (one season), 126 days (a half-year), and 252 days (a year). It is worth highlighting that the green-to-black connectedness in longer term, such as 126 or 252 days, witnesses a faster and stronger recovery. Compared with the Fig. 5 (a) that shows a significant increase of green-to-black connectedness in the estimation window with the midpoint of Aug 2020, the Fig. 6 (a) gives evidence that the long-term impacts from green to black bonds started to climb up and approach to the pre-crisis level (around 8. 5) from the window with the midpoint of Feb 2020. This result suggests that the long-term influences of green bonds are relatively stable than the short-term influences. Consequently, it should be also stressed that for a particular portfolio with a long rebalancing period, the green bonds' risk exposure and spillover deserves greater attention.

[3] The level of market efficiency in a given country also play a role in this argument, however this has not been analyzed as it is beyond the scope of this paper.

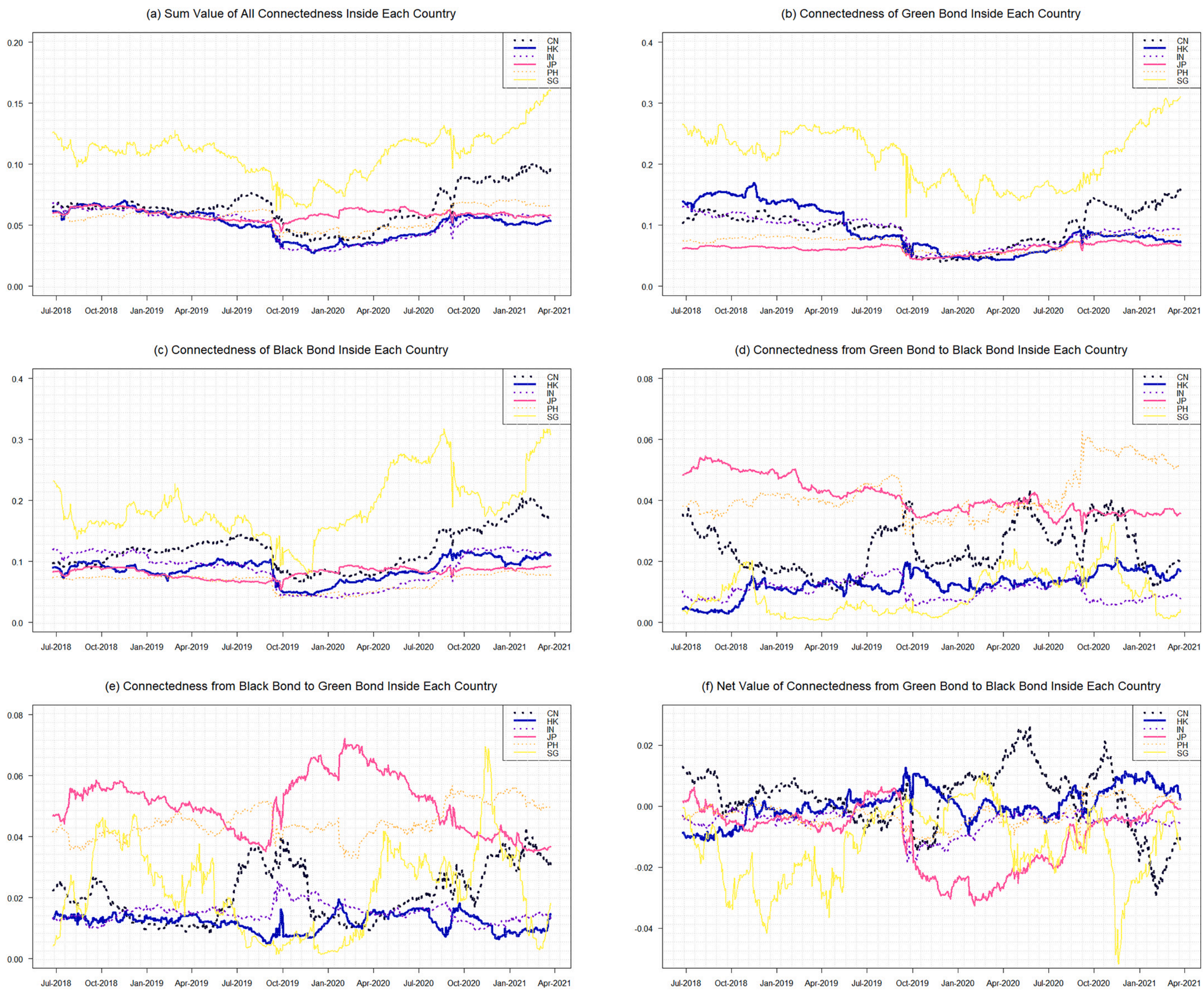

Fig. 8. Time-varying connectedness among green and black bonds in six countries and territories. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Notes. Countries of China Mainland, Hong Kong, India, Japan, Philippines, and Singapore are abbreviated to CN, HK, IN, JP, PH, SG. The connectedness value is calculated by generalized variance decomposition in eq. (5–6), estimated by rolling window, with $T = 250$, $P = 1$, H = 12, and rolling step = 1. The net value of the connectedness from green bonds to black bonds is obtained by taking the difference between the green-to-black and black-to-green connectedness in one country or territory. The x-ticks show the midpoint of each rolling window, e.g., the value ticked at "Jul-2019" shows the result of window from Jan 2019 to Jan 2020.

4.2. *Connectedness inside each country or territory*

In this subsection, we turn attention to the dynamics inside each country or territory that impact the investors' decision to invest in domestic green v. s. black bonds. We first look at the features of the risk profile for each country or territory, to understand the impacts of typical events in the environment, financial market, and economic conditions. Afterwards, we focus on domestic connectedness within the six countries and territories to gain a better insight into the directional connectedness among the green bond market and the conventional bond markets.

The Fig. 7 presents the volatility, i.e., standard deviation of returns, of green and black in six countries and territories. It shows that the risk profile of green and black bonds differ from country to country. In Hong Kong, India and Philippines, green bonds have higher levels of risk. Hong Kong is the territory which exhibits the most significant difference in terms of risk between green and black bonds. In Nov 2018 and Sep 2019, there were extreme risks for the green bonds in Hong Kong, while the risks of black bonds are relatively low. In Nov 2018, stock markets in Hong Kong crashed after a sharp sell off on Wall Street, because of fears that the historic rise in tech companies was coming to an end. The price of green bonds experienced a larger shock than black bonds, as shown in Fig. 1. The increased price indicates lower expectation of yields, lower risks, and higher safe-haven demands from investors (Kuang, 2021). When green bonds experience larger upward shocks than black bonds, the investor prefer to take a long position of green bonds as safe-haven assets, indicating a stronger confidence in green bonds. In Sep 2019, green bonds' price increased possibly coinciding with the political crisis effecting financial markets as short sellers took positions against Hong Kong, which is a flight in search of safe-havens. In Aug 2018, the stock market of the Philippines experienced a bear market. The higher volatility observed in green bond No.15 also shows a strong safe-haven preference of investors. The fluctuation of bond price in India in Mar 2019 could be attributed to the policy that stimulates foreign investors and overseas capital inflows (IIMA (Institute for International Monetary

Table 3
Drivers and investor implication of connectedness dynamics.

Connectedness type	Direction	Possible drivers	Short term investor implication	Long term investor implication
Green to Green	Increasing	• Significant change of market expectation • Green policy with wide impacts	• Decreased diversification benefits in green investment market • Pay attention to the spillover risk from other green bonds • If the change of market expectation is negative, majority of green bonds could be used as a potential hedge against economic weakness or deflation	• It is a possibility that green bonds are better safe-haven investments, as the green policy guarantees the low risk of green projects • If the change of market expectation is negative, majority of green bonds could be used as a potential hedge against economic weakness or deflation
Green to Green	Decreasing	• Green policy with narrow impacts • Crisis outbreak point, disorder market with market sell-off	• Increased diversification benefits in green investment market • Low spillover risk from other green bonds • Some of green bonds could be used as a potential hedge against economic weakness or deflation	• Investors should be cautious to select green bonds because their safe-haven ability and risk-return performance could be entirely different
Black to Black	Increasing	• Significant change of market expectation	• Decreased diversification benefits in black investment market. • Pay attention to the spillover risk from other black bonds • If there is a downward market expectation, make early safe-haven decision and take a long position, to get the benefit from the rapid increase of bond price	• Pay attention to the spillover risk from other black bonds
Black to Black	Decreasing	• Normal status of financial market with small fluctuations and small events • Crisis outbreak point, disorder market with market sell-off	• Increased diversification benefits in black bonds • Low spillover risk from other black bonds	• Investors should be cautious to select black bonds because their safe-haven ability and return-risk performance could be entirely different
Green to Black	Increasing	• Green policy • Post-crisis period	• Black investors should manage their risk by paying attention to green-related event.	• Long-term black bond investors should re-evaluate the black bonds' risk, by considering the environmental changes and green policy.
Green to Black	Decreasing	• Economic or financial recession • Rational investors and mature financial market	• Black bond is not vulnerable and could be used as diversification of green bonds • Black bond could be used as a potential hedge against economic weakness or deflation	• The black bond investors shouldn't worry about the environmental changes and green policy. • Black bond could be used as a potential hedge against economic weakness or deflation
Black to Green	Increasing	• Economic or financial recession	• Green investor can get quick hedging benefit in economic or financial recession	• Green investors should re-evaluate the green bonds' risk, by considering the economic and financial fluctuations.
Black to Green	Decreasing	• Green policy and increased confidence on green projects • Recovery period from an economic or financial crisis	• If it's in a post-crisis period, fixed-income asset may not be a good choice because the yield will increase and price will decrease.	• Conditional on green policy and increased confidence on green projects, green investments could be more attractive, with fewer risk exposure and imported risk. • If it's in a post-crisis period, fixed-income asset may not be a good choice because the yield will increase and price will decrease.

Affairs), 2020). As can be seen in Fig. 1 and Fig. 7, green bonds in India have faster price growth and higher volatility than black bonds. It shows a stronger willingness of foreign capital to invest in green bonds instead of conventional financial markets.

In Singapore and Japan, green bonds have lower levels of risk, which can be attributed to the lower yield of green bonds (Zerbib, 2019). It is observed that the risk of green bonds in Singapore have lower risk than black bonds most of the of time, while in the time point of Jan 2019, Aug 2019 and May 2020, the green bonds have relatively higher value of extreme risk. The flash crash in Jan 2019 and the stock market crash in Aug 2019 caused fear with the Singaporeian investors. The higher volatility of green bonds than black bonds reflects the higher price increase of green bonds shown in Fig. 1, which indicates the risk diversification role of green bonds that helps to shield and absorb the loss coming from the conventional financial market.

In China Mainland, there are similar levels of risks for green and black bonds, while in the beginning of the year 2020, the volatility of green bonds increased tenfold, perhaps as a result of the crisis of Covid-19. As shown in Fig. 1, the price of green bonds in China Mainland has a larger magnitude of increase than black bonds, indicating that China Mainland's green bonds also play the risk minimisation and safe-haven roles in certain circumstances.

Fig. 8 displays the dynamics of connectedness in six countries and territories. The subfigures (a), (b) and (c) present the dynamics of the internal connectedness in all-to-all, green-to-green, and black-to-black direction respectively. There are similar results as international connectedness shown in Fig. 5, providing evidence that the Covid-19 decreased the risk spillover magnitude inside each country and territory. The sample period is split into three stages, i.e., pre-covid, covid, and recovery period. In connectedness within one type of bond slumped due to the Covid-19, and then recovered gradually. The explanation is that the Covid-19 increased the proportion of the cross-national and cross-type (specifically, black-to-green) connectedness, and consequently reduced the proportion of connectedness in the domestic market and for the same type of bond. It suggests that if there is an impending global recession, the investors should pay more attention to the dynamics of cross-national and cross-type safe-haven assets, to make precautionary decisions, instead of reacting to the domestic changes in the bond market.

The subfigures (d) and (e) present the dynamics of the internal connectedness in green-to-black and black-to-green direction, and (f) presents the dynamics of net value of the connectedness from green bonds to black bonds obtained by taking the difference between the green-to-black and black-to-green connectedness in one country. Compared with Fig. 5, the new finding is that the Covid-19 have different impacts on the green & black relationship for different countries or territories. Countries of India, Philippines and Japan have similar dynamics as the Asia overall connectedness shown in Fig. 5, including the disruption of the equal black & green relationships in Covid-19 period and the recovery of green bonds' impact.

It can be observed that China Mainland also had equal green & black relationship before the covid crash, decreased green-to-green, black-to-black and black-to-green connectedness that caused by the Covid-19, and the recovered connectedness after the disruption. However, the green-to-black connectedness exhibits different characteristics in comparison to others. As can be seen, there are several peaks of green-to-black connectedness after 2020. These peaks are related to the green policy of China Mainland. For example, in Sep 2020, General Secretary Xi Jinping announced that China Mainland pledges to become carbon neutral before 2060 increased the impact of green bonds, shown by the rolling window results estimated with the midpoint of March 2020. It proves that the green policy will firstly cause the change of green bonds price and then spillover the impact to conventional markets.

In Hongkong, there was an unequal black & green relationship before Covid-19. Green bonds had lower impacts than black bonds in the beginning. Subsequently, the Hong Kong green bonds' impact gradually increased from 2018 to early 2019, becoming a dominant holder. When the Covid-19 spread heightened, the same disruption happened to the green-to-black connectedness. Finally, the leading role of green bonds recovered when covid risk was released.

In Singapore, black bonds dominate the spillover exporter. The green-to-black connectedness is lower than black-to-green bonds most of the time. The explanation is that the green bonds had lower volatility (as shown in Fig. 7), i.e., lower value of the source for spillover risk. In addition, Singapore is the country with best environmental performance following Japan, with low CO2 Emissions (Huang & Xu, 2020) and a long history of green policy (Azhgaliyeva et al., 2020; Chang, 2015). The limited risk exposure controls the spillover from the green bonds to black bonds at its source. Another finding is that the green-to-green and black-to-black connectedness in Singapore is higher than other countries, indicates a well-developed financial market and high systemic relationship in Singapore.

Finally, based on all of the empirical results in this paper, we summarize the possible drivers of connectedness changes, and provide some investor implications for diversification, hedging and safe-haven decision, and risk management, shown in Table 3.

5. Conclusion

This paper investigates the dynamic, complex interrelationship between Green vs Black investment in the Asian region including six countries and territories: China Mainland, Hong Kong, India, Japan, Philippines, and Singapore during the period from Jan 1st 2018 to Sep 15th 2021.

This paper presents a picture of the risk spillover relationship of green & black bonds in Asia. In normal situations and the long-term horizon, green bonds and black bonds have similar impacts with each other, with a slight predominance of black bonds. From the dynamic connectedness results, the sample period is classified into three stages. The first stage is a period with equal role of green and black bonds from Jan 2018 to Feb 2020, which is regarded as a normal situation of the bond market. The second stage is the unbalanced period with a turning point of the Covid-19, with the increased gap of the connectedness exported by green and black bonds. The third stage is the recovery period after Oct 2020, with the role of green and black bonds recovered slowly to the equal status. In addition, the green-to-black connectedness in longer term witnesses faster and stronger recovery, which suggests that the long-term influences of green bonds are relatively stable than the short-term influences. Moreover, the paper tests the effects of the same issuer. Our analysis shows that there are strong connections among bonds in the Philippines that are issued by the same institution. However, the same issuer is not a sufficient condition for a strong connectedness.

This paper characterizes the features of six countries and territories in terms of risk profile and connectedness. The results of risk profile of six countries and territories include: (1) In Hongkong, India and Philippines, green bonds have higher levels of risk; In Singapore and Japan, green bonds have lower levels of risk; In China Mainland, there are similar levels of risks for green and black bonds; (2) Although The green bonds have lower risk for some countries, in the presence of extreme financial risk (e.g., stock market crash), the green bonds always exhibit higher volatility. The higher risk of green bonds is found related to the risk minimisation and safe-haven roles to the risk of conventional financial markets. The country level findings show that: (1) Japan and Philippines are the major exporters of connectedness; (2) India, Philippines and Japan have similar dynamics as the Asia overall connectedness, including the disruption of the equal black & green relationships in Covid-19 period and the recovery of green bonds' impact. (3) In Hong Kong, there was an unequal black & green relationship before Covid-19. (4) In China Mainland, there are several peaks of green-to-black connectedness after 2020. These peaks are related to the green policy of China Mainland such as the target of carbon neutrality before 2060. It suggests that the green policy will firstly cause the change of green bonds price and then spillover the impact to conventional markets. (5) Singapore shows good risk minimisation capability and risk regulation, with the lowest level of both input and output spillover risks with other countries. Black-to-green spillover risk dominates the domestic connectedness, while the limited risk exposure controls the spillover from the green bonds to black bonds at its source. Another finding is that the domestic green-to-green and black-to-black connectedness in Singapore is higher than other countries, indicating a well-developed financial market and high systemic relationship in Singapore.

Our empirical findings are crucial for investors and policymakers future decisions and actions, especially regarding the "go green or stay black" investment decisions, as well as the acceleration of sustainable development and green investments. Accordingly, it is not appropriate to consider the green and black bonds as unrelated assets, or ignore the impacts from green to black bonds, as the stronger safe-haven properties of green bonds in crisis would be masked. For policymakers, evidence of green policy intensifies the dominant role and safe-haven of green bonds offers suggestions to stimulate green investment by proposing wide-range of green policy and setting bail-out mechanisms. As for investors, our analysis gives important insights for making decisions regarding risk management and return predictability under various market conditions. Regarding the drivers of the green & black connectedness, they would be useful to predict the risk spillover directions and help investors to get hedging benefits. Furthermore, time-varying risk spillovers matter to traders and portfolio managers who can make adjustments to their trading and investment positions according to various market states.

CRediT authorship contribution statement

Gazi Salah Uddin: Methodology, Software. **Ranadeva Jayasekera:** Conceptualization, Writing – review & editing. **Donghyun Park:** Supervision. **Tianqi Luo:** Data curation, Writing – original draft. **Shu Tian:** Supervision.

Data availability

Data will be made available on request.

Acknowledgements

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Appendix A. Figures of connectedness shown by countries and territories

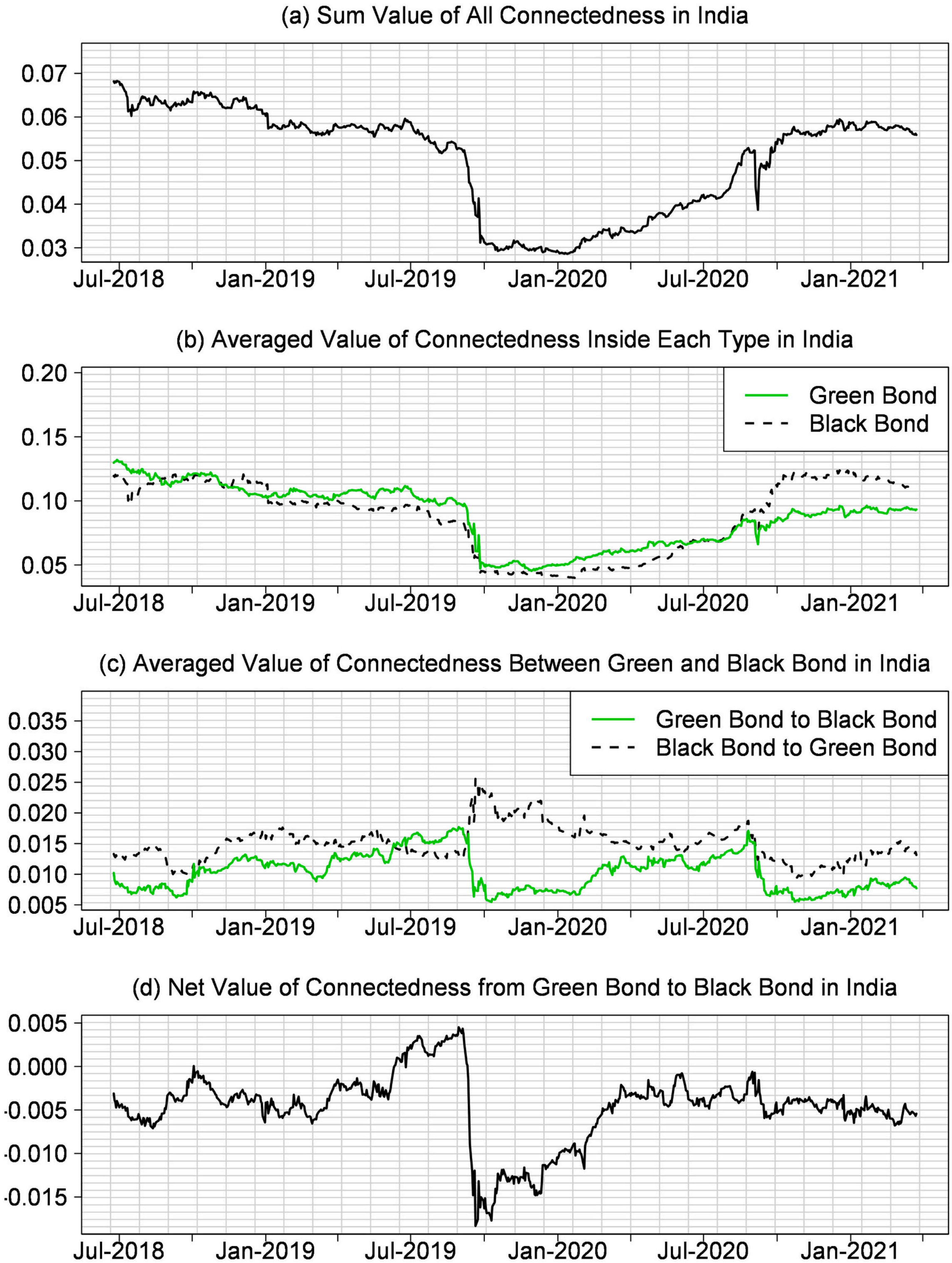

Fig. A1. Dynamic connectedness in India.
Notes. All subfigures show the time-varying dynamics in the connectedness in India. The connectedness is calculated by generalized variance decomposition in eq. (5–6), estimated by rolling window, with $T = 250$, $P = 1$, $\mathrm{H} = 12$, and rolling step = 1.

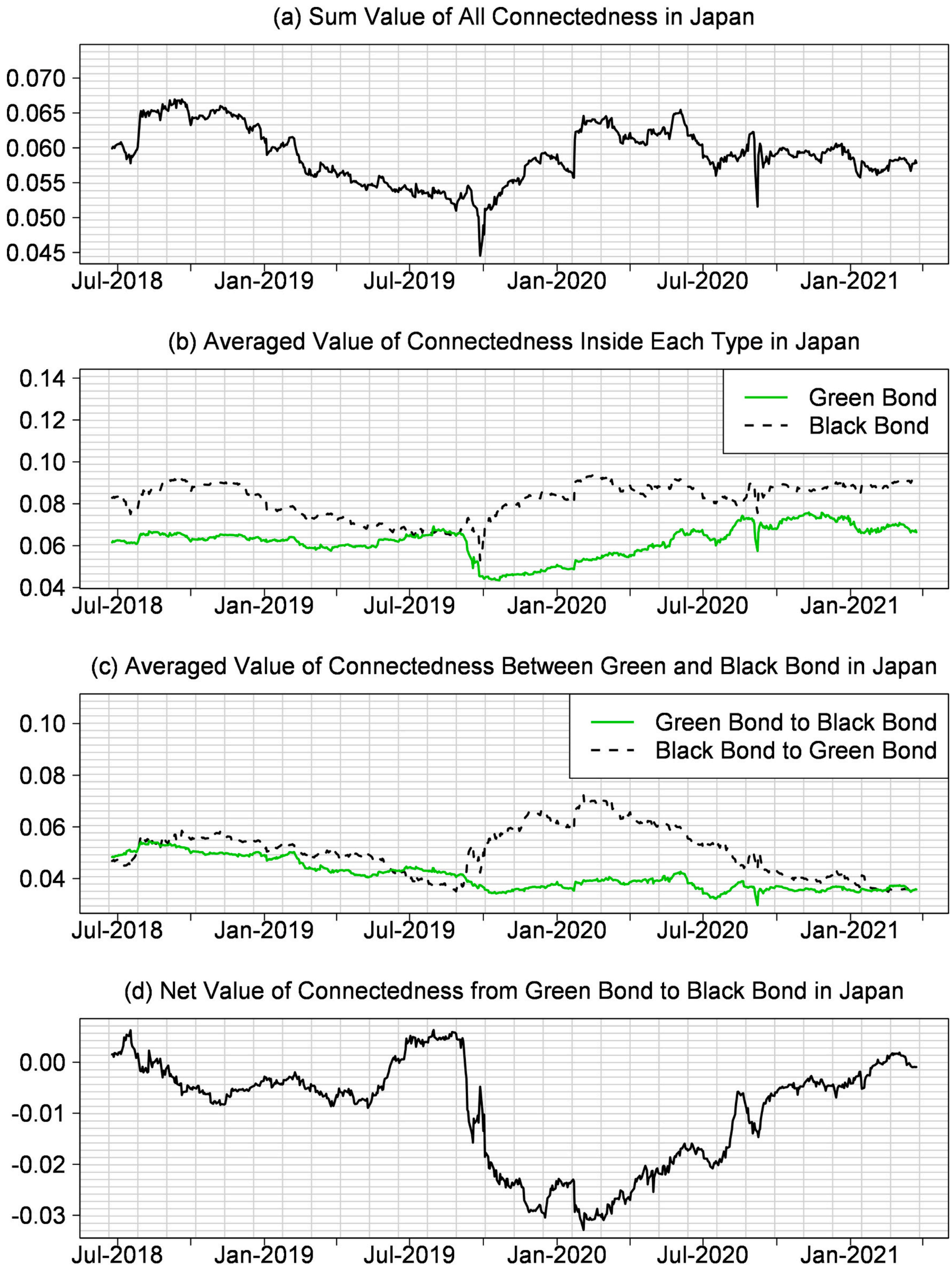

Fig. A2. Dynamic connectedness in Japan.
Notes. All subfigures show the time-varying dynamics in the connectedness in Japan. The connectedness is calculated by generalized variance decomposition in eq. (5–6), estimated by rolling window, with $T = 250$, $P = 1$, H = 12, and rolling step = 1.

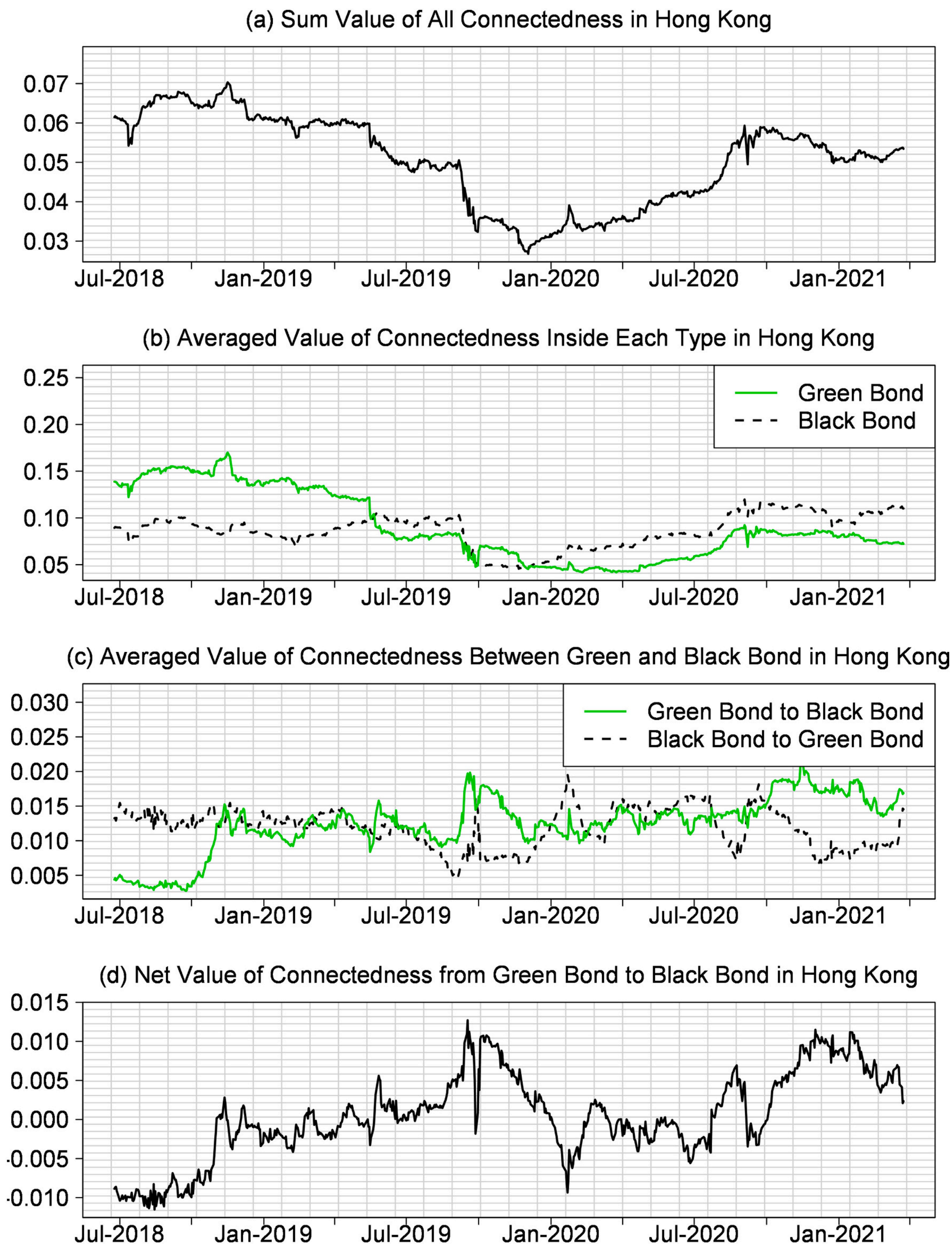

Fig. A3. Dynamic connectedness in Hong Kong.
Notes. All subfigures show the time-varying dynamics in the connectedness in Hong Kong. The connectedness is calculated by generalized variance decomposition in eq. (5–6), estimated by rolling window, with T = 250, P = 1, H = 12, and rolling step = 1.

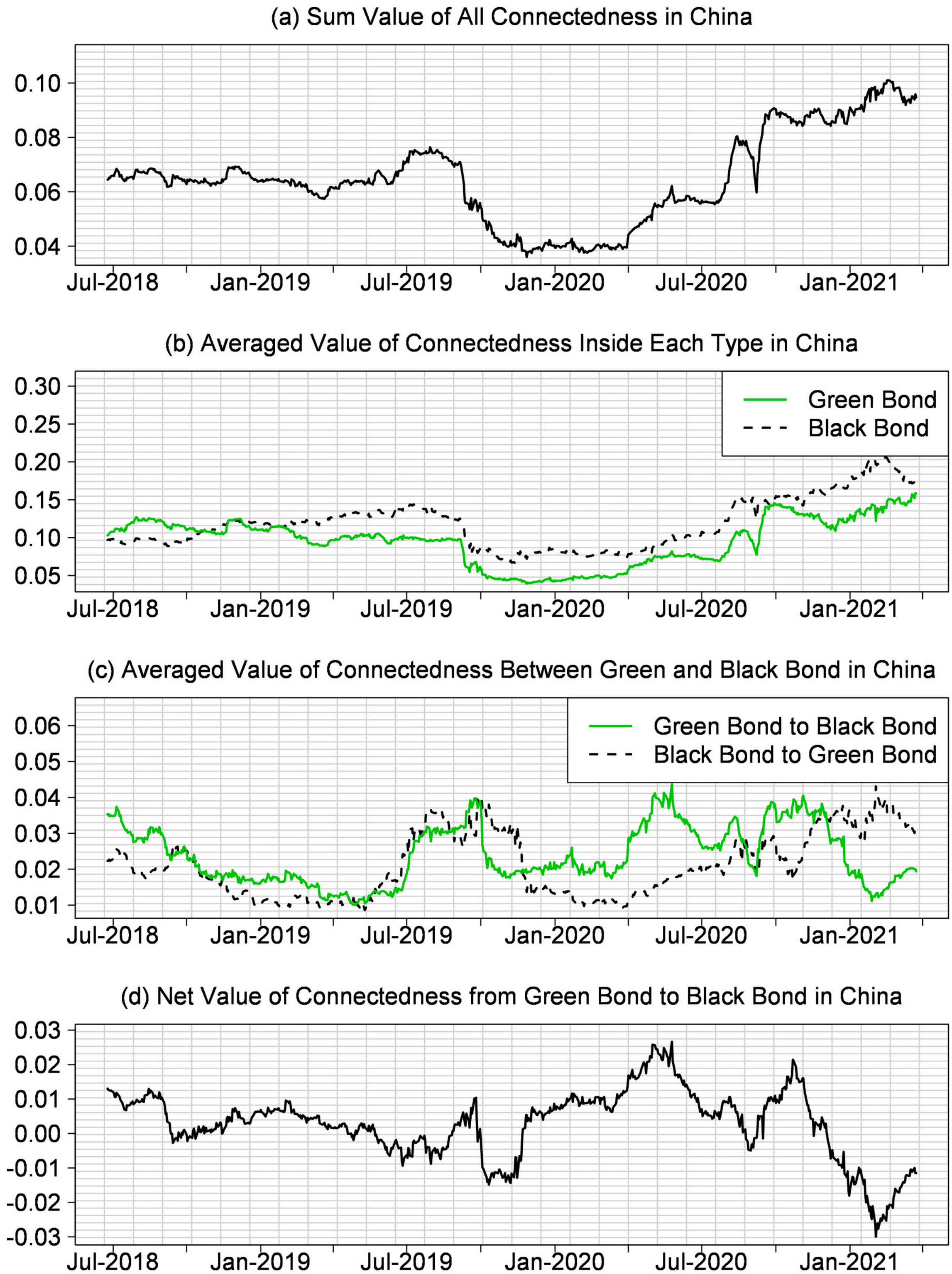

Fig. A4. Dynamic connectedness in China Mainland.

Notes. All subfigures show the time-varying dynamics in the connectedness in China Mainland. The connectedness is calculated by generalized variance decomposition in eq. (5–6), estimated by rolling window, with T = 250, P = 1, H = 12, and rolling step = 1.

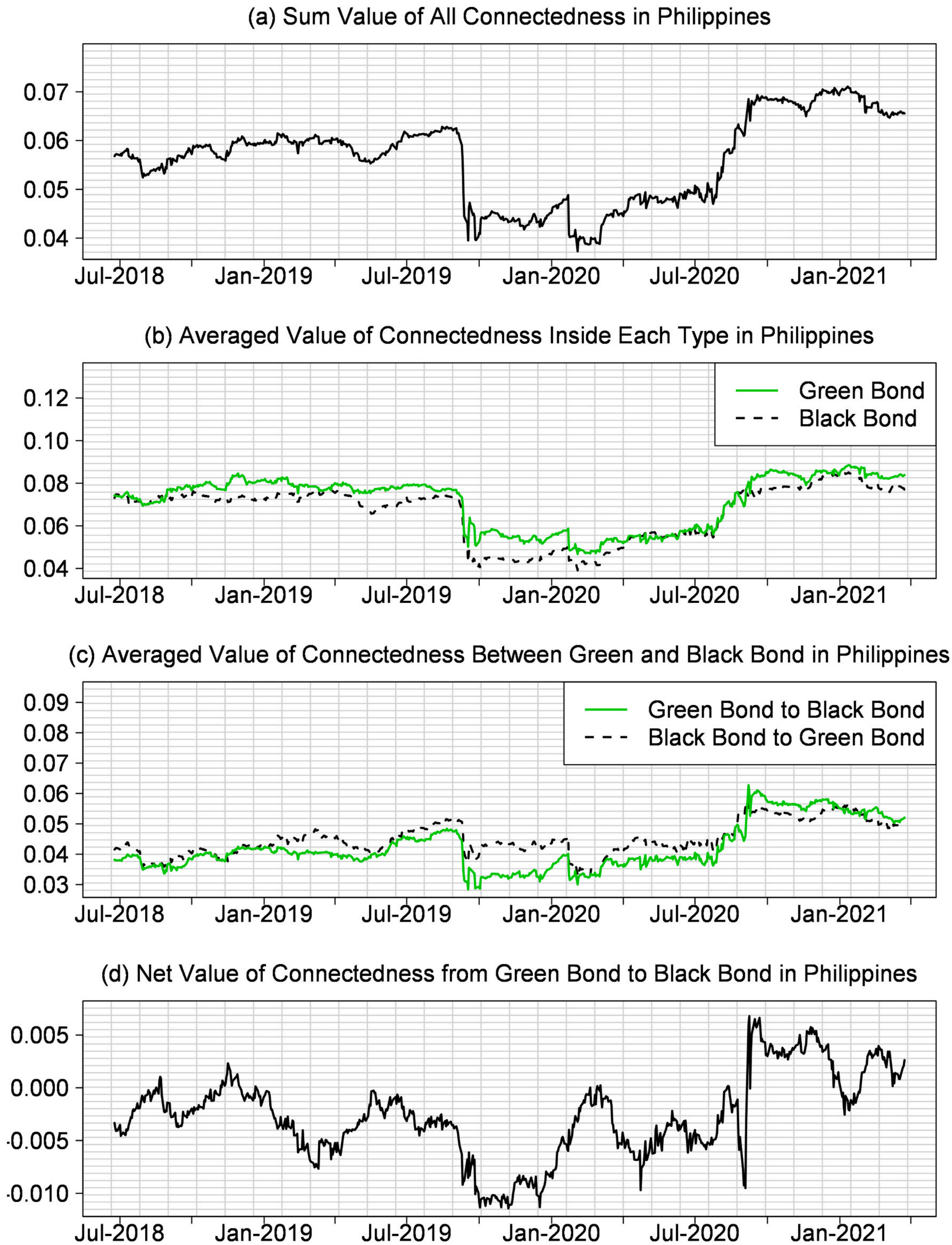

Fig. A5. Dynamic connectedness in Philippines.

Notes. All subfigures show the time-varying dynamics in the connectedness in Philippines. The connectedness is calculated by generalized variance decomposition in eq. (5–6), estimated by rolling window, with T = 250, P = 1, H = 12, and rolling step = 1.

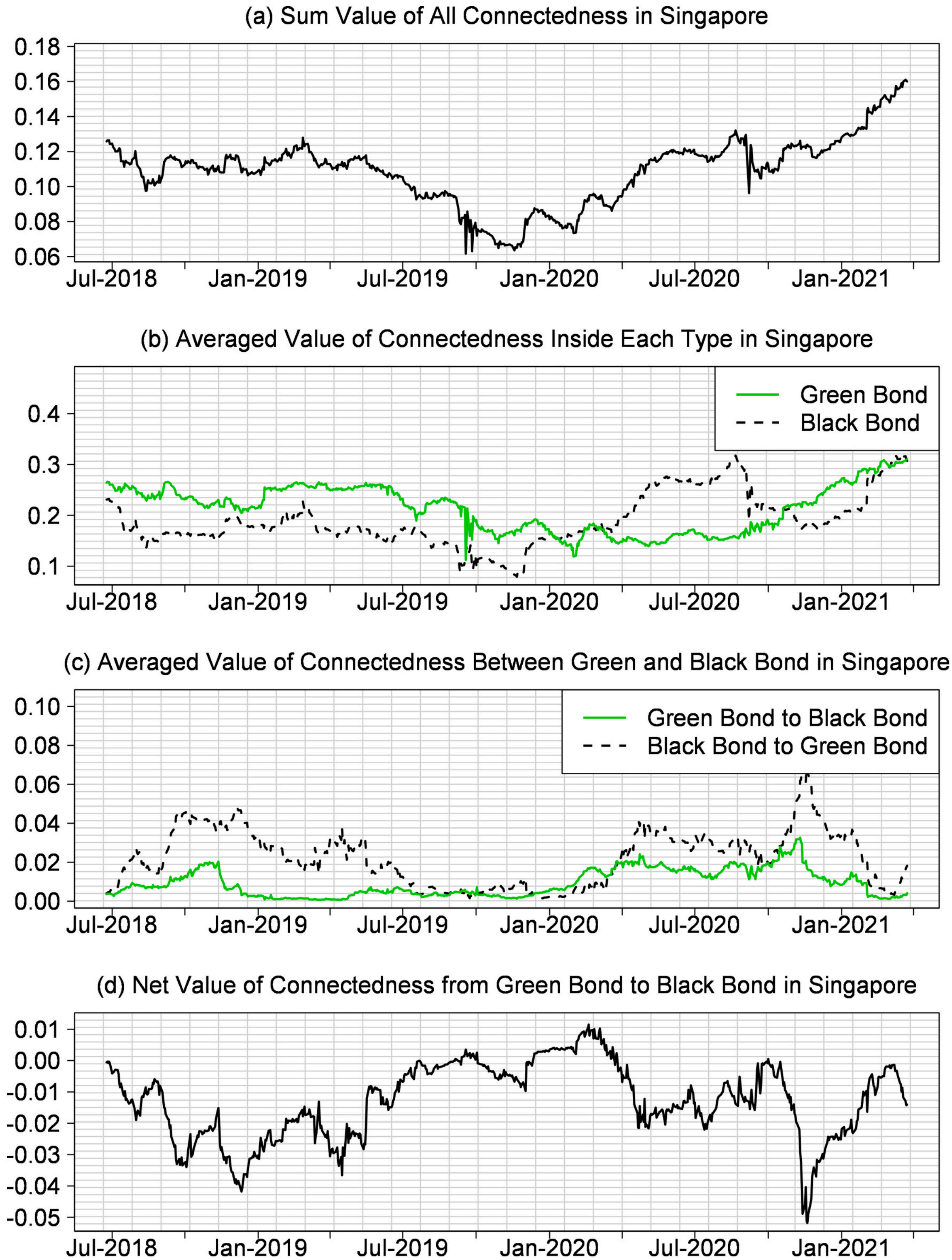

Fig. A6. Dynamic connectedness in Singapore.

Notes. All subfigures show the time-varying dynamics in the connectedness in Singapore. The connectedness is calculated by generalized variance decomposition in eq. (5–6), estimated by rolling window, with T = 250, P = 1, H = 12, and rolling step = 1.

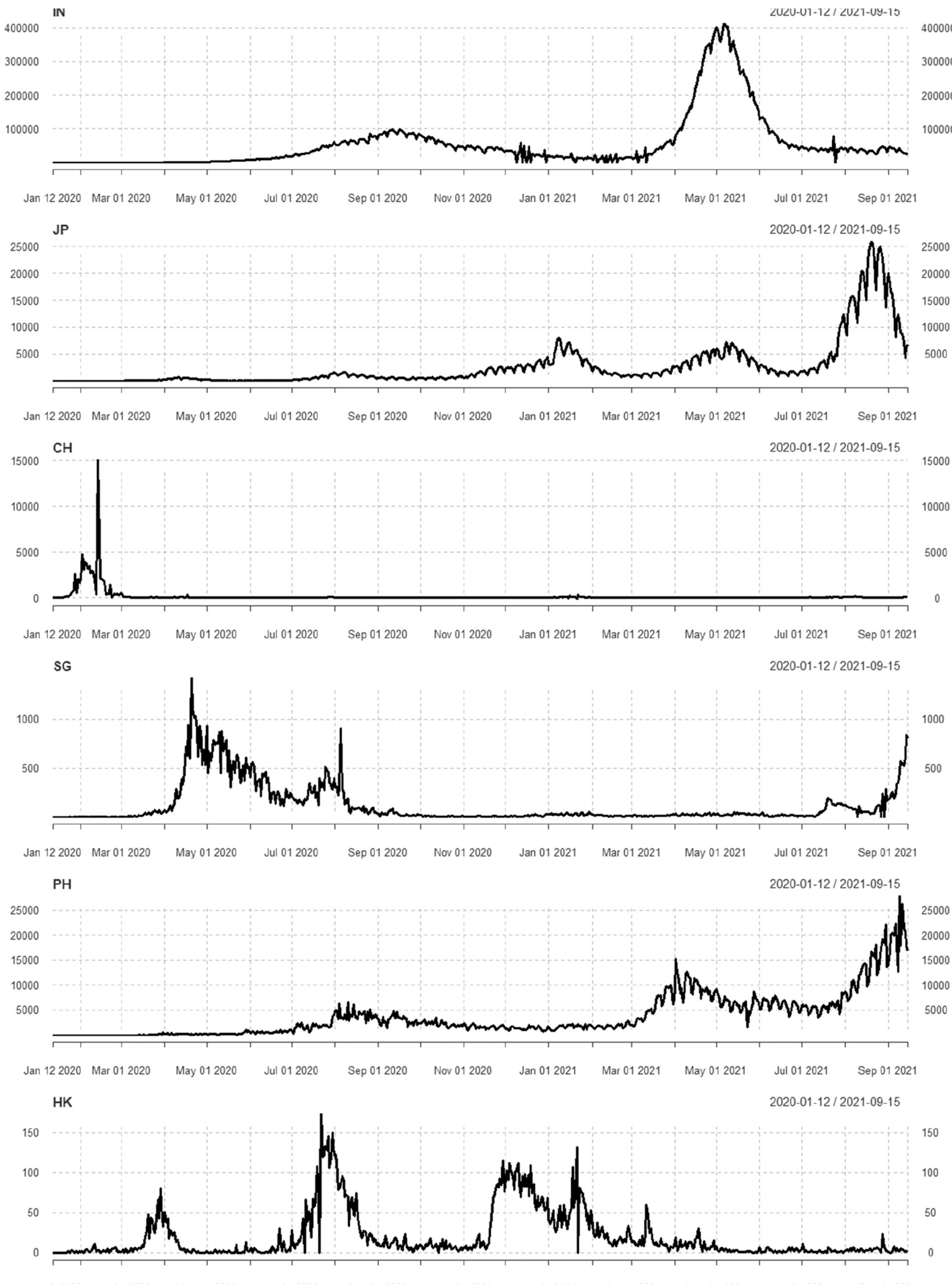

Fig. A7. The covid daily incremental case for 6 countries and regions.

Notes. Countries of India, Japan, China Mainland, Singapore, Philippines, and Hong Kong are abbreviated to IN, JP, CH, SG, PH, HK, downloaded from Bloomberg Database.

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