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Price Co-Movement between Electrical Equipment and Metal Commodities—A Time-Frequency Analysis

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Abstract: The rising uncertainty of the global markets has caused the price fluctuation of the equipment and materials in PT&D (Power Transmission and Distribution) projects to be more complicated. As the cost of equipment and materials accounts for a large proportion of the total investment of the PT&D projects, this study investigates the co-movement of the equipment and materials price and metal commodities' price with the use of wavelet coherency and partial wavelet coherency analysis under a time-frequency framework. Our results indicate that (i) the co-movement manifests mainly in the short term and long term; (ii) there is no clear lead-lag relationship in the co-movement; (iii) the short-term co-movement is activated by the continuous rising of metal commodity price; (iv) the long-term co-movement is largely driven by the overall market price movement, but this effect is weakened when the metal is of high importance in producing the equipment. Our study shed light on the planning and investment in the PT&D projects for both the purchase and production sides.

Keywords: wavelet; power transmission and distribution; price co-movement; time-frequency analysis

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1. Introduction

Due to black swan events such as the Sino-US trade war, the COVID-19 pandemic and the Russia-Ukraine conflict, the rising uncertainty of the global markets has caused the price fluctuation of the equipment and materials in PT&D (Power Transmission and Distribution) projects to be more drastic and elusive [1]. PT&D is one of the most important components of the energy infrastructure for a country [2,3]. For example, it is reported that China's State Grid invested over 500 billion yuan (74.5 billion dollars) in PT&D projects in 2022 (data from the government website of China). As the generating capacity of wind and solar power rises, PT&D, as the infrastructure, plays an increasingly important role in energy transition and conservation, CO_2 emission reduction, and carbon neutralization [2,4].

In the investment of PT&D projects, the cost of equipment and materials accounts for the majority of the total investment and thus has a great influence on the implementation of the projects [5]. The market price fluctuation of the equipment and materials will induce a great impact on the procurement and resource supply of the PT&D projects and further affect the construction of the projects [6]. Thus, understanding the market trend of critical equipment and materials for PT&D can stabilize PT&D investments. Furthermore, the critical equipment and materials are, in substance composition, mostly made of aluminum, copper, and steel. Specifically, the price of the PT&D equipment is affected by the cost of production, and the cost of raw materials (i.e., metals listed above) is the important composition of the cost of production. Thus, although the industrial product market and commodity market are two distinct systems, they interact with each other through value transfer [7]. Besides, the future market serves as a well-performed predictor for the real economy [8]. For example, Tule et al. [9] use agricultural commodity prices to predict inflation. Reboredo [10] focuses on the price co-movement between oil and agriproducts. Idrovo-Aguirre and Contreras-Reyes [11] study the effect of copper commodity price shock on the housing construction industry. In this context, the price co-movement of the critical equipment (and materials) and metal commodities can be predictive in capturing the price fluctuation trend of the equipment (and materials) for PT&D projects.

On the topic of price co-movement, the wavelet theory has been commonly accepted, especially in financial and commodity markets [12,13], energy markets [14,15], and interdisciplinary fields [16,17] to capture such co-movement. It decomposes the co-movement relationships from the multi-scale time-frequency perspective. Different scales in frequency incur different effects on the co-movement in terms of strength and lead/lag relations. For example, Pappaioannou et al. [18] conduct a wavelet analysis to investigate the price co-movement between the Italian and Greek electricity markets. They have pointed out that the wavelet method outperforms traditional approaches of dynamic correlation and cohesion by revealing the informative interdependencies between the two markets. The results indicate that the co-movement manifests at lower frequencies only for a certain period of time and is driven by material policy and operation change. Pal and Mitra [19] study the price co-movement between crude oil and food from a time-frequency perspective. They demonstrate the co-movement relationship and the leading position of crude oil prices. Goodell and Goutte [20] apply a wavelet coherence method on the co-movement between COVID-19 world deaths and Bitcoin prices and discuss whether Bitcoin can be a safe haven under such a risk environment. The above literature shows that the wavelet method is widely adopted to analyze co-movements between two distinct markets.

Therefore, we investigate the co-movement of the equipment and materials price and metal commodity price with the use of wavelet coherency (WTC) and partial wavelet coherency (PWC) analysis. Firstly, the critical equipment and material in PT&D projects are recognized as well as the major metal commodities. Then, the WTC analysis is conducted followed by the PWC with a focus on the overall market price movement. By discussing the effectiveness of metal commodity price as the warning factor under different times and frequencies for critical equipment and materials in PT&D projects, this study offers advice and implications to policymakers and industry practitioners. We believe that this is the first paper focusing on the price co-movement between power grid equipment and related metal commodities with first-hand data. Besides, current studies involving commodity price co-movements mainly focus on the cross-asset price transmission or co-movement, while the multi-scale price co-movement characteristics between commodities and products are still unknown. Our study fills in the gap by investigating the multi-scale characteristics of price co-movement between metal commodities and PT&D equipment. Furthermore, since price co-movement between commodities and products is investigated from the perspective of the industrial chain [21], prior studies often ignore controlling the effect of overall economic factors. Our study conducts the PWC analysis controlling for the Producer Price Index (PPI) and finds that the price co-movement is highly driven by the overall economic fundamentals in the long term.

This study contributes to the industry by providing a management tool to understand and monitor the market trend of PT&D equipment on short and long scales. On the procurement side, it is beneficial and urgent to make PT&D equipment prices foreseeable. Apart from saving the purchase cost, it offers an early warning of potential default or contractual risk on the supply side. In fact, when the market prices rise dramatically, it breeds the risk that suppliers or manufacturers of equipment are likely to breach the signed contracts for higher profits. It leads to the PT&D projects being unable to obtain sufficient supplies. On the manufacturing side, monitoring the price fluctuation of their products can help to schedule and adjust production and thus improve profits.

The rest of this paper is organized as follows. Section 2 recognizes the critical equipment and materials in PT&D projects based on project classification and material intensiveness. Section 3 selects the most related metal commodities. In Section 4, the WTC and PWC method are introduced. In Section 5, the wavelet results are presented and analyzed as well as a robustness check. In Section 6, we summarize and discuss the findings, and propose managerial implications for both the procurement and production sides. In Section 7, the conclusion is presented.

2. Recognition of Critical Equipment and Materials in PT&D Projects

The data is acquired from the State Grid Corporation of China (SGCC). The prices of the equipment and materials for PT&D are extracted from the historical procurement records of SGCC between June 2014 and Dec 2020 (78 months in total). The PT&D projects can be categorized into three classes, namely, Substation Construction, Overhead Transmission Construction, and Cable Line Construction. According to The General Cost Of Power Transmission And Transformation Project Of State Grid Corporation Of China, we take typical designs for different project classes. For every typical design, the cost composition is presented based on every piece of equipment and material. As well, for the major equipment and materials, we further divide them into technology-oriented equipment and material-intensive equipment. Compared to technology-oriented equipment, material-intensive equipment has a larger correlation to metal raw materials. Through the above process, we finally recognize five different pieces of equipment and materials as listed below in Table 1.

Table 1. Five Critical Equipment and Materials for PT&D.

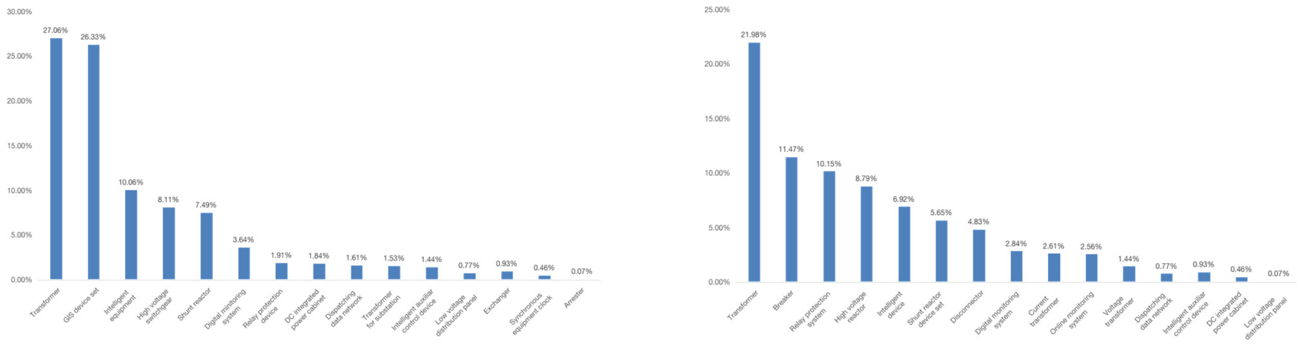
PT&D Projects	Critical Equipment and Materials
Substation Construction	Transformers Shunt reactors
Overhead Transmission Construction	Tower materials Steel strands Steel-aluminum conductors
Cable Line Construction	Cable lines

2.1. Substation Construction

For the substation construction projects, we choose two typical designs, namely, 220 kV A3-1 module and 500 kV C-1 module. The purchase costs of the components of these two typical designs are exhibited in Figure 1. As the figures have shown, the total cost of the major equipment of the substation construction projects accounts for about 50% of the total project investment (48.56% for the 220 kV A3-1 module and 51.72% for the 550 kV C-1 module), thus is imperative in the project investment. For the equipment in large proportions, we further divide them into technology-oriented equipment (such as intelligent equipment, computer monitoring systems and relaying protection equipment) and material-intensive equipment (such as transformers and shunt reactors). Since technology-oriented equipment is the integration of produced products, the price of raw materials does not have a large impact. Thus, we leave the technology-oriented equipment outside the investigation.

2.2. Overhead Transmission Construction

For the overhead transmission construction projects, we take the 220 kV 2C2-P module as the typical design. The cost of major materials accounts for 65% of the overhead transmission construction project, which has a large impact on the project investment. The 220 kV 2C2-P module consists of tower materials, conductors and other materials. More specifically, the conductors and the tower materials are of the largest (44%) and the second-largest proportions (37%) respectively, while other materials, including insulators, accessories and foundation bolts, are of a relatively small proportion (19%) in cost. Thus, we choose the tower materials and the conductors as the critical materials for PT&D projects.



(**a**) for 220kV A3-1 module (**b**) for 500kV C-1 module

Figure 1. Purchase price of the major equipment for 220 kV A3-1 module and 500 kV C-1 module. The left subfigure (**a**) is for the 220 kV A3-1 module's cost composition and the right is for the 500 kV C-1 module. These two modules are both typical designs of substation construction projects.

2.3. Cable Line Construction

For the cable line construction projects, the major varieties of centralized procurement by State Grid Corporation of Chinn include the cable lines, the cable terminals, the cable joints, the grounding boxes and the arresters. Among the above equipment and materials, the cable lines account for the majority of the total project investment at 80%, while the rest takes around 20% whose price fluctuation does not have a large impact on the project investment and thus is considered in our study.

3. Selection of Related Metal Commodities

According to the physical components of the critical equipment and materials listed above, we select three metal commodities, namely aluminum (AL), copper (CU) and deformed steel (RB). To obtain a sufficient time series of the prices for those metal commodities, we choose to use the price data from the Shanghai Futures Exchange. We extract the monthly average prices of 78 observations from June 2014 to December 2020.

The reason for choosing monthly data is that the procurement cycle of SGCC is in months. Thus, the time interval of the metal commodities should be the same.

4. THE Multi-Scale Wavelet Methodology

The wavelet is an effective method for the multi-scale time-frequency analysis of the nonlinear time series. The main body and concept of the theory were proposed by Morlet in the 1980s [22], which now has been widely adopted in financial and signal processing areas for its strong capability of extracting the local characteristics in different scales and frequencies.

4.1. Continuous Wavelet Transform (CWT)

The wavelet function $\psi_{\tau,s}(t)$ is established both on time and frequency as the following equation:

$$\psi_{\tau,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right). \tag{1}$$

In the equation, τ represents the time scale and s represents the frequency scale. $\frac{1}{\sqrt{s}}$ is a standardized measure of the wavelet transform to make it comparable.

The wavelet transform contains both the father wavelet $\varphi(t)$ and the mother wavelet $\psi(t)$ to act as a filter for the time series X_t. The father wavelet $\varphi(t)$ represents the trend components ($-\int \varphi(t)dt = 1$). And the mother wavelet $\psi(t)$ represents the high-frequency detail components ($-\int \psi(t)dt = 0$).

The Morlet wavelet is the most commonly used basis function which is defined as follows:

$$\psi_{\tau,s}(t) = \pi^{-\frac{1}{4}} e^{js_0 t} e^{-\frac{1}{2}t^2}. \tag{2}$$

According to Gençay et al. [23], we can use the mother wavelet $\psi(t)$ to reconstruct a time series X_t from its wavelet transform $W^X_{\tau,s}$ as follows:

$$x_t = \frac{1}{C_\psi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right)W^X_{\tau,s}d\tau\frac{ds}{s^2}. \tag{3}$$

Furthermore, the CWT of a discrete sequence x_t is defined as below:

$$W^X_{\tau,s} = \frac{1}{\sqrt{s}}\sum_{t=1}^{N} x_t\psi_0\left[(t-\tau)\frac{d\tau}{s}\right]. \tag{4}$$

The wavelet power spectrum (WPS) of a time series X_t can be defined as $\left|W^X_{\tau,s}\right|^2$ [24]. Therefore, the cross-wavelet power spectrum of two time series X_t and $Y_t(\left|W^{XY}_{\tau,s}\right|^2)$ and the phase difference $\Phi^{XY}_{\tau,s}$ can be constructed as below:

$$\left|W^{XY}_{\tau,s}\right|^2 = \left|W^X_{\tau,s}\right|^2\left|W^Y_{\tau,s}\right|^2 e^{j\Phi^{XY}_{\tau,s}}. \tag{5}$$

4.2. Wavelet Coherence (WTC)

The WTC presents the advantage of being normalized by the power spectrum of two time series [25], which allows us to identify the lead-lag relations and might be considered as the local correlation of the two time series both in time and frequency. As proposed by Torrence and Webster [26], the WTC of two time series with $W^X_{\tau,s}$ and $W^Y_{\tau,s}$ respectively is as below:

$$R^2_{\tau,s} = \frac{\left|S\left(s^{-1}W^{XY}_{\tau,s}\right)\right|^2}{S\left|\left(s^{-1}\left|W^X_{\tau,s}\right|^2\right)\right| \times S\left|\left(s^{-1}\left|W^Y_{\tau,s}\right|^2\right)\right|}. \tag{6}$$

In the equation, S is the smoothing operator that ascertains the balance between significance and resolution.

4.3. Partial Wavelet Coherence (PWC)

To remove the third-party effect on the relation between two time series, the PWC is proposed and exploited [27–29]. Here we have three time series X_t, Y_t and Z_t, while Z_t is the third-party variable affecting the relation between X_t and Y_t. The preparatory calculations are presented below.

$$R(Y,X) = \frac{S\left(s^{-1}W^{YX}_{\tau,s}\right)}{\sqrt{S\left|\left(s^{-1}\left|W^Y_{\tau,s}\right|^2\right)\right| \times S\left|\left(s^{-1}\left|W^X_{\tau,s}\right|^2\right)\right|}}, \tag{7}$$

$$R^2(Y,X) = R(Y,X)\cdot R(Y,X)^*, \tag{8}$$

$$R(Y,Z) = \frac{S\left(s^{-1}W^{YZ}_{\tau,s}\right)}{\sqrt{S\left|\left(s^{-1}\left|W^Y_{\tau,s}\right|^2\right)\right| \times S\left|\left(s^{-1}\left|W^Z_{\tau,s}\right|^2\right)\right|}}, \tag{9}$$

$$R^2(Y,Z) = R(Y,Z)\cdot R(Y,Z)^*, \tag{10}$$

$$R(Z,X) = \frac{S\left(s^{-1}W^{ZX}_{\tau,s}\right)}{\sqrt{S\left|\left(s^{-1}\left|W^Z_{\tau,s}\right|^2\right)\right| \times S\left|\left(s^{-1}\left|W^X_{\tau,s}\right|^2\right)\right|}}, \tag{11}$$

$$R^2(Z,X) = R(Z,X)\cdot R(Z,X)^*. \tag{12}$$

Based on the above calculation, the PWC is then computed as below.

$$RP^2(X,Y,Z) = \frac{\left|R(Y,X) - R(Y,Z)\cdot R(Y,X)^*\right|^2}{[1-R(Y,Z)]^2[1-R(X,Z)]^2}. \tag{13}$$

Then, we use the biwavelet package in R as the tool to realize the WTC and PWC process. It is a mature toolkit for wavelet transformation and wavelet coherency. The results of the calculation are presented in the following sections.

5. Results

Here we present the results in the following figures. For each figure, there are three subfigures representing the price co-movement between a certain type of equipment and metal commodity. In each subfigure, the top part is the PWC result, the middle part is the WTC result, and the bottom part is the price movements of each metal commodity. For the WTC and PWC results, the area with more vivid colors is the cone of influence (COI). The white contour inside the COI in each figure is the 5% significant level for the lead-lag relations. The area outside the COI is of no statistical significance. The horizontal axis is the time period (78 observations of the two time series from June 2014 to December 2020). The vertical axis is the scale of frequency (period in months in the figures), ranging from the short run (1- to 2-month cycle) to the medium run (2- to 8-month cycle), and the long run (8- to 16-month cycle). The color bar located on the right side of each figure indicates the extent of the co-movement relationships between the price for each critical equipment/material and the price for each metal commodity. The blue color represents a low co-variance, while the red color represents a high co-variance. The arrows inside the COI represent the lead-lag relations or otherwise called phase difference. The meanings of the different directions of arrows are concluded below in Table 2. The boxes with different colors exhibit different price movement phases of each metal commodity. The analysis of each figure is structured as follows: (1) WTC co-movements and lead-lag relations; (2) PWC co-movements and lead-lag relations; (3) differences of co-movements between WTC and PWC with respect to the price movement phase of metal commodities.

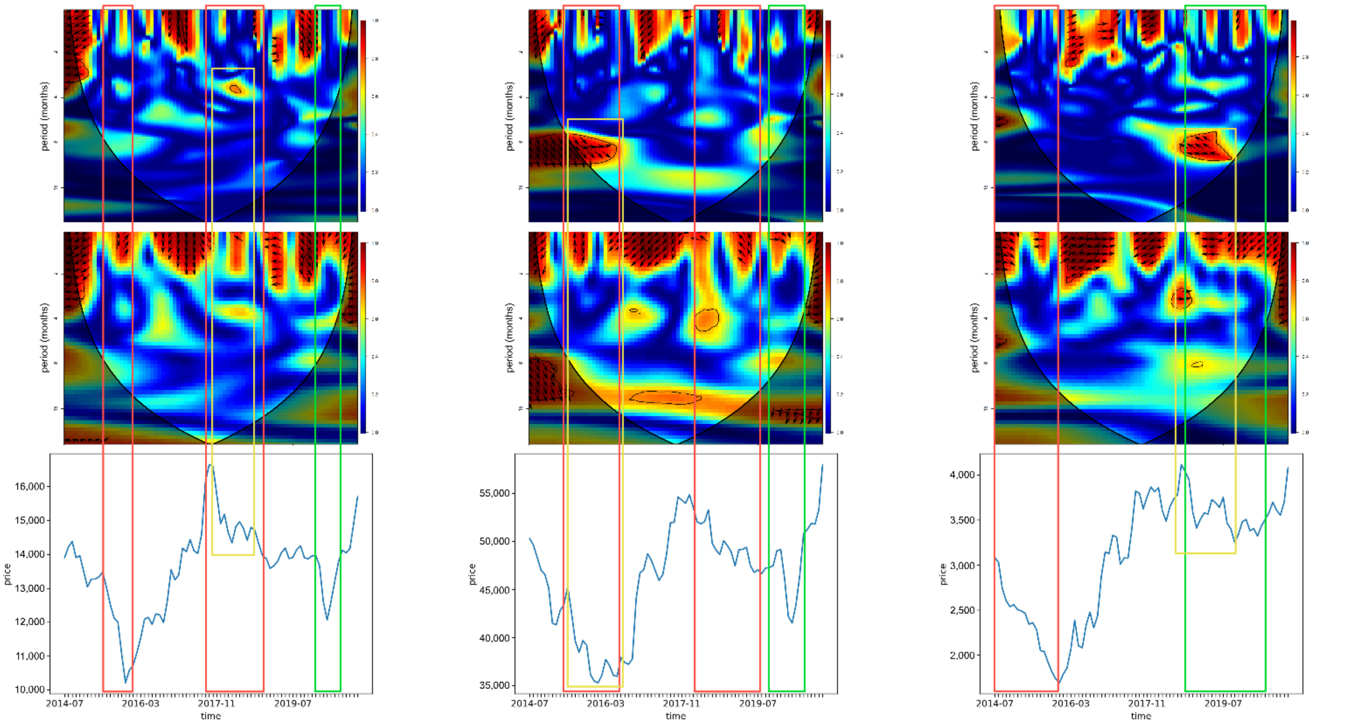
Table 2. Meanings of arrows in the figures of WTC and PWC results.

Direction of Arrow	Lead-Lag Representation
To the right	In phase.
To the right and up	Commodity price is lagging.
To the right and down	Commodity price is leading.
To the left	Out of phase.
To the left and up	Commodity price is leading.
To the left and down	Commodity price is lagging.

Since the price evolution of metal commodities and equipment & materials for the PT&D projects is highly correlated to the overall industry and market volatility environment, it is necessary to control and remove the effect of the external environment in order to investigate whether and to what extent the price co-movement is affected by the overall market price movement. Thus, in this section, we apply the PWC analysis controlling for the effect of the Producer Price Index (PPI), that is, we remove the third-party effect of the PPI.

5.1. Price Co-Movement between Transformers and Metal Commodities

For WTC results of the transformers and price of metal commodities (Figure 2), we see that co-movements take place in the short (1- to 2-month cycle) and long run (8- to 16-month cycles). As for the medium run (2- to 8-month cycle), the co-movements only manifest for several periods of time. Besides, the short-term co-movements manifest cyclically, while the long-run co-movements manifest continuously. The results can be explained by the fact that the critical equipment and materials price co-movements are driven by macro fundamentals and short-term fluctuations. The impact of short-term fluctuations is time-sensitive and declines with the passage of time, while the impact of long-term macro fundamentals has a continuous effect. Furthermore, the long-term co-movements are only observed in CU and RB, which indicates the heterogeneity of these metals' function and importance in producing transformers.



(**a**) Transformers—AL (**b**) Transformers—CU (**c**) Transformers—RB

Figure 2. Co-movement between the price of transformers and the price of metal commodities.

When we evaluate the lead-lag relations, we notice that only for several small islands the relations are significant at 5%. For instance, in the case of the transformers—AL pair, we observe that the metal is lagging in the short run in 2019, but the relations only show up in 2019 for a short interval. Thus, no clear lead-lag relations exist in the pair of transformers—AL. In the case of transformers—CU, no clear lead-lag relations exist. In the cases of transformers –RB, we observe that the metal is leading on a short scale in 2016.

Similar to the WTC section, the PWC section includes an analysis of the same set of equipment, materials, and metal commodities. For the transformers and price of metal commodities, the scales and time intervals manifesting co-movements are reduced, which indicates that the PPI does have a remarkable third-party effect on the co-movement relations.

First, in all three pairs, we see that co-movements only take place in the short run. Thus, in this case, the price co-movements between transformers and aluminum, in the long run, are largely driven by the movements of PPI (i.e., the overall market price level received by producers). Besides, it appears that the short-term co-movements are covered by that in the medium and long term. After removing the effect of PPI volatility, the short-term price co-movements only show up in several time intervals such as 2014 and 2017. Second, in the pair of transformers—CU, besides the major short-run co-movements, long-run co-movements are still manifested but mainly between 2015 and 2016 instead of a continuous period. Third, in the pair of transformers—RB, the co-movements take place on a long scale only between 2018 and 2019. Fourth, there are no clear lead-lag relations in the case of CU and RB on the short scale, while in the case of AL, the metal is still lagging in 2019. Besides, the prices of CU and RB manifest lagging positions on the long scale between 2015 and 2016, and 2018 and 2019 respectively. It suggests that the lead-lag relations are highly related to the overall market environment on the short and long scales and depend on the specific situations and circumstances of the year.

Furthermore, having seen that the short-term co-movements remarkably decline or even disappear for some time intervals, we attribute this change to the impact of overall market price movement, but it is still not explained why the decline or disappearance happens in those certain intervals. Thus, we combine the price movement of each metal commodity with the PWC and WTC results to see whether different phases of the metal commodity's price movement influence this kind of decline or disappearance. The price movement phases are categorized as the up phase, down phase, volatile phase, and stable phase. The red boxes represent the down phase, and the green boxes represent the volatile phase. Besides, we also observe that there exist situations where the medium-term co-movements become stronger after controlling for PPI, which is marked with yellow boxes.

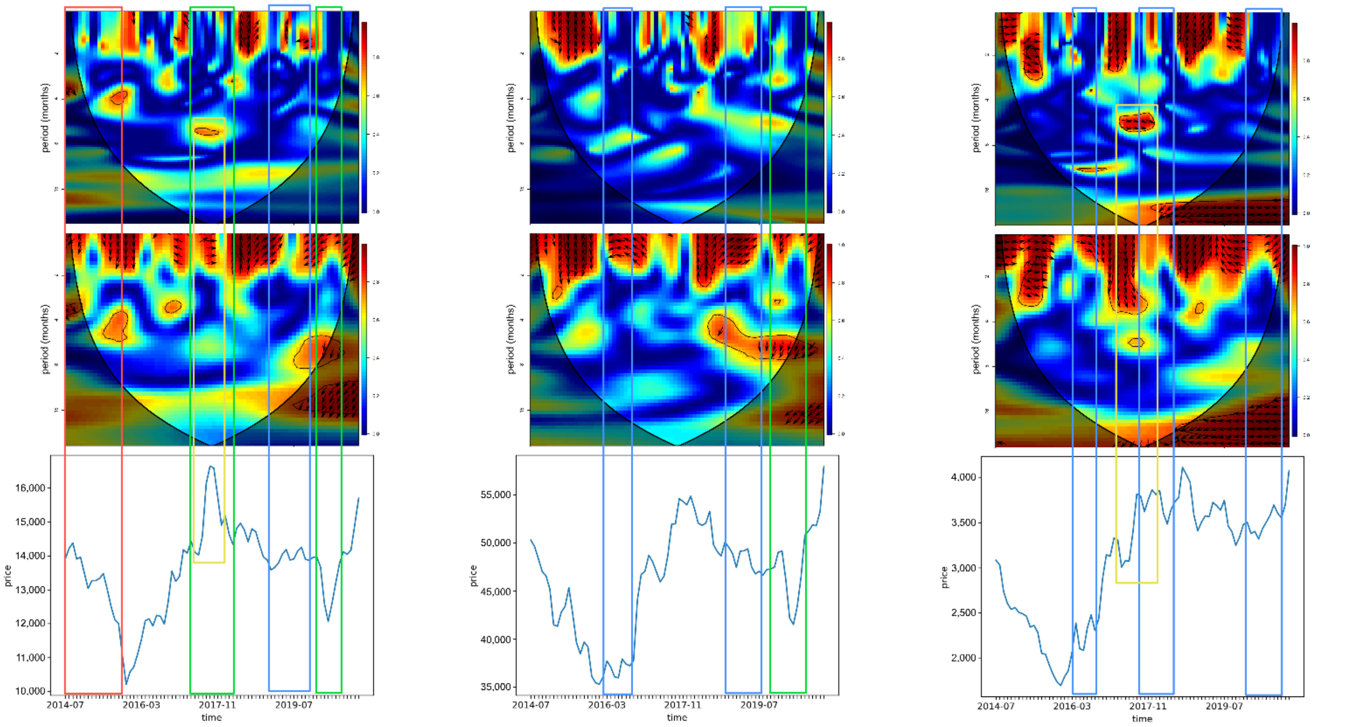
In the case of AL, we find two intervals where the short-term co-movements decline remarkably in PWC compared to that in WTC. It appears that those two intervals are during the down phase of the AL's price movement. The time interval between 2016 and 2017, which is the up phase, manifests similar intensity of short-term co-movements between PWC and WTC. It indicates that when AL's price is in the up phase, the short-term co-movement is strong and depends less on the overall market price movement. When AL's price is in the down phase, the short-term co-movement is weak or even disappears and is driven largely by the overall market price movement. In 2020, which is the volatile phase, we also observe such a decline in short-term co-movements, which indicates that when AL's price is during a severe fluctuation, the short-term co-movement is mainly driven by the overall market price movement. Besides, during 2018 we observe that the medium-term co-movement becomes stronger after controlling for PPI. It seems that the global crisis in 2018 weakens the influence of PPI on the medium-term co-movement. In the cases of CU and RB, the situations are similar. As for the case of CU, it appears that the medium-term co-movement is affected by the 2015 crisis. As for the case of RB, it appears that the medium-term co-movement is affected by the 2018 crisis.

5.2. Price Co-Movement between Shunt Reactors and Metal Commodities

For WTC results of the shunt reactors and metal commodities (Figure 3), we see that co-movements take place in the short and long run for the cases of AL and RB, and in the short and medium run for the case of CU. The short-term co-movements also manifest a cyclic trend, and the long-term co-movements manifest a continuous trend. As for the lead-lag relations, the cases of AL and CU show leading positions in the short-term co-movements. As for the case of RB, the lead-lag relations can be seen in 2015, 2017 and 2018. The metal's price is lagging in 2015 and 2017, and in 2018. The lead-lag results are similar to that of WTC.

As for the PWC results, we see that the price co-movements take place in the short and long run. The pair of shunt reactors—RB also manifests co-movements in the medium run in 2015, 2017, and 2018. Besides, the short-term co-movements in the cases of AL and CU reduce a lot in terms of consistency and duration compared to the WTC results. It appears that the overall market price movement has a wide-range impact on the co-movements on the short and long scales. As for the lead-lag relations, the cases of AL and CU show no clear lead-lag relations compared to the leading position in the WTC results. The case of RB exhibits a similar situation to that in the WTC results, that is, lagging in 2015 and 2017 and leading in 2018. It suggests that the AL and CU cases are remarkably driven by PPI in terms of their leading positions, while the RB case is not.

Considering the price movement phases of metal commodities, the difference in co-movements between PWC and WTC results are presented below. In the case of AL, between 2014 and 2015 (the down phase) and in 2017 and 2020 (the volatile phase), the short-term co-movement declined remarkably. In 2017 (the volatile phase), we also observe that the medium-term co-movement is strengthened, which indicates that when AL's price is severely fluctuating, the medium-term co-movement is weakened by the overall market price movement. Furthermore, we observe the stable phase marked by blue boxes. In 2019, when AL's price is stable, the short-term co-movement declines. It indicates that the price co-movement between shunt reactors and AL is not activated in the short term when AL's price keeps stable, and the major driving force for the short-term co-movement is from the overall market price movement.



(**a**) Shunt reactors—AL (**b**) Shunt reactors—CU (**c**) Shunt reactors—RB

Figure 3. Co-movement between the price of shunt reactors and the price of metal commodities.

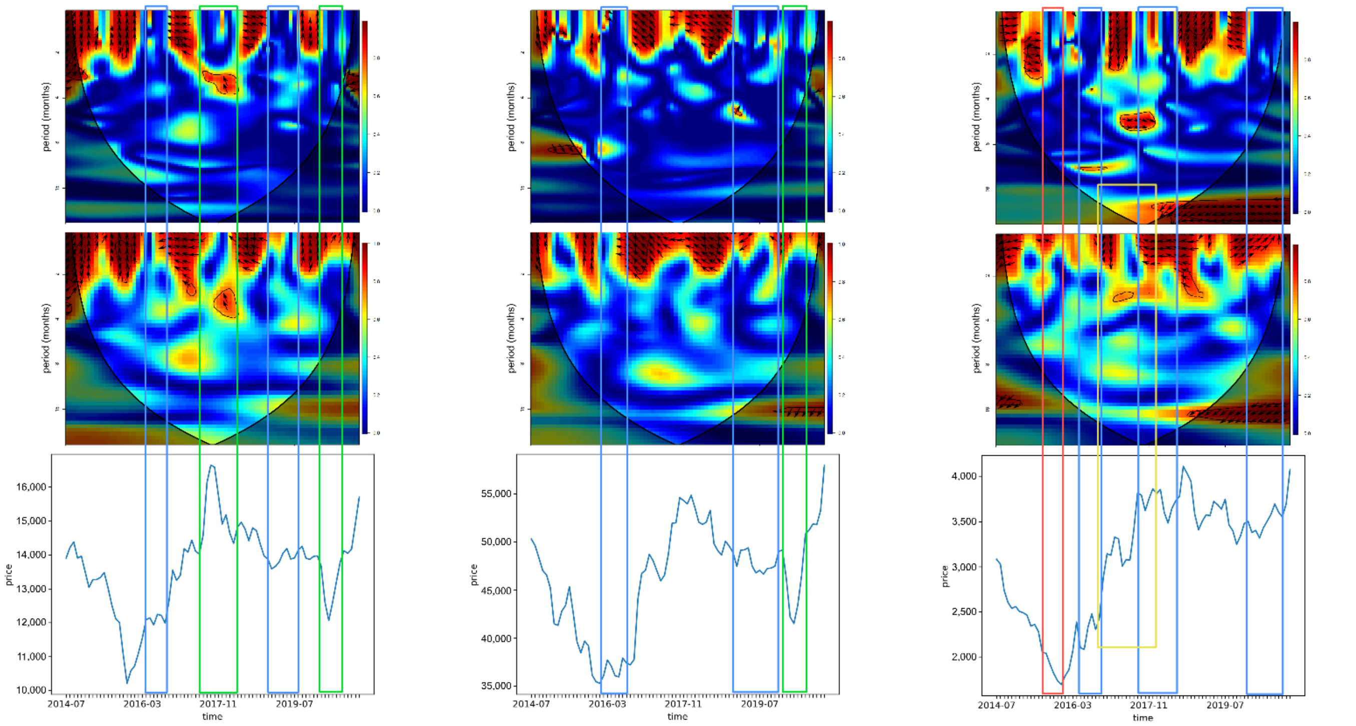
In the case of CU, the major decline of short-term co-movement happens when CU's price is in the stable phase (2016 and 2019) and the volatile phase (2020). In the case of RB, we observe the existence of three stable phases when the short-term co-movement declines. Besides, we also observe that the medium-term co-movement is stronger in 2017, but it presents no clear relation to the phase of RB's price movement.

5.3. Price Co-Movement between Tower Materials and Metal Commodities

For the WTC results of tower materials and metal commodities (Figure 4), we see that co-movements take place in the short run cyclically. As for the medium run, the co-movements happen in several periods of time. Besides, in the case of RB, the long-term co-movements are visible, and the medium-term co-movements cover more periods of time than that in the cases of AL and CU. For the lead-lag relations, there are only a few small islands. Thus, it is hard to determine a clear lead-lag relation in price co-movements between tower materials and metals, though those small islands present that the metals are leading in the short run.

As for the PWC results, price co-movements are mainly seen in the short term. In the pair of tower materials—AL, the short-term co-movements are quite cyclic. In the pair of tower materials—CU, the short-term co-movements manifest mainly between 2017 and 2018, while in the pair of tower materials—RB, the co-movements manifest mainly during 2017 and 2018. Besides, the case of RB exhibits long-term co-movements which are even stronger than that in WTC results. No clear lead-lag relation is observed.

Considering the price movement phases of metal commodities, the difference in co-movements between PWC and WTC results are presented below. In the case of AL, the major declines of short-term co-movement take place when AL's price movement is in the stable phase (2016 and 2019) and the volatile phase (2017 and 2020). In the case of CU, the declines of short-term co-movement take place when CU's price is in the stable phase (2016 and 2019) and the volatile phase (2020). In the case of RB, the major declines of short-term co-movement take place when RB's price is in the stable phase (2016, 2018, and 2020) and the down phase (2015). Besides, we observe that the long-term co-movement is strengthened when RB's price is in the up phase. It indicates that the continuous rising of RB's price activates the long-term co-movement, and the overall market price movement weakens it.



(a) Tower materials—AL (**b**) Tower materials—CU (**c**) Tower materials—RB

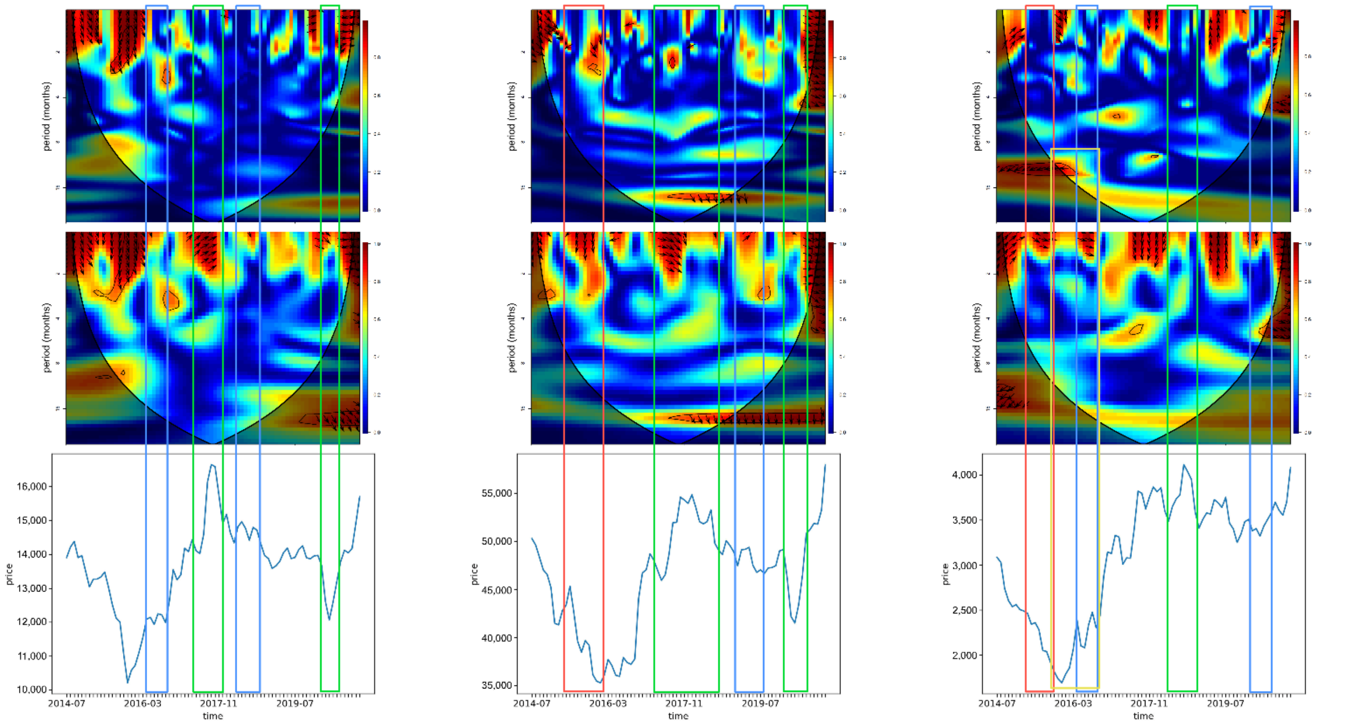
Figure 4. Co-movement between the price of tower materials and the price of metal commodities.

5.4. Price Co-Movement between Steel Strands and Metal Commodities

For the WTC results of steel strands and metal commodities (Figure 5), we see that co-movements take place in the short run. The medium-term co-movements are observed in a few periods of time and cover more periods of time in the case of CU and RB. In the case of CU and RB, the long-term co-movements are observed and the relationship is continuous. Thus, the cases of CU and RB seem to show more co-movements on a longer scale than the case of AL. For the lead-lag relations, the case of AL shows that AL is lagging on the short scale only in 2015. The cases of CU and RB show no clear lead-lag relations.

As for the PWC results, the price co-movements manifest on the short scale for several time intervals. In the pair of steel strands—AL, the short-term co-movements mainly take place from 2014 to 2015, while for the other two pairs, the short-term co-movements happen occasionally and end up quickly. The case of AL shows the short-term leading position between late 2018 and early 2019, while no clear lead-lag relation is observed in the cases of CU and RB. The results are consistent with that of WTC. It seems that the overall market price movement affects intensively the short-scale co-movements, especially in the cases of AL and CU. As steel is the major raw material of steel strands, the co-movements in the case of RB are less impacted by PPI on the short scale compared to the other two cases.

Considering the price movement phases of metal commodities, the difference of co-movements between PWC and WTC results are presented below. In the case of AL, the major declines of short-term co-movement take place when AL's price is in the stable phase (2016 and 2018) and the volatile phase (2017 and 2020). In the case of CU, the major declines of short-term co-movement take place when CU's price is in the short phase (2015) the stable phase (2019), and the volatile phase (2018 and 2020). In the case of RB, the major declines of short-term co-movement take place when RB's price is in the short phase (2015), the stable phase (2016 and 2020), and the volatile phase (2018). Besides, we observe that the long-term co-movement is strengthened between late 2015 and early 2016 (marked with the yellow box), during which RB's price is in the up phase. It indicates that the rising of steel price activates the long-term co-movement. Furthermore, as copper and steel are the major components of steel strands, the long-term co-movements are seldomly affected and even strengthened for some periods whether we control for PPI or not. It indicates again that when the metal is of high importance in producing a specific type of equipment, the long-term price co-movement between this metal commodity's price and this type of equipment is strong and independent of the overall market price movement.



(**a**) Steel strands—AL (**b**) Steel strands—CU (**c**) Steel strands—RB

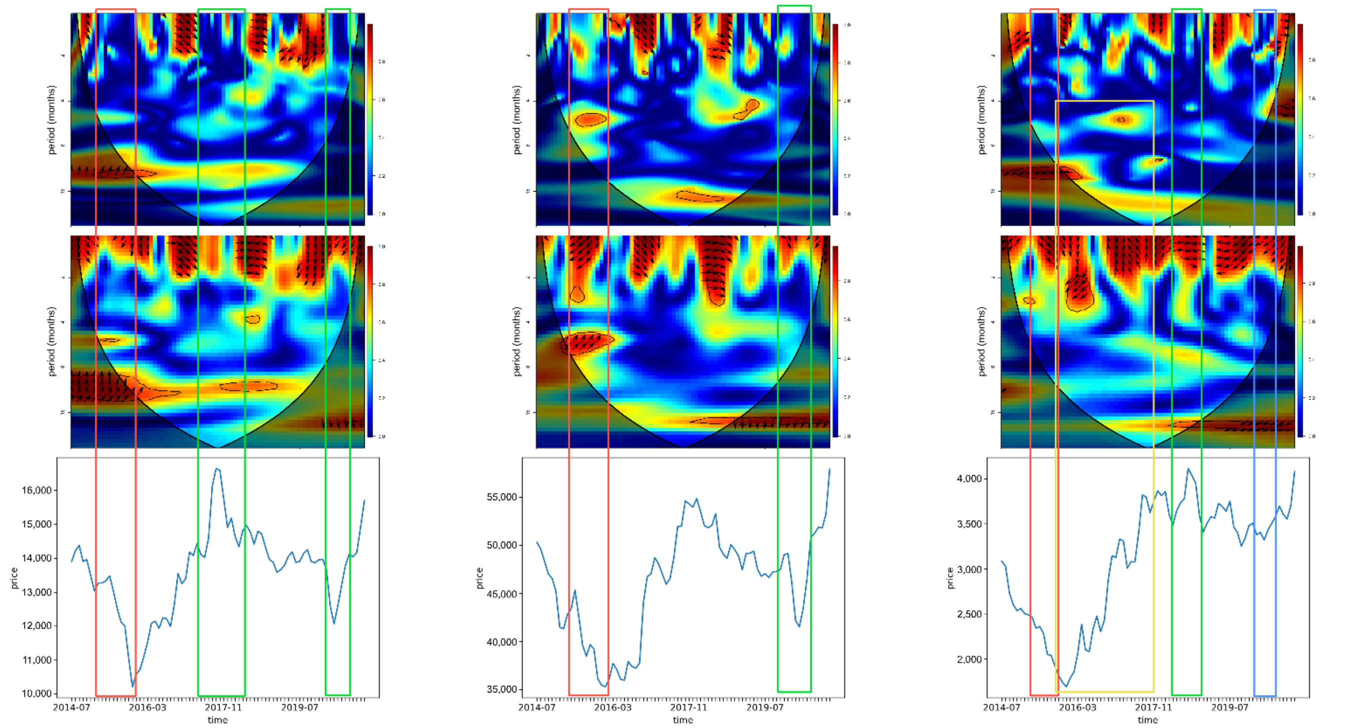
Figure 5. Co-movement between the price of steel strands and the price of metal commodities.

5.5. Price Co-Movement between Steel-Aluminum Conductors and Metal Commodities

For the WTC results of steel-aluminum conductors and metal commodities (Figure 6), we see that co-movements take place in the short and long run. The medium run also shows co-movements in several periods of time. The long-term co-movements in the case of AL present the most remarkable results among the three cases. For the lead-lag relations, the case of AL shows no clear lead-lag relations. The case of CU shows that the metal is leading on the medium scale in 2015 and lagging on the short scale in 2018. The case of RB shows that the metal is leading on the medium scale in 2016.

As for the PWC results, we see that the price co-movements manifest in the short and long run. In the pair of steel-aluminum conductors—AL, the co-movements show a certain cyclic trend. In the pair of steel-aluminum conductors—CU, the co-movements mainly happen during 2016 and 2018, while in the pair of steel-aluminum conductors—RB, the co-movements happen continuously from 2016 to 2018. The case of AL shows that the metal is leading on the short scale in late 2018, while the case of RB shows that the metal is leading on a medium scale in 2016. No clear lead-lag relation is observed in the case of CU. The results keep with that of WTC.

Considering the price movement phases of metal commodities, the difference of co-movements between PWC and WTC results are presented below. In the case of AL, the major declines of short-term co-movement take place when AL's price is in the down phase (2015) and the volatile phase (2017 and 2020). The long-term co-movement still manifests after controlling for PPI during the up phase of AL's price. In the case of CU, the major declines of short-term co-movement happen when CU's price is in the down phase (2015) and the volatile phase (2020). But we also observe that in 2017 (the up phase) the short-term co-movement declined remarkably, which is an exception so far. As copper is not an important component of steel-aluminum conductors, the price co-movement is deemed to be mostly influenced by the overall market price movement. In the case of RB, the major declines of short-term co-movement happen when RB's price is in the short phase (2015), volatile phase (2018) and stable phase (2020). The long-term co-movement keeps with that of WTC during the up phase of RB's price. Besides, we again observe the enhancement of the long-term co-movement during the up phase of RB's price. Those results concerning the long-term co-movement again reveal that the long-term price co-movement is highly dependent on the importance of the metal in producing certain types of equipment.



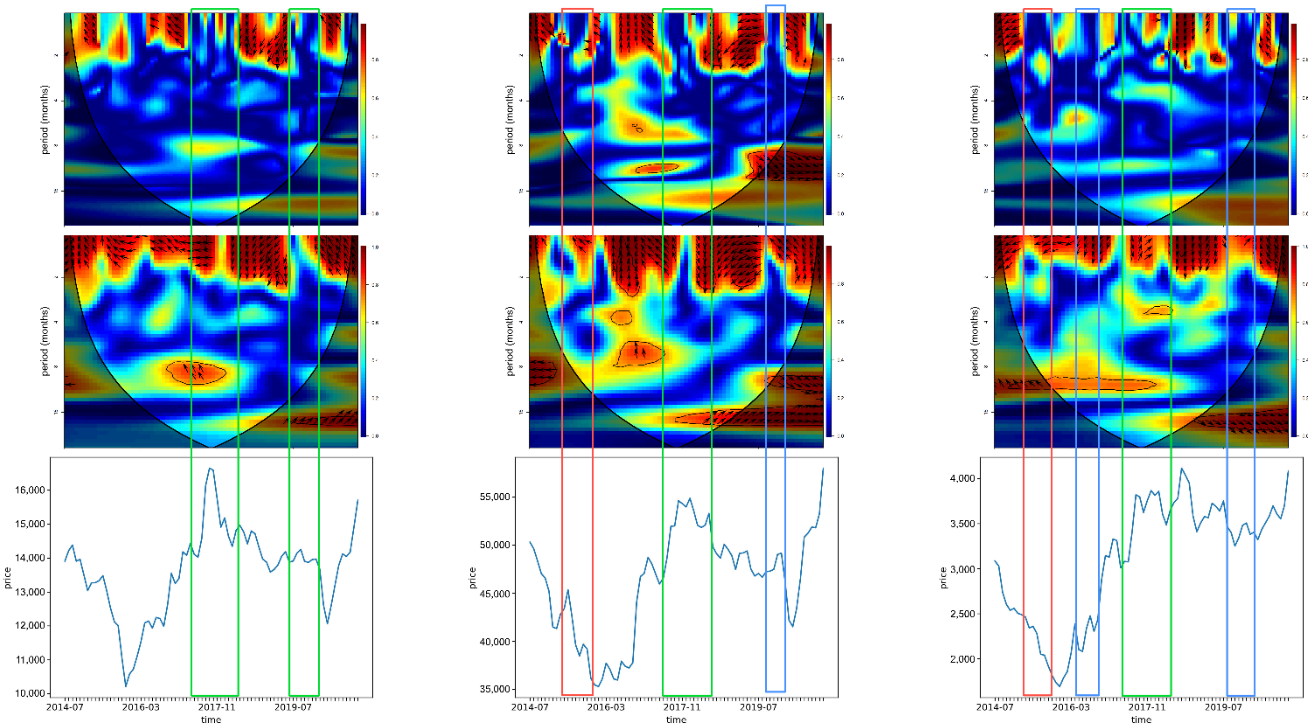
(**a**) Steel-aluminum conductors—AL (**b**) Steel-aluminum conductors—CU (**c**) Steel-aluminum conductors—RB

Figure 6. Co-movement between the price of steel-aluminum conductors and the price of metal commodities.

5.6. Price Co-Movement between Cable Lines and Metal Commodities

For the WTC results of cable lines and metal commodities (Figure 7), we see that co-movements take place in the short and long run. In the case of CU, the medium-term co-movements manifest between 2016 and 2017, while in the case of RB, the medium-term co-movements manifest between 2017 and 2019. It appears that copper and steel have closer relationships with cable lines in price movement. For the lead-lag relations, the case of AL shows that the metal is lagging on a long scale in 2017. The case of CU shows that the metal is leading on the short scale in 2016 and 2019 and on the long scale in 2018. The case of RB shows no clear lead-lag relations.

As for the PWC results, the price co-movements manifest in the short and long run. Compared to the results of WTC, the long-term co-movements in the case of AL and RB almost disappear, while the case of CU keeps a certain extent of long-term co-movements. It suggests that the long-term co-movements are largely driven by the movements of PPI in the cases of AL and RB but are relatively less impacted in the case of CU. The long-term co-movements in the case of CU almost keep with that of WTC. As copper is the major component of cable lines, it indicates that the more important the metal is, the less influential the overall market trend is on the price co-movement. As for the lead-lag relations, the cases of AL and RB show no clear relations, while the case of CU shows that the metal is leading on a short scale between 2018 and 2019.



(**a**) Cable lines—AL (**b**) Cable lines—CU (**c**) Cable lines—RB

Figure 7. Co-movement between the price of Cable lines and the price of metal commodities.

Considering the price movement phases of metal commodities, the difference in co-movements between PWC and WTC results are presented below. In the case of AL, the major declines of short-term co-movement take place when AL's price is in the volatile phase (2017 and 2019). But we also observe such a decline during the up phase of AL's price in 2016. As aluminum is not the major component of cable lines, the price co-movement exhibited is deemed to be mainly under the influence of overall market price movement. In the case of CU, the major declines of short-term co-movement happen when CU's price is in the down phase (2015), the volatile phase (2018) and the stable phase (late 2019). The long-term co-movement keeps with that of WTC during the up phase of CU's price. In the case of RB, the major declines of short-term co-movement happen when RB's price is in the down phase (2015), the stable phase (2016 and 2019) and the volatile phase (between late 2017 and early 2018).

5.7. Robustness Check

To check the robustness of our findings, we conduct the following additional PWC analysis which controls for the PPI of raw materials (PPI_rm). While PPI is the overall market price received by producers for all goods and services sold, PPI_rm focuses on the price level of raw materials. As raw materials are used a lot in producing equipment and materials for PT&D, PPI_rm is deemed to have a close relation to AL, CU and RB. The figures are presented in Figure A1 of Appendix A.

In the robustness check controlling for PPI_rm, we see a similar manifestation to those controls for PPI. All the selected equipment and materials exhibit fewer and weaker short- and long-scale price co-movements with metal commodities of aluminum, copper, and steel. Since the WTC results manifest the short- and long-term price co-movements, it indicates that the short- and long-term co-movements largely result from the movement of the overall market price level. After controlling for the third-party effect of PPI_rm, the co-movement exhibits that it depends on the specific situations of the year. Furthermore, the strongest short-term co-movements happen occasionally rather than continuously. It appears that the short-term co-movements take place suddenly and end up rapidly, and the continuity of the short-term co-movements is affected by the overall market prices. Besides, the co-movements, in the long run, are influenced by the importance of the metal in producing the equipment. It appears that in the cases of the metal with high importance, the extent that the price co-movement is affected by the overall market price level is relatively lower than that with less importance. As for the lead-lag relations, the situations keep with that of WTC and PWC controlling for PPI. The lead-lag relations exhibit heterogeneity and stochastic for different metals and different equipment. Besides, the lead-lag relations show up occasionally. We cannot see stable and consistent lead-lag relations among all the cases we have. Thus, from the perspective of generalization, we demonstrate that there are no clear lead-lag relations in the price co-movements between the metals and equipment (and materials) for PT&D projects.

6. Discussion

The investigation of price co-movement between metal commodities and equipment (and materials) for PT&D projects is useful in understanding the price movement of the equipment and searching for predictive factors among those metal commodities in the short, medium, and long run. As far as we know, this is the first paper concentrating on this issue, with a focus on the overall market price movement and price movement phases of each metal commodity in impacting the co-movement on different scales. Our results show that (1) the co-movement manifests mainly in the short term and long term; (2) there is no clear lead-lag relationship in the co-movement; (3) the short-term co-movement is largely dependent on the price movement phases of metal commodities, that is, the up phase is an activator of the short-term co-movement; (4) the long-term co-movement is largely driven by the overall market price movement, but this effect is weakened when the metal is of high importance in producing a specific type of equipment.

First, the price co-movement manifest in the short run (1 to 2 months) and long run (8 to 16 months). Thus, by combining these two effects, procurement managers and producers can build a comprehensive view of the price fluctuation of electrical equipment. Since metal commodity prices are continuously provided and easily accessed, by analyzing the short-term and long-term development of metal commodity prices, we then have a tool to see the potential price evolution of electrical equipment. Besides, short-term co-movement can offer timely tracking, and long-term co-movement can help to build a long-term plan of purchasing and producing. Based on the financialization view, the price co-movement phenomenon exists among markets and assets [30]. The reason for the co-movement is that assets are interconnected, and the shock that happens to one asset will be transmitted to another [31]. Besides, trading in futures markets can feed back to the metal's demand of PT&D equipment producers [32], which then brings the price volatility in the futures market to the goods market.

Second, no clear lead-lag relationships are observed. Although the metal's price is leading for several years, the entire trend observed does not support that the leading position is stable and consistent. Furthermore, we observe that the leading positions mostly take place during global crises. For example, RB's price is leading in the price co-movement between shunt reactors and RB on the short scale in 2018, and CU's price is leading in the price co-movement between cable lines and CU on the long scale in 2018. It indicates that when the market is severe, the metal commodity's price works better as a predictor of the equipment's price. It is aligned with the findings in the research by [33] that the connectedness among commodities is more significant during economic crises. In other words, although no consistent lead-lag relations are exhibited, the metal commodity's price can still be used as a leading factor when the market is in a period of shock.

Third, the short-term co-movement is activated if the metal commodity's price is in the up phase. We have observed that the short-term co-movements decline remarkably, after controlling for PPI, when the metal commodity's price is not in the up phase but in the down phase, stable phase, and volatile phase. It indicates that only when the metal commodity's price exhibits a continuous rising, does the price of equipment co-move. When metal prices rise, the cost for producers rises and the cost for procurement co-moves with metal prices. When metal prices fall, the cost for producers is saved but the cost for procurement does not co-move. It reveals an asymmetric situation in that the risk and burden induced by the rise of raw materials are shared by both parties, while the benefit induced by the fall of raw materials is only possessed by producers. It is not a healthy pattern for purchasers and producers to collaborate. The buyer-supplier relationship should be redesigned to fairly share the benefit and risks induced by the price fluctuation of raw materials.

Fourth, the long-term co-movement is largely driven by the overall market price movement. Besides, when certain metal is an important component of the equipment, the long-term price co-movement is then strengthened. It indicates that the physical relationship can influence the long-term price co-movement. Thus, when using the price co-movement relationships to grasp the equipment price trend, we should focus more on those largely consumed in equipment production.

7. Conclusions

The co-movement between the price of the equipment & materials for the PT&D projects and the price of metal commodities can help to understand and predict the price movement of the equipment and materials. It can offer a warning tool for procurement managers and producers of electrical equipment and materials to better monitor the market, adjust purchase plans and production schedules, and lower contractual risks. Firstly, we classify and recognize the critical equipment and materials for the PT&D projects as well as the related metal commodities. Secondly, we construct the WTC analysis to find the co-movements and lead-lag relations between the critical equipment & materials and the metal commodities in different scales of frequency. Thirdly, we isolate the impact of the overall market price movement with PPI to conduct the PWC analysis combined with the price movement phase of the selected metals. Lastly, we apply a robustness check by using the PPI of raw materials instead of the overall PPI.

Our study shows that the critical equipment & materials co-move, in terms of price, with aluminum (AL), copper (CU), and steel (RB) on the short (1 to 2 months) scale and long (8 to 16 months) scale. The short-term co-movement is activated by the continuous rising of metal's price. The long-scale co-movement is largely driven by the overall market price movements and is particularly strong when the metal is intensively used in the equipment. As for the lead-lag relations, the leading position of the metal commodities manifests around global crises, which indicates that during severe market volatility, the price movement of metal commodities can play a better predictive role.

Our work effectively reveals the price co-movement pattern and lead-lag relation between the critical equipment & materials and the related metal commodities from a multi-scale perspective. Our results shed light on the planning and investment for the PT&D projects and provide the following implications. First, since PT&D projects are vital and critical in infrastructure development, corresponding policies should be implemented to stabilize the prices of resources and equipment largely used in PT&D constructions. Besides, regulators and policymakers can monitor the price trend of metal commodities like AL, CU, and RB, which can serve as warning signals of the price fluctuation of PT&D equipment, especially when the market is during severe volatility. Furthermore, since the short-term price co-movement is activated by the continuous rising of metal commodity prices, it suggests that pol and practitioners should pay more attention to the situation where prices of metal commodities rise continuously. It is a strong signal indicating that the price of PT&D equipment will start to rise as well. Thus, practitioners can be prepared to respond in advance to the future rise of equipment pricymakersice and adjust the PT&D investment plan and construction schedules to reduce losses. In addition, practitioners should concentrate on the price trend of metal commodities used intensively in PT&D

equipment to obtain a long-term prediction of the price trend of PT&D equipment because the long-term price co-movement is significant when the metal is intensively used in producing PT&D equipment. For academics, we suggest that research discussing multi-scale price co-movement or transmission control the impact of common factors such as macro economic fundamentals, which current research often ignores to do [21]. It will give more robust results since prices are highly correlated to the overall market trend.

Author Contributions: Conceptualization, C.X. and K.J.; methodology, C.X. and Y.L.; software, Y.L.; validation, C.X. and Y.-Q.L.; formal analysis, C.X., K.J. and H.C.; investigation, C.X. and K.J.; resources, C.X. and K.J.; data curation, Y.-Q.L. and H.C.; writing—original draft preparation, C.X.; writing—review and editing, K.J. and H.C.; visualization, H.C. and Y.-Q.L.; supervision, C.X.; project administration, C.X.; funding acquisition, C.X. All authors have read and agreed to the published version of the manuscript.

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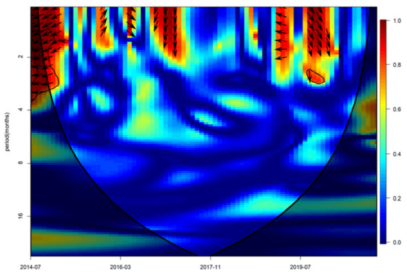
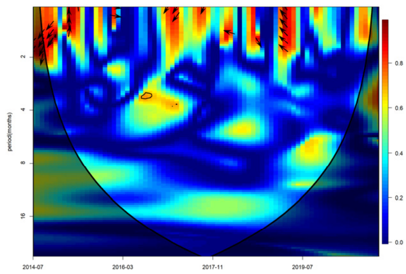
Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflict of interest.

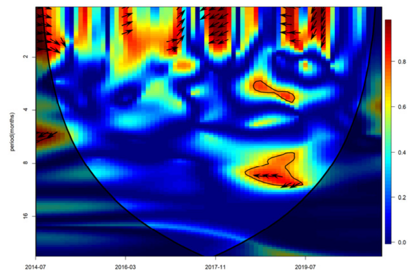
Appendix A



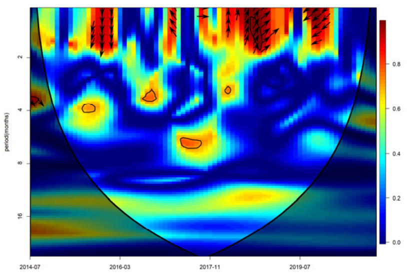
(**a1**) Transformers - AL



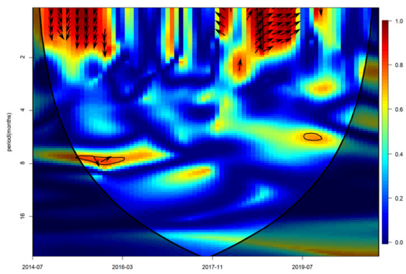
(**b1**) Transformers - CU



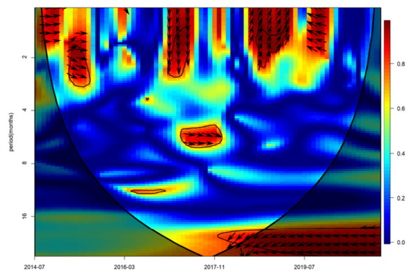
(**c1**) Transformers - RB



(**a2**) Shunt reactors - AL

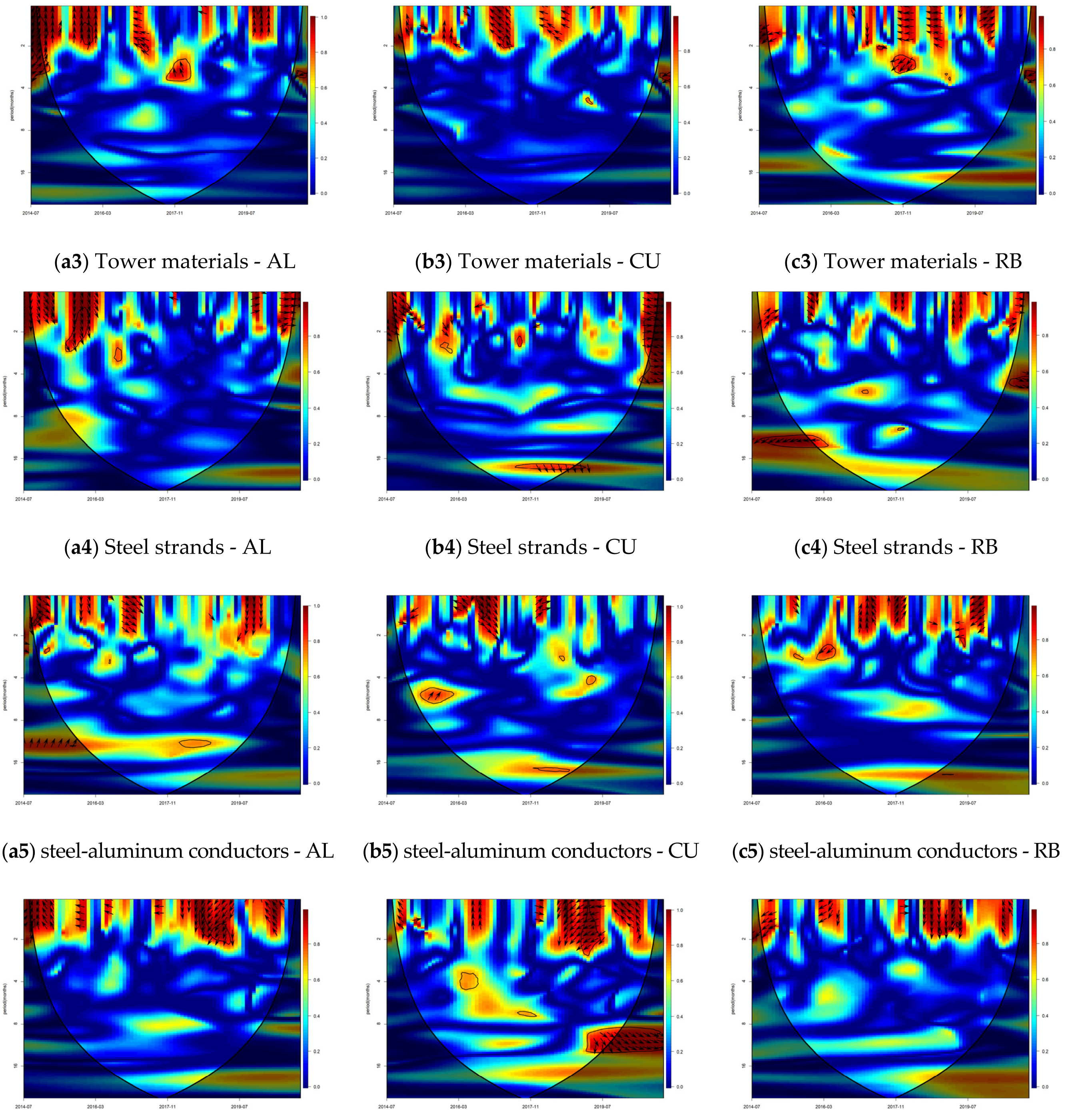


(**b2**) Shunt reactors - CU



(**c2**) Shunt reactors - RB

Figure A1. *Cont.*



(**a3**) Tower materials - AL (**b3**) Tower materials - CU (**c3**) Tower materials - RB

(**a4**) Steel strands - AL (**b4**) Steel strands - CU (**c4**) Steel strands - RB

(**a5**) steel-aluminum conductors - AL (**b5**) steel-aluminum conductors - CU (**c5**) steel-aluminum conductors - RB

(**a6**) Cable lines - AL (**b6**) Cable lines - CU (**c6**) Cable lines - RB

Figure A1. Robustness check for PWC price co-movement between equipment and materials in PT&D and metal commodities (control for PPI_rm).

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