Do gasoline and diesel prices co-move? Evidence from the time–frequency domain

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Abstract
This study investigates the co-movements of gasoline and diesel prices in three European countries (i.e. Germany, France, and Italy) with different fuel tax systems in place. The methodology follows a time–frequency approach, allowing us to analyse the co-movements at different frequencies and moments in time. As a novelty, we study the impact of fuel tax systems and international oil price dynamics on gasoline and diesel price co-movement. Using weekly data spanning the period from January 2005 to June 2021, the wavelet coherence analysis shows co-movements between gasoline and diesel at all frequencies, as well as during specific periods, but stronger in the long run. This evidence is recorded across all three countries, regardless of their tax systems. However, in decoupling the effect of international oil prices, the partial wavelet coherence analysis shows co-movements emerging also in the short run, with them being stronger around the global financial crisis (2008–2009). Although gasoline taxes are generally higher than diesel taxes, the analysis highlights that fuel tax systems do not influence the co-movements of fuel prices. Thus, shedding new light on the co-movement between commodity prices is fundamental, particularly in light of the current international geopolitical scene.

Keywords Gasoline prices · Diesel prices · Price co-movements · Time–frequency domain · Wavelets · Tax systems · Germany · France · Italy

JEL Classification C32 · L13 · Q41

Introduction
Fuel prices represent one of the main cost elements for all goods and services. They are largely influenced not only by international oil prices but also by fuel tax systems, cost prices, and profit margins of oil companies. Therefore, understanding how fuel prices co-move has multiple economic implications. First, gasoline and diesel prices have different effects on transportation costs. If households mainly use gasoline engines, diesel engines dominate the industrial transportation sector. Second, given the different

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impact that gasoline and diesel combustion has on the environment, governments might apply different excise and value-added taxes on these two categories of fuels.

This is especially the case for European Union (EU) countries resorting to different strategies to reduce carbon dioxide (CO₂) emissions. Despite the presence of different taxes on gasoline and diesel, their average prices evolved in tandem over 2005–2022 (Fig. 1). However, their co-movements seem to be stronger in some periods compared to others. In this context, two questions arise: Do the fuel tax systems influence the gasoline and diesel prices’ co-movements? To what extent do the international oil price dynamics impact the fuel price co-movement?

Fuel prices markedly increased at the beginning of 2021 as producers intensified their post-pandemic production accompanied by a sharp increase in transportation demand. More worrying is the explosion of their levels at the debut of 2022, as the Ukrainian war is dramatically increasing geopolitical risk, especially in the European region. Herein, the gasoline and diesel prices surpassed their maximal levels of the post-financial 2007–2008 crisis and the Arab Spring uprisings from 2010–2012.

Three EU countries are of particular interest to this general framework: Germany, France, and Italy. In France, where 80% of electricity comes from nuclear power plants and the lowest price in Europe is seen, carbon emissions are one-fifth of those in Germany, which is fascinated with coal. At the same time, Italy has renounced nuclear power in two referendums undertaken with questionable timing. Between 1988 and 2013, gasoline consumption in France steadily decreased (with a minimum of 167.29 thousand barrels per day in 2013, and a maximum of 434.71 thousand barrels per day in 1988), and then increased until 2020, when there was a sharp fall due to the COVID-19 pandemic crisis. Germany is witnessing a very similar evolution; in fact, gasoline consumption in this country continuously declined in the 1993–2016 period (with a minimum of 421.07 thousand barrels per day in 2016 and a maximum of 729.9 thousand barrels per day in 1993), and then increased until 2019 before the fall in 2020. In Italy, a slightly different dynamic has emerged since gasoline consumption increased between 1980 and 1996, then we see a constant decline up to 2020.¹

Germany recently applied lower taxes for unleaded gasoline than for diesel to reduce carbon emissions. Tax rebates are decreasing and are more reduced compared to those in France. The public transportation sector as well as agricultural businesses have benefited from diesel tax reductions since 2003, according to Sect. 57 of the Energy Tax Act. Given these measures and incentives, it is expected that the intensity of interaction between gasoline and diesel prices will decrease over time. In contrast, France traditionally has large state involvement in the energy sector but limited fossil energy resources. In general, France employs carbon taxes with a levy on fuels. However, starting in 2015, energy-intensive industries, which are not part of the EU Emissions Trading System (EU ETS), are partially exempt from paying the carbon tax, and the exemptions are increasing. Those industries, such as food and extractive, consume more diesel than gasoline. Finally, Italy has the highest level of fuel prices in the EU, being strongly dependent on oil imports. Italy applies different fuel excise taxes based on whether consumers constitute a business or a household. At the same time, rail transportation benefits from a higher reduction in

¹ https://www.theglobaleconomy.com/France/gasoline_consumption/; https://www.theglobaleconomy.com/Germany/gasoline_consumption/; https://www.theglobaleconomy.com/Italy/gasoline_consumption/
the rate of excise taxes that normally apply to sales of diesel fuel. After 2012, Italy recorded a nominal increase in diesel tax credits for lorries, which may also affect fuel price co-movements.

The fiscal measures recorded over the last decade indicate that different tax exemptions negatively impact fuel price co-movements across the countries considered. Moreover, taking into account the characteristics of each fuel tax regime, we expect that the co-movements regarding the “gasoline–diesel prices” pair to be different in the countries analysed.

The comparison of fuel tax co-movements between France, Germany, and Italy is further motivated as follows. First, although EU members are with a unique environmental policy, these three countries have adopted different paths to achieve their environmental protection targets. We can therefore conclude that the three countries have a different approach to achieving their environmental targets and their economic objectives.

Second, we analyse the gasoline–diesel price interaction in the three most important EU economies, which compete with each other for cost reductions and market shares. These economies represent about 55% of the GDP of EU countries in 2020, thus being the EU’s largest economies with the largest energy consumption.

Third, France, Germany, and Italy record among the highest fuel prices in the EU, positioning them in top 20 worldwide importers of oil and the main consumers in the EU. Their interest in renewables consumption is noteworthy. Although the oil production of the top 3 world producers (i.e. United States (US), Saudi Arabia, and Russia) increased over 2005–2019, the oil consumption of the targeted EU countries slightly decreased, proving their preoccupation with identifying alternative energies (Fig. 2).

For example, fossil fuels still represent the dominant share of Germany’s primary energy supply, although the share of renewable electricity rose to more than 40% of consumption in 2019. Germany, however, has one of the largest photovoltaic and wind power-installed capacities in the world and has made huge steps in the use of renewables. Since the 1970s, France has developed its nuclear energy industry, which now represents over 40% of its total primary energy supply. Although France has the second-largest wind potential in Europe, the renewable energy share of the total energy production is comparably smaller than that of Germany. Italy also recorded important steps in renewable energy production. Over 40% of its electricity comes from renewable sources, whereas its hydroelectric capacity is dominant. However, Italy’s import dependence on fossil fuels has been increasing in recent years. In this context, authorities in Italy have supported investment in the production of renewables, especially in the solar power-installed capacity. Likewise, investors and consumers on the one hand and regulators on the other hand are interested in gasoline and diesel price co-movements in order to optimise their decisions.

Finally, the new forms of energy used in these countries are leading to different degrees of substitution between renewable and conventional energy sources, which can also influence fuel price co-movements. Additionally, notable changes have been observed in the share of public transport in passenger traffic, with a reduction from 23 to 15% of total traffic from 1990 to 2008. This negative trend in public transport puts pressure on fuel consumption for private cars, which consume four times more energy per passenger km than public transport according to the European Environment Agency (2010).

Fig. 2 Oil consumption and production in several major world players from 2005 to 2019 (refined petroleum products consumption in Mb/d). Source: International Energy Statistics 2021

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2 https://www.oecd.org/fossil-fuels/Germany-Peer-Review.pdf
3 https://www.oecd-ilibrary.org/environment/inventory-of-estimated-budgetary-support-and-tax-expenditures-for-fossil-fuels/france_9789264128736-8-en
4 https://www.oecd.org/publications/inventory-of-estimated-budgetary-support-and-tax-expenditures-for-fossil-fuels-2013-9789264187610-en.htm
In this light, the purpose of our paper is to investigate the co-movements of gasoline and diesel prices in three European countries (i.e. Germany, France, and Italy) with different fuel tax systems in place. We use a wavelet approach to identify the co-movements and lead-lag situations at different frequency cycles and moments in time, covering the period from January 2005 to June 2021. The wavelet approach is very useful in assessing gasoline and diesel price co-movements as it allows to explore how the two series of prices are related at different frequencies. For example, if the co-movements are stronger in the short run (that is, at higher frequencies), this implies that elements other than fuel tax systems are responsible for this situation. The evolution of international oil prices and the profit margins practices by oil companies might explain this behaviour. In contrast, the tax systems and tax exemptions will instead have an influence on gasoline and diesel price interaction in the long run. Furthermore, this approach allows us not only to assess the lead-lag status between fuel prices at various frequencies but also to identify the structural breaks in the analysed relationship. Changes in the fuel tax systems can either contribute to an intensification of co-movements or to a reduction of co-movements’ intensity.

The theoretical core of the study is represented by the “rockets and feathers” hypothesis of Bacon (1991), with extension on diesel prices offered by Zhang and Yao (2016). The “rockets and feathers” hypothesis highlights the asymmetric responses of gasoline price to international oil prices, taking into account the indirect taxes. It assumes that no tax changes are absorbed by retailers. That asymmetry can be also extended by the interaction between gasoline and diesel prices via a theoretical channel suggested by Zhang and Yao (2016). This supposes that diesel prices significantly react to oil bubbles compared to gasoline prices, which are sensitive rather to fundamentals, such as strong oil demand in the advanced economies and emerging economies.

Moreover, the work touches on the theoretical discussion about the role of price asymmetries at various levels of adjustment to gasoline and diesel prices in response to the impact of positive and negative costs; this theoretical framework demonstrates the presence of potential rigidities in price adjustments where changes in oil prices are not immediately and completely transmitted to gasoline and diesel prices. In the presence of an oligopolistic market, and gasoline and diesel markets are characterised as such markets, the system is controlled by a small number of players, and the literature has documented that gasoline and diesel price asymmetries are attributed to the collusive behaviour of retailers or governments. In cases where the cost of crude oil decreases, sellers in an oligopolistic market collude to maintain current retail prices to experience higher retail profits. In contrast, when the cost of crude oil increases, retailers in this oligopolistic market immediately increase prices to prevent any reduction in their profits. The collusive behaviour of retailers in this market leads gasoline and diesel prices to show an adjustment pattern of rapid increase and slow decrease in response to changing oil prices (Al-Gudheia et al. 2007; Verlinda 2008). Finally, the theoretical background of this work is also based on Alvarez et al. (2016) and Alvarez et al. (2021) theoretical work, which illustrates that in a sticky-price modelling framework (based on the menu cost hypothesis), the cumulated output response to an aggregate nominal shock can be asymmetric. The intuition is quite simple: if prices are sticky, they tend to respond slowly to a given shock (thus, generating real effects) and the frequency of price changes is capable of capturing the speed of price adjustment asymmetrically. If the firms that adjust their prices are those in which prices are the furthest from the price that would have prevailed with price flexibility, then the price response is expected to be stronger and quicker, and the cumulated output response is expected to be smaller.

The contribution of this paper to the existing literature is threefold. First, as far as we know, this is the first paper investigating gasoline and diesel price co-movement within a wavelet framework, considering the role of international oil prices and different taxes on gasoline and diesel. Certainly, it is noteworthy that the regime of fuel tax influences the co-movements of gasoline and diesel prices. Although in all analysed countries, there are no significant differences between VAT and excise tax applied to gasoline and diesel prices, we record different measures in terms of fiscal incentives and tax discounts. Second, the study resorts to a non-linear empirical approach to instigate fuel price co-movements. Our analysis uses time–frequency (wavelets) analysis to ascertain if co-movements manifest in specific periods and at different time frequencies (cycles). The classical econometric time-domain methods arduously check the non-linearity using dummies, thresholds, or polynomial approaches. Unlike them, the wavelet allows to directly test any non-linearity with high accuracy but across periods and subperiods, indicating also the lead-lag status of variables, intensity of interactions, durability effect over time, and structural breaks. Moreover, no pre-estimation diagnostics are required. Thus, this approach is particularly appealing to investigate the co-movement cycles (the necessary amount of time for a price series to adjust to other price series) and the lead-lag relationship (i.e. gasoline prices lead the diesel prices or the opposite applies). Thus, we use the wavelet transform coherence (WTC) of Torrence and Webster (1999) to assess whether co-movements manifest at high, medium, or low frequencies. Indeed, this approach is largely used in the price co-movements literature, including commodity prices behaviour (Chowdhury et al. 2021; Tiwari et al. 2018). Unlike the existing studies, our approach takes into account an extended

\[5\] https://www.oecd-ilibrary.org/sites/5a3efe65-en/index.html?itemId=/content/publication/5a3efe65-en.
data set, also covering the period when fuel price dynamics might be affected by COVID-19 pandemic. Third, for model verification and quality purposes, the analysis implements a robust alternative tool as shown by Rua (2010). Furthermore, the co-movement is controlled for the influence of international oil prices by applying the partial wavelet coherency (PWC) proposed by Mihanović et al. (2009). Consequently, we are able to isolate the action of crude oil prices on fuel price interactions and see how important the international oil prices are for fuel price co-movements. Finally, the study checks the presence of co-movements by considering fuel prices without taxes. In doing so, we can validate the effect of long-term fuel tax systems on co-movements.

The layout of the paper is as follows: the “Literature” section reviews the literature, the “Data and methodology” section briefly explains the data and wavelet methodology employed, and the “Empirical results” section shows the wavelet coherency results. The “Robustness checks” section presents robustness checks to validate the estimated model and the findings of the PWC approach. Finally, the “Conclusions and policy implications” section presents a summary and policy implications of the study.

**Literature**

There is an extensive body of literature investigating gasoline and diesel price dynamics. The results are very heterogeneous, as they are influenced by the methodologies used, the data sets considered and the targeted subjects. Generally, the literature often shows asymmetric responses of gasoline prices to international oil prices, with diesel prices not being included in this equation. Almost all existing works investigate the “rockets and feathers” hypothesis of Bacon (1991) and find asymmetric responses of gasoline to international oil prices (Apergis and Vouzavalis 2018; Kisswani 2019). For example, Galeotti et al. (2003) re-examined the issue of asymmetries in the transmission of shocks to crude oil prices onto the retail price of gasoline, highlighting widespread differences in both adjustment speeds and short-run responses. Thus, the dynamics of crude oil prices may affect co-movements between gasoline and diesel. Furthermore, while gasoline prices are explained by economic fundamentals, diesel prices can be driven by bubbles (Zhang and Yao 2016). Moreover, gasoline and diesel prices can contribute differently to technological changes (Kumar 2008). A number of papers have explored the impact of the oil price on the retail gas price, deciphering differential reactions to oil price variations as proof of market power (Bachmeier and Griffin 2003). Ogbuabor et al. (2019) findings indicate that the 2007–2008 global financial crisis induced significant structural break in the oil–gasoline price relationship in the UK and the US.

Although the analysis of fuel price responses to the movement of international oil prices is well addressed in the literature, studies investigating the co-movement of fuel prices are lacking. The literature raises three main hypotheses to explain the co-movement of commodity prices in the more recent years. Frankel (2006) ascribed commodity price co-movements to monetary growth. Kilian and Hicks (2013) underlined the role of emerging market economies in stimulating the demand. Kilian and Murphy (2014) highlighted the role of speculation in commodities traded on exchanges as futures.

The analysis of the relationship between different commodity prices is also very relevant for financial markets. Indeed, in financial markets contracts are negotiated, the price of which depends on the price of an underlying commodity (Miljkovic and Goetz 2020). As outlined by Frankel and Hardouvelis (1985), the prices of several goods are sticky in the short run, mirroring the growth of money only in the long run. In addition, price expectations might be influenced by commodity prices co-movements. In this line, Labys (2006) tried to supply an explanation about risk and price expectations of metals futures’ prices, shedding light on noisy chaotic price-generating processes. Schaeffer (2004) provided several different applications of econometric methods for forecasting commodity prices, whereas Pirrong (2008) provided several different applications of econometric methods for forecasting commodity prices, whereas Pirrong (2004) proposed a structural approach to the commodity prices dynamics, providing valuable insights into the drivers of commodity prices. Similarly, Gargano and Timmermann (2014) selected various macroeconomic and financial predictors for commodity prices. A different approach has been proposed by Drachal (2018), who applied several Bayesian models to 69 spot commodities prices, showing that dynamic model averaging (DMA) produced a statistically significant more accurate forecast than benchmark forecasts (like the naive method or ARIMA). In the same spirit, Barkoulas et al. (1997, 1999) and Cromwell et al. (2000) reported tests for long memory across a variety of commodity spot and futures prices, while Alvaro et al. (2017) tested for the presence of a long memory process in the volatility of commodities, estimating the volatility and its components as latent variables. The results in Magazzino and Cai (2019) and Tiwari and Albulescu (2016) showed that the stationarity property of natural gas consumption series and respectively of renewable-to-total electricity consumption series can be sensitive to the specific approach adopted in the estimation strategy. Empirical findings of Arango et al. (2012) and Byrne et al.

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6 Frey and Manera (2007) provided a survey of the existing empirical literature on price asymmetries in commodities.

7 Several papers (e.g. Adrangi et al. 2001; Hammoudeh et al. 2003) assessed the energy price dependencies, with a focus on futures markets.
Several empirical works focused on the behaviour of fuel prices, most of them analysing the situation in Germany, France, and Italy in separate settings. Likewise, Schweikert (2019) developed a bootstrap cointegration test for the US and German gasoline and diesel markets. The empirical findings indicated that asymmetries may be traced back to the early stages of the production chain, even though they are not completely transferred to retail prices. Dewenter et al. (2017) analysed the impact of increased market transparency through the introduction of a market transparency unit for fuels in Germany, finding evidence of an increase in both gasoline and diesel prices. Frondel et al. (2016) found a cointegrating relationship between fuel and crude oil prices for Germany. Kihm et al. (2016) isolated several factors in addition to costs—like the absence of nearby competitors and regional market concentration—able to exert a mediation role on the effects of oil price on retail gas price. Gautier and Le Saout (2015) estimated that the duration for a shock to be fully transmitted into prices in France is about 10 days. In addition, no significant asymmetry emerges in the transmission of wholesale price to retail prices. Sofiane (2014) investigated the relationship between gasoline volatility and crude oil price volatility. The results evidenced that gasoline volatility tends to overreact to changes in crude oil volatility. Wittmann (2014), studying the gasoline retail markets in Germany, concluded that a customised tax on price has the capacity to result in an unprofitable business in the case of collusion by collecting marginal profits. Lamotte et al. (2013) examined the response of gasoline prices in France to shocks to crude oil prices in the international market. Empirical results revealed that gasoline prices gradually adjust towards a long-run equilibrium after a shock to the crude oil price but in an asymmetric way. Kirchgässner and Kübler (1992) found rapid, symmetric, and full adjustment of the German prices to the Rotterdam prices in the eighties. Alderighi and Nicolini (2019) found no evidence that odd pricing leads to higher prices in the Italian market. Romano and Scandurra (2012), analysing the Italian gasoline market, evidenced that the effects of a downstream price decrease are larger than those of a price increase, without reflecting consumers’ expectations. Grasso and Manera (2007) discovered that short-run asymmetries are present at the distribution level only in Spain and the UK, while affecting the production stage in Italy and the UK.8 Adedoyin and Zakari (2020) provided evidence of the role of economic policy uncertainty in the energy consumption–emission nexus in the UK. Adedoyin et al. (2021) investigated the long-run relationship between energy consumption, tourists’ arrivals, economic policy uncertainty, and ecological footprint in the top 10 earners from international tourism in 1995–2015. Empirical results suggest that economic policy uncertainties, in addition to tourism and energy consumption, are drivers of environmental degradation.

The macroeconomic role of international oil price dynamics has caught the attention of many researchers. As such, the sharp increase in oil prices since the 2000s has had important effects on many economic variables, particularly stock prices (Alamgir and Amin 2021; Apergis and Miller 2009; Bashir 2022; Reboredo et al. 2017; Zhang and Hamori 2021), exchange rates (Albulescu et al. 2019; Tiwari et al. 2013), inflation (Albulescu et al. 2017; Sun et al. 2019), and economic growth (Akinsola and Odhiambo 2020; Charfedine et al. 2020). However, most of the previous research has focused on crude oil prices and not on the role of fuel prices.

Fuel price dynamics have direct implications for the real economy given their place in the transportation and production costs, as well as in influencing the general price level (Albulescu and Mutascu 2021). Therefore, understanding the co-movements of different fuel prices is important not only for investors and cost optimisation but also for authorities and regulators. At long last, it ought to be highlighted that, with the exception of different previously existing empirical techniques and constant enhancements and improvement of new ones, understating commodities prices co-movements represents a truly challenging assignment. This challenge is even more important in the case of fuel prices given their recent dynamics. On the one hand, at the EU level, the road fuel demand shifted from gasoline to diesel in the context of favourable excise taxes on diesel.9 On the other hand, in the context of the recent pandemic crisis, fuel prices recorded significant volatility after an initial drop in April 2020. Moreover, the EU has recently experienced a sharp spike in energy prices, including fuel prices, which may lead to an energy crisis.

Only a few papers have employed the wavelet approach to investigate the co-movements of energy prices (Albulescu and Mutascu 2021; Alzahrani et al. 2014; Chien et al. 2021; Lee et al. 2021). None of these papers, however, investigates the gasoline and diesel price co-movements. While Alzahrani et al. (2014) resorted to a wavelet based test to assess causality between oil spot and futures prices, Albulescu and Mutascu (2021) analysed the fuel price integration across a set of EU countries. They did not analyse any co-movements between gasoline and diesel prices. Their study did not cover the recent period either, when fuel price dynamics might be affected by

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8 Other studies investigated the gasoline price asymmetric reaction to the economic policy uncertainty and crude oil prices at a global level. Likewise, Olanipekun et al. (2019) evidenced an asymmetric causal relationships between gasoline prices and economic policy uncertainty for a panel of 18 countries. De Salles (2014) inspected the gasoline prices evolution and its relationship between crude oil prices on the international market for a sample of eight countries.

9 https://www.fuelseurope.eu/wp-content/uploads/SR_FuelsEurope_-2020.pdf
COVID-19 pandemic. Differently, Chien et al. (2021) considered the COVID-19 pandemic but focused only on world oil prices by using wavelet-based Granger causality methodology. The sample includes the US, Europe, and China, with the oil price interacting with the stock market, geopolitical risks, and uncertainty in economic policy. Herein, strong co-movements are observed during COVID-19 in both short and long runs. In the same vein, Lee et al. (2021) highlighted the role of geopolitical risks in the oil price volatility but did not provide any information about gasoline and diesel prices. The findings are supported by a Granger causality test in the frequency domain, a non-parametric test for nonlinear causality, a leveraged bootstrap causality test, and a Fourier Toda-Yamamoto causality test. Recently, Magazzino et al. (2021a) used the wavelet analysis to investigate the relationship between energy consumption and economic growth for Italy, whereas Magazzino et al. (2021b) adopted a machine learning (ML) approach to determine the presence of any causal link between natural gas consumption and economic growth for Germany and Japan. Nevertheless, none of the existing literature explores co-movements of fuel prices. To the best of our knowledge, no paper explores the role of fuel tax regimes in influencing price co-movements.

Rechsteiner (2021) analysed the German energy transition (Energiewende) process, emphasising that cost-based compensation schemes decided by the German Bundestag were inspired by the idea of dynamic efficiency and by the polluter pays principle. Di Nucci and Prontera (2021) investigated drivers as well as coordination mechanisms and instruments for the energy transition in Italy from a multi-level governance perspective. With an original perspective, Mauger (2018) tried to understand the relationship between the voluminous energy transition legal framework recently created in France and the creation of a new autonomous branch of law.

Studying the co-movement of gasoline and diesel prices can help understand the dynamics of both series as well as provide new insights for policymakers. In many countries, commodity prices are closely linked to macroeconomic fundamentals, having significant repercussions on GDP, balance of payments and the public budget. Furthermore, the interrelationship between prices in the energy sector has become the spotlight for researchers in the energy economics field.

**Data and methodology**

**Data description**

The analysis employed weekly fuel price data, spanning the period 3 January 2005 to 28 June 2021, with data extracted from the Weekly Oil Bulletin (European Commission). International oil prices were considered for robustness purposes in the PWC analysis and were captured via the West Texas Intermediate (WTI) prices (Energy Information Administration). As Fig. 3 reveals, fuel prices were accompanied by higher taxes for gasoline across the sampled countries (i.e. Germany, France, and Italy). We also noticed a higher volatility of fuel prices when taxes were excluded. At the same time, Figs. 3(a) and (b) show that fuel prices in Italy were decoupling from those in Germany and France starting in 2011, evidence that might be explained by a different manifestation of the debt crisis in Italy compared to its neighbour countries.

The variables were used in their logarithm growth form in order to obtain a higher volatility, as this characteristic is required in the wavelet analysis. Moreover, as white noise is a serious threat in the time–frequency domain, representing source of bias, the Portmanteau test for white noise was also employed (Mutascu 2018).

**Methodology**

In what follows, we briefly present the wavelet approach adopted in this paper. We start with a general presentation of a wavelet function, localised both in time ($\tau$) and frequency ($s$):

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

where $\frac{1}{\sqrt{s}}$ indicates the level of transformation over time $\tau$ at scaling factor $s$.

The time–frequency transformation for each of our series (i.e. gasoline and diesel prices) represents a filter which identifies the trend component (the father wavelet) and the high frequency details components which are the deviations from the trend (mother wavelet). For the mother wavelet case, in line with most of the previous papers using this approach in the literature, we resorted to a particular type called the Morlet wavelet. The $s_0$ was set to 6, following the recommendation of Torrence and Compo (1998) for daily time series. In this case, the Morlet wavelet is defined as follows:

$$\psi_{\tau,s}(t) = \pi^{-\frac{1}{4}} e^{j\omega_0 t} e^{-\frac{1}{2} t^2}.$$

Now, for two series $X$ and $Y$, with wavelet transformation in time ($\tau$ is the time scale) and frequency ($s$ is the frequency scale), WTC of the two series can be expressed as follows (Torrence and Webster 1999):

$$R_{\tau,s}^2 = \frac{\left| S(s^{-1}W_{\tau,s}^{XY}) \right|^2}{S \left| S(s^{-1}W_{\tau,s}^X) \right|^2 S \left| S(s^{-1}W_{\tau,s}^Y) \right|^2}.$$

For more details, please refer to Ng and Chan (2012).
where $|W_X|^2$ and $|W_Y|^2$ are the wavelet power spectrum of the two series, $|W_X Y|^2$ is the cross-wavelet power spectrum, and $S$ denotes the smoothing operator capturing a trade-off between resolution and significance.

As an alternative tool to WTC, Rua (2010) splits the cross-wavelet spectrum of $X$ and $Y$ into real and imaginary parts and develops the concept of wavelet cohesion (WC), allowing to identify co-movements between the series but without the lead-lag status. WC can be expressed as

$$\rho_{X,Y}^{WC} = \frac{\Re(W_{X,Y})}{\sqrt{|W_X|^2 |W_Y|^2}}.$$  

where the real part of the spectrum is $\Re$, while $\rho_{X,Y}^{WC}$ denotes the wavelet-based correlation coefficient. A new wavelet method was proposed by Mihanović et al. (2009), called PWC. It allows to insert a control determinant having this form:

$$RP^2(X, Y, Z) = \frac{|R(Y, X) - R(Y, Z) \cdot R(Y, X)^\ast|^2}{[1 - R(Y, Z)]^2[1 - R(X, Z)]^2}.$$  

The PWC allows to see the co-movement between the two variables $X$ and $Y$ by removing the effect of a third series $Z$. In other words, the method better isolates the co-movement between two variables under the influence of a control determinant (which is the crude oil prices in our case).

Figure 4 shows a graphical representation of the proposed methodology, ranging from data set treatment and time–frequency estimations to the interpretation of the generated results.

### Empirical results

The descriptive statistics of variables for both with and without taxes are shown in Tables 1 and 2, in the Appendix. The Portmanteau test for white noise in Table 3 (in the Appendix) clearly shows that all considered variables were not affected. 

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**Fig. 3** Fuel prices in Germany, France, and Italy. a Gasoline (taxes included). b Diesel (taxes included). c Gasoline (taxes excluded). d Diesel (taxes excluded). Source: Weekly Oil Bulletin 2022
by any white noise process; thus, the variables ensured a good quality of estimations in their current form. Moreover, Elliott et al. (1996) and Ng and Perron’s (2001) unit root tests results clearly showed that the selected variables were non-stationary, regardless of both the specification of the deterministic component (only intercept or intercept and trend) and whether or not taxes were included (see Table 4 in the Appendix).

We first present WTC results considering retail prices (Fig. 5). As a general observation, we noticed that the variables (i.e., gasoline and diesel prices) were in phase and co-moved. The arrows pointing to the right indicate that an increase in one price was accompanied by an increase in the other price. Moreover, we noticed strong similarities between Germany, France, and Italy. That is, the co-movements were stronger in the long runs (32- to 256-week cycles), and to a smaller extent in the short (up to 8-week cycles) and medium runs (8- to 16-week cycles). In all countries, the interactions between gasoline and diesel prices were not conclusive in the medium run during the global crisis from 2008 to 2009 as well as the recent COVID-19 pandemic. Although the co-movements were rather idiosyncratic in the short run, diesel prices positively led gasoline prices throughout both economic and pandemic shocks (i.e. the arrows pointed to the right and down). Hence, an additional pressure on diesel supply or demand can be observed during crises, with the diesel prices triggering the gasoline prices. This underlines the important role of diesel fuel during shocks in the countries under consideration.

Our general results seem to align with a number of studies reported in the current literature (Asche et al. 2003; Borenstein and Kellogg 2014; Chouinard and Perloff 2007; Cook and Fosten 2019; Ederington et al. 2018; Ogbuabor et al. 2019).
In contrast, others have identified no such causality patterns across the two markets under consideration (Kilian 2010). Finally, during crises, the literature also offers solid support for our findings (Asane-Otoo and Schneider 2015; Bragoudakis and Sideris 2021; Ogbuabor et al. 2019). This literature evidence provides solid support for our empirical findings commensurate with the goal and the novelty of this work.

In addition, in the medium runs (8- to 16-week cycles), we observed significant co-movements of gasoline and diesel prices between 2010 and 2012, especially in the case of Italy. This evidence shows that the debt crisis, which affected the analysed countries in different ways, also impacted the fuel price co-movements. More specifically, during crises, fuel price co-movements become much stronger. In addition, the VAT for fuels increased in Italy between 2010 and 2013, and the excise taxes continued to increase until 2018. This evidence explains the stronger co-movement recorded in Italy in the short run between 2010 and 2013, and especially after 2017. This is not the case for Germany and France.

Finally, in the long runs (32- to 64-week cycles), we noticed that between 2007 and 2013, the arrows point up (the gasoline prices lead diesel prices), whereas the opposite applies...
starting from 2013. Nevertheless, a two-way interaction is rarely noticed. Thus, fluctuations (i.e. increase or decrease) in prices of gasoline and diesel occurred at the same time.

**Robustness checks**

The robustness checks were developed in two sequences. The first sequence considered an alternative wavelet method, namely the WC (Rua 2010), whereas the second one controlled for the role of WTI price, using the PWC (Mihanović et al. 2009).

The WC analysis in Fig. 8 (Appendix) reinforces the WTC findings, recommending the robustness under an alternative time–frequency tool. Furthermore, this part of the analysis accounts for WTI oil prices by removing their effect on interactions between gasoline and diesel prices (Fig. 6). In other words, the PWC approach allows the identification of specific moments in time when the fuel prices co-move by removing the effect of crude oil prices.

First, it is noteworthy that the international oil prices strongly showed both medium- and long-run co-movements in fuel prices. Isolated co-movements were observed; however, in the medium run, it was under the control of WTI prices. WTI is

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**Fig. 6** Fuel prices co-movements (tax included)—control for international oil prices. **a** Germany. **b** France. **c** Italy. Notes: (i) The X-axis denotes the time period in weeks, running from 3 January 2005 to 26 June 2021, whereas the Y-axis reveals the frequency; (ii) the cone of influence (COI), where the edge effects alter the spectrum, appears as a lighted shadow. The thick black line reflects the 5% significance, calculated based on Monte Carlo simulations with phase-randomised surrogate series; (iii) the colour code ranges from blue (low co-movements) to yellow (high co-movements)
one of the main fuel price drivers, representing also a veritable signal for the international oil market. Therefore, the variable induces ample mutations at the level of gasoline and diesel prices, with direct impact on their co-movements (Bachmeier and Griffin 2003). According to Albulescu and Mutascu (2021), such implications also offer important information regarding the price leaders inside the considered group of countries.

Second, in all three countries, we noticed some co-movements in the short run (up to the 8-week band of scale), similar to those provided by the WTC analysis, which could be rather idiosyncratic. At the same time, very long-run co-movements (64- to 256-week cycles) were observed between 2009 and 2016. In this case, the co-movements recorded in Germany before and immediately after the global crisis (2008 to 2009) are stronger compared with the observations recorded for the case of France. This means that during that period, the fuel tax system in Germany affected the gasoline and diesel prices in a more similar way, compared with the French case. Interesting results are also offered in the case of Italy, as gasoline and diesel prices strongly co-moved independently of WTI over the periods 2009–2015 and 2017–2021, up to 32-week cycles.

In what follows, we consider fuel prices without taxes, while controlling for the effect of WTI prices (Fig. 7). Here, we can observe the extent of instituted fuel tax systems on co-movements.

As observed in all countries, the results were very similar to those reported in Fig. 6. Although the taxation of gasoline and diesel prices differs, taxes do not seem to distort the co-movements between gasoline and diesel prices.

Finally, in order to check the sensitivity of the findings to the shocks of recent COVID-19, the main estimations were revised by withdrawing the related pandemic period (i.e. from 11 March 2020 to 26 June 2021, according to the official declaration of pandemic by World Health Organisation [WHO] starting on 11 March 2020). The results in Fig. 9 (Appendix) clearly illustrate that the WTI prices do not exercise any influence on the results during pandemic shock. In other words, the findings were not sensitive to WTI prices during the pandemic disease and thus did not affect the quality of the conclusions reached.

The findings partially confirm those of Albulescu and Mutascu (2021), who underlined the role of oil price in both gasoline and diesel prices but not over the course of the pandemic. Moreover, our outputs are not in line with those of Alzahrani et al. (2014), Chien et al. (2021), Lee et al. (2021), and Olanipekun et al. (2019). Those studies neglected the importance of oil prices in the interaction between gasoline and diesel prices.

**Conclusions and policy implications**

This paper investigated the co-movements of fuel prices in a time–frequency framework by drawing a comparison between Germany, France, and Italy, the largest EU economies, with different instituted fuel tax systems. Variations in commodity prices generated a trickle-down effect, which affected stock market prices. As commodities constitute the building blocks of all economic goods, the price of commodities influences the operational costs of corporations.

First, the outputs evidenced strong co-movements of fuel prices manifested in the medium and long runs, being strongly driven by crude oil prices. Second, significant co-movements in both short and long runs were observed when we decoupled the influence of international oil prices. Third, we highlighted that short-run co-movements were stronger between 2007 and 2010, especially in Germany, during the crisis. Moreover, in the short run, diesel prices have been leading during the pandemic crisis, highlighting the role of diesel fuels in such special contexts. Fourth, the findings also documented that fuel tax systems did not influence co-movements of fuel prices. Italy also revealed a curious finding in the short run, with co-movements being prominent over both the 2009–2015 and 2017–2021 periods but under WTI price mediation.

Finally, we posited that gasoline and diesel price interactions in Germany, France, and Italy illustrated strong similarities, although those countries follow different tax strategies for fuel prices to regulate the environment.

Certain policy implications can be derived from the findings obtained. First, if European countries were to target the reduction of fuel emissions, they could apply more differentiated taxes on gasoline and diesel prices to stimulate a reduction in the consumption of the most polluting fuel sources. Second, policymakers from considered countries could strategically use medium- and long-term domestic policies to safeguard fuel prices and circumvent changes in international oil prices. Thus, differentiated taxes on gasoline and diesel prices might be effective in the short run (a couple of months), albeit to a smaller extent during crises. Moreover, based on the homogeneity of the findings across three different European countries with different tax systems, the findings cast serious doubt on the efficacy of fuel taxes as a policy instrument to raise tax revenues from gasoline consumption. In other words, if the government targets high tax revenues, then the tax authorities should increase their tax collection system by levying taxes at all stages of the fuel system, from oil to gasoline stations. In that sense, tax policymakers will avoid overestimating the impact of tax increases on revenues, while avoiding underestimating the role of pollution and climate change phenomena.

Trying to understand the relationships between the prices of raw materials is very timely in the light of both the energy transition process—about which the EU is very concerned—and the recent hikes in these prices, also due to the conflict between Russia and Ukraine.
Finally, the European Green Deal announced by the European Commission in 2019 aims to transform the EU into a sustainable economy. However, it is very likely that it will have geopolitical repercussions through its impact on the EU energy balance and global markets. Furthermore, the ambitious plan presented by the European Commission, called “Fit for 55”, should also be rethought. First of all, because the EU is responsible for less than 10% of global emissions and without an international agreement that binds economies such as China and India, the European effort is of little use. Taxing more CO₂-intensive imports then risks producing a trade war and increasing costs for the European economy and consumers. An alternative route should be based on complete technological and fiscal neutrality as well as on a much greater effort in R&D without any foreclosures (as too often happens for nuclear energy).

Future research may investigate the co-movements between gasoline and diesel prices using ML or artificial neural networks analysis to shed further light on the unobserved common component (Magazzino and Mele 2021).

Fig. 7 Fuel prices co-movements (without taxes)—control for international oil prices. a Germany, b France, c Italy. Notes: (i) The X-axis denotes the time period in weeks, running from 3 January 2005 to 26 June 2021, whereas the Y-axis reveals the frequency; (ii) the cone of influence (COI), where the edge effects alter the spectrum, appears as a lighted shadow. The thick black line reflects the 5% significance, calculated based on Monte Carlo simulations with phase-randomised surrogate series; (iii) the colour code ranges from blue (low co-movements) to yellow (high co-movements).
## Appendix

### Table 1 Descriptive statistics of variables (tax included), including WTI

| Statistics | Gasoline Price (tax included) | Diesel Price (tax included) | WTI |
|------------|-------------------------------|-------------------------------|------|
|            | Germany                       | France                       | Italy | Germany | France | Italy | Germany | France | Italy |
| Mean       | 1,404.884                     | 1,383.883                    | 1,484.325 | 1,231.095 | 1,230.086 | 1,367.962 | 69.90856 |
| Median     | 1,387.625                     | 1,375.325                    | 1,489.735 | 1,210.25  | 1,229.59  | 1,368.96  | 65.91 |
| Maximum    | 1,773                         | 1,666.4                      | 1,889.81 | 1,569     | 1,533.09  | 1,777.8   | 145.16 |
| Minimum    | 1,077                         | 1,015.1                      | 1,082.64 | 940.8     | 914.48    | 1,004.31  | -36.98 |
| Std. Dev   | 135.467                       | 133.3436                     | 180.1089 | 142.3637  | 150.027   | 192.546   | 22.80517 |
| Skewness   | 0.181457                      | -0.26927                     | 0.024085 | 0.323572  | -0.05752  | 0.131905  | 0.31634 |
| Kurtosis   | 2.498013                      | 2.237187                     | 2.186691 | 2.115873  | 1.848613  | 2.045397  | 3.107137 |
| Jarque–Bera| 13.01378                      | 29.572                       | 22.5136 | 40.71617  | 45.41185  | 33.26758  | 13.94849 |
| Probability| 0.001493                      | 0                            | 0      | 0        | 0        | 0        | 0.000936 |
| Sum        | 1,143,576                     | 1,126,481                    | 1,208,241 | 1,002,111 | 1,001,290 | 1,113,521 | 56,835.66 |
| Sum sq. dev| 14,918,890                    | 14,455,554                   | 26,373,079 | 16,477,415 | 18,299,079 | 30,141,138 | 422,301.4 |
| Observations| 814                          | 814                          | 814     | 814      | 814      | 814      | 813     |

### Table 2 Descriptive statistics of variables (tax excluded)

| Statistics | Gasoline Price (tax excluded) | Diesel Price (tax excluded) |
|------------|-------------------------------|-------------------------------|
|            | Germany                       | France                       | Italy | Germany | France | Italy | Germany | France | Italy |
| Mean       | 530.2044                      | 525.1906                     | 565.4286 | 567.6933 | 544.3081 | 594.3023 | 594.3023 |
| Median     | 514.725                       | 518.12                       | 557.585 | 546.62   | 529.255  | 579.055  | 579.055  |
| Maximum    | 835.42                        | 780.81                       | 833.43  | 848.09   | 787.94   | 851.86   | 851.86   |
| Minimum    | 250.54                        | 259.55                       | 338.2   | 325.4    | 322.47   | 354.85   | 354.85   |
| Std. Dev   | 0.23073                       | 0.100634                     | 0.310605 | 0.354955  | 0.255774  | 0.381996  | 0.381996  |
| Skewness   | 2.55767                       | 2.296229                     | 2.342128 | 2.166815  | 2.049928  | 2.21476  | 2.21476  |
| Kurtosis   | 109.2287                      | 104.9496                     | 105.1521 | 116.2709  | 111.7376  | 116.6087  | 116.6087  |
| Jarque–Bera| 0.000979                      | 0.000113                     | 0.00001  | 0        | 0        | 0        | 0        |
| Probability| 431.5864                      | 427.5052                     | 460.2589 | 462.1023  | 443.0668  | 483.7621  | 483.7621  |
| Sum        | 8,906,685                     | 8,954,724                    | 8,989,304 | 10,990,889 | 10,150,547 | 11,054,847 | 11,054,847 |
| Sum sq. dev| 9,806,685                     | 8,954,724                    | 8,989,304 | 10,150,547 | 11,054,847 | 11,054,847 | 11,054,847 |
| Observations| 814                          | 814                          | 814     | 814      | 814      | 814      | 814     |

### Table 3 Portmanteau test for white noise

| Statistics | Gasoline price (tax included) | Diesel price (tax included) |
|------------|-------------------------------|-------------------------------|
|            | Germany                       | France                       | Italy | Germany | France | Italy | Germany | France | Italy |
| Portmanteau test | Q-stat. = 14,538.6 | Q-stat. = 15,677.9 |
|               | Prob. = 0.0000               | Prob. = 0.0000               |       |        |       |       |        |       |       |
| Gasoline price (tax excluded) | Q-stat. = 21,876.8 | Q-stat. = 16,530.6 |
|               | Prob. = 0.0000               | Prob. = 0.0000               |       |        |       |       |        |       |       |
| Diesel price (tax excluded)  | Q-stat. = 17,707.2 | Q-stat. = 22,180.1 |
|               | Prob. = 0.0000               | Prob. = 0.0000               |       |        |       |       |        |       |       |
| WTI         | Q-stat. = 15,572.6           | Q-stat. = 18,132.5           |       |        |       |       |        |       |       |
|             | Prob. = 0.0000               | Prob. = 0.0000               |       |        |       |       |        |       |       |
### Table 4 Unit roots and stationarity tests

| Country      | Variable      | Test                | NP Intercept | NP Intercept and trend | ERS Intercept | ERS Intercept and trend |
|--------------|---------------|---------------------|--------------|------------------------|---------------|-------------------------|
|              |               |                     | Intercept    |                        | Intercept     |                        |
| (Tax included) |               |                     |              |                        |               |                        |
| Germany      | Gasoline price| −0.4696             | −2.9100      | −1.8136                | −1.9800       | −1.4707                 |
|              |               |                     |              |                        |               | −1.8208                 |
| France       | Gasoline price| −0.2846             | −2.9100      | −1.8340                | −1.9800       | −0.2716                 |
|              |               |                     |              |                        |               | −1.8345                 |
| Italy        | Gasoline price| −0.2855             | −2.9100      | −1.8811                | −1.9800       | −0.2856                 |
|              |               |                     |              |                        |               | −1.8889                 |
| Germany      | Diesel price  | −0.6197             | −2.9100      | −1.7345                | −1.9800       | −0.6208                 |
|              |               |                     |              |                        |               | −1.7406                 |
| France       | Diesel price  | −0.3370             | −2.9100      | −2.0834                | −1.9800       | −0.3266                 |
|              |               |                     |              |                        |               | −2.0850                 |
| Italy        | Diesel price  | −0.3067             | −2.9100      | −1.5470                | −1.9800       | −0.2970                 |
|              |               |                     |              |                        |               | −1.5587                 |
| WTI          |               | −1.4473             | −2.9100      | −1.8764                | −1.9800       | −1.4409                 |
|              |               |                     |              |                        |               | −1.8905                 |
| (Tax excluded) |               |                     |              |                        |               |                        |
| Germany      | Gasoline price| −0.4785             | −2.9100      | −1.8122                | −1.9800       | −0.4797                 |
|              |               |                     |              |                        |               | −1.8195                 |
| France       | Gasoline price| −0.4509             | −2.9100      | −1.6086                | −1.9800       | −0.4394                 |
|              |               |                     |              |                        |               | −1.6099                 |
| Italy        | Gasoline price| −0.9262             | −2.9100      | −1.8530                | −1.9800       | −0.9352                 |
|              |               |                     |              |                        |               | −1.8939                 |
| Germany      | Diesel price  | −0.6901             | −2.9100      | −1.8036                | −1.9800       | −0.6912                 |
|              |               |                     |              |                        |               | −1.8105                 |
| France       | Diesel price  | −0.9498             | −2.9100      | −1.8444                | −1.9800       | −0.9401                 |
|              |               |                     |              |                        |               | −1.8470                 |
| Italy        | Diesel price  | −1.2929             | −2.9100      | −1.8514                | −1.9800       | −1.2824                 |
|              |               |                     |              |                        |               | −1.8621                 |
| WTI          |               | −1.9293*             | −2.9100      | −2.4847                | −1.9800       | −1.9133*                |
|              |               |                     |              |                        |               | −2.4680                 |

NP, Ng-Perron Modified test; ERS, Elliott-Rothenberg-Stock DF-GLS test. If required, the lag length was chosen following the Schwarz Bayesian Information Criterion (SBIC). For NP tests, *MZt* statistics are reported; for ERS tests, *t* statistics are reported. Five percent critical values are given in parentheses. ***p < 0.01, **p < 0.05, *p < 0.10
Fig. 8 Fuel prices co-movements: robustness analysis based on WC approach (Rua 2010). 
(a) Germany. 
(b) France. 
(c) Italy. Notes: (i) The X-axis denotes the time period in weeks, running from 3 January 2005 to 26 June 2021, whereas the Y-axis reveals the frequency; (ii) the colour code shows both intensity and sign of co-movement, going from blue (negative and strong co-movement) to yellow one (positive and strong co-movement).
Fig. 9 Fuel prices co-movements in Germany, France, and Italy (tax included), COVID-19 pandemic period excluded. a Germany. b France. c Italy. Notes: Notes: (i) The X-axis denotes the time period in weeks, running from 3 January 2005 to 26 June 2021, whereas the Y-axis reveals the frequency; (ii) the cone of influence (COI) where the edge effects alter the spectrum, appears as a lighted shadow. The thick black line reflects the 5% significance, calculated based on Monte Carlo simulations with phase-randomised surrogate series; (iii) the colour code ranges from blue (low co-movements) to yellow (high co-movements); (iv) the arrows indicate the phase differences (i.e. arrows pointing to the right show that the variables are in phase and co-move, arrows pointing up implying that the gasoline prices lead diesel prices)
Author contribution Mihai Ioan Mutascu: conceptualisation, methodology, data curation, software, writing of original draft preparation, supervision, project administration.
Claudia Tiberiu Albulesc: conceptualisation, investigation, writing of original draft preparation, supervision.
Nicholas Apergis: visualisation, investigation, reviewing and editing.
Cosimo Magazzino: validation, methodology, software, investigation.

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Data availability The data that support the findings of this study are openly available in the EUROMICRO data set at https://data.europa.eu/data/datasets/eu-oil-bulletin/locale=en

Declarations

Ethics approval Not applicable because this article does not contain any studies with human or animal subjects.

Consent to participate Not applicable.

Consent for publication Not applicable.

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