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Diesel demand elasticities and sustainable development pillars of economy, environment and social (health): comparing two strategies of subsidy removal and energy efficiency

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Abstract
For reducing fossil fuel demand and its environmental damages in Iran, the UN suggests removal of fossil fuel subsidies in this developing country which has the largest amount of energy subsidies in the world within 2010s. This research investigates the effectiveness of subsidy removal as a price policy in reducing the consumption of diesel which has the highest share in the total fossil fuel demand portfolio. The novelty of this research is that it compares the effects of price policy and energy efficiency on reducing diesel demand and improving sustainability to reveal which one is a more effective policy. To this aim, our study employs dynamic model, static model and error-correction model for estimating the diesel demand elasticities during 1976–2017. The results show that the diesel demand responds to changes in energy efficiency substantially, while it responds to changes in price slightly. Based on our findings, energy efficiency is about 30 times more effective than the price policy on reduction of diesel demand and improvement of the sustainable development pillars including economy, environment and social (health). A 10% improvement in energy efficiency at the first year of the studied period could reduce more than 87 billion liters of diesel consumption, 3 billion tons of CO_2 emissions and 65 thousand deaths from the air pollution during the period. Therefore, the strategists should improve the technology especially the efficiency of energy-consuming utilities like cars, rather than increasing the price and removal of subsidy, to reduce diesel demand and improve sustainability.

Keywords Sustainability · Fossil fuel · Demand elasticities · Diesel demand · CO_2 emissions · Health

JEL Classification Q01 · Q31 · Q58

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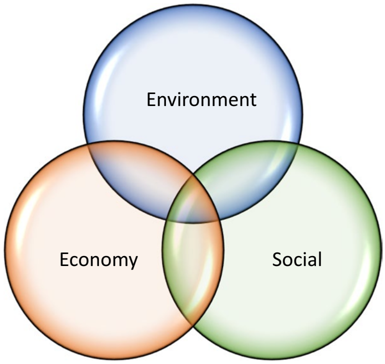


Fig. 1 Sustainable development pillars. *Source*: (Nasrollahi, Hashemi, Bameri, & Taghvaee, 2018)

1 Introduction

Since the oil price shocks during 1970s, the researchers are interested in investigating the fossil fuels demand (Taghvaee & Hajiani, 2014). The fossil fuel consumption impacts the three pillars of sustainable development including the environment (Nasrollahi et al., 2018), economy (Parsa et al., 2019) and social (Nodehi et al., 2021; Taghvaee et al., 2021) as in Fig. 1. It encourages them to study demand-side management of the oil-exporting countries like Iran with the first rank in subsidizing fossil fuel consumption all over the world as in Fig. 2 (IEA, 2020).

The availability of energy can stimulate the economic growth since the economic firms need energy as an input for their production (Nyangarika et al., 2018; Taghvaee et al., 2016; Jouzi et al., 2020). The more accessible the energy is, the more the firms produce goods and services. The key role of energy availability in production promotes many oil-exporting countries to subsidize the fossil fuel aiming at stimulating their economies (Shirazi et al., 2020; Aldy & Armitage, 2020). Iran holds the first rank in subsidizing fossil fuel in the world for many years as in Fig. 3, to benefit the economic pillar of sustainable development (Ahmadian et al., 2007; Chepeliev & Mensbrugghe, 2020). Figure 3 displays the natural logarithm of fossil fuel subsidization in the top 5 five fossil fuel subsidizing countries within 2010s. In the most of the period, Iran offers the biggest subsidy to the fossil fuel consumption. Only in three years (2011, 2015 and 2016), China and Saudi Arabia show a higher volume of subsidy, compared with Iran (IEA, 2020). Thus, Iran with a paramount amount of fossil fuel subsidies tries to boost the economic pillar of sustainable development (Moshiri, 2020).

However, subsidizing fossil fuel consumption damages the other pillars of sustainable development: environment (Shehabi, 2020) and social (Hadian et al., 2020). This subsidization lowers the price and increases the demand of fossil fuel leading to increment in energy importation, especially about diesel with 27% share in the fossil fuel consumption portfolio as in Fig. 4 (Energy Balance Sheet, 2010). It causes the energy dependency of Iran on the other countries, weakening the energy security and the social pillar of sustainable development. In addition, the fossil fuel consumption increase is impacting the environment due to its polluting character (Mousavi et al., 2017; Taghvaee et al., 2017a). Fossil fuel is the one of the biggest drivers of carbon dioxide (CO_2) emissions as the main greenhouse gas, followed by construction industry (Nodehi, 2022; Nodehi & Taghvaee, 2021a, b). According to Fig. 4, CO_2 emissions account for more than 98% share of the total greenhouse gas

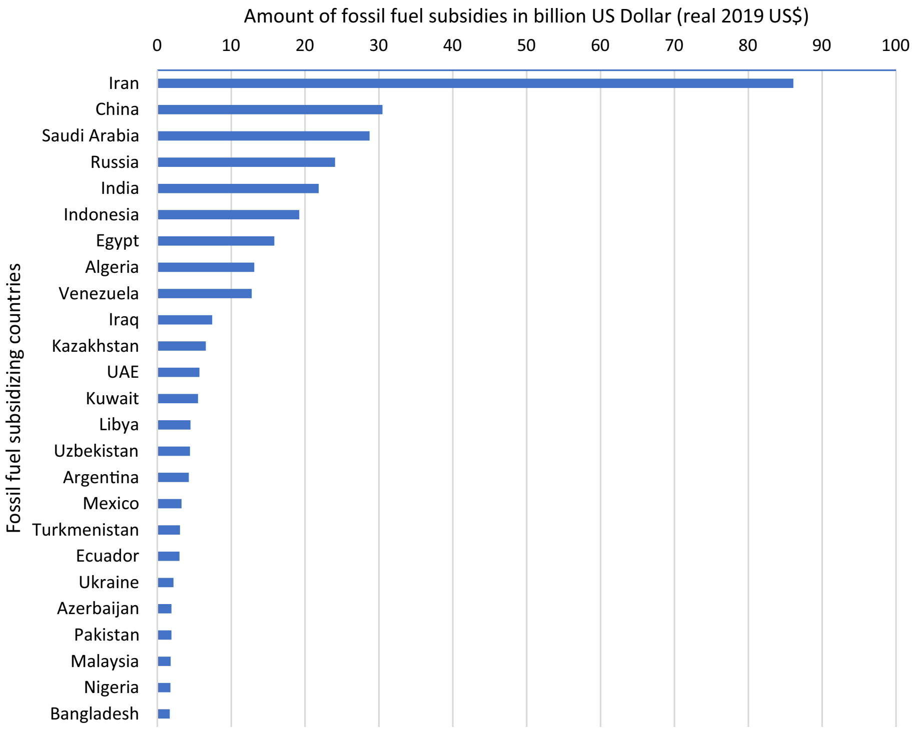


Fig. 2 Ranking the fossil fuel subsidizing countries in 2019 in billion real 2019 US Dollar. *Source*: (IEA, 2020)

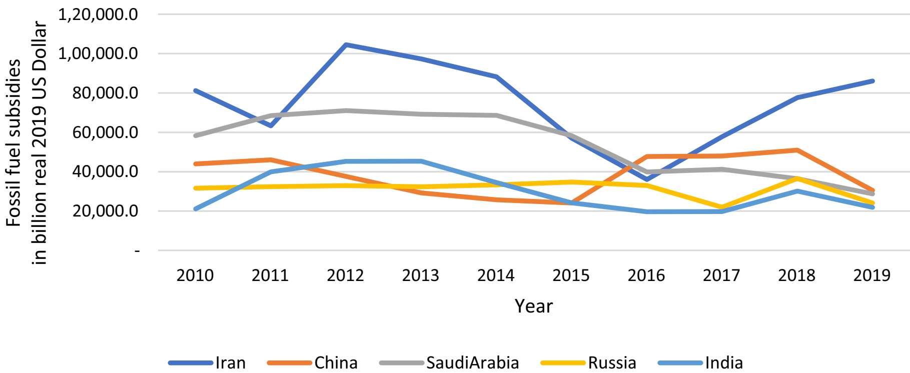
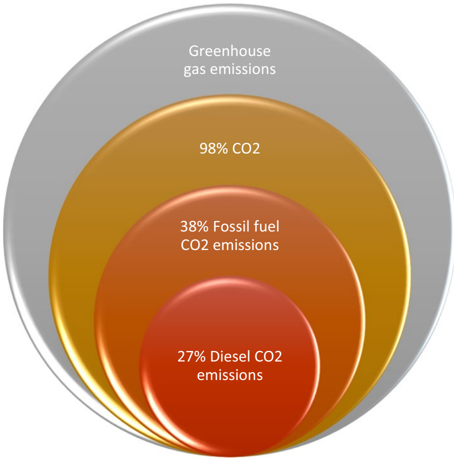


Fig. 3 Top 5 fossil fuel subsidizing countries in 2010s in billion real 2019 US Dollar. *Source*: (IEA, 2020)

emissions, and more than 38% of the CO_2 emissions is the result of fossil fuel consumption in Iran in 2010. Among the fossil fuels, the diesel consumption causes about 46% of the total CO_2 emissions (Energy Balance Sheet, 2010). As in the Intended Nationally Determined Contributions (INDCs) in the context of the Paris Climate Agreement, Iran should reduce 4% or 12% of its CO_2 emission up to 2030 based on the conditional and

Fig. 4 Dominant role of diesel consumption in CO2 emissions in Iran in 2010. *Source*: (Energy Balance Sheet, 2010)



unconditional mitigation targets of the United Nations (UN) (Rasoulinezhad & Saboori, 2018) to save the environmental pillar of sustainable development (Ghadaksaza & Saboohi, 2020; Godarzi & Maleki, 2020).

Iran needs to reduce the fossil fuel consumption especially the diesel with its big share in the energy portfolio and CO_2 emissions due to the socio-economic and environmental reasons. Fossil fuel consumption is the main cause of greenhouse gas emissions in Iran, degrading the environmental quality and health (Energy Balance Sheet, 2010). Additionally, it damages the economy of Iran since it allocates a great share of its economic budgets to the fossil fuel subsidy, leading to budget deficit and inflation (Atamanov et al., 2020). This share is about 86,095.5 real 2019 million US Dollars in 2019 (IEA, 2020). This volume of subsidy decreases the price and increases the demand of fossil fuel. There are two ways to meet the increasing demand: import and domestic resources. Both of them are unreliable. The importation increases the dependency of energy use on the other countries, threatening the energy security, and the domestic resources are limited (Arzaghi and Squalli, 2015). The projections show that the resources of fossil fuels are close to be depleted in the near future. Thus, Iranian policy-makers should select the best strategies to reduce the fossil fuel demand, especially the diesel consumption (subsidy removal suggested by the UN and energy efficiency suggested by researchers).

Regarding the Paris Agreement, for achieving the mitigation targets, the UN suggests subsidy removal of fossil fuel in Iran. By subsidy removal, the price of fossil fuel rises, and it reduces its demand which, in turn, causes to CO_2 emission (Taghvaee et al., 2017b; Taghvaee & Parsa, 2015). Although the increase in price level reduces the fossil fuel demand, the researchers believe that price policy is insufficient to manage the demand side of energy sector effectively and efficiently. The researchers claim that the demand of fossil fuel (e.g., diesel) responds to the price changes slightly and slowly due to the low price elasticities (Yeh et al., 2016). Despite different methodologies, time period and samples, all of them reach a consensus: diesel demand is price inelastic (Dahl, 2012). It raises the question of whether subsidy removal and price policy is sufficient to reduce the fossil fuel consumption in Iran (Jewell et al., 2018).

This study aims to investigate whether price policy is sufficiently effective in reducing the diesel demand in Iran. To achieve this aim, we estimate the price elasticities of diesel demand in Iran to find out whether the diesel demand is price inelastic as the previous studies claim (see the next section, literature review). In addition, this research estimates the energy efficiency elasticity of diesel demand to compare the response of diesel demand to technology improvement with the price policy to find out which one is more effective in the reduction of diesel demand. This study makes a comparison between the effects of the two strategies: price policy and promotion of energy efficiency, which is a novelty in this study. Another novelty is the estimation of the effects of the diesel demand reduction as a result of price policy and energy efficiency on sustainable development in Iran. The previous studies merely estimate the diesel demand elasticities, while this paper goes further to estimate the effects of reduction in diesel demand on sustainable development which provides a basis for comparing the effectiveness of price policy with energy efficiency.

To describe the structure of this paper, the next section reviews the most fundamental studies on the demand management of fossil fuels, specifically the diesel fuel. Then, Sect. 3 or methodology presents the econometric models and techniques employed in the estimations of the diesel demand elasticities and the effects of reduction in diesel demand on sustainability. In Sect. 4 (result), this study offers the estimated elasticities of diesel demand as the output of the models. Section 5 or discussion represents the most significant findings of this research which is about how to manage the diesel demand in Iran for improving sustainable development in the best way. Section 6 is conclusion which explains whole the research shortly.

2 Literature review

The UN suggests and emphasizes on subsidy removal of fossil fuel as a price policy to reduce energy demand and CO_2 emissions in Iran (Ghadaksaza & Saboohi, 2020; Godarzi & Maleki, 2020). The previous studies, however, show that price change has insufficient effect on reducing the fossil fuel consumption (Liddle et al., 2020). Many studies, instead, recommend improvement of technology and energy efficiency as a much more effective strategy in comparison with the subsidy removal and price policy (Brockway et al., 2021).

There is a wide range of studies with the estimations of price elasticities of various fossil fuel kinds such as diesel which has one of the biggest shares in energy consumption portfolio. Table 1 shows a summary of the previous studies which represent estimations of the price elasticities of diesel demand in short and long run. Although they employed various methodologies, approaches and data in different countries and regions, they are in broad consensus on the low price elasticity of diesel demand. Table 1 displays that the price elasticities of diesel demand are lower than one, implying that price policy is an inefficient plan to manage diesel demand since it responds to price changes very slightly.

Many other studies and reports from the international organizations, however, investigate the effectiveness of energy efficiency improvement on reducing the energy consumption. Based on their findings, energy efficiency plays a pivotal role in the reduction of energy consumption and CO_2 emissions (Alola, 2019; Bekun et al., 2019) to achieve the UN goals both in the Paris Agreement (United Nations 2015) and in the Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and clean energy) (UN 2015). In addition, the International Energy Agency (IEA) believes that up to 40% of the envisaged reduce in the greenhouse gas emissions in the next two decades is the result of improvement in energy efficiency (IEA, 2014; IEA, 2019).

Table 1 Selected previous studies on diesel demand elasticities

Study	Period	Geographic region		Estimated elasticities	
				Short run	Long run
(Agheli, 2015)	1973–2012	Iran	Price	– 0.16	– 0.32
			Income	0.36	0.74
(Ajanovic et al., 2012)	1977–2010	Review	Price	– 0.10	– 0.31
			Income	0.39	1.36
(Basso & Oum, 2007)	1980s–2000s	Critical assessment	Price	– 0.13	– 0.67
			Income	2.14	2.16
(Dahl, 2012)	1929–2006	Review	Price	– 0.16	
			Income	1.23	
(Labandeira et al., 2017)	1990–2016	Review	Price	– 0.15	– 0.44
(Goodwin et al., 2004)	1929–1991	Review	Price	– 0.25	– 0.64
			Income	0.39	1.08
(Lim et al., 2012)	1986–2011	Korea	Price	– 0.35	– 0.54
(Mousavi & Ghavidel, 2019)	1988–2016	Iran	Income	0.33	0.52
(Mundaca, 2017)	1998–2013	OECD	Price	– 0.01	–
		World Bank countries	Price	– 0.05	– 0.45
		World Bank countries	Income	0.13	1.07
(Polemis, 2006)	1978–2003	Greece	Price	– 0.07	– 0.71
			Income	0.42	5.35
(Raghoo & Surroop, 2020)	1996–2017	Mauritius	Price	–	– 0.69
			Income	–	0.43
(Vita et al., 2006)	1980–2002	Namibia	Price	–	– 0.11
			Income	–	2.07

Despite numerous studies in each strand of energy efficiency and price policy, there is a lack in comparing the two in a single research to reveal the most effective strategy for decreasing fossil fuel consumption, especially for the most consumed ones such as diesel.

3 Methodology

To estimate the elasticities of diesel demand, it employs econometric techniques, log-linear models and time series data within 1976–2017.

The time series analysis in this case is helpful since it considers only the individual characteristics of the diesel demand behavior in Iran, and it focuses only on one economy with its own unique features and idiosyncrasies (Taghvaee & Parsa, 2015).

The log-linear models in natural logarithmic form pave the way not only for estimating the elasticities but also for the stationarity of the variables in level which prevents the risk of spurious regression (Taghvaee & Hajiani, 2014). The log-linear models of the study consist of dynamic model, static model and error-correction model (ECM) since they provide us with elasticities in two intervals of long run and short run. The static model can estimate the long-run elasticities of diesel demand (Raghoo & Surroop, 2020), while ECM can estimate short-run ones and adjustment speed (Chang et al., 2019). The dynamic model has the capability to estimate both the short- and long-run elasticities (Sene, 2012). In contrast with the previous researches which employed one single model, this study uses various models to offer a double estimation of the short- and long-run elasticities. In this way, the results are highly valid and reliable if they confirm each other.

Although the previous studies only estimate the demand elasticities, this paper go further to use these estimated elasticities for evaluating the effects of reducing diesel demand on sustainable development as a novelty. Based on the estimated diesel demand elasticities, this research examines how energy efficiency and price policy affect the three pillars of sustainable development: economy, environment and social. Finally, it compares the energy efficiency with price policy to find the best strategy for reducing the diesel consumption.

3.1 Diesel demand elasticities

Following (Dahl & Sterner, 1991; Taghvaee et al., 2019), the dynamic model is as Eq. 1, referred also as to "partial adjustment model" and "lagged endogenous model."

$$\text{Ln } Q_t = \alpha_0 + \alpha_1.\text{Ln } P_t + \alpha_2.\text{Ln } Y_t + \alpha_3.\text{Ln EE}_t + \alpha_4.R_t + \alpha_5.\text{Ln } Q_{t-1} + \alpha_6.\text{Ds}_t + e_t \quad (1)$$

where Ln is the natural logarithm; Q is the diesel quantity demanded; P is the diesel price; Y is income; EE is energy efficiency; R is the exchange rate; Ds is the dummy variable for the year after implementing the Subsidy Reform Plan; e is the error terms; t is year; α_1, α_2,α_3 and α_4 are the corresponding short-run diesel demand elasticities; and $\alpha_1/1-\alpha_5$, $\alpha_2/1-\alpha_5$, $\alpha_3/1-\alpha_5$ and $\alpha_4/1-\alpha_5$ are the corresponding long-run demand elasticities.

Following (Baranzini & Weber, 2013; Taghvaee & Hajiani, 2014), the static model is as Eq. 2.

$$\text{Ln } Q_t = \beta_0 + \beta_1.\text{Ln } P_t + \beta_2.\text{Ln } Y_t + \beta_3.\text{Ln EE}_t + \beta_4.\text{Ln } R_t + \beta_5.\text{Ds}_t + u_t \quad (2)$$

where β_1, β_2, β_3 and β_4 are the corresponding long-run elasticities of the static model; and u is the error terms which must be stationary in level to be used in the ECM estimation.

Following (Dahl & Sterner, 1991; Baranzini & Weber, 2013), the ECM is as Eq. 3.

$$\text{dLn } Q_t = \theta_0 + \theta_1.\text{dLn } P_t + \theta_2.\text{dLn } Y_t + \theta_3.\text{dLn EE}_t + \theta_4.\text{dLn } R_t + \theta_5.\text{Ds}_t + \theta_6.\hat{u}_{t-1} + \varepsilon_t \quad (3)$$

where θ_1, θ_2, θ_3 and θ_4 are the short-run elasticities of diesel demand; $\hat{u}$ is the estimated residuals of the static model; and its coefficient (θ_6) is adjustment velocity, showing the speed to fill the gap between the short- and long-run equilibria. It represents the periods which the diesel consumption needs to reach the long-run equilibrium. The adjustment velocity should be statistically significant, negative and lower than one in absolute value (Alves & Bueno, 2003).

The low elasticities confirm that the diesel consumption responds to the changes in the variables slightly. A low price elasticity confirms the inefficiency of price policy in reducing the diesel consumption (Mousavi & Ghavidel, 2019). A low exchange rate elasticity affirms that combating the diesel smuggling has insignificant impact on reducing the diesel consumption since a high exchange rate is expected to increase the incentive of smuggling the diesel into the other countries as in illegal export. Worth mentioning that diesel is subsidized in Iran and it is cheaper than in the other countries, increasing the incentive of smugglers for exporting this fuel into the other countries through illicit trade channels. However, a high energy efficiency elasticity is a strong evidence for the great effect of technology improvement on reducing the diesel consumption.

Before running the models, the variables are put into the preliminary unit root tests including augmented Dickey–Fuller (ADF), Phillips–Perron (PP), Dickey–Fuller (DF), Kwiatkowski–Phillips–Schmidt–Shin (KPSS), Elliott–Rothenberg–Stock (ERS), Ng–Perron modified, Zivot Andrews and break point augmented Dickey–Fuller (BP ADF). They show the integration degree of the variables to prevent the spurious regression since a regression on the variables with different integration degree can be spurious (Taghvaee & Hajiani, 2014) (see Appendix).

After running the models, the results are put into the robustness tests including Cumulative Sum (CUSUM), CUSUM of squares, one-step forecast, N-step forecast and recursive residuals, recursive coefficients and leverage tests plots (see Appendix). They show whether the estimated coefficients, statistics and residuals are reliable and robust.

3.2 Effects on sustainable development

Based on the estimated diesel demand elasticities, this research estimates the effect of a hypothetical energy efficiency improvement and price policy on the three pillars of sustainable development: economy, environment and social. This study hypothesizes a 10% improvement in energy efficiency and 10% increase in the price of diesel as two distinctive policies. Then, it estimates how each affects the diesel consumption as an economic element, the CO_2 emissions as an environmental factor and health as a social component.

For estimating the effects of price policy and energy efficiency on reducing the diesel consumption, this study follows (Mundaca, 2017; Sterner, 2007) to specify Eqs. 4 and 5. These equations show the hypothetical diesel demand quantities in two cases of 10% increase in price and energy efficiency, respectively. In another word, how much the quantity of diesel demand changes if the diesel price or energy efficiency has a 10% increase throughout the studied period. In this way, Eqs. 4 and 5 estimate how the price policy and energy efficiency affect the diesel consumption in the two hypothetical trends. Consider a given country, whose consumption Q is a response to changes in price (P) or energy efficiency (EE). If the country instead had different prices or energy efficiency, not only today but sufficiently long for the demanded quantity to be in equilibrium, then that country's hypothetical demand HQ would be given by Eqs. 4 and 5 (Mundaca, 2017; Sterner, 2007).

$$\mathrm{HQ}_t = Q_t\left(\frac{P_t + 0.1P_t}{P_t}\right)^{\text{Price elasticity}} \tag{4}$$

$$\mathrm{HQ}_t = Q_t\left(\frac{\mathrm{EE}i_t + 0.1\mathrm{EE}i_t}{\mathrm{EE}i_t}\right)^{\text{Energy efficiency elasticitiy}} \tag{5}$$

where HQ is the hypothetical quantity of diesel consumption and the remaining symbols are described previously.

To estimate the effects of price policy and energy efficiency on reducing the CO_2 emissions resulted from the reduction in diesel consumption, this methodology follows Eqs. 6 and 7.

$$\mathrm{HCO}_{2t} = \mathrm{CO}_{2t}\left(\frac{P_t + 0.1P_t}{P_t}\right)^{\text{Price elasticity}} \tag{6}$$

$$HCO_{2t} = CO_{2t}\left(\frac{EEi_t + 0.1EEi_t}{EEi_t}\right)^{\text{Energy efficiency elasticitiy}} \tag{7}$$

where HCO_2 is the hypothetical CO_2 emissions and CO_2 is the CO_2 emissions.

Equation 8 is for estimating the health effects of reducing diesel consumption and the resulted reduction in CO_2 emissions since this greenhouse gas causes air pollution and respiratory diseases. This research uses the *health damage factors*. Tang et al., 2019 estimated the relative risks (RR) of CO_2 emissions for human health to calculate the *health damage factors*, measured in DALY/kg CO_2. It converts the CO_2 emissions into the health status as a conversion factor. They are 1.3×10^{-6}, 1.5×10^{-6} and 2.0×10^{-6} for the three shared socioeconomic pathway (SSP) scenarios (i.e., SSP1, SSP2 and SSP3, respectively) in the World Health Organization (WHO) report, updated in 2014 (Hales et al., 2014).

$$\begin{aligned} &DALY_{SSP_x} = HDF_{SSP_x} \times CO2 \qquad x = 1, 2, 3, \text{ and } \bar{x} \\ &HDF_{SSP_1} = 1.3 \times 10^{-6}; HDF_{SSP_1} = 1.5 \times 10^{-6}; HDF_{SSP_1} = 2.0 \times 10^{-6}; \text{and} \\ &HDF_{SSP_{\bar{x}}} = 1.6 \times 10^{-6} \end{aligned} \tag{8}$$

where DALY is the Disability-Adjusted Life Years. "Each DALY can be thought of as one lost year of healthy life" (WHO, 2020). It means that one person's life is equal to 76 DALYs in Iran since its life expectancy is about 76 in 2018 (World Bank 2019). HDF is the *health damage factor,* and $SSP_{\bar{x}}$ is the average value of SSP1, SSP2 and SSP3 conversion factors. They represent the changes in DALY resulted from the changes in the CO_2 emissions of the hypothetical fossil fuel consumptions. This study only employs the average value.

3.3 Data

This research employs three datasets for estimating the demand elasticities of diesel during 1976–2017 in Iran. The diesel price is from (National Iranian Oil Refining and Distribution Company, 2014), divided by Consumer Price Index (CPI) 2011 to remove the inflation effect, measured by Rial of Iran. The gross domestic product (GDP) is from (Statistics Center of Iran, 2017) in Rial of Iran, divided by the CPI and population to have per capita GDP with constant price 2011. All the other variables are derived from (Central Bank of the Islamic Republic of Iran, 2020). The diesel consumption is divided by population to make per capita diesel consumption in barrels per day. Exchange rate is the non-official exchange to reflect the market exchange rates (1 US Dollar to Rial of Iran). Energy efficiency is the inverse of energy intensity (i.e., energy intensity/GDP) which is the proxy for technology. The data are available at the following link reference (Taghvaee et al., 2022) which is a Mendeley link https://data.mendeley.com/datasets/w2y9dccpvx/4.

Figure 5 demonstrates the natural logarithm of diesel consumption, diesel price, energy efficiency and exchange rate in Iran during 1976–2017. It shows that the diesel consumption is continuously increasing within the period, threatening all the pillars of sustainable development. It threats the environmental pillar since diesel consumption is one of biggest CO_2 emissions drivers according to Fig. 4 (Energy Balance Sheet, 2010) and CO_2 is one of the most dangerous greenhouse gas for the environment. The diesel consumption also harms the social pillar due to the dangerous effects of CO_2 emissions on the air pollution and its health consequences. Air pollution, among the environmental threats, is a leading cause of death. It is affecting nearly all of us with more than

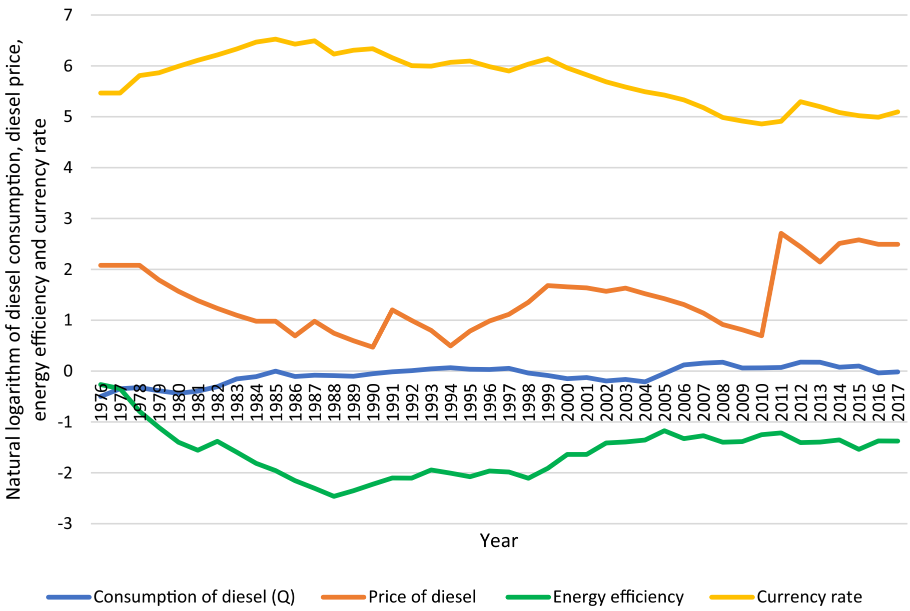


Fig. 5 Natural logarithm of diesel consumption and price, energy efficiency and exchange rate in Iran during 1976–2017. *Source*: (Central Bank of the Islamic Republic of Iran, 2020) (National Iranian Oil Refining and Distribution Company, 2014) (Statistics Center of Iran, 2017)

10% of all the world deaths. This invisible killer causes about one-third of the deaths from lung cancer, stroke and heart diseases (WHO, 2016). In addition, the energy security risks increase due to the increment in dependency to energy carrier's imports as a strategic good. The economic pillar is also at risk since the increase in diesel consumption means the increase in depletion of fossil resources (Taghvaee et al., 2016) despite common engineering practices that are taking place to reduce this tendency (Khorsandi et al., 2021). The diesel price, although, is fluctuating throughout the span, and it has a sudden increase in 2010 when the subsidy reform plan implemented to remove the fossil fuel subsidies. Energy efficiency shows no continuous increase in Iran, despite the considerable increase in technology advancement in the globe. Exchange rate, however, is decreasing throughout the span, especially in 1984 making incentive for the smugglers to export the subsidized and cheap diesel from Iran to the other countries such as Afghanistan as an illicit trade, paving the way for crimes which is threatening the social pillar of sustainable development (Taghvaee et al., 2021). Thus, the trends of the variables show high threats to sustainable development from the energy sector, especially the fossil fuel and diesel consumption.

4 Result

All the estimated models show that the diesel demand is inelastic in respect of price and exchange rate, while it is elastic in respect of the energy efficiency and income.

The unit root tests (i.e., preliminary tests) confirm that all the variables are stationary at level, paving the way for running the dynamic, static and ECM models without any worry about spurious regression problem (see Appendix: Tables A-1 to A-5).

Table 2 demonstrates the results of dynamic model estimations. According to Table 2, the price, income, energy efficiency and exchange rate elasticities of diesel demand are, respectively, − 0.03, 0.94, − 0.96 and 0.02 in the short run; and − 0.03, 1.04, − 1.06 and 0.02 in the long run. In the short run, it implies that diesel demand decreases 3% and 96% in response to each unit increment of diesel price and energy efficiency, and it increases 94% and 2% in response to each unit increment of income and exchange rate, respectively. In the long run, the response rates of diesel demand to price and exchange rate are identical to those in the short run. It implies that the short- and long-run equilibria converge to each other rapidly in case of varying the diesel price or exchange rate. However, the diesel demand in long run increases 104% and decreases 106% in response to each unit increase of income and energy efficiency, respectively, which are greater than the corresponding values in the short run. It claims that the diesel demand is elastic in response to changes in the income and energy efficiency specifically in the long run, while it is inelastic in response to changes in price and exchange rate.

Table 2 Diesel demand elasticities in the dynamic model *Source*: Researchers' findings

Variable	Coefficient	S.E	*t*-statistic	Prob.
α_0	− 1.1503***	0.2459	− 4.6776	0.00
Ln P	− 0.0354***	0.0200	− 1.7684	0.08
Ln Y	0.9403***	0.1364	6.8939	0.00
Ln EE	− 0.9626***	0.1540	− 6.2488	0.00
Ln R	0.0203***	0.0406	0.4990	0.62
Ln Q_t-_1	0.0959***	0.1413	0.6788	0.09
Ds	− 0.0732***	0.0336	2.1791	0.03
$\alpha_1/1-\alpha_5$	− 0.0391***	Long-run price elasticity		
$\alpha_2/1-\alpha_5$	1.0400***	Long-run income elasticity		
$\alpha_3/1-\alpha_5$	− 1.0647***	Long-run energy efficiency elasticity		
$\alpha_4/1-\alpha_5$	0.0224***	Long-run exchange rate elasticity		
*R*2			0.93	
Adjusted *R*2			0.91	
F-statistic			75.8439	0.00
Normality test (Jarque–Bera)			1.3544	0.30
D.W. statistic			2.0366	
Breusch-Godfrey Serial Correlation LM test (F-statistic)			0.1751	0.84
Breusch-Pagan-Godfrey Homoscedasticity test (*F*-statistic)			0.7542	0.61
Ramsey RESET test				
t-statistic			0.9734	0.33
F-statistic			0.9483	0.33
Likelihood ratio			1.1666	0.28

Table 3 shows the estimated coefficients and statistics of the static model. The price, income, energy efficiency and exchange rate elasticities of diesel demand are − 0.03, 1.01, − 1.06 and 0.006, respectively, in the long run. In another word, the long-run diesel demand increases 101% and less than 1% in response to each unit increase in income and exchange rate, and it decreases 3% and 106% in response to each unit increase in diesel price and energy efficiency, respectively. For the short-run elasticities, Table 4 represents the coefficients and statistics of the ECM. According to Table 4, the price, income, energy efficiency and exchange rate elasticities of diesel demand are − 0.01, 1.02, − 1.06 and 0.04 in the short run, respectively. It means that in the short run, the response rates of diesel demand to price and exchange rate are identical to the corresponding values in the long run. It supports the rapid convergence of the short- and long-run equilibrium after a shock to income or energy efficiency. Another evidence for this rapid modification is the adjustment velocity which is expectedly a negative value (− 0.99), expressing that the diesel consumption responds to changes in the explanatory variables rapidly. However, they are different in case of changes in price and exchange rate. The diesel demand in the short run decreases 1% and increases 4% in response to each unit increment in diesel price and exchange rate, respectively. These estimations show that the diesel demand responses insufficiently to the variations in price and exchange rate but sufficiently to the changes in income and energy efficiency, especially in the long run.

These results are reliable and robust according to the post-estimation tests. Their reliability is supported by R2 and adjusted R2. They show that the explanatory variables can explain a large part of changes in the diesel demand. F-statistics are statically significant at 1% level. In addition, the residuals follow the classical econometric assumptions. Durbin-Watson statistics and F-statistics of LM tests are statistically insignificant, accepting the null hypothesis of no-autocorrelation among the residual series. F-statistics of the

Table 3 Diesel demand elasticities in the static model *Source*: Researchers' findings

Variable	Coefficient	S.E	*t*-statistic	Prob.
β_0	− 1.1972***	0.2351	− 5.0907	0.00
Ln P	− 0.0347***	0.0196	− 1.7645	0.08
Ln Y	1.0174***	0.0842	12.0804	0.00
Ln EE	− 1.0658***	0.0545	2.5612	0.01
Ln R	0.0055***	0.0349	7.1583	0.87
Ds	− 0.0763***	0.0327	2.3321	0.02
*R*2			0.93	
Adjusted *R*2			0.93	
F-statistic			111.3487	0.00
Normality test (Jarque–Bera)			3.1743	0.20
D.W. statistic			2.0884	
Breusch-Godfrey Serial Correlation LM test (*F*-statistic)			0.3713	0.69
Breusch-Pagan-Godfrey Homoscedasticity test (*F*-statistic)			0.5608	0.72
Estimated residuals ADF test (no intercept and no trend)			− 6.3043	0.00
Ramsey RESET test				
t-statistic			1.1786	0.24
F-statistic			1.3891	0.24
Likelihood ratio			1.6347	0.20

Table 4 Diesel demand elasticities in the ECM model
Source: Researchers' findings

Variable	Coefficient	S.E	*t*-statistic	Prob.
θ_0	– 0.0001***	0.0086	– 0.0178	0.98
d Ln P	– 0.0127***	0.0200	– 0.6371	0.52
d Ln Y	1.0292***	0.1357	7.5813	0.00
d Ln EE	– 1.0676***	0.1515	– 7.0459	0.00
d Ln R	– 0.0415***	0.0671	– 0.6178	0.54
Ds	– 0.0044***	0.0194	0.2314	0.81
$\hat{u}$	– 0.9989***	0.2441	– 4.2334	0.00
*R*2			0.65	
Adjusted *R*2			0.59	
F-statistic			10.044	0.00
Normality test (Jarque–Bera)			2.1687	0.33
D.W. statistic			1.45	
Breusch-Godfrey Serial Correlation LM test (*F*-statistic)			2.0469	0.14
Breusch-Pagan-Godfrey Homoscedasticity test (*F*-statistic)			0.2929	0.96

Breusch-Pagan-Godfrey homoscedasticity tests accepts the homoscedasticity of the residual variances. The Ramsey RESET tests confirm the reliability of the estimated models and their coefficients and statistics. Furthermore, the estimated elasticities are confirmed by the robustness tests performed after running the models including Cumulative Sum (CUSUM), CUSUM of squares, one-step forecast, N-step forecast, and recursive residuals, recursive coefficients and leverage tests plots (see Appendix: Figures A-1 to A-9). Thus, the estimated elasticities are reliable and robust.

Therefore, the results of all the models including the dynamic, static and ECM unanimously show that the diesel demand is more responsive to the variations in energy efficiency than to the price changes or exchange rate (as a proxy for diesel smuggling to the neighboring countries) both in short and long run. It implies that the technological and energy efficiency policies are successful alternatives for reducing the diesel demand, and they are more effective than the price policies and combating with diesel smuggling. The diesel demand is price inelastic due to the lack of substitute goods for diesel fuel in Iran. In addition, the diesel demand response in the long run is relatively greater than those in the short run. It suggests that the policies for the management of diesel demand need sufficient time to create their full effects. Based on this analysis, the strategist should focus on technological policies, especially from a long-run view point, in adopting their policies toward diesel demand reduction.

5 Discussion

Table 5 offers the diesel demand elasticities in Iran. They show that the diesel demand responds to the changes in price and exchange rate slightly. It is consistent with the results of previous studies about energy demand in Iran (Agheli, 2015; Ahmadian et al., 2007; Moshiri, 2020; Mousavi & Ghavidel 2019; Taghvaee & Hajiani 2014), diesel demand

Table 5 Estimated diesel demand elasticities *Source*: Researchers' findings

Diesel demand elasticities	Price	Income	Energy efficiency	Exchange rate
Short run	– 0.01 to 0.03	0.94–1.02	– 0.96 to – 1.06	– 0.04 to 0.02
Long run	– 0.03	1.01 to 1.04	– 1.06	0.01 to 0.02
Short run (average values)	– 0.02	0.98	– 1.01	– 0.01
Long run (average values)	– 0.03	1.02	– 1.06	0.01

in other countries (Lim et al., 2012), demand of other kinds of fossil fuels (Baranzini & Weber, 2013; Dahl, 2012; Raghoo & Surroop 2020) and energy as whole (Labandeira et al., 2017; Liddle et al., 2020). It confirms that there is lack of substitute goods for diesel fuel, and the price policy or subsidy removal is an inefficient policy to reduce the diesel demand just like combating diesel smuggling which is consistent with (Jewell et al., 2018). To increase the responsiveness of diesel demand to price change, the policy-makers should provide the consumers with substitute fuels, especially the renewable ones. However, the energy efficiency elasticity is high, suggesting the technology improvement for reducing the diesel consumption. As a comparison, technology improvement is a considerably more effective strategy to reduce the diesel consumption than the price policy and combating the diesel smuggle which is consistent with (Brockway et al., 2021).

Table 6 illustrates the effects of energy efficiency improvement and price policy on the pillars of sustainable development including economy, environment and social. According to Table 6, the 10% improvement in energy efficiency in the first year of the period could save more than 87 billion liters of diesel, while this value is more than 2.6 billion liters for 10% increase in price. In this way, the energy efficiency is 33 times stronger than the price policy in recovering the economic pillar of sustainable development. This paper considers the availability of energy as an economic factor since energy is an important input for the economic growth and output (Yasmeen et al., 2021; Liu et al., 2021; Liua et al., 2020), especially about Iran whose economy is on the basis of energy sector. In addition, the energy efficiency has the capability to reduce more than 3 billion tons of CO_2 emission in the period, while it is only 92 million for the price policy. Again, the energy efficiency is 32 times more effective in improvement of the environmental pillar of sustainable development. Furthermore, the energy efficiency survives more than 65 thousand lives, but the price policy does less than 2 thousand lives. It confirms that the energy efficiency is considerably more sufficient strategy in enhancement of health pillar of sustainable development. Worth mentioning that, the time periods are different for the economic, environmental and social effects due to the availability of the data needed for the estimations. The data of GDP are available within 1976–2017, while the CO_2 emissions data are available during 2000–2017; this is why this research considers two distinctive time periods in this

Table 6 Effect of 10% improvement in energy efficiency versus 10% increase in price on the sustainable development pillars *Source*: Researchers' findings

	Period	Energy efficiency	Price policy
Economy (diesel consumption in thousand liters)	1976–2017	87,535,860	2,600,962.5
Environment (reduction in CO2 emissions in ton)	2000–2017	3,098,988,022.5	92,080,567.5
Social (health: surviving people's lives)	2000–2017	65,241	1,938

estimation. Therefore, energy efficiency or rather technology improvement is considerably stronger approach to improve the sustainable development.

6 Conclusion

This study estimates the elasticities of diesel demand in Iran during 1976–2017 using dynamic, static and ECM models to investigate whether price policy and subsidy removal is capable to reduce diesel demand in Iran. Although the previous studies investigate the fossil fuel demand elasticities, this study goes further and estimates the effects of changes in price and energy efficiency on diesel demand. Actually, the novelty of this research is that it compares the effects of price policy and energy efficiency on reducing diesel demand and improving sustainability to reveal which one is a more effective policy. It also estimates how these two policies affect sustainability in Iran to reveal which strategy is more consistent with sustainable development. The research findings are as follows.

i. Diesel demand responds significantly and swiftly to changes in income and technology, but slightly and slowly to price changes.

   According to the results, the price and exchange rate elasticities of diesel demand are very lower than one, while the energy efficiency and income elasticities are greater than or close to one both in the short and long run. The price and exchange rate elasticities of diesel demand are − 0.03 and 0.01 in the long run, and they are − 0.02 and − 0.01 in the short run, respectively. The income and energy efficiency elasticities of diesel demand are 1.02 and − 1.06 in the long run and 0.98 and − 1.01 in the short run, respectively. In other words, the diesel demand is inelastic in response to changes in price and exchange rate, while it is elastic in response to changes in energy efficiency and income. It shows the shortage of substitute fuels for diesel which can be eliminated by promoting the renewable energy carriers. It suggests that the diesel consumption is irresponsive to changes in price and exchange rate, while it responds to energy efficiency more considerably. In another word, energy efficiency is a more effective policy than the price policy and subsidy removal. In addition, it shows that combating diesel smuggling is an ineffective way for reducing diesel consumption since diesel demand is irresponsive to increase in exchange rate which is an incentive for diesel smuggling.

ii. Technological policies are more effective than price policies to reduce diesel demand and improve sustainable development.

   Based on the demand elasticities, this study compares the effects of a 10% increase in diesel price with the case of 10% enhancement in energy efficiency on sustainable development pillars in Iran: economy, environment and social. The results show that the energy efficiency policy is higher than 30 times more effective on the management of diesel demand and more beneficial on sustainable development pillars. On all the three pillars of sustainable development, the energy efficiency has more beneficial effects as it saves more diesel (about 85 billion liters), reduces more CO_2 emissions (more than 2900 million tons) and survives more lives (more than 63 thousand lives) in the study period. Thus, energy efficiency, compared with price policy, is more consistent with sustainable development.

iii. This research casts doubt on the effectiveness of the UN suggestion for subsidy removal to reduce fossil fuel demand considerably.

Our findings show that subsidy removal is an ineffective policy to decrease diesel demand and to achieve the mitigation target in 2030. Hence, it would be substituted by an effective strategy. This study acknowledges technology improvement as a more efficient strategy to decrease diesel demand and CO_2 emissions. Actually, this strategy has the capability to achieve the mitigation targets in 2030.

iv. The strategists should improve the technology especially the efficiency of energy-consuming utilities like cars, rather than increasing the price and removal of subsidy.

There are numerous ways to develop this technology, for example the policy-makers can decrease the customs duties which are set on importing the cars with high energy efficiency. In addition, they should make a more competitive environment in the domestic car producing industries to increase their quality and their energy efficiency. They should set stricter environmental standards for the domestic car producers to boost the energy efficiency of their products. However, the car Mafia in Iran supports the monopoly of car production which is a formidable obstacle to improve technology in car production and to import modern and energy-efficient cars easily. Thus, the policy-makers should combat with this Mafia by paving the way for a competitive environment in car market to reduce the consumption of diesel demand and its concomitant risks to sustainable development in Iran. In addition, the strategists should promote the renewable energies as substitute fuels for diesel fuel to increase the price elasticities of diesel demand which, in turn, increases the effectiveness of the subsidy removal and price policy.

The limitation of this research is the consideration of only one fossil fuel type (i.e., diesel). Although diesel has the biggest share in the Iranian consumers' energy portfolio, they might exhibit various behaviors in case of the other fossil fuel kinds such as gasoline, fuel oil, kerosene or liquefied petroleum gas (LPG). Based on this analysis, the researchers can continue this research for estimating the elasticities of the other fossil fuels and test their effects on the sustainable development. In case of conflicting results, our findings are reliable only for diesel fuel; otherwise, our results are valid for all types of fossil fuels.

Appendix

Preliminary tests (unit root test)

See (Tables 7, 8, 9, 10, 11).

Table 7 Augmented Dickey–Fuller and Phillips–Perron unit root resulted statistics of the variables in level

	ADF (τ statistic)			PP (adjusted t-statistic)		
	C	C & T	None	C	C & T	None
LnQd	− 2.6089 (0.09)	− 2.2505 (0.45)	− 2.8595 (0.00)	− 2.6130 (0.09)	− 2.4666 (0.34)	− 2.8153 (0.00)
LnPd	− 1.7879 (0.38)	− 2.4030 (0.37)	− 0.5452 (0.47)	− 1.7733 (0.38)	− 2.2505 (0.45)	− 0.4303 (0.52)
LnEE	− 3.0331 (0.04)	− 3.4569 (0.05)	0.1986 (0.73)	− 2.8290 (0.06)	− 3.4613 (0.05)	− 0.0852 (0.64)
LnY	− 2.7224 (0.07)	− 2.9319 (0.16)	− 1.1677 (0.21)	− 2.2690 (0.18)	− 3.3109 (0.07)	− 1.0316 (0.26)
LnR	− 0.4498 (0.89)	− 3.0549 (0.13)	− 0.4610 (0.50)	− 7.7308 (0.82)	− 3.0336 (0.13)	− 0.4083 (0.53)

Parentheses represent the Prob. values

Table 8 Dickey–Fuller, Kwiatkowski–Phillips–Schmidt–Shin and Elliott–Rothenberg–Stock test resulted statistics of the variables in level

	DF (τ statistic)		KPSS (LM statistic)		ERS (P statistic)	
	C	C & T	C	C & T	C	C & T
LnQd	− 1.1068	− 1.9223	0.5365	0.1156	28.1057	18.9720
LnPd	− 1.6452	− 2.0706	0.2909	0.1706	5.5235	16.9365
LnEE	− 1.0798	− 1.5021	0.1722	0.1669	53.3121	109.1792
LnY	− 1.4802	− 2.0517	0.2493	0.1628	14.4218	60.5903
LnR	− 0.5652	− 1.6239	0.5592	0.1635	20.4070	63.6555
Critical values						
1% level	− 2.6225	− 3.7700	0.7390	0.2160	1.8700	4.2200
5% level	− 1.9490	− 3.1900	0.4630	0.1460	2.9700	5.7200
10% level	− 1.6118	− 2.8900	0.3470	0.1190	3.9100	6.7700

Table 9 NP–Perron modified unit root test resulted statistics of the variables in level

	C				C & T			
	MZa	MZt	MSB	MPT	MZa	MZt	MSB	MPT
LnQd	− 1.5456	− 0.7785	0.5037	13.9065	− 5.8496	− 1.5915	0.2720	15.3871
LnPd	− 5.1182	− 1.5190	0.2967	4.9879	− 6.5851	− 1.7212	0.2613	13.8697
LnEE	− 0.9377	− 0.6525	0.6958	24.3530	− 1.4850	− 0.8018	0.5399	55.0310
LnY	− 3.3789	− 1.2942	3.3830	7.2473	− 4.8235	− 1.5363	0.3185	18.7908
LnR	− 0.8985	− 0.5480	0.6099	20.4955	− 2.3349	− 1.0616	0.4546	38.1674
Asymptotic critical value								
1% level	− 13.8000	− 2.5800	0.1740	1.7800	− 23.8000	− 3.4200	0.1430	4.0300
5% level	− 8.1000	− 1.9800	0.2330	3.1700	− 17.3000	− 2.9100	0.1680	5.4800
10% level	− 5.7000	− 1.6200	0.2750	4.4500	− 14.2000	− 2.6200	0.1850	6.6700

Table 10 Zivot Andrews unit root test resulted statistics of the variables in level

	C	BP	T	BP	C & T	BP
LnQd	− 3.5470 (0.02)	1998	–	–	− 4.2105	1998 (0.00)
LnPd	− 4.6446 (0.00)	2011	− 3.4317	1987	− 3.8891 (0.31)	2011 (0.00)
LnEE	− 4.5457 (0.00)	1999	− 3.1866 (0.18)	2011	− 3.1535 (0.00)	1984
LnY	− 5.2333 (0.03)	1999	− 4.4949 (0.02)	2011	− 4.3150 (0.75)	2010
LnR	− 4.5768 (0.04)	2000	− 3.5495 (0.06)	2011	− 3.3993 (0.01)	2007

With 4 lags

Parentheses represent the Prob. values

Table 11 Break point augmented Dickey–Fuller (BP ADF) unit root test resulted statistics with innovation and additive outliers of the variables in level

Basic Breaking	C –	BP –	C & T C	BP	C & T C & T	BP	C & T T	BP
LnQd	− 3.4222 (0.42)	1981	− 3.5050 (0.68)	1997	− 4.1597 (0.41)	1997	− 2.5570 (0.89)	1984
LnPd	− 4.7169 (0.02)	2010	− 4.6713 (0.08)	2010	− 3.9248 (0.57)	2010	− 3.4317 (0.44)	1987
LnEE	− 4.7455 (0.02)	1998	− 3.8172 (0.48)	1998	− 3.5239 (0.80)	1982	− 3.9863 (0.18)	1980
LnY	− 5.3931 (0.00)	1999	− 4.6940 (0.07)	1997	− 4.4105 (0.27)	2013	− 4.5445 (0.04)	2013
LnR	− 3.6542 (0.30)	1999	− 3.9423 (0.40)	1999	− 6.0319 (0.00)	1996	− 3.3732 (0.48)	1980

The results of BP ADF are the same both with innovation and additive outliers

Parentheses represent the Prob. values

Robustness tests

See (Figs. 6, 7, 8, 9, 10, 11, 12, 13, 14).

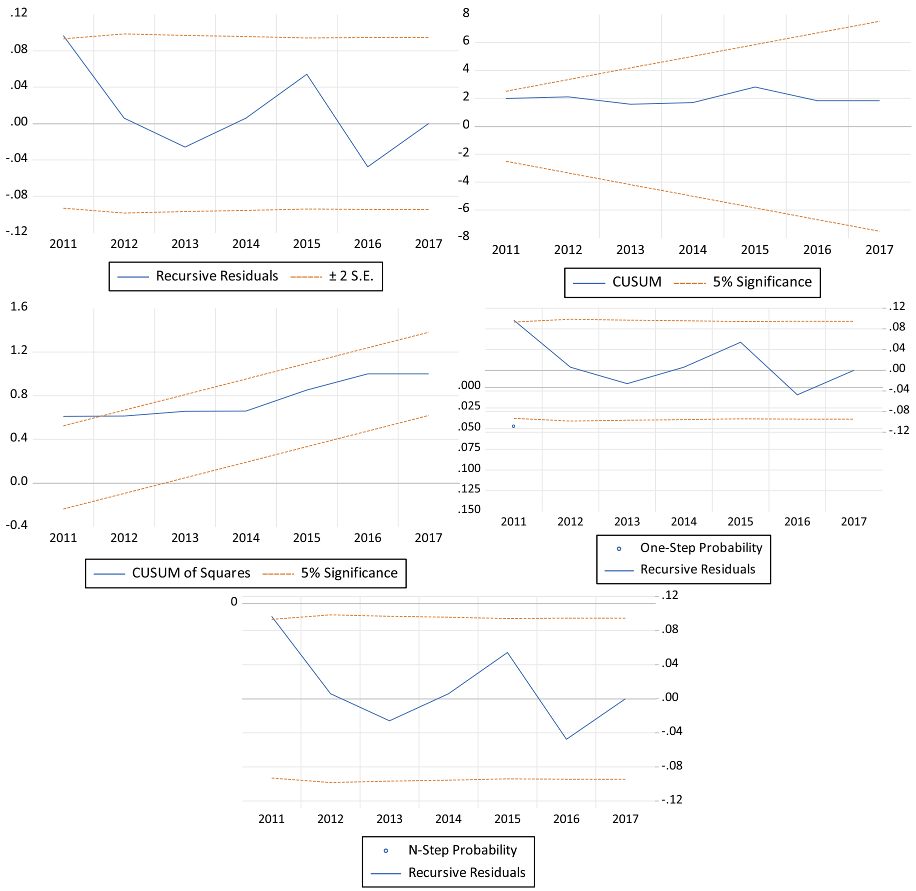


Fig. 6 CUSUM, CUSUM of squares, one-step forecast, N-step forecast and recursive residuals test results in the dynamic model

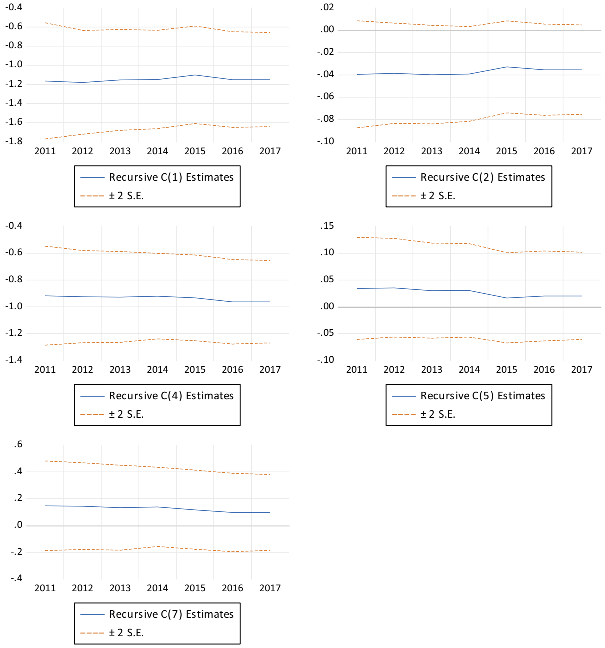


Fig. 7 Recursive coefficients test results in the dynamic model

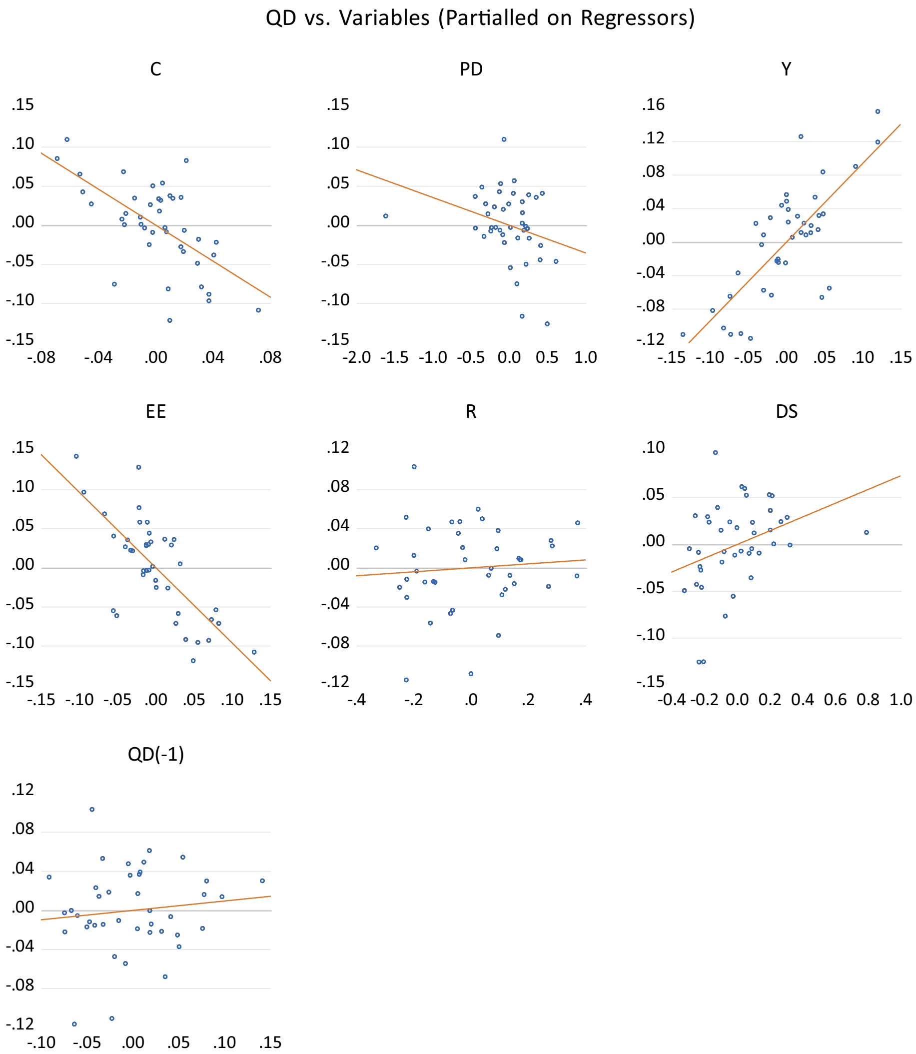


Fig. 8 Leverage plots of the dynamic model

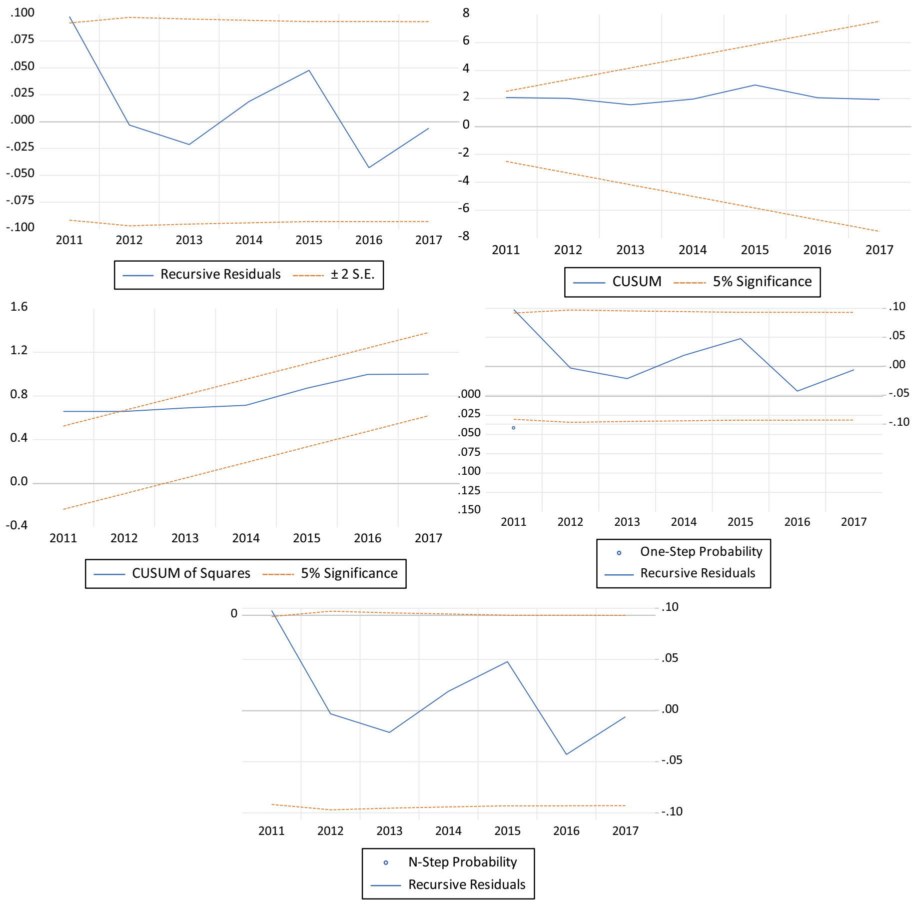


Fig. 9 CUSUM, CUSUM of squares, one-step forecast, N-step forecast and recursive residuals test results in the static model

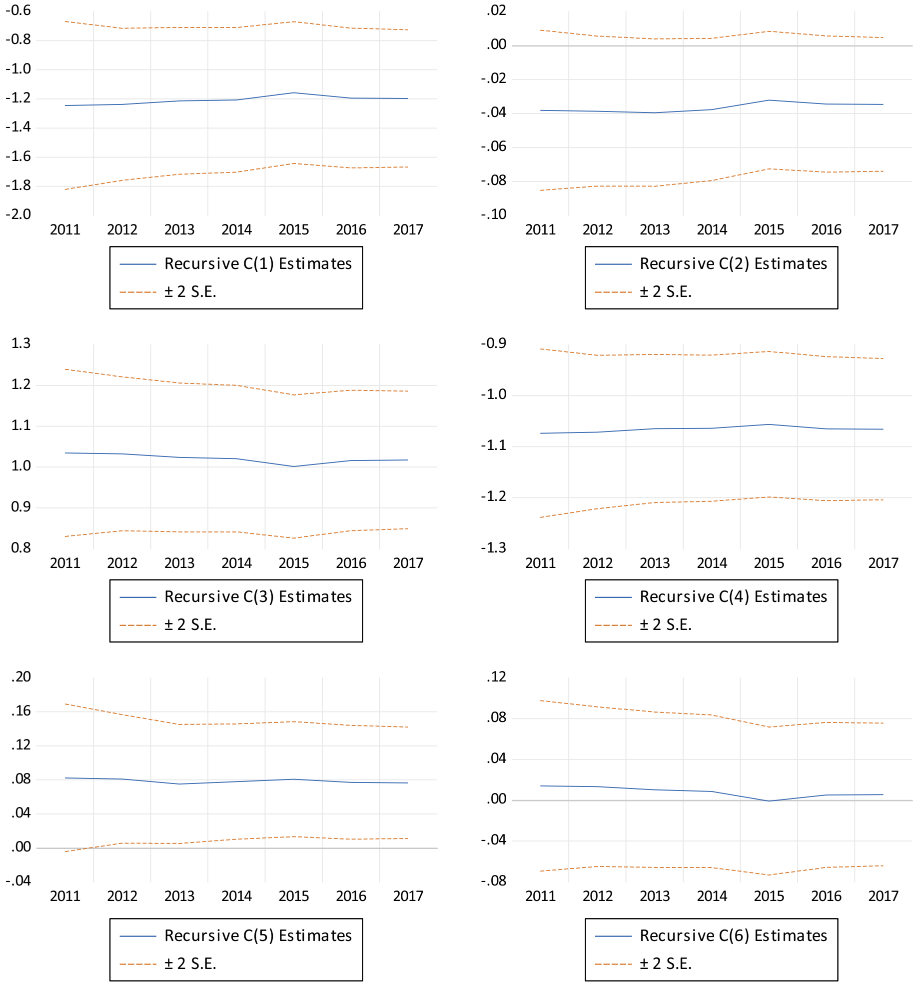


Fig. 10 Recursive coefficients test results in the static model

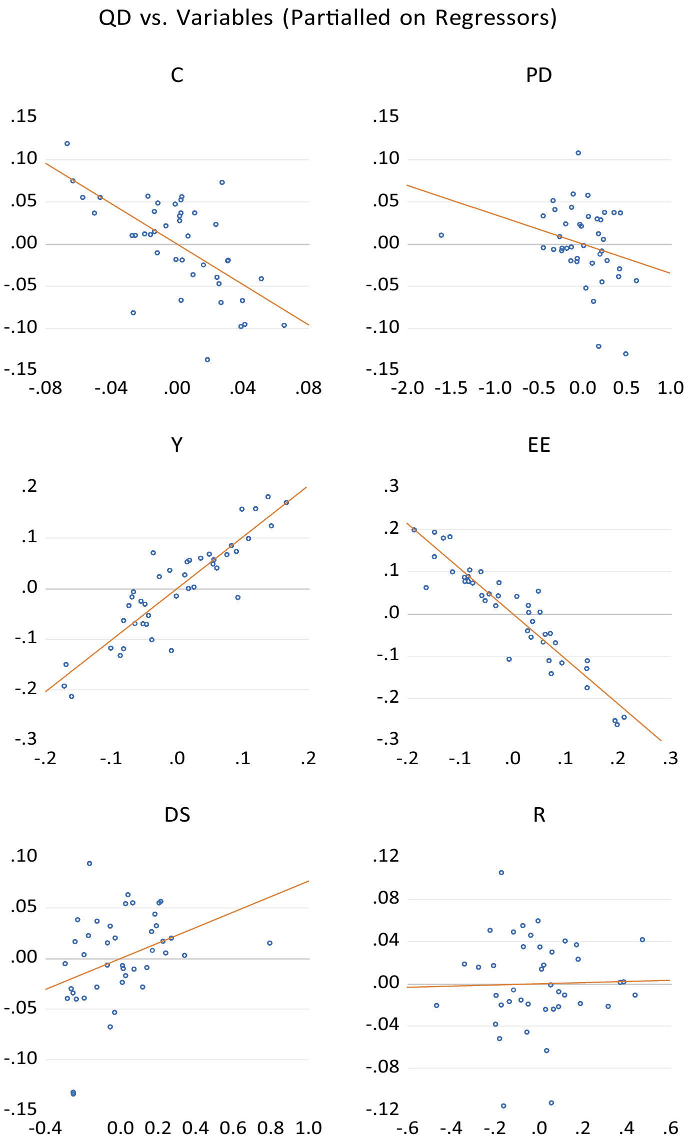


Fig. 11 Leverage plots of the static model

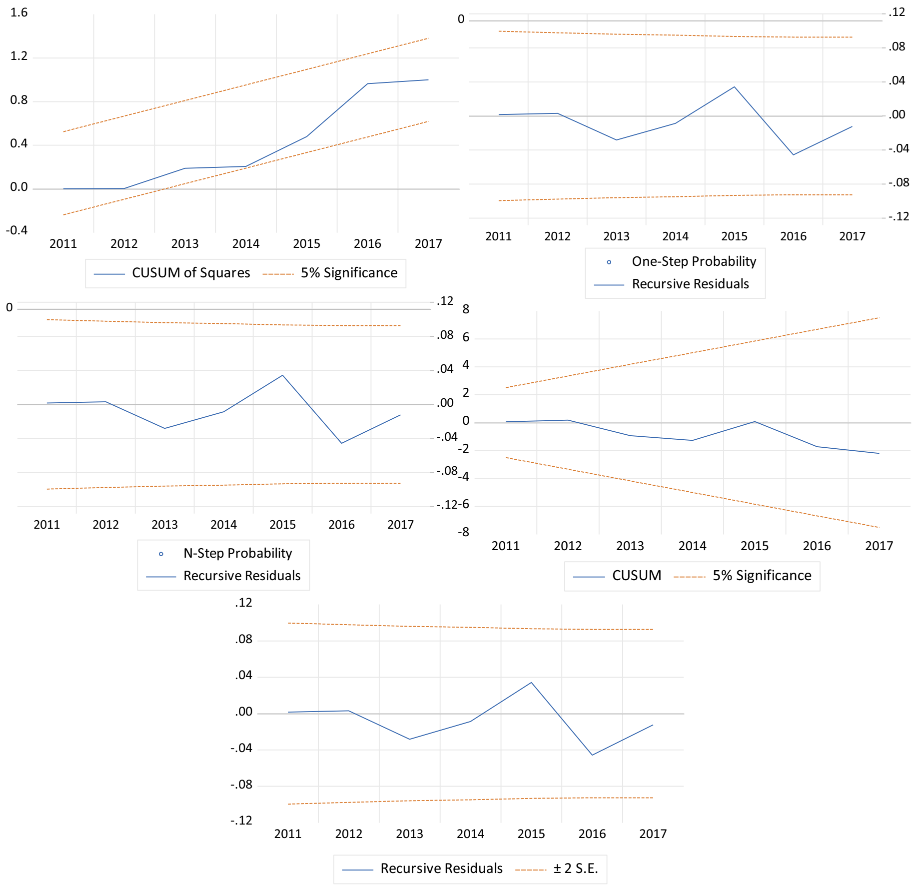


Fig. 12 CUSUM, CUSUM of squares, one-step forecast, N-step forecast and recursive residuals test results in the ECM model

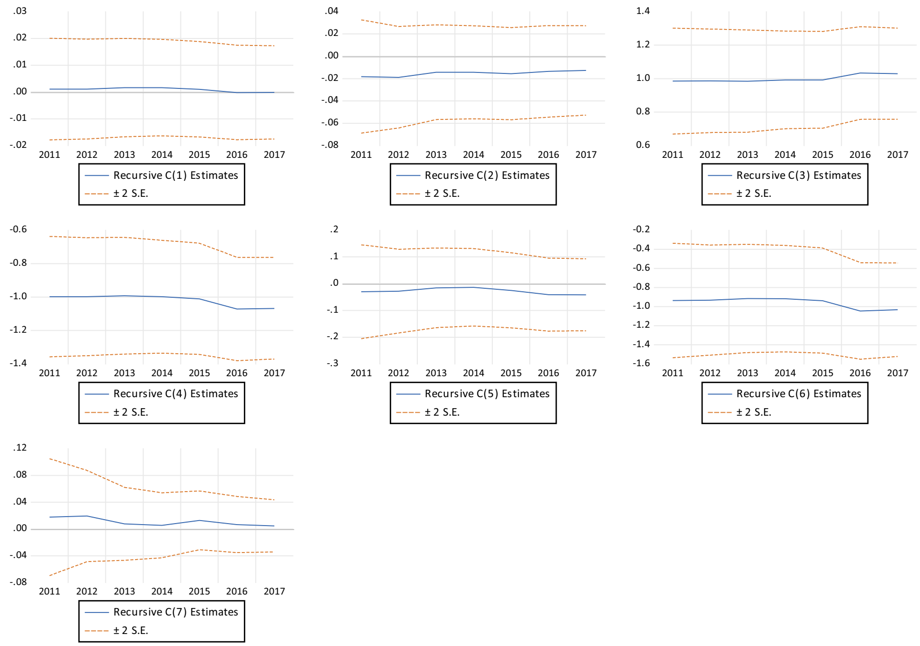


Fig. 13 Recursive coefficients test results in the ECM model

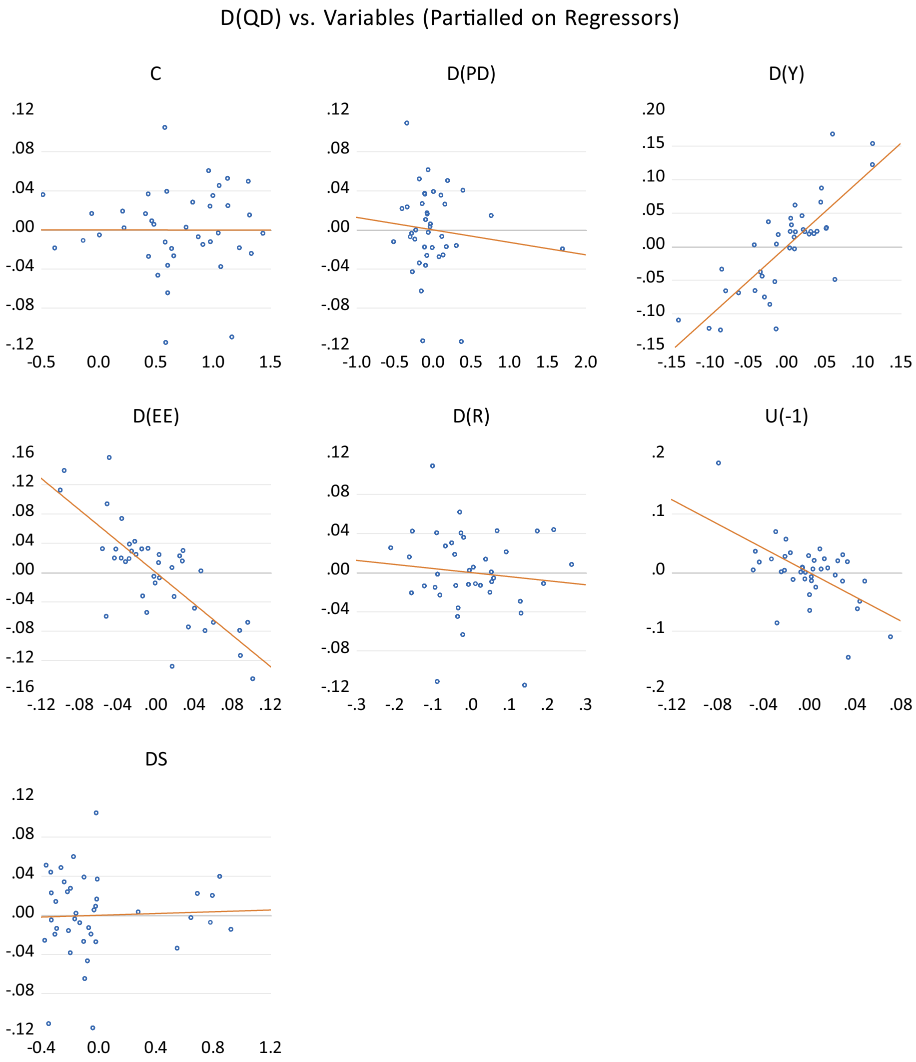


Fig. 14 Leverage plots of the ECM model

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Data availability The data of this research are in the following link to the Mendeley (Taghvaee et al., 2022) https://data.mendeley.com/datasets/w2y9dccpvx/4.

Code availability The EViews Work File and the data of this research are in the following link to the Mendeley (Taghvaee et al., 2022) https://data.mendeley.com/datasets/w2y9dccpvx/4.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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