Navigating geopolitical crises for energy security: Evaluating optimal subsidy policies via a Markov switching DSGE model

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Abstract: This paper aims to provide insights on the design of optimal subsidy policies to enhance energy security amidst energy disruptions triggered by geopolitical conflicts. We introduce a novel Markov switching dynamic stochastic general equilibrium (MS-DSGE) model to address the limitations of existing integrated assessment models in environmental evaluation. These models often fail to adequately consider the environmental and economic impacts of geopolitical conflicts and do not prioritize energy security sufficiently in policymaking. Our application of the MS-DSGE model to the Russia–Ukraine conflict reveals significant decreases in output, social welfare, and energy consumption during disruptions. The mere anticipation of an energy crisis influences household behaviors, leading to a reduction in energy, output, and consumption volatility, while concurrently increasing volatility in social welfare. We show that an optimal subsidy policy should be contingent upon productivity levels, energy imports, and the economy's responsiveness to economic shocks. Moreover, the policy should also be adaptable to prevailing economic conditions and the likelihood of an upcoming crisis.

Keywords: Energy resilience, Energy security, Geopolitical crises, MS-DSGE model, Optimal subsidy policy

Introduction

The recent geopolitical crisis between Russia and Ukraine has highlighted the vulnerability and dependence of European countries on a single energy supplier. Russia, which supplied 34% of the gas consumed by the European Union countries (EU27) plus Great Britain (GB) in 2019 (Pedersen et al., 2022), has cut off its exports, causing a scramble for alternative energy sources and exposing the need for energy security. How can countries navigate shocks, secure a stable energy supply, and pursue sustainable energy solutions during crises?

The concept of energy security is multifaceted and includes aspects such as the diversification of energy sources and the self-sufficiency of an economy in its energy resources.[1] In the context of energy security, this study focuses specifically on the dimension of energy self-sufficiency. Our objective is to assess the probability of an economy adequately meeting the energy needs of its households, with less emphasis on the range of energy sources present within the economy. In this study, we use the term "energy resilience" to refer to this specific aspect of energy security. This chosen definition closely aligns with the current concerns that have arisen due to Russia's decision to suspend its energy exports to the EU. Bolstering energy resilience enables countries to improve their capacity to withstand and recover from disruptions from geopolitical conflicts, natural disasters, cyberattacks, or infrastructure failures. The interruption in Russian energy supplies to Europe serves as a reminder that diversifying energy sources and providers is critical for improving energy resilience and reducing reliance on a single country.[2] Some countries, such as Germany, have resorted to restarting coal-fired power plants to compensate for the shortage of natural gas (Maliszewska-Nienartowicz, 2023, Pereira et al., 2022). Consequently, achieving global decarbonization goals becomes more uncertain, partially damaging the achievements of global environmental governance (Berahab, 2022).

The typical approach to environmental evaluation, using the integrated assessment models (e.g., Hope, 2013, Nordhaus, 2018) is centered on balancing the negative economic impacts of environmental policies against their environmental advantages. However, these policies often involve costs and can negatively impact the economy.

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[1] A comprehensive discussion of various aspects of energy security will be provided in the literature review section.

[2] There are also some other negative consequences of the Russia–Ukraine war, such as the extensive damage to wildlife habitats and human living environments (Pereira et al., 2022; Rawtani et al., 2022), increase in commodity prices, particularly energy (Wang et al., 2023a; Nwonye et al., 2023; Belaïd et al., 2023), and the pollution of soil and groundwater resources (Shumilova et al., 2023; Wenning and Tomasi, 2023).

For example, industries may incur higher expenses to adopt cleaner technologies or reduce emissions, leading to increased costs and a negative impact on profitability (Rassier and Earnhart, 2010; Feichtinger et al., 2005).[3] Environmental policies, on the other hand, seek to solve pressing environmental challenges such as pollution, climate change, and resource depletion. Adhering to these regulations can yield substantial environmental advantages, including improved air and water quality, reduced greenhouse gas emissions, preservation of ecosystems, and sustainable resource management. In the wake of the Russia–Ukraine conflict, there is an increasing acknowledgment of the need to incorporate energy resilience considerations into the development of environmental policies (Belaïd et al., 2023; Zakeri et al., 2022; Gatto, 2022). Policymakers need to ensure the resilience and adaptability of the energy system to cope with unforeseen catastrophes. This entails evaluating its capacity to withstand shocks, sustain functionality during disturbances, and quickly recover afterward.

This paper aims to explore how countries can enhance energy resilience and implement effective energy policies in preparation for potential geopolitical conflicts. The existing analytical tools have limitations in understanding these issues and fail to incorporate energy crises or recognize the importance of energy resilience. To address this gap, there is an urgent need for an analytical framework that can comprehensively assess the impacts of these conflicts and inform energy policy formulation. The primary objective of this paper is to present such an analytical tool focusing on sustainable development policies and incorporating energy resilience considerations. It further aims to provide policymakers with potential solutions for effectively managing these challenges and improving energy resilience.

We introduce a Markov switching dynamic stochastic general equilibrium (MS-DSGE) model to assess the environmental, welfare, and economic effects of unexpected disruptions in energy imports. The model incorporates two distinct economic regimes: the normal regime, characterized by a significant reliance on imported energy, and the energy-crisis regime, which entails a sudden decrease in foreign energy supply. We use the model to analyze how the government should implement policies to support domestic energy production and prepare for potential energy crises. By addressing the Ramsey social planner problem, we also calculate the optimal subsidy policies for domestic energy production firms in response to various economic shocks.

The main findings of this paper show that a disruption in energy imports causes a significant decrease in output, social welfare, and energy consumption. Furthermore, the mere expectation or anticipation of an energy crisis can impact household consumption and saving behavior, making households more conservative. This changed behavior diminishes the volatility observed in energy, output, and household consumption, in response to economic shocks, while simultaneously augmenting the volatility of social welfare. Therefore, we propose that a well-crafted subsidy policy should account for variations in productivity levels and energy imports, progressively increasing the subsidy in tandem with the expansion of the economy.

By solving a Ramsey planner problem in each economic regime, we find that the optimal subsidy policy should be responsive to positive supply shocks while reducing its responsiveness to positive demand shocks. In situations where the probability of an energy supply termination is high, the government should adopt a subsidy policy with lower sensitivity to ongoing economic shocks. However, implementing this strategy poses challenges, such as increased tax burden and the necessity to establish a potential energy-crisis regime. The effectiveness of the subsidy policy depends on the prevailing economic conditions, with an upsurge during insufficient demand and a decrease in other circumstances. The extent to which the government prioritizes these concerns varies in accordance with the probability of an impending crisis.

The paper is structured as follows: Section 2 offers a brief literature review. Section 3 presents the main model setting. The calibration procedure and key findings are outlined in Sections 4 and 5, respectively. Finally, Section 6 concludes and discusses policy implications.

2. Literature review

Starting from Heutel (2012) and Fischer and Springborn (2011), an increasing number of researchers have been using DSGE models for analyzing environmental and energy policies (e.g., Punzi 2019, Annicchiarico and Di Dio 2015). Apart from the deterministic dynamic model (e.g., Kotlikoff et al., 2021), DSGE models are particularly well-suited for handling stochastic environmental factors within a dynamic modeling framework. However, the existing DSGE models employed for energy policy analysis do not typically take into account the regime-switching nature, which is a crucial aspect for characterizing the dynamics of an economy.

It is important to note that the problem addressed in this paper differs from those examined in previous studies. The standard DSGE model focuses on a single steady state and assumes that shocks are small and temporary, having no impact on the steady state. Therefore, these shocks need to be sufficiently minor to justify the use of perturbation techniques for model solving. In essence, economic agents, such as households and firms, acknowledge that despite the occurrence of various economic shocks, the economy will eventually converge to its steady state over time. However, this assumption does not hold true for the specific scenario we are investigating in this paper. In our case, the disruption in energy supply can be significant and long-lasting, potentially altering the model's steady state. Moreover, we examine a situation where the timing of this disruption is uncertain. The anticipation of this disruption can lead to different decisions by firms and households, thereby affecting the overall economy. In summary, while standard DSGE models analyze the effects of small and temporary deviations from equilibrium to the steady state, the MS-DSGE model assesses the consequences of potential changes in the steady state.

The consideration of regime-switching in economic modeling, led by the work of Sims and Zha (2006), has prompted a growing focus on studying its effects on the economy. This trend has fostered the development of MS-DSGE models. In the literature, most MS-DSGE models assume regime switches in the policy regime, particularly monetary policy, as well as shifts in the volatility of exogenous shock processes. Studies by Liu et al. (2011), Choi and Hur (2015), and Bianchi (2013) demonstrate the significance of incorporating regime-switching effects in various economic contexts, such as shock volatilities, monetary policy rule coefficients, and inflation-output trade-offs. Other studies, including those by Liu et al. (2011) and Davig and Doh (2014), also apply regime-switching approaches to the monetary policy rule.

Furthermore, there are studies that incorporate regime shifting into analyses of different policy types. A notable example is the work by Cúrdia and Finocchiaro (2013), who develop an MS-DSGE model to capture the transition from exchange rate targeting to inflation targeting that occurred in 1993. Additionally, Bianchi and Ilut (2017) posit a regime-switching framework in the dynamics between monetary and fiscal authorities, showing that such a regime change can explain shifts in inflation persistence and volatility observed in the United States. Our approach differs from these studies as we define regimes based on levels of energy imports. This stands in stark contrast to the characteristics outlined in those papers' models.

Energy security is a complex concept that lacks a universally accepted definition. Various studies have employed different approaches to measure and evaluate energy security, using distinct dimensions

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[3] Several studies have found that certain companies can experience greater profitability under stringent environmental regulations (Testa et al., 2011; Porter, 1996; Ambec et al., 2013; Murty and Kumar, 2003), but macroscopically and at least in the short term, this finding is generally not supported (Brännlund et al., 2009).

and indicators based on their objectives and perspectives. For example, Sovacool et al. (2012) survey 16 dimensions of energy security, encompassing factors such as energy supply availability and transparency in energy decision-making. Roege et al. (2014) introduce a matrix-based approach to evaluate energy resilience, which refers to an energy system's capacity to recover from adversity. Le and Nguyen (2019) utilize five measures of energy security, capturing its availability, accessibility, acceptability, affordability, and developability. Similarly, Metcalf (2014) defines energy security as the ability of households, businesses, and the government to cope with disruptions in energy markets. Lee and Wang (2022) calculate energy security by selecting 20 indicators from the perspectives of energy industry construction, energy supply availability, energy demand affordability, and environmental sustainability.

Similar to Spanjer (2007) and De Rosa et al. (2022), Bigerna et al. (2021) propose dependence and diversity as measures of energy security, which are commonly used in the field. They define energy independence as the ratio of a country's total primary energy supply to its own energy production, while diversity is measured by the variety of energy sources. The ratio of energy imports to domestic energy consumption is widely used in studies on energy security, such as Gong et al. (2022) and Wang et al. (2023b). It is worth noting that the International Energy Agency (IEA) defines energy security as the uninterrupted availability of energy sources at an affordable price, a definition also emphasized by Ranjan and Hughes (2014).[4] In our study, we emphasize energy independence as a crucial aspect of energy security, focusing on a country's ability to meet household energy requirements rather than the range of energy sources available in its economy. We refer to this concept as energy resilience.

The concept of energy resilience has attracted considerable attention among scholars, as demonstrated by studies such as Jasiūnas et al. (2021), Thomas and Kerner (2010), and Sharifi and Yamagata (2016). Gatto and Drago (2020a,b) have provided definitions of energy resilience, highlighting its ability to withstand, respond to, overcome, and effectively manage disruptions arising from various economic, social, environmental, and institutional disturbances. In accordance with this definition, our focus is to explore how countries can enhance energy resilience in preparation for potential geopolitical conflicts. Furthermore, our model takes into account that a decrease in energy supply would lead to an increase in energy prices, ultimately affecting the affordability of energy for households. As a result, our model captures the affordability aspect of energy security. Up until now, no research has fully integrated this concept into energy policy analysis, making it the primary contribution of our paper.

3. Model

3.1. Firm

The firms' maximization problem is well-established in the literature, assuming perfect competition in the market for consumption goods. The production process of the standard consumption good uses capital K_t, labor L_t, and imported energy input E_t. Both capital and labor are contributed by households within the economy, while energy is sourced from a combination of imports and domestic production. The production function employed in this context can be accurately described as Cobb–Douglas.

$$Y_t = A_t K_t^{\alpha_K} E_t^{\alpha_E} L_t^{1-\alpha_K-\alpha_E}, \tag{1}$$

where the capital share of production is denoted by α_K and the energy share of production is denoted by α_E. We examine the total factor productivity (TFP) level of the economy denoted by A_t. Consistent with the literature, we make the assumption that the TFP level follows an AR(1) process. This implies that the TFP level at time t can be represented as:

$$\log(A_t) = (1-\rho_A)\log(A) + \rho_A \log(A_{t-1}) + \varepsilon_{A,t}. \tag{2}$$

The parameter $\rho_A \in [0,1]$ governs the persistence of the process, while $\varepsilon_{A,t}$ represents a white noise with a mean of zero and a standard deviation of $\sigma_A > 0$. The variable A denotes the steady-state value of A_t.

We can express the maximization problem of the representative firm as follows:

$$\max_{K_t,E_t,L_t} A_t K_t^{\alpha_K} E_t^{\alpha_E} L_t^{1-\alpha_K-\alpha_E} - r_t K_t - w_t L_t - p_t^E E_t. \tag{3}$$

In period t, the variables r_t, w_t, and p_t^E represent the real rate of capital return, real wage rate, and real energy price, respectively. The price of the final good has been normalized to 1. The first-order conditions for K_t, L_t, and E_t can be expressed as follows:

$$\alpha_K \frac{Y_t}{K_t} = r_t, \tag{4}$$

$$(1-\alpha_K-\alpha_E)\frac{Y_t}{L_t} = w_t, \tag{5}$$

$$\alpha_E \frac{Y_t}{E_t} = p_{E,t}. \tag{6}$$

The above equations establish that the marginal return of the factor input, as depicted on the left-hand side, should be equivalent to the factor price, as represented on the right-hand side.

The existing literature assumes that energy is either entirely imported or entirely domestically produced. This paper deviates from this convention by assuming a scenario where energy is both imported and domestically produced, thus incorporating a combination of the two sources. Specifically, we consider a situation where energy is partially imported and partially produced domestically:

$$E_t = E^M(s_t) + E_t^D, \tag{7}$$

where E_t^D is the domestically produced energy, $E^M(s_t)$ is the imported energy. Typically, the provision of imported energy remains stable due to a contractual agreement between the involved countries. However, it is important to acknowledge the potential risks associated with the uninterrupted supply of energy. Factors such as the sudden termination of a contract can lead to an unexpected interruption in the energy flow.

We categorize energy based solely on its origin – whether it is domestically produced or imported from foreign countries – without differentiation by energy source. In the event of an energy crisis, a country can enhance its energy resilience through various strategies, such as developing additional energy sources, diversifying energy imports, or increasing reliance on domestic energy production. Our focus is on examining the consequences of a sudden reduction in foreign energy supply, therefore not considering specific energy types.[5] While our current model suggests that a sudden disruption in foreign energy supply would have certain effects, it is expected that these negative impacts would be mitigated if the country were able to transition to alternative energy sources. Thus, the main conclusion of this paper should remain valid.

One notable instance that exemplified the possibility of sudden termination of a contract was the Russian–Ukrainian war, during which the gas supplies from Russia to Europe were disrupted. This occurrence highlighted the vulnerability of energy supply chains. The European Union (EU) has been actively pursuing energy source diversification, particularly emphasizing the adoption of renewable energies such as

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[4] See https://www.iea.org/about/emergency-response-and-energy-security. Retrieved October 13, 2023.

[5] However, expanding the model to include different energy sources can be accomplished by adding additional variables, as demonstrated by Argentiero et al. (2018) in their study on renewable energy.

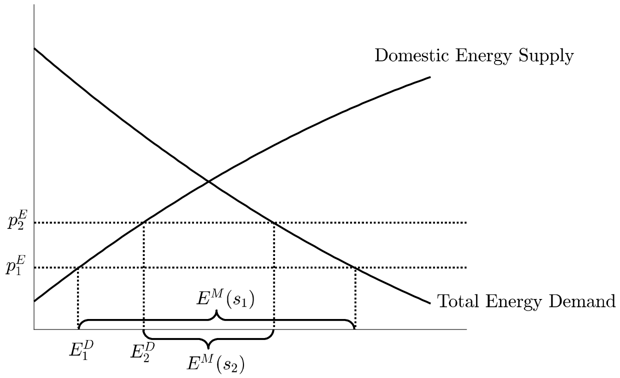

Fig. 1. The demand and supply curves of energy market.

wind and solar power. In 2018, EU leaders set a target for renewables to contribute 32% of the EU's final energy consumption by 2030, which was later increased to 42.5% in March 2023. However, despite these aspirations, as of 2021, the EU still had a high energy import dependency rate of 55.5%, indicating a significant reliance on imported energy. Russian pipeline gas accounted for approximately 154 billion cubic meters (bcm) of EU supplies in 2021. Replacing this substantial volume in the short term would pose challenges. However, by the end of 2023, the EU had made significant progress in reducing its dependency on Russian gas supplies. Factors contributing to this achievement included changes in Moscow's gas supply regulations for European customers and the temporary suspension of gas transportation through the Nord Stream 1 pipeline. As a result, Russian gas exports to the EU decreased by around 80 bcm. To compensate, the EU substantially increased its imports of liquefied natural gas (LNG), including from Russia, by an impressive 60% compared to the previous year. Additionally, the EU diversified its gas imports by increasing inflows through pipelines from Azerbaijan and Norway.

Note that the share of the two sources and the energy price are endogenously determined. As shown in Fig. 1, Under normal regime s_1, a greater amount of energy is brought in from import, resulting in a higher overall energy supply and consequently an increased energy price. In such cases, the proportion of domestically produced energy is relatively low. As the economy transitions into the energy crisis regime s_2, the import of energy diminishes, causing a decline in the total energy supply and subsequently driving up the energy price from p_1^E to p_2^E. As a result, a portion of the energy is substituted with domestically produced energy, leading to a larger proportion of the domestic energy supply.

To characterize this phenomenon, we posit the existence of two distinct economic regimes: the normal regime, where the level of energy import is denoted as E_1^M, and the crisis regime, where the energy import is reduced to E_2^M, with $E_2^M < E_1^M$. The variable $E^M(s_t)$ follows a first-order discrete Markov process with two states, namely $\{E_1^M, E_2^M\}$. The transition matrix for this process is given by:

$$p = \begin{bmatrix} p_{11} & 1 - p_{11} \\ 1 - p_{22} & p_{22} \end{bmatrix}. \tag{8}$$

Here, the term $p_{ii} = \Pr(s_t = i | s_{t-1} = i)$ represents the probability of the economy being in regime i in the previous period and remaining in regime i in the current period.

By combining Eqs. (6) and (7), we can determine the demand for domestically produced electricity:

$$E_t^D = \alpha_E \frac{Y_t}{p_{E,t}} - E^M(s_t), \tag{9}$$

The decrease in energy prices is evidently causing a decline in domestic energy consumption. Furthermore, the importation of energy is directly linked to the decrease in domestic energy demand. Consequently, a sudden reduction in imported energy results in an increase in the demand for domestic energy.

Next, we shall characterize domestic energy production. Let us assume that the cost of energy production is:

$$C(E_t^D) = \phi_1 (E_t^D)^{\phi_2}, \tag{10}$$

where the scale parameter of the production cost $\phi_1 > 0$ plays a crucial role in determining the overall magnitude of the cost function. This parameter is influenced by the economy's technological level of energy generation. Technological advancements and innovations have the potential to enhance energy production methods, making them more efficient and cost-effective. For instance, the advent of renewable energy technologies like solar or wind power allows for the utilization of natural resources with minimal fuel or material expenses. As a result, the production cost of energy decreases, leading to a reduction in the value of ϕ_1. In addition, we assume that $\phi_2 > 1$, indicating that the marginal cost of domestic energy production increases in E_t^D. This implies that the country is inclined to import energy from another nation as a means to mitigate rising production costs as the production scale increases.[6]

The maximization problem faced by the representative energy producer can be expressed as follows:

$$\pi_t = \max_{E_t^D} p_t^E E_t^D - C(E_t^D).$$

In the above equation, both imported energy and domestically produced energy are assumed to have the same energy price. Consequently, the domestic energy producer considers the energy price as a given variable. The first-order condition for E_t^D is derived as:

$$p_{E,t} = \phi_1 \phi_2 (E_t^D)^{\phi_2 - 1}, \tag{11}$$

which indicates that the domestic producer will produce until the energy price equals the marginal cost of production. As a result, the profit earned by the producer can be calculated as $\pi_t = (\phi_2 - 1)\phi_1 (E_t^D)^{\phi_2} > 0$.

3.2. Household

We examine the household problem within the context of an economy comprising an infinite number of identical households, all of which consistently make the same decisions. In this regard, it suffices to model the behaviors of a representative household, whose expected lifetime utility can be expressed as follows:

$$\mathbb{E}_{t_0} \sum_{t=t_0}^{\infty} \beta^t a_t \left(\frac{C_t^{1-\sigma_c}}{1-\sigma_c} - \mu_L \frac{L_t^{1+\phi}}{1+\phi} \right). \tag{12}$$

In the above equation, the discount factor $\beta \in [0, 1]$ determines the weight placed on future utility, while the parameter $\sigma_c > 0$ controls the level of risk aversion. Additionally, μ_L governs the magnitude of labor disutility, and $\phi > 0$ represents the inverse of the Frisch elasticity. The variable a_t captures changes in the household's preferences. While the TFP shock mentioned earlier accounts for the increase in the economy's supply of goods, a_t captures the corresponding rise in households' demand for goods. It is assumed that the preference shock follows an AR(1) process, given by:

$$\log(a_t) = \rho_a \log(a_{t-1}) + \varepsilon_{A,t}, \tag{13}$$

where the parameter $\rho_a \in [0, 1]$ determines the persistence of the process. The term $\varepsilon_{a,t}$ represents a white noise variable with a mean of zero and a standard deviation of $\sigma_a > 0$. Within each period t, the household has a budget constraint:

$$C_t + I_t \leq w_t L_t + r_t K_t + \pi_t - T. \tag{14}$$

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[6] To ensure the fulfillment of the second-order condition for the maximization problem outlined below, it is necessary to have $\phi_2 > 1$.

The household's income stems from various sources, including labor earnings $w_t L_t$, capital earnings $r_t K_t$, and profits obtained from operating the domestic energy producer firm π_t. The household has the option to allocate its income towards either consumption C_t or investment I_t. It is important to note that in this model, the final goods market operates under perfect competition, implying that firms earn zero profits, and households solely derive profits from energy producers. The government levies a tax denoted as T_t.

In addition to the aforementioned budget constraint (14), the household also adheres to the law of motion governing capital:

$$K_{t+1} = (1 - \delta_K) K_t + I_t, \tag{15}$$

where $\delta_K \in [0, 1]$ is a depreciation rate of capital. We can combine the first-order conditions for labor supply L_t, investment I_t, capital K_{t+1}, and consumption C_t into two conditions:

$$w_t C_t^{-\sigma_C} = \mu_L L_t^{\phi}, \tag{16}$$

$$C_t^{-\sigma_C} = \beta \mathbb{E}_t C_{t+1}^{-\sigma_C} [r_{t+1} + (1 - \delta_K)]. \tag{17}$$

The labor supply curve, represented by Eq. (16), captures the intratemporal tradeoff between consumption and labor. This equation quantifies the relationship between the amount of time individuals allocate to work and their consumption choices. Eq. (17) corresponds to the well-known Euler equation. This equation governs the intertemporal decisions made by households regarding consumption and saving. It outlines the optimal allocation of resources over time, considering factors such as interest rates and future utility.

Furthermore, the equilibrium in the final goods market is achieved through the following equation:

$$Y_t - p_t^E E_t^M = I_t + C_t + \phi_1 (E_t^D)^{\phi_2}, \tag{18}$$

where the left-hand side of this equation represents the revenue generated by domestically produced goods. The right-hand side encompasses the total demand for final goods, which includes consumption and capital investment by households, as well as the resources utilized for domestic energy production. A full list of our model equations is shown in the Online Appendix.

4. Calibration

In the numerical analysis section, we present our approach to parameter selection, wherein a quarter is considered as a period in our model. To ensure consistency with works such as Annicchiarico and Di Dio (2015), Heutel (2012) and Punzi (2019), we carefully choose parameter values that closely align with those specified in these papers.

Regarding the household utility, we adopt a private discount rate of 0.01 (Galí, 2008), corresponding to a discount factor of 0.99. Following Christensen and Dib (2008), we set the inverse of the Frisch elasticity ϕ to 1. The scale parameter μ_L for labor disutility is calibrated at 1, as suggested in Punzi (2019). The depreciation rate of capital δ_K is established as 0.025, in accordance with the setting in Christensen and Dib (2008). We assign a value of 0.3 to the share of capital in production α_K, adhering to commonly used values in the literature. Similarly, the share of energy in production is determined to be 0.1, similar to the choice of Keen et al. (2019).

The shock processes in this study adopt the values of TFP and monetary policy from Annicchiarico and Di Dio (2015) and Smets and Wouters (2007). Specifically, we set the parameter ρ_A in Eq. (2) to 0.95. The parameters for the household preference shock process closely follow Basu and Bundick (2017), with ρ_a set to 0.194.

The standard deviation of the TFP shock σ_A is assigned a value of 0.45, following the value used in Smets and Wouters (2007). The standard deviation of the preference shock σ_a is set to 0.3, similar to Basu and Bundick (2017), it was adjusted to align the magnitude of the preference shock with that of the TFP shock. It is worth noting that the standard deviations' values only affect the magnitude of the impulse response functions but do not alter their directionality.

Table 1
Parameter values.

Parameters	Value	Description
α_K	0.3	Share of capital in production
α_E	0.1	Share of energy in production
ϕ_1	0.0065	Parameter in cost functions of energy production
ϕ_2	2	Parameter in cost functions of energy production
δ_K	0.025	Capital depreciation rate
ρ	0.01	Discount factor rate
σ_C	1	Risk aversion
ϕ	1	Inverse of Frisch elasticity
μ_L	1	Scale of labor disutility
A	1	Steady-state value of TFP level
ρ_A	0.95	TFP shock persistence
σ_A	1	TFP shock standard deviation
ρ_a	0.194	Preference shock persistence
σ_a	1	Preference shock standard deviation

By assuming a quadratic cost function for domestic energy production with $\phi_2 = 2$, we ensure that $\phi_2 > 1$ to satisfy the second-order condition for the maximization problem of the domestic producer. The quadratic cost function is also used in previous studies Kwoka (2002), Jara-Dıaz et al. (2004), and Fetz and Filippini (2010). According to Jara-Dıaz et al. (2004), the quadratic form has several advantages over the translog form and requires fewer behavioral assumptions. It is particularly effective in measuring economies of scope, which could involve zero outputs. In 2020, the EU imported 58% of the energy it consumed, according to Eurostat.[7]

To align with this target, we calibrate the values of ϕ_1 and E_1^M in the normal regime. Specifically, we find that $\phi_1 = 0.0065$ and $E_1^M = 15$. Additionally, we set E_2^M to 3 to represent a scenario where energy imports decrease exogenously to approximately 11%. To maintain simplicity in the benchmark, we set the transition probabilities of the regimes, p_{12} and p_{21}, to 0.5. However, in the subsequent numerical analysis, we will vary these parameters to explore different scenarios.

The main conclusion of this paper is primarily derived from the direction of change of the variables rather than the estimation of their actual values. Therefore, it is important to note that a reasonable range of parameter choices will not alter the main conclusion. We perturb the model in the third order and employ the Newton algorithm of Maih (2015) to solve the model. The summarized parameter values can be found in Table 1.

5. Numerical results

5.1. Long-term and short-term impacts of economic shocks in the two regimes

We begin our analysis by examining the diverse impacts of economic shocks in two regimes, with an initial focus on long-term analysis. Fig. 2 presents the steady-state values of energy, economic variables, and social welfare, effectively comparing different levels of productivity in both regimes. The figure provides a clear illustration of the relationship between the technology level and the overall increase in all variables. A firm that possesses enhanced productivity will naturally produce more, thereby necessitating a greater demand for energy. As the energy imports remain constant but are set at different values in each regime, the higher energy demand corresponds to an increased

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[7] In 2020, the EU-27 had a reliance of approximately 57.5% on imported energy, encompassing solid fossil fuels, natural gas, and oil & petroleum products. For further information, please refer to: https://www.statista.com/statistics/1301609/european-union-eu-27-energy-import-dependency-by-country/.

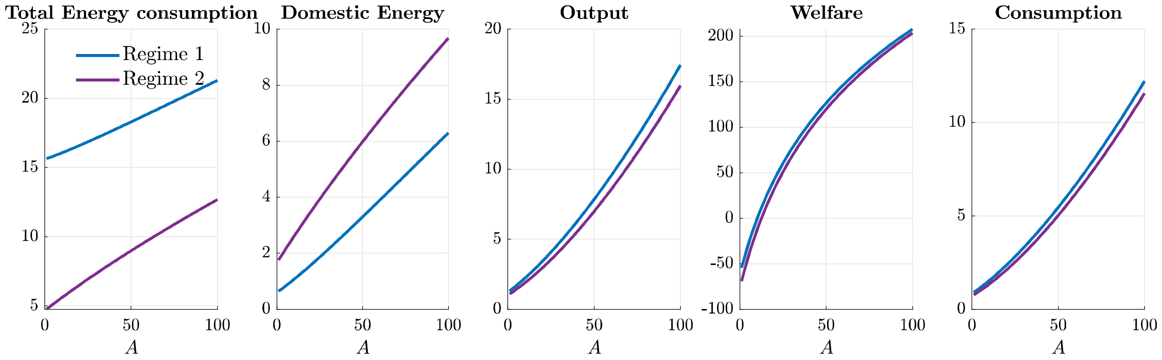


Fig. 2. The long run effects of TFP level in the two regimes.

usage of domestic energy. Additionally, households with higher productivity levels experience increased consumption levels, resulting in an overall improvement in welfare.

Moreover, the transition between regimes significantly impacts energy consumption and production, yielding noticeable changes. When shifting from a normal region to an energy-crisis regime, there is a decrease in energy imports, resulting in an overall decline in energy supply. As a result, firms adjust their production scale, reducing their demand for energy to attain equilibrium. Moreover, firms modify their energy compositions, showing a preference for domestic sources, which leads to an increase in domestic energy production. Additionally, the rise in energy prices and the subsequent increase in production costs for firms contribute to a decrease in output. Alongside the regime switch, there is a concurrent decline in consumption and welfare, primarily attributable to reduced spending by households with lower incomes. This decline in consumption further exacerbates the impact on overall welfare. In this analysis, we solely focus on the long-term impact of productivity growth. The rise in the steady-state preference level a does not exert any influence on the overall economy. Since it only increases households' marginal utility to consume proportionally in each period, it does not affect their decision-making.

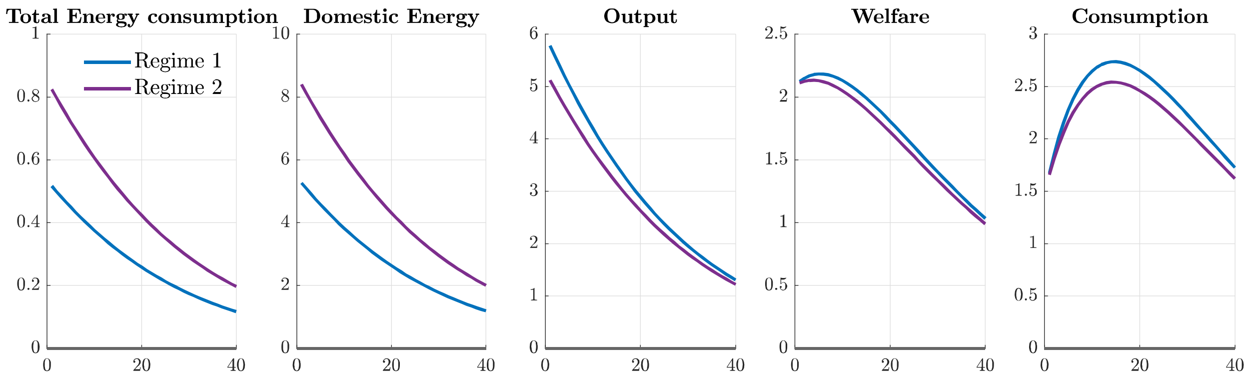
Next, we direct our attention to the examination of the short run. Fig. 3 illustrates the impact of a TFP and preference shock on energy, welfare, and overall economic indicators. It is important to highlight that when a positive productivity shock occurs, the economy experiences an immediate increase in output due to the firms' ability to use the same input to generate greater output. Consequently, firms with higher productivity levels expand their production capacities, leading to a greater demand for energy. As the supply of foreign energy remains constant, the heightened energy demand translates into increased domestic energy demand. Consequently, the households reap the benefits of this shock, as they earn higher incomes through capital returns and profits from owning domestic energy firms. This increased income prompts them to consume more, thereby contributing to an overall enhancement in social welfare. The measurement of social welfare in this context is based on the lifetime utility of households, which demonstrates an improvement as a result of the aforementioned factors.

The impact of the shocks on different regimes reveals an intriguing pattern. Specifically, when transitioning from the normal regime to the energy-crisis regime, both total energy and domestic energy experience a more significant percentage increase in response to the shock. This phenomenon arises due to the reduced importation of energy in the economy, which necessitates a complete reliance on domestic energy sources to meet the higher energy demand from the final goods producer, prompted by the productivity shock. Due to the constrained growth in energy demand in the energy-crisis regime, the final goods producer is compelled to limit the expansion of their production scale. Consequently, the overall output experiences a less significant increase compared to the normal regime. Households experience a relatively lower income, leading to a decrease in their consumption and a subsequent reduction in their overall welfare improvement compared to the normal regime.

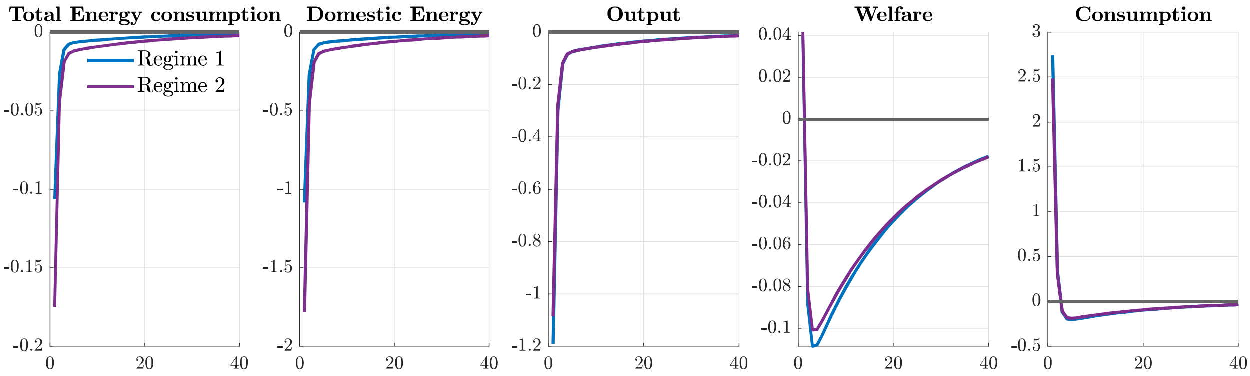
In the following analysis, we delve into the role of the regime in determining the effects of a preference shock. When households experience a positive preference shock, their focus shifts towards immediate satisfaction rather than future satisfaction. Consequently, households tend to consume more in the present and reduce their capital investment. This behavioral change leads to an increase in the demand for final goods and a decrease in labor supply in the short run. However, this pattern is detrimental to the economy in the long run due to the reduction in accumulated capital. The impact of the preference shock on consumption and social welfare can be observed in Fig. 3. Initially, both consumption and social welfare experienced an immediate increase in response to the shock. However, over time, both indicators decline due to the diminishing capital and output of the economy. It is important to note that the reduction in labor supply results in higher labor costs for final goods producers, compelling them to downsize their production scale. Consequently, there is an initial decrease in output, total energy consumption, and domestic energy production. This downward trend in these economic indicators has a feedback effect on households, leading to a decrease in household income. Thus, the preference shock not only affects consumption and social welfare but also has impacts on the labor market and overall economic performance.

The transition from a normal economic regime to an energy-crisis regime leads to a decrease in energy imports, thereby intensifying the reduction in overall energy consumption and domestic energy usage. As household income declines, household consumption experiences a lesser increase, while households become more willing to provide labor within the energy-crisis regime due to the decline in their income. Consequently, we observe a comparatively smaller decrease in output under the energy-crisis regime. Despite these changes, the welfare level remains similar under both regimes.

In summary, the transition of the economy from a normal regime to an energy-crisis regime has long-term effects, resulting in a decreased energy demand and increased domestic energy production. However, this shift also leads to higher energy costs, which subsequently reduce output and consumption in equilibrium, thereby negatively impacting social welfare. Conversely, in the short run, regime-switching has the potential to magnify the responses of energy to various shocks. This implies that in the absence of energy imports, the economy's energy consumption would exhibit greater volatility. In contrast, economic variables and social welfare would demonstrate greater stability compared to the normal regime. This stability arises because, in the absence of energy imports, a larger proportion of the economy's revenue is distributed to households, incentivizing them to adjust their behavior more actively to mitigate the effects of the shock.



(a) TFP shock



(b) Preference shock

Fig. 3. Regime-specific dynamic responses of energy, social welfare and economic variables to positive TFP and preference shocks.Notes: The responses are shows in percent.

5.2. *The importance of transition probability*

So far, we have demonstrated the distinct effects of technology and households' preferences on energy usage, welfare, and economic variables under the two regimes, both in the short run and the long run. However, a crucial aspect of this paper is the recognition that the potential transition to the energy-crisis regime itself has implications for how these variables respond to shocks, even if the economy has not yet undergone such a transition.

Fig. 4 illustrates the accumulated responses of the variables in relation to the probabilities of transitioning from the normal regime to the energy-crisis regime p_{12}. These responses are influenced by both TFP and preference shocks. To calculate the accumulated responses, we sum the values of all impulse responses from period 0 to infinity. A higher value of p_{12} suggests a greater likelihood of the foreign country reducing its energy imports. In our model, we assume that this probability is common knowledge and is fully known to the government, firms, and households within the economy. Consequently, these rational agents would adjust their decisions in anticipation of a potential regime shift.

Panel a of Fig. 4 demonstrates that a high probability of transitioning to an energy-crisis regime diminishes the response of household consumption to a technology shock. This outcome arises due to the influence of the Euler equation that governs households' consumption behavior. If households anticipate a higher risk of the economy entering an energy-crisis regime, implying a substantial likelihood of a sharp decline in their income, they would curtail their present consumption and allocate more towards savings as a precautionary measure. Consequently, despite witnessing an increase in productivity, households refrain from significantly increasing their consumption. The resultant decrease in final goods demand subsequently leads to a decline in overall output. Moreover, the constrained expansion of the production scale restricts the increase in demand for total energy consumption and domestic energy. Nonetheless, this choice by households to save more in preparation for a potential long-term crisis ultimately enhances social welfare.[8]

Similarly, in panel b, the effects of transition probability under the preference shock are depicted. First of all, consumption decreases in response to the preference shock. As previously mentioned, although consumption increases temporarily, the reduction in household savings ultimately leads to a decrease in consumption over the long run. However, we observe that the extent of this consumption reduction diminishes as the transition probabilities increase. In other words, households' consumption becomes less responsive to the preference shock when the transition probability is high. This phenomenon can be explained by the fact that households anticipating a higher likelihood of entering an energy crisis are incentivized to save more, thereby counteracting the reduction in savings resulting from the preference shock. Similarly, households also tend to increase their labor supply compared to cases with low transition probabilities. Consequently, we observe a lesser decline in output. Firms, benefiting from increased access to labor and capital resources, possess a greater capacity to demand higher levels of energy. As a result, total energy consumption and domestic energy production also experience a lesser decline. However,

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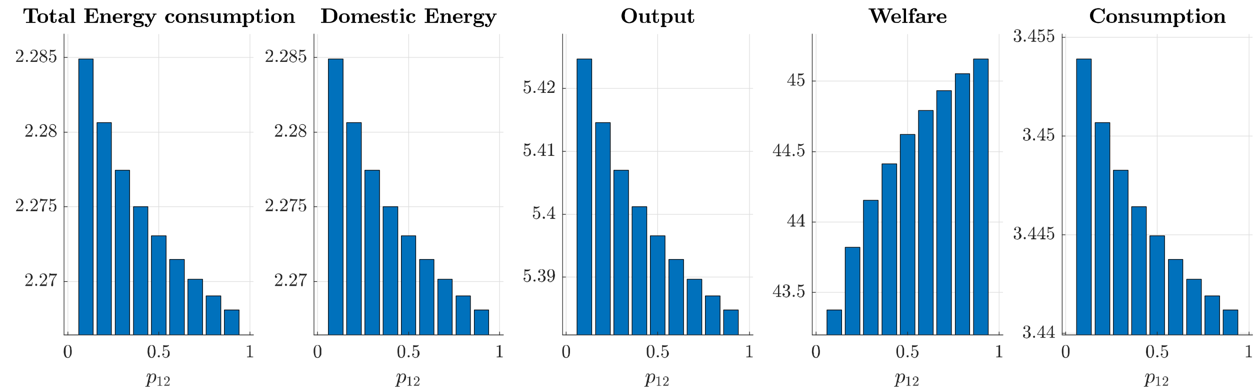
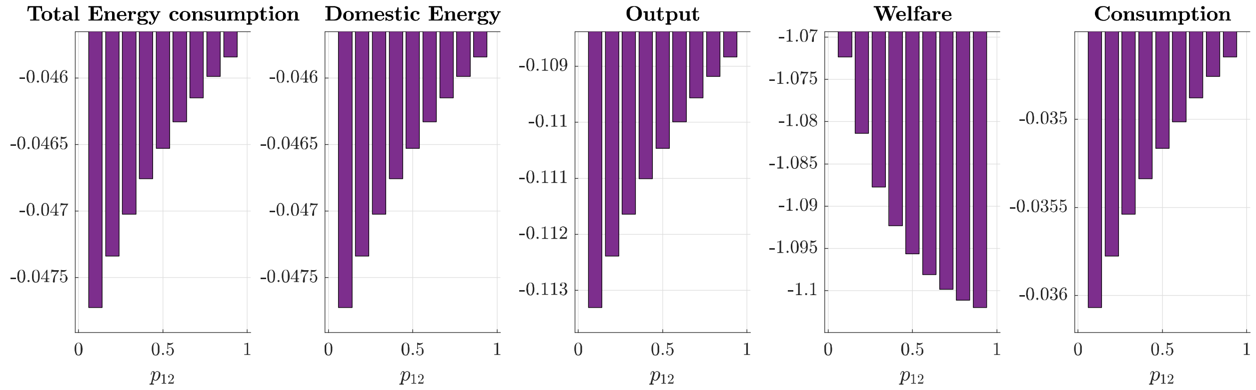
[8] It is important to note that this result does not imply that households must be better off when the transition probability is high. The dynamic responses of social welfare, as depicted in Fig. 4, represent the responses under the condition that the economy remains in the normal regime. Since the transitional probability is higher, there is a greater chance for the economy to enter the energy crisis. As a result, social welfare is worse off unconditionally. Instead, we can only assert that if households perceive a higher probability of entering the energy crisis and the economy ultimately does not experience the crisis, then social welfare would increase in response to the productivity shock.



(a) TFP shock



(b) Preference shock

Fig. 4. The accumulated responses of energy, welfare and economic variables to positive TFP and preference shocks with different values of regime-switching probability p_{12}.

it is important to note that as the transition probability increases, social welfare decreases to a greater extent. This can be attributed to the higher labor supply by households, which leads to a lower level of utility overall.

In summary, when households are aware of the likelihood of an impending energy crisis, they can proactively modify their consumption and saving decisions to minimize the adverse impact caused by the regime-switching. Consequently, we observe that households' consumption, as well as energy and economic variables, exhibit reduced sensitivity to these shocks. Conversely, the cautious responses of households result in increased responsiveness of social welfare to such shocks. This implies that the overall well-being of society becomes more susceptible to fluctuations in the face of conservative household behavior.

If the economy were to actually enter an energy crisis, what would be the resulting consequences? To depict this scenario, we conducted a simulation involving a time series spanning 200 periods. In our simulation, we assume that the crisis occurs in the 100th period and persists until the 200th period. Additionally, we consider the occurrence of both TFP shock and preference shock in each period, assuming they happened simultaneously. To ensure the reliability of our findings, we repeated this simulation process 1000 times. By doing so, we were able to compute the 95% confidence interval of the variables, which is visually represented by the shaded areas in Fig. 5.

During an energy crisis, there is a noticeable decline in overall energy consumption, which can be attributed to the reduced importation of energy from foreign sources. Since part of the total energy consumption is supported by an increase in domestic energy production, as indicated in the figure, the reduction in total energy consumption would not be as large as the drop in energy imported. Consequently, with a diminished total energy supply, it becomes evident that output levels would decrease, resulting in households earning less factor income from firms and subsequently experiencing a decline in social welfare. It is important to acknowledge that the reduction in output and welfare is not as severe as the decrease in total energy consumption. This is due to households adapting their decisions to partially mitigate the adverse effects of the regime-switching process. Specifically, the lower income levels prompt households to supply more labor within the new regime. Additionally, the figure reveals that the confidence interval for both total energy consumption and domestic energy production expands during regime 2. This finding aligns with the information presented in Fig. 2, illustrating that energy series exhibit greater volatility during the energy-crisis regime.

In the model, it is important to note that we do not make any assumptions about economic growth, leading us to solely concentrate on short-term fluctuations. Consequently, the economy would not be able to fully recover to its previous level. However, if we take into account the notion that the economy would actively promote the development of domestically produced energy in order to confront the crisis, there is a possibility that total energy consumption could gradually rise back to its previous peak over time.

5.3. The optimal subsidy policy

In the preceding analysis, we have demonstrated the significant impact on the economy resulting from the transition to an energy-crisis regime triggered by a sudden termination of energy imports. Additionally, the probability of such a transition itself can have a substantial effect. These findings compel us to consider the necessity of adequate government assistance to domestic energy firms in their preparedness for the potential onset of a crisis. Consequently, we delve into this matter in this section, wherein we modify our model to incorporate government policies. Specifically, we posit that the magnitude

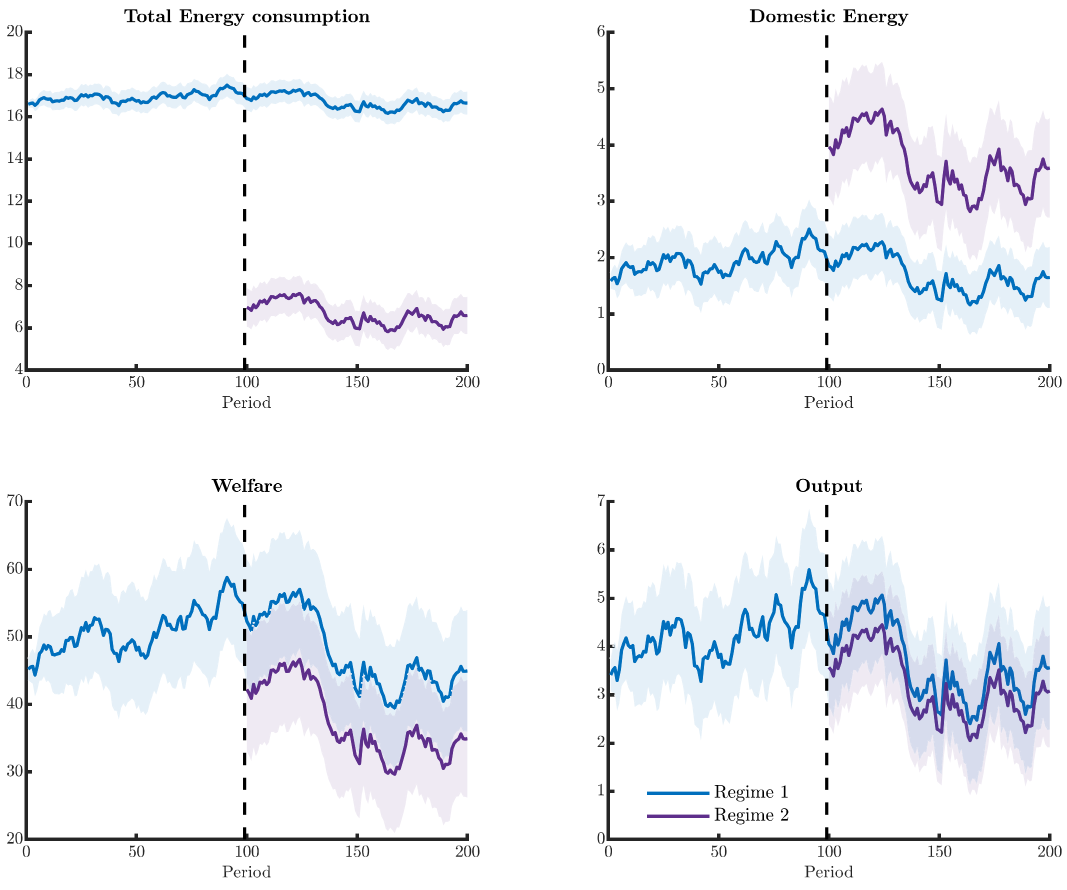


Fig. 5. The simulated series of energy, social welfare, and output.

Notes: The shaped areas are the 95% confidence interval of the series. The regime switches from regime 1 to regime 2 in period 100. The blue lines from period 100 to 200 are the counterfactual paths of the series if the regime does not shift. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of domestic energy production costs is contingent upon government expenditures, as described by the following function:

$$\phi_1(G_t) = \psi_1(G_t)^{-2}, \tag{19}$$

which reveals a negative relationship between the scale parameter and government spending. This relationship intuitively suggests that greater government support leads to a reduction in production costs for domestic energy firms. To achieve this objective, the government can adopt a range of strategies aimed at minimizing production costs. These strategies encompass the provision of subsidies, investment in infrastructure development, support for research and development initiatives, implementation of regulatory reforms, facilitation of capital access, and promotion of skill development and training programs. By employing these measures, the government can effectively alleviate the financial burden on domestic energy firms and enhance their overall competitiveness in the market.[9] In this paper, our primary focus lies in assessing the impact of subsidies on energy resilience, specifically considering their influence on the occurrence of energy crises. These subsidies typically involve supporting the development of renewable energy sources within the country. For instance, the EU has implemented various practices to subsidize domestic renewable energy initiatives, exemplified by the EU renewable energy financing mechanism and support schemes. Although our model assumes a single variable, E_t^D, for home energy production without differentiating between energy types, similar approaches have been adopted in other studies examining energy subsidy policies, such as those conducted by Bigerna et al. (2023, 2019).

The government's expenditures are funded through the collection of lump-sum taxes levied on households. Consequently, the GDP accounting relationship can be expressed as follows:

$$Y_t - p_t^E E_t^M = I_t + C_t + G_t + \phi_1(E_t^D)^{\phi_2}. \tag{20}$$

In the above equation, an additional demand for goods by the government is represented on the right-hand side. Furthermore, the parameter ϕ_1 is defined by Eq. (19). There are two important observations to be made. Firstly, the government subsidy G_t is subject to change over time, contingent upon the prevailing economic conditions and the realization of the two economic shocks. Secondly, when determining the level of subsidy G_t, the government must consider the equilibrium conditions of the economy. In other words, the government has the ability to select G_t, but it lacks the authority to directly manipulate the production and consumption decisions made independently by firms and households.

In order to determine the optimal subsidy policy, we adopt the approach proposed by Heutel (2012), which involves examining the Ramsey social planner problem. This problem revolves around a social planner whose objective is to maximize the aggregate expected lifetime utility of households. The planner achieves this by selecting a dynamic subsidy policy G_t, while taking into account the equilibrium conditions of the decentralized economy. The specific formulation of the problem can be found in the Online Appendix. To conduct our numerical

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[9] Extensive research has been conducted to examine the welfare implications of domestic energy production subsidies (e.g., Ebeke and Ngouana, 2015; Kalkuhl et al., 2013; Brennan, 2010; Kruse-Andersen and Sørensen, 2022).

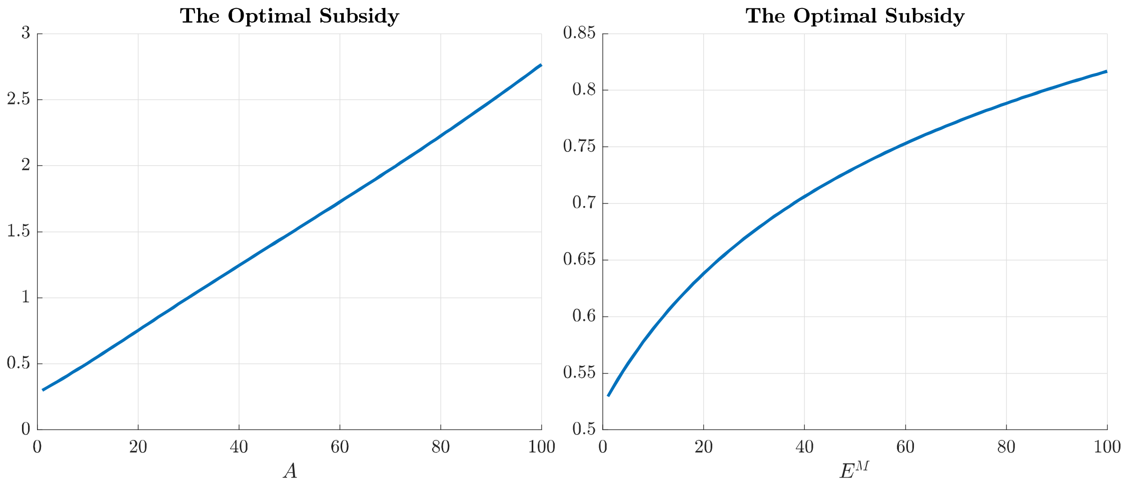

Fig. 6. The steady-state optimal subsidy against the TFP level and imported energy.

analysis, we assign a value of $\psi = 0.008$, which ensures that the steady-state value of ϕ_1 closely aligns with the value obtained in the previous section.

In our analysis, We begin by examining the long-run implications. The steady-state depiction in Fig. 6 illustrates the relationship between optimal subsidy policies and varying levels of productivity and imported energy. It becomes evident that the optimal subsidy level rises in tandem with both productivity and imported energy levels. In economies characterized by high productivity, there exists a larger economic scale. Consequently, households generate higher incomes, enabling the government to impose higher taxes for domestic energy subsidies. This subsidy serves to reduce production costs for domestic energy firms, thereby benefiting the overall economy. The latter result also aligns with intuition: when the quantity of imported energy increases, two factors come into play. Firstly, the production scale and subsequently the overall economy expands. Secondly, the economy becomes more reliant on foreign energy support. As a result, the government has the ability to gather taxes for subsidies while also having a stronger motivation to increase domestic energy production, resulting in a higher level of optimal subsidy.

In the subsequent analysis, we focus on the short-run analysis. As depicted in Fig. 7, our findings reveal that the optimal subsidy level rises in response to the positive TFP shock, whereas it decreases when confronted with the positive preference shock. This pattern aligns with our previous discussion. When a positive TFP shock occurs, the output increases, resulting in higher household incomes derived from supplying factor inputs. Consequently, the increased household income enables the government to impose a higher lump-sum tax, which can be utilized to subsidize domestic energy production. Thus, we observe an increase in subsidies following a TFP shock. Moreover, because of the pressing need for domestic energy during an energy crisis, our analysis reveals that the government ought to distribute higher subsidies in normal periods compared to the energy-crisis period following a TFP shock. This recommendation stems from the fact that income levels are lower during the energy-crisis regime. In summary, according to Eq. (20), more resources are allocated to government subsidies during normal periods, while a greater allocation is directed towards domestic energy production during energy crises.

It is more intriguing to note that the optimal subsidy level falls as the positive preference shock increases. This outcome arises from the potential crowding-out effect induced by higher government expenditure on households, leading to increased taxes and reduced disposable income for consumption. When faced with a positive preference shock, households prioritize immediate utility satisfaction over future satisfaction. Consequently, it is not optimal to burden households with higher taxes in the present since the government's objective is to maximize their satisfaction. In pursuit of this goal, the government curtails its spending, allowing households to allocate more resources to present consumption. Consequently, the implementation of the subsidy policy is delayed in the presence of a preference shock.

In summary, our findings suggest that the optimal subsidy policy should be adjusted based on the levels of productivity and energy imports, taking into account the expansion of the economy and its increasing reliance on foreign energy sources. To elaborate, as productivity levels rise and the economy becomes more dependent on energy imports, it is crucial to proportionally increase the subsidy to facilitate its growth. However, in the short run, it is advisable to increase the optimal subsidy policy only in the event of a positive supply (productivity) shock. Conversely, it should be decreased in response to a positive demand (households' preferences) shock. The decrease in the subsidy policy is necessary to allocate more resources to households for consumption, as the government must prioritize meeting the demands of its citizens. A positive supply shock leads to increased output and tax revenue, making it advisable for the government to augment the subsidy policy to fully utilize the generated taxation. On the other hand, a positive demand shock signifies a shift in consumer preferences towards increased consumption of goods and services. To accommodate this shift and ensure the availability of resources for households, the government should reduce the subsidy policy. In essence, the optimal subsidy policy should exhibit flexibility and responsiveness to changes in both productivity and consumer preferences. By considering the scale of the economy and its reliance on energy imports, the government can devise effective strategies to support economic growth while simultaneously meeting the needs of its citizens.

The variation of the optimal subsidy policy in relation to transition probabilities is examined in Fig. 8. The figure illustrates the accumulated responses of the optimal subsidy level of positive TFP and preference shocks with different values of regime-switching probability p_{12}. The results indicate that as the transition probability increases, the optimal subsidy levels become less responsive to both TFP and preference shocks. This finding suggests that in an economy with a higher likelihood of transitioning into an energy-crisis regime, the government does not necessarily need to increase the subsidy level in the short run. Instead, it is more optimal to assign less importance to the current economic conditions and adopt a more stable subsidy policy. In other words, a greater emphasis should be placed on maintaining stability rather than reacting to short-term fluctuations in economic conditions.

When implementing the subsidy policy, the government faces two primary concerns. The first concern pertains to the potential implications of increasing the subsidy policy, as it would resemble any other government expenditure, leading to an augmented tax burden

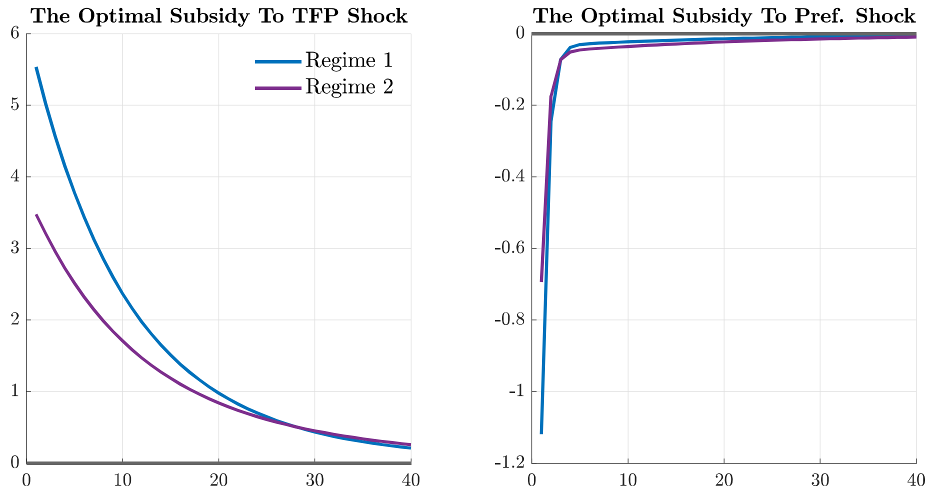

Fig. 7. Regime-specific dynamic response of the optimal subsidy level to positive TFP and preference shocks.Notes: The responses are shows in percent.

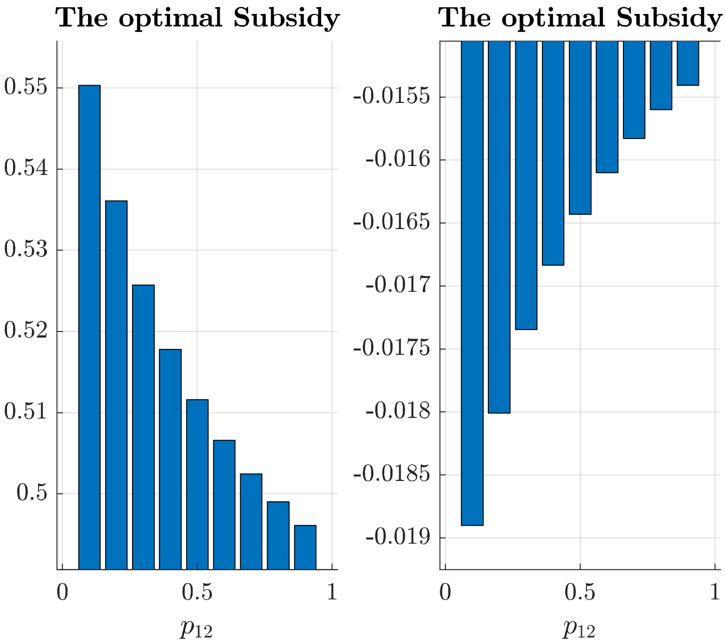

Fig. 8. The accumulated responses of the optimal subsidy levels to positive TFP and preference shocks with different values of regime-switching probability p_{12}.

on households and a surge in demand for final goods. Consequently, the decision to increase the subsidy policy hinges on the prevailing economic conditions. If the economy exhibits a dearth of demand for goods, the government would increase its expenditure; conversely, it should curtail government spending. The second concern revolves around preparing for the possibility of transitioning into an energy-crisis regime. This concern remains independent of the realization of economic shocks and relies on the probabilities associated with the regime-switching process. The findings depicted in Fig. 8 suggest that if the transition probability is high, the government would prioritize the second concern and opt for a subsidy that exhibits less responsiveness to the current economic shocks that materialize.

Finally, we investigate what happens to economic variables when an economy has a higher subsidy in domestic energy production, resulting in lower energy production costs and decreased reliance on energy imports. We will explore this scenario in two cases, each representing different energy production costs. Specifically, we will examine an economy characterized by a high cost of energy production, indicated by $\phi_1 = 0.0065$, as discussed in Section 4. Additionally, we will explore another economy with a lower cost, represented by $\phi_1 = 0.0065/2$, illustrating a scenario where the production costs are slashed by 50%.

Fig. 9 plots the time series of energy, output, and social welfare, presenting data for two scenarios: one with a high cost of energy production (solid line) and the other with low cost (dashed line). In this analysis, a 200-period series is generated, and the economy transitions from the normal regime to the energy-crisis regime at period 100. The fluctuations observed in these variables are primarily influenced by shocks in TFP and preferences, which have identical values across both economies.

When the economy benefits from lower energy production costs, it experiences an evident increase in both total energy consumption and domestic energy production. This occurs because firms tend to utilize more energy overall, resulting in an increase in total energy on the external margin. At the same time, the lower production costs of domestic energy lead to a higher proportion of domestic energy in the total energy, causing an increase in the internal margin. It is crucial to highlight that during an energy crisis, regardless of the scenario, there is a significant decline in total energy consumption.

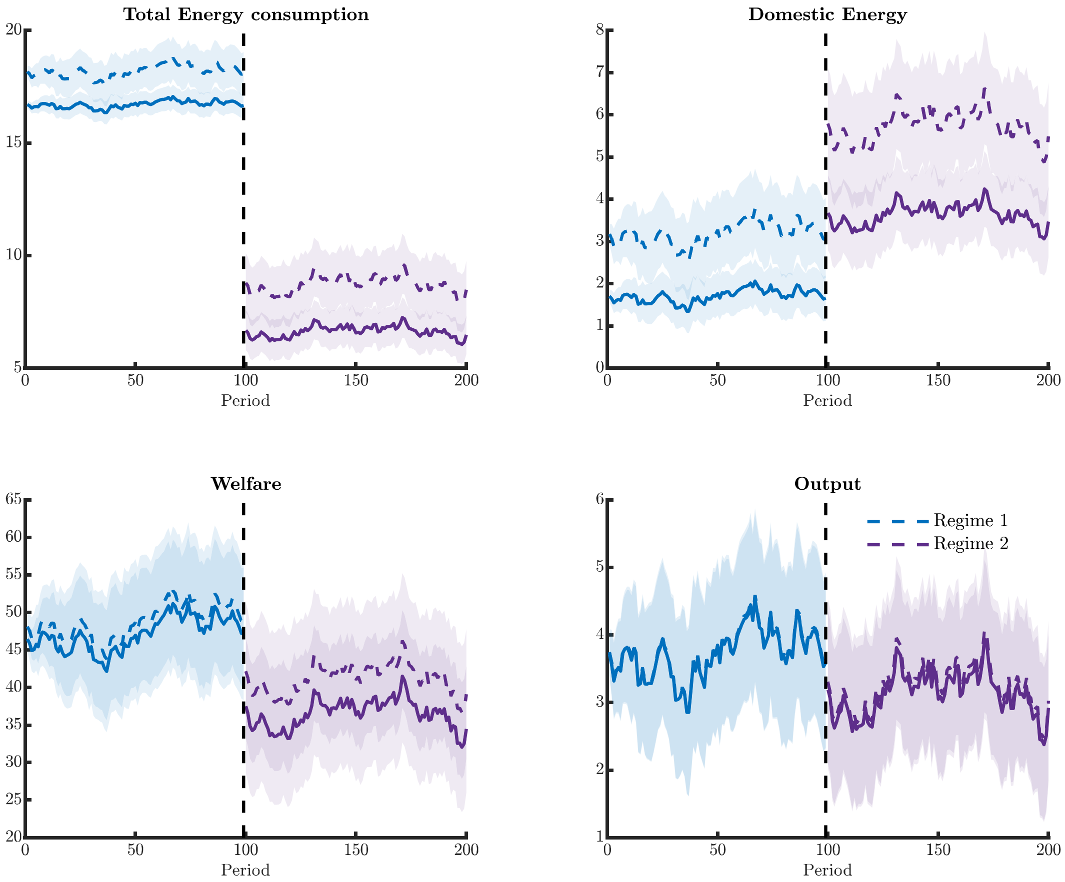

Fig. 9. The simulated series of energy, social welfare, and output.
Notes: The shaped areas are the 95% confidence interval of the series. The regime switches from regime 1 to regime 2 in period 100. The solid and dashed lines are simulated under the models with $\phi_1 = 0.0065$ and $\phi_1 = 0.0065/2$, respectively.

However, an economy with lower production costs of energy can still maintain a relatively higher level of total energy consumption. This is precisely why the welfare of an economy with lower energy production costs is comparatively higher, particularly following an energy crisis. Furthermore, it is noteworthy that there is no substantial disparity in output fluctuations between the two economies. As mentioned earlier, this can be attributed to differences in household behavior. In an economy with higher production costs, households tend to consume less and supply more labor. This tendency partially offsets the higher energy costs from the perspective of firms. Consequently, the production scale of firms in both economies does not exhibit a significant difference.

6. Conclusion and policy implications

Recent geopolitical crises, such as the Russia–Ukraine conflict, have highlighted the vulnerability of nations that heavily rely on a single energy source or supplier. These events have particularly impacted Europe's energy supplies, prompting a growing interest in enhancing energy resilience. In this context, energy resilience pertains to the ability to withstand and recover from disruptions or shocks in energy supply. However, there is currently a limited understanding of the environmental and economic ramifications associated with these conflicts. Moreover, existing integrated assessment models do not encompass energy crises or energy resilience considerations.

This paper presents an analytical framework that facilitates understanding of the impacts of geopolitical conflicts and the development of energy policy, and provides potential solutions for policymakers. Our proposed MS-DSGE model investigates environmental, welfare, and economic effects resulting from sudden energy supply termination. It considers two economic regimes – normal and energy-crisis – to determine optimal subsidy policies for domestic energy production firms. This framework improves preparedness for potential energy crises and aims to formulate sustainable development policies that prioritize energy resilience.

The main findings of this paper can be summarized as follows. An interruption in energy supply from foreign countries leads to a significant reduction in output, social welfare, and energy consumption. During an energy crisis, energy consumption becomes more sensitive to economic shocks in the short run. The effects of an energy crisis can be felt even without its occurrence; the mere expectation or anticipation of a crisis is enough to induce an impact. Household behavior adjusts in response to the anticipation of an energy crisis, mitigating potential negative effects and reducing volatility in energy, output, and household consumption. However, the volatility of social welfare increases in the face of economic shocks when households adopt a conservative approach.

Furthermore, our findings indicate that a well-designed subsidy policy must take into account the variations in productivity levels and energy imports. Specifically, the subsidy should be proportionally increased as the economy expands and productivity levels rise, reflecting the growing dependence on energy imports. However, in the short term, it is advisable to increase the optimal subsidy policy only in response to a positive supply shock, such as an increase in productivity. Conversely, if a positive demand shock occurs, such as a shift in households' preferences, it is recommended to decrease the subsidy.

Finally, when the economy faces a significant risk of energy imports disruption, the optimal approach for the government is to select a subsidy policy that is less responsive to current economic shocks. However, implementing such a strategy presents two main challenges. Firstly, it necessitates an increase in the tax burden on households, resulting in lower demand for finished goods. The strength of the subsidy policy depends on the current economic state. If there is insufficient demand, the government should increase the subsidy; otherwise, it is advisable to reduce it. Secondly, the government needs to prepare for a potential transition to an energy-crisis regime. Our analysis shows that when the probability of a crisis is high, the government places greater importance to this concern, leading to a reduced dependency of the subsidy policy on economic conditions.

The findings of this paper have several significant policy implications. Firstly, they highlight the vulnerability faced by nations that heavily rely on a single energy source or supplier. To enhance energy resilience, policymakers should prioritize diversifying the energy mix. This can be achieved by promoting multiple energy sources and engaging a wide range of energy suppliers. Governments should also invest in renewable energy technologies and stimulate domestic energy production to reduce dependence on foreign energy sources.

The EU has made notable progress in this regard. In May 2022, the EU launched the REPowerEU plan to accelerate its green transition and decrease reliance on Russian gas. This plan focuses on energy conservation, clean energy generation, and energy diversification. Furthermore, as part of the Next Generation EU recovery instrument, EU countries are incorporating dedicated chapters into their national recovery and resilience plans to finance key investments and reforms aligned with the REPowerEU objectives.

Lastly, it is vital to acknowledge that the anticipation and expectation of an energy crisis already impact households' consumption and saving behavior. To mitigate the negative effects of energy crises, policymakers should develop comprehensive energy crisis preparedness plans. These plans should include strategies to educate households about potential energy supply disruptions, promote energy conservation and efficiency measures, and establish mechanisms for coordinated responses in the event of an actual energy crisis. Implementing such preparedness plans can effectively mitigate the economic, social, and welfare impacts of energy shocks.

This paper introduces the first model that incorporates regime-switching dynamics of the economy into sustainable policy analysis. While previous economic models have examined the implications of energy policy in various contexts, we are pioneering the examination of energy policy effectiveness from the perspective of energy resilience. Our objective is to establish a conceptual framework that enables policymakers to comprehend the economic impacts of geopolitical conflicts on energy resilience and to design optimal subsidy policies that take energy resilience into careful consideration. Such an approach has the potential to result in more effective policy interventions that not only alleviate the negative effects of energy supply disruptions but also promote economic stability and growth.

Our model does not account for energy consumption in households, as our primary emphasis is on the balance between energy provided by domestic and foreign energy firms. During an energy crisis, households bear a significant financial burden as energy costs skyrocket, leading to changes in their consumption patterns and overall well-being. We believe that an extended model that incorporates household energy consumption would yield results consistent with our current findings, as both scenarios involve a shift in regime resulting in reduced household income and increased expenditure.

In future research, it would be worthwhile to investigate the concept of output resilience, which has attracted scholarly attention due to the decline in output following the onset of the COVID-19 pandemic (Klimek et al., 2019; Han and Goetz, 2019). Furthermore, a more comprehensive model that explores the interplay between subsidy policy, carbon taxation, and green monetary policy (Schoenmaker, 2021; Ferrari and Landi, 2023) presents an intriguing direction for future studies in this field. It is important to note that we have assumed the regime-switching process to be exogenous. However, there exist papers such as Leeper and Davig (2006) and Mao et al. (2023) that delve into the exploration of endogenous regime-switching, which offers an intriguing avenue for expanding our research in this area.

Another direction for advancement involves extending our model to incorporate a broader range of energy sources, including renewable and non-renewable options, and assessing their respective roles in enhancing energy resilience. So far, our focus has primarily been on examining energy resilience in relation to reliance on foreign energy sources. However, by considering multiple energy types, we can conduct a more comprehensive analysis that includes dimensions such as energy diversity and sustainability.

CRediT authorship contribution statement

Ying Tung Chan: Conceptualization, Validation, Formal analysis, Writing – original draft. **Maria Teresa Punzi:** Methodology, Software, Formal analysis, Writing – review & editing. **Hong Zhao:** Conceptualization, Validation, Formal analysis, Writing – original draft.

Declaration of competing interest

We hereby declare that the paper is original and it has not been published elsewhere or submitted simultaneously for publication elsewhere.

We certify that we have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119619.

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