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The intertemporal substitution effect of energy consumption under climate policy changes

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ABSTRACT

Based on the intertemporal substitution effect, the high inflation expectations can stimulate agents to consume now rather than in the future. However, under the background of global climate policy changes, how inflation expectations affect energy consumption? Using the bootstrap Granger full-sample causality test and sub-sample rolling window tests, this study examines the intertemporal substitution effect of energy consumption in the U.S. The results based on the full-sample data indicate no causality between inflation expectations and energy consumption, which suggests that the intertemporal substitution effect of energy consumption does not exist. Nevertheless, the rolling window method which estimates a time-varying causality identifies a short-lived positive effects of inflation expectations on energy consumption in a distinct sub-period before the global Paris agreement, but disappears since then. Therefore, the intertemporal substitution effect regarding energy consumption does not exist under the background of pressing carbon targets. The effects of energy consumption on inflation expectations can be positive or negative, which tells a cautionary tale about climate policies aiming at engineering lower carbon emissions.

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1. Introduction

Despite the current ambivalence of the U.S. towards the Paris Agreement, national and local jurisdictions are seeking ways to increase the effectiveness of their climate policies (Erickson et al., 2018). However, climate policy changes have casted a shadow over economic development through affect environmental costs (Xu, 2021). Economists and policymakers alike used to suggest an engineering of higher inflation expectations to stimulate agents to consume now rather than in the future, i.e., the

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intertemporal substitution effect, to rescue the slumping economy (Ichiue & Nishiguchi, 2015; Romer, 2014). Battered by the global pandemic in 2020, should policymakers consider the effect of inflation expectations in managing energy consumption so that the carbon peak and carbon neutrality can be achieved on time? Nevertheless, significant climate policy changes ever since the Paris agreement in 2016 cast doubt on the relationship between energy consumption and inflation expectations. Under the pressing carbon peak and carbon neutrality targets, does the intertemporal substitution effect of inflation expectations on energy consumption exist? This article is thus motivated to empirically investigate the intertemporal substitution effect through testing the causal relationship between inflation expectations and energy consumption.

Energy consumption is undoubtedly closely linked with inflation and many other important macroeconomic indicators (e.g., Bassey & Ekong, 2019; Qin et al., 2022; Su et al., 2022d), which is demonstrated to have tight inner-connections with inflation expectations (Xu, 2019; Xu et al., 2017; Zhang et al., 2022). Thereby, the relationship between inflation expectations and energy consumption has solid foundations (Abildgren & Kuchler, 2021; Binder, 2018). Theoretically, the proposition that temporary higher inflation expectations stimulate current consumption and depress future expenditures hinges on two premises. First, the Fisher equation suggests that the real interest rate approximately equals the nominal interest rate less the expected inflation. Consequently, if the nominal interest rate is fixed, higher inflation expectations will lead to lower real interest rates. Second, according to the Euler equation, the intertemporal substitution effect shows that a lower real interest rate helps reduce households' savings and thus stimulate agents to consume now rather than in the future, thus inducing the increase in current consumption expenditures (Ichiue & Nishiguchi, 2015). Besides, a wealth-redistribution channel enables higher inflation expectations to boost consumption spendings. Therefore, the literature suggests that the relationship between energy consumption and inflation expectations is an empirical problem, which motivates this study.

This article contributes to previous literature in tow aspects. First, this is the first study that investigates the intertemporal substitution effect regarding energy consumption, which has significant implications for monetary and energy policies. Previous studies focusing on general consumption or consumption of durable goods, which ignores the important role of energy products under frequency climate policy changes. Second, we consider structural changes in the causal relationships between inflation expectations and energy consumption in the U.S. under the background of significant climate policy changes. There is some literature focusing on whether inflation expectations are positively related to current consumption which is susceptible to misleading conclusions on the validity of the intertemporal substitution effect because of uncertain effects of other factors, e.g., implicit tax effect and financial frictions (Wieland, 2019). We study the causalities between inflation expectations and energy consumption. If higher inflation expectations cause lower future energy consumption, we tend to believe that the intertemporal substitution effect works in stimulating agents to consume in advance. The U.S. has experienced many significant changes in climate policies, including the United States Climate Change Action Plan of 1993, the

American Clean Energy and Security Act of 2009, the Clean Power Plan of 2015, the sign of Paris Agreement in 2016 and the withdrew from it in 2019, etc. These significant changes are influential for industries and capital markets, which may have resulted in fluctuations in the relationships between inflation expectations and energy consumption (Balcilar & Ozdemir, 2013; Xu et al., 2022; Xu & Salem, 2021). Therefore, we use the rolling window Granger causality test which allows for estimations of dynamic relationships between inflation expectations and energy consumption. Relying on monthly micro-data in the U.S., the bootstrap rolling-window method suggests some causal relationships between inflation expectations and energy consumption during certain periods. On the one hand, both positive and negative causalities running from energy consumption growth rates to inflation expectations are found. On the other hand, the intertemporal substitution effect can be effective with a positive causality running from inflation expectations to energy consumption, but not after the sign of Paris Agreement and the pandemic period. Therefore, climate policies aiming to reduce carbon emissions can change consumers' inflation expectations which have potential significant effects on the macro-economy.

This study proceeds as follows. Section 2 illustrates the theoretical and empirical relationships between inflation expectations and energy consumption. Section 3 explains the empirical methodology. Section 4 describes the corresponding data. Section 5 presents the empirical results, and Section 6 concludes.

2. Theoretical and empirical relationships between inflation expectations and energy consumption

2.1. Theoretical analysis

Advocates of the idea that temporary higher inflation expectations depress future consumption depends on the following proposition. The Fisher equation effect supports that a higher inflation expectation leads to a lower real interest rate, which further depresses future consumption through the intertemporal substitution effect, i.e., the Euler equation effect. Based on the simple model in Weber et al. (2015), we sketch the theory which suggests a negative nexus between inflation expectations and future consumption.

Assuming that the flow utility of a representative agent is from stocks of durable and nondurable consumption, i.e., D_t and C_t, respectively. Each period, agents are subject to a nominal endowment of Y_t and hold bond B_t which earns a nominal return of R_t. Furthermore, agents are assumed to have Constant Relative Risk Aversion (C.R.R.A.) preferences. Therefore, coefficients of relative risk aversion for durable and nondurable consumption are the same. The representative agent maximises the following utility function subject to certain flow budget constraint.

$$\left\{\begin{array}{l} \max \beta^s \sum_{s=0}^{\infty} \left(\frac{C_{t+s}^{1-\gamma}}{1-\gamma} + \frac{D_{t+s}^{1-\gamma}}{1-\gamma} \right) \\ s.t. \quad P_t C_t + P_t \left[D_t - (1-\theta) D_{t-1} \right] + B_{t+1} = Y_t + R_t B_t \end{array}\right. \tag{1}$$

where θ denotes the depreciate rate of durable consumption, and β is the discount rate of future utility, which satisfies $0 \leq \theta \leq 1$ and $0 \leq \beta \leq 1$. The price index in t is represented by P_t, applying to both durable and nondurable consumption. The flow budget constraint means that the sum of nominal consumption for nondurable and durable goods and bond purchases includes two parts: the payoff from previous-period bond purchases and the nominal endowment Y_t. We use λ to denote the Lagrange multiplier on the budget constraint. Thereby, we have the following representations of the first order conditions for durable and nondurable consumption and bond holdings.

$$C_t^{-\gamma} = \lambda_t P_t \tag{2}$$

$$D_t^{-\gamma} = \lambda_t P_t - \beta \lambda_{t+1} P_{t+1} (1 - \theta) \tag{3}$$

$$\lambda_t = \beta \lambda_{t+1} R_{t+1} \tag{4}$$

We get the intertemporal Euler equation as follows by combining Equations (2) and (4).

$$\left(\frac{C_{t+1}}{C_t} \right)^{\gamma} = \beta \frac{R_{t+1}}{\pi_{t+1}} \tag{5}$$

where π_{t+1} is the inflation during t and $t + 1$. According to Equation (5), when the nominal interest rate R_{t+1} is fixed and $\gamma > 0$, a higher inflation induces a lower nondurable consumption growth rate. On the other hand, we can gain the intuition for the possibility that consumption affect future inflation from Equation (2) with the durable goods depreciation rate of $(1 - \theta)$. Therefore, the future discounted marginal utility of the undepreciated stock of durables should be considered in equating the marginal cost and utility of durable goods. Future marginal utility of durable goods purchased today will increase the future price level, thus indicating that current consumption may cause inflation expectations.

While the intertemporal substitution effect suggests that higher inflation expectations stimulate current nondurable consumption including energy consumption, the implicit tax effect and precautionary-savings channel argue the opposite effect (Pástor & Veronesi, 2013; Wiederholt, 2012). Consequently, the theoretical relationship between inflation expectations and current energy consumption becomes ambiguous.

2.2. Empirical evidence

Previous studies suggest the potential that higher inflation expectations induce more consumption expenditures (Mian et al., 2013). Through estimating the wealth redistribution caused by a moderate inflation episode, Adam and Zhu (2016) document that a higher inflation transfers resources from rich and old households to young and middle-class agents who have higher marginal propensities to consume out of wealth. Furthermore, inflation is a boon for the government and a tax on foreigners, thus indicating that a higher inflation implies a significant inflation-induced wealth transfer from foreigners to domestic households. A temporary higher inflation allows underwater households to deliver and thus increases the aggregate demand (Krugman, 2013). As a result, if inflation expectations are demonstrated to be effective in increasing current energy consumption, the other factors such as the wealth-redistribution channel may also work except for the intertemporal substitution effect. In other words, it is suspicious to identify whether the intertemporal substitution effect validates by testing the link between inflation expectations and current energy consumption.

Moreover, some other economic channels exist that confuse the theoretical relationship between inflation expectations and current energy consumption, which leads to more uncertainty in determining whether the intertemporal substitution effect works. As pointed out by Coibion et al. (2012), an increase in inflation enhances the opportunity cost of holding money and other short-term saving instruments that are commonly used as the exchange medium, thereby reducing real money balances and consumption. Less consumption indicates lower returns in holding capital, thus leading to reduced investments. Therefore, higher inflation expectations may damage economic activities by serving as an implicit tax. Similarly, the imperfect information model supports that a higher inflation expectation implies a lower consumption expenditure by functioning as a tax on economic activity (Wiederholt, 2012). An increase in inflation expectations may also lead to higher uncertainties, which reduces consumption expenditures via a precautionary-savings channel (Pástor & Veronesi, 2013). Given that inflation expectations are driven partially by expectations of gasoline prices, higher inflation expectations may constitute negative wealth shocks and depress consumption expenditures (Bachmann et al., 2015). Therefore, whether inflation expectations stimulate or suppress current energy consumption is an empirical question.

Economic theory does not explicitly point out the association between higher expected inflations and current energy consumption. Empirical investigations also provide evidence that the sign of the relation between inflation expectations and current consumption expenditures is uncertain. Wieland (2019) suggests that temporary negative supply shocks that raised inflation expectations are contractionary during episodes of low policy interest rates. The result contradicts the standard Fisher relationship logic which argues that these shocks should be expansionary if real interest rates are low. Analogously, using survey data, Bachmann et al. (2015) demonstrate that the impact of inflation expectations on the reported readiness to spend on durables is economically small and statistically insignificant. Wieland (2019) attributes the negative effect of inflation expectations on current consumption expenditures to financial frictions and the decline in asset prices and net worth. Nevertheless, Bachmann et al. (2015) explain the negative or insignificant effects by relying on the nominal interest rate illusion, thus suggesting that most households cannot distinct nominal from real interest rates. Therefore, justifying the validity of the intertemporal substitution effect by estimating the contemporaneous relation between inflation expectations and consumption expenditures appears to be misleading.

The link between inflation expectations and current energy consumption is affected by various factors. Even if inflation expectations are demonstrated to increase energy consumption, it could only be indicated that the intertemporal substitution effect exceeds other adverse effects (Ichiue & Nishiguchi, 2015). If the intertemporal substitution effect works, we expect that higher inflation expectations will lower future energy consumption, which has been demonstrated in the literature for durable goods, e.g., Starr (2012). More recently, Ichiue and Nishiguchi (2015) document that higher inflation expectations tend to result in greater current household spending and less future consumption using the survey data in Japan, thus supporting the validity of the intertemporal substitution effect. Although the above studies support that higher inflation expectations lower future consumption, possible changes in the effects are ignored. Bachmann et al. (2015) illustrate a significantly negative association between the readiness to spend on durable consumption goods and inflation expectations inside the recent zero-lower bound (Z.L.B.) period, but not outside it. Conversely, Ichiue and Nishiguchi (2015) document a positive nexus between these two series at the Z.L.B. period. The above investigations reveal possible changes in the intertemporal substitution effect.

On the one hand, theoretical analysis indicates a tight causal relationship between inflation expectations and energy consumption. On the other hand, empirical evidence suggests that the intertemporal substitution effect changes under various macroeconomic environments. Given that climate policy changes are always connected to economic fluctuations, we propose the following hypothesis in testing the relationship between inflation expectations and energy consumption:

> **Hypothesis:** The intertemporal substitution effect of energy consumption is unstable under frequency climate policy changes.

3. Methodology

3.1. Bootstrap full-sample causality test

The Granger noncausality test from the bivariate Vector Autoregression model (V.A.R.) is used to investigate whether the intertemporal substitution effect works, particularly after the sign of Paris Agreement. If the intertemporal substitution effect exists, we expect that higher inflation expectations depress future energy consumption. As emphasised in Kontonikas (2004), the results of Granger noncausality tests are sensitive to sample periods. Thus, we test a 'temporary' rather than a 'permanent' Granger causality, which means that the causality between inflation expectations and energy consumption only holds during certain periods (Balcilar & Ozdemir, 2013). The Granger noncausality statistics are based on the prerequisite that the time series estimated are stationary. Inaccurate estimations caused by the non-standard asymptotic distributions of variables may generate (Sims et al., 1990). The residual-based bootstrap *(R.B.)* method ensures comparatively accurate power and size of critical values of the Wald test statistics in small- and medium-size samples. Meanwhile, the *R.B.* method dominates standard asymptotic tests, particularly when the variables are not co-integrated (Balcilar et al., 2010; Hacker & Hatemi-J, 2006). Considering that small sample corrected *L.R.* tests have better power and size properties (Shukur & Mantalos, 2000), we resort to the *R.B.*-based modified-*L.R.* statistic to examine the causality between inflation expectations and energy consumption.

We construct the following bivariate V.A.R.(p) model to measure the *R.B.*-based modified-*L.R.* statistics:

$$y_t = \phi_0 + \phi_1 y_{t-1} + \ldots + \phi_p y_{t-p} + \varepsilon_t \quad t = 1,\ 2,\ \ldots,\ T \tag{6}$$

where $\varepsilon_t = (\varepsilon_{1t},\ \varepsilon_{2t})^T$ is an independent white noise process with nonsingular covariance matrix and zero-mean. The optimal lag length p is determined by the Schwarz Criterion (S.C.). We test the causal relationship between inflation expectations and energy consumption. Thereby, the dependent variable $y_t = (S_t,\ \pi_t^e)^T$ is partitioned into energy consumption growth rate in period t (S_t) and the inflation expectation for the future that agents hold in period t (π_t^e). We represent Equation (6) as follows:

$$\begin{bmatrix} S_t \\ \pi_t^e \end{bmatrix} = \begin{bmatrix} \phi_{10} \\ \phi_{20} \end{bmatrix} + \begin{bmatrix} \phi_{11}(L)\phi_{12}(L) \\ \phi_{21}(L)\phi_{22}(L) \end{bmatrix} \begin{bmatrix} S_t \\ \pi_t^e \end{bmatrix} + \begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \end{bmatrix} \quad t = 1,\ 2,\ \ldots,\ T \tag{7}$$

where $\phi_{ij}(L) = \sum_{k=1}^{p+1} \phi_{ij,k} L^k,\ i,j = 1,\ 2$ and $L^k x_t = x_{t-k}$ in which L denotes the lag operator.

By imposing the restriction of $\phi_{12,k} = 0$ for $k = 1,\ 2,\ \ldots,\ p$ to Equation (7), we can calculate the modified-*L.R.* statistics and the *R.B.*-based p-values to statistically test the null hypothesis that inflation expectations do not Granger cause energy consumption. Similarly, by imposing the restriction of $\phi_{21,k} = 0$ for $k = 1,\ 2,\ \ldots,\ p$, we test the null hypothesis that energy consumption do not Granger cause inflation expectations. Inflation expectations cause energy consumption statistically if the first null hypothesis is rejected. Furthermore, if the effect is negative, the intertemporal substitution effect can be demonstrated empirically (Ichiue & Nishiguchi, 2015). Energy consumption statistically causes inflation expectations if the second null hypothesis is rejected, which suggests that energy consumption contains useful information in predicting inflation expectations.

3.2. Parameter stability test

The full-sample Granger causality test assumes a constant relationship between two variables by setting fixed parameters in the V.A.R. model. However, if structural changes affect the relationship between inflation expectations and energy consumption, the parameters in the V.A.R. model will show instability, thus indicating that the full-sample causalities can be inaccurate (Balcilar & Ozdemir, 2013). Therefore, we apply the most widely used tests of *Sup-F*, *Mean-F*, and *Exp-F* tests (Andrews, 1993; Andrews & Ploberger, 1994) to investigate the short-run parameter stability. Meanwhile, we use the L_c test to estimate the long-run stability of parameters (Hansen, 1992; Nyblom, 1989). Along with Andrews (1993) and Andrews and Ploberger (1994), we measure the critical values and p-values based on the asymptotic distribution from Monte Carlo simulations using 10,000 samples that are generated from a V.A.R. model with constant parameters. Samples in the fraction of (0.15, 0.85) are used because the *Sup-F*, *Mean-F*, and *Exp-F* tests require 15% trimming from both ends of the sample to ensure a robust estimation (Andrews, 1993).

3.3. Sub-sample rolling-window causality test

If parameters in the V.A.R. model show short- or long-run instability, the causalities between inflation expectations and energy consumption are likely to be time-varying rather than constant as indicated in the full-sample estimation. Thus, the rolling-window bootstrap method (Balcilar et al., 2010) is adopted to re-estimate the causal relationships between inflation expectations and energy consumption.

By adopting the rolling window method, the window size is assumed to be fixed including l observations. Therefore, the full sample is separated into $T-l$ sub-samples, i.e., $\tau-l+1,\ \tau-l,\ \dots,\ T\ for\ \tau=l,\ l+1,\ \dots,\ T$, where T denotes the size of the full sample. Then, we estimate the *R.B.*-based modified-*L.R.* statistics in each sub-sample. Consequently, we obtain $T-l$ causality estimations including the bootstrap p-values and coefficients of observed *L.R.*-statistics and thus can capture possible structural changes. Besides, the coefficients of the causality are measured by calculating the value of the effect. Specifically, the coefficient of the causality running from energy consumption to inflation expectations is $N_b^{-1}\sum_{k-1}^{p}\phi_{21,k}^{\hat{*}}$, where N_b denotes the times of bootstrap repetitions. Analogously, the coefficient of causality running from inflation expectations to energy consumption is measured by $N_b^{-1}\sum_{k-1}^{p}\phi_{12,k}^{\hat{*}}$. Both $\phi_{21,k}^{\hat{*}}$ and $\phi_{12,k}^{\hat{*}}$ are bootstrap estimates of $\phi_{ij,k}$ using the V.A.R. models. Meanwhile, we provide the lower and upper bounds of the coefficients which correspond to the 5% and 95% quantiles of $\phi_{21,k}^{\hat{*}}$ and $\phi_{12,k}^{\hat{*}}$, respectively.

To set the rolling window size l, two conflicting indicators should be considered, i.e., the accuracy and the magnitude. The window size is denoted by the number of observations, which determines the precision of estimates. The estimation accuracy increases with the window size. However, the magnitude measuring the representativeness of the model is anti-correlated with the number included in the sub sample. A larger window size is accompanied by the possibility that multiple shifts be included in the same sub-sample, thus weakening the representativeness. Therefore, we follow the rule proposed by Pesaran and Timmermann (2005) who find that the optimal window size based on the Monte Carlo simulations should include more than 20 observations considering frequent breaks of variables.

4. Data

In this article, data of inflation expectations and energy consumption in the U.S. are needed. The University of Michigan conducts a Survey of Consumer Attitudes and Behavior which interviews averagely 500 respondents each month since 1978 (Carroll, 2003). The survey asks responds about their quantitative inflation expectations for the next 12 months. The energy consumption is the total energy consumed by the residential sector from the U.S. Energy Information Administration. We use the monthly growth rate of energy consumption. Overall, the monthly data during January 1978

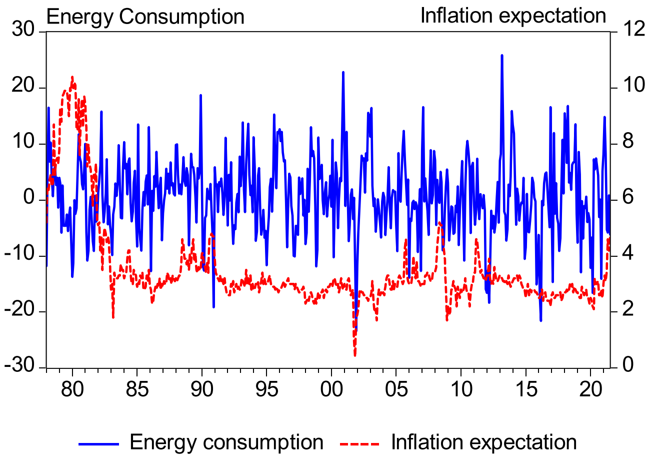

Figure 1. Inflation expectation and consumption growth rate in the U.S. (January 1978 to July 2021).
Source: authors' calculations.

to July 2021 for which both inflation expectations and energy consumption are available are used in this article.

Figure 1 compares the median value of 12-months ahead inflation expectations and the growth rate of energy consumption, indicating that the inflation expectations and energy consumption in the U.S. experienced significant changes. Under frequent climate policy changes, energy transitions have caused significant effects the economy, including consumption, stock markets, etc. (Pirtea et al., 2021; Su et al., 2022a, 2022b, 2022c; Tao et al., 2022; Wang et al., 2021; Xu & Lien, 2022a). As can be observed, during 1978–1986, the inflation expectation fluctuated severely. The inflation expectation in the U.S. rose sharply during 1978–1980 after decades of high inflation rates. However, in 1980, it began to decline when the nominal interest rate of federal funds rate increased rapidly to 19%. The movement of energy consumption was similar with that of inflation expectations during 1980–1982, but on the contrary after that. Hence, the correlation between inflation expectations and energy consumption is not evident during this period. During 1980–1986, both the expected and actual inflation decreased, thereby implying an increase in the real interest rate. The aggregate energy consumption growth rate maintains extremely fluctuating during the sample period. This phenomenon contradicts the Fisher equation and the Euler equation, which supports a constant and close relationship between inflation expectations and energy consumption.

Overall, energy consumption are more fluctuating comparing with the stable inflation expectations. The policy regulation around the mid-1980s induced a significant rise in inflation expectations. As can be observed from Figure 1, when the Asian financial crisis and 9/11 shock pummeled the economy in the U.S., the comparatively high inflation expectation after 1995 did not match the relatively low growth rate of energy consumption around 2001. Although the Federal Reserve conducted a low-interest rate policy to stimulate economic growth and thus appeared a sharp rise in future energy consumption in February 2000, this policy does not turn around the slump in the economy. Meanwhile, inflation expectations drop dramatically. The deviation between inflation expectations and energy consumption is intensified by the financial crisis around 2008. Inflation expectations show many 'sharp ups and downs' after the crisis, whereas the energy consumption fluctuations slash. Since January 2020, when the COVID-19 pandemic breaks out, a co-movement between inflation expectations and energy consumption shows up.

We find that the movements of inflation expectations and energy consumption are not always align with the Fisher equation and the intertemporal substitution effect (Bachmann et al., 2015). Conversely, negative relationships can be observed for many periods, which can be explained by the adverse forces such as the income effect (Attanasio et al., 2009). Figure 1 shows that the relationship between energy consumption and inflation expectations changes over time. Whether higher inflation expectations induce lower future energy consumption remains an empirical matter (Weber et al., 2015).

5. Empirical results

According to the results of the Augmented Dickey-Fuller unit root test (Dickey & Fuller, 1981), Phillips and Perron's test (Phillips & Perron, 1988), and Kwiatkowski et al.'s test (1992), both the inflation expectation and energy consumption growth rate are stationary processes. Considering that both the inflation expectation π_t^e and aggregate energy consumption growth rate S_t are $I(0)$, the full-sample causality test based on the V.A.R. model in Equation (7) can be estimated directly. The optimal lag-lengths are determined by the S.C. Table 1 summarises the *R.B.*-based modified-*L.R.* causality tests of the full-sample period. The bootstrap *p*-values suggest that there is no Granger causality between S_t and π_t^e. The full-sample result contradicts that of D'Acunto et al. (2015), in which households' willingness to purchase is positively associated with their inflation expectations. Similarly, Duca-Radu et al. (2021) also find a positive relationship between inflation expectations and the probability to make major purchases. Therefore, it appears that the intertemporal substitution effect does not exist for the full-sample period.

Nevertheless, previous literature mainly tests a constant full-sample causality. Possible structural changes exist as shown in Figure 1, and thus indicates that full-sample results can be suspicious. If the parameters in the V.A.R. models change over time, the causalities between energy consumption and inflation expectations will accordingly vary. Thus, the constant parameters across the full-sample period can be meaningless (Zeileis et al., 2005). We test the temporal and long-term parameter stabilities through adopting the *Sup-F, Mean-F, Exp-F* tests, and L_c test. Table 2 summarises the results of parameter stability tests. The results of *Sup-F* tests reject the null hypothesis that the parameters in the V.A.R. model are constant, thus accepting the alternative hypothesis that the parameters show a one-time sharp shift. The

Table 1. Full-sample Granger causality tests.

	H$_0$: S_t does not Granger cause π_t^e		H$_0$: π_t^e does not Granger cause S_t	
Tests	Statistics	*p*-values	Statistics	*p*-values
Bootstrap *LR* Test	1.275	0.885	3.453	0.491

Notes: We calculate *p*-values using 10,000 bootstrap repetitions. S_t *and* π_t^e denote energy consumption growth rate and inflation expectations, respectively.
Source: authors' calculations.

Table 2. Parameter stability tests.

	Aggregate Consumption Equation		Inflation Expectation Equation		*VAR* System	
	Statistics	*p*-value	Statistics	*p*-value	Statistics	*p*-value
Sup-F	31.385***	0.000	25.744***	0.000	89.136***	0.000
Mean-F	12.158***	0.006	9.377***	0.000	27.136***	0.000
Exp-F	19.047***	0.000	10.758***	0.005	45.358***	0.000
L_c^b					4.257***	0.005

Notes: We calculate *p*-values using 10,000 bootstrap repetitions. *** denotes significance at the 1% level, respectively. Hansen-Nyblom parameter stability test for all parameters in the V.A.R. jointly.
Source: authors' calculations.

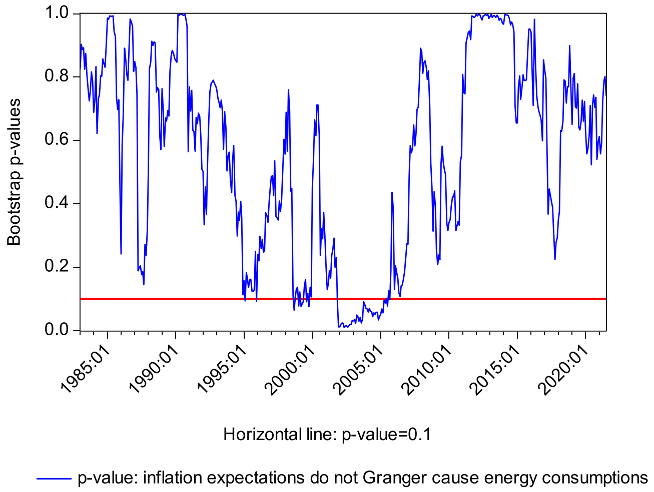

Figure 2. Bootstrap *p*-value of rolling test statistic testing the null that the inflation expectations do not Granger energy consumption.
Source: authors' calculations.

results of *Mean-F* and *Exp-F* tests reject the null hypothesis that the parameters follow a martingale process. Therefore, the parameters change gradually and show significant short-term instabilities for two equations and the V.A.R. system. Finally, the results of L_c statistics rejects random walk parameters in the long-run. Significant parameter instabilities are supported by the above tests.

Given that the full-sample causality is unstable with the parameters in the V.A.R. models change in different periods, conclusions based on full-sample results are not credible. This article considers the structural changes in inflation expectations and energy consumption through the rolling window estimation, which reports time-varying causalities. The null hypothesis of the *R.B.* bootstrap-based modified-*L.R.* tests assumes no causality between inflation expectations and energy consumption. We set the window size of the rolling window estimation as 60 months[1] to balance the magnitude and accuracy (Pesaran & Timmermann, 2005). Figures 2–5 show the coefficients and *p*-values of each rolling window. As shown in Figure 2, significant causalities running from inflation expectations to energy consumption can be demonstrated at the 10% significance level during November 2001 to July 2005. The coefficients in Figure 3 show that the effect of inflation expectations on energy consumption is positive.

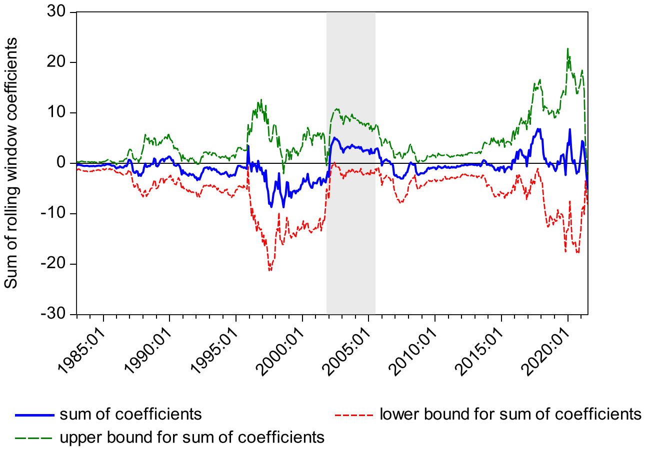

Figure 3. Bootstrap estimates of the sum of the rolling window coefficients for the effect of the inflation expectations on energy consumption.
Source: authors' calculations.

According to Figures 2 and 3, the significant positive Granger causality running from inflation expectations to energy consumption during November 2001–July 2005 indicates that consumers tend to spend more on energy now than in the future. In the early 1950s, the U.S. was self-sufficient in energy consumption. However, ever since the mid-1950s, the import volume of crude oil, refined oil products, and natural gas increased significantly in the U.S., thus making it a net energy importer. In 2005, energy imports in the U.S. peaked, accounting for 30% of total energy consumption that year. Therefore, the intertemporal substitution effect exists during this period should be attributed to the rapid growth in energy consumption to a certain extent. Nevertheless, on August 8, 2005, the U.S. passed the Energy Policy Act of 2005. This law is based on the National Energy Policy of the U.S. promulgated by the Bush administration in 2001, which has undergone about five years of adjustment and modification. The Energy Policy Act of 2005 covers the production, consumption, research, and development of energy, aiming to reduce the over-dependence of the U.S. on foreign energy and safeguard its energy security, economic security, and national security by reducing expenditure. Consequently, the energy consumption growth declined since 2005 and the intertemporal substitution effect vanishes.

Nonetheless, no such significant causalities are demonstrated in other periods, particularly after the outbreaks of the 9/11 shock and the COVID-19 pandemic which destroy the stable inflation expectations. Affected by the pandemic, many aspects of the economy are deeply affected, including stock markets, foreign exchange markets (Tao et al., 2022; Xu & Lien, 2022a, 2022b). Therefore, the intertemporal substitution effect does not always exist. The finding is consistent with Bachmann et al. (2015), in which no significant effect of inflation expectations on current consumption expenditures is demonstrated outside the Z.L.B. period. However, our results contradict Weber et al. (2015), in which the intertemporal substitute effect is believed to validate particularly in the Z.L.B. period because the nominal interest rate cannot adequately and immediately rise to offset anabatic inflation expectations. In general, the

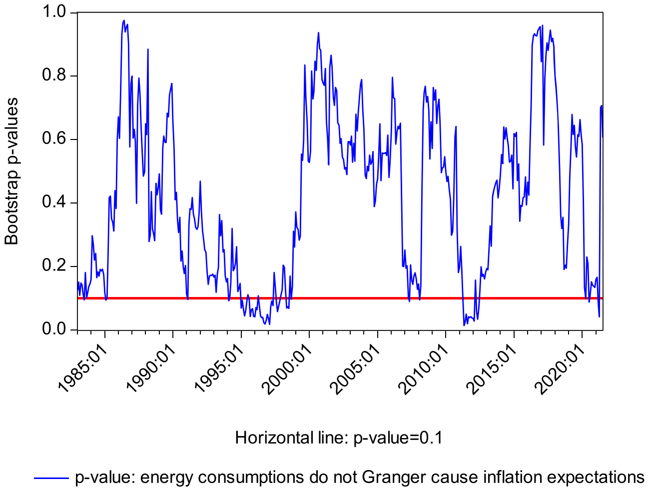

Figure 4. Bootstrap *p*-value of rolling test statistic testing the null that energy consumption does not Granger cause inflation expectations.
Source: authors' calculations.

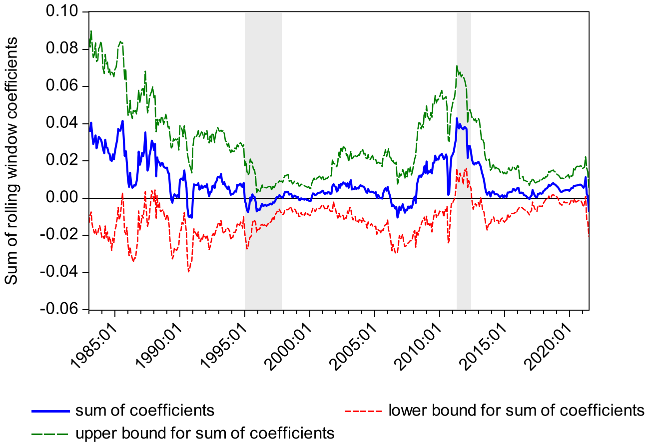

Figure 5. Bootstrap estimates of the sum of the rolling window coefficients for the effect of energy consumption on inflation expectations.
Source: authors' calculations.

bootstrap sub-sample rolling estimates in Figure 3 indicate that inflation expectations exert positive effects on energy consumption only during a short period.

Figure 4 reports the *p*-values of causalities running form energy consumption to inflation expectations, and Figure 5 presents the rolling estimates of causalities. The *p*-values in Figure 4 suggest the rejection of the null hypothesis in periods of January 1995–November 1997 and November 2011–June 2012. Comparatively, the causalities running from energy consumption to inflation expectations are shorter-lived. As shown in Figure 5, the effects of energy consumption on inflation expectations can be positive (November 2011–December 2016) or negative (January 1995–November 1997).

The causality running from energy consumption to inflation expectations during January 1995–November 1997 is generally negative, which suggests that current energy consumption depress the expected price level in the next 12 months. Theoretically, a positive relationship between energy consumption and inflation expectations is expected. Nevertheless, in 1994, the Federal Reserve conducts emergency measures of tight-money policies to cope the cyclical inflation when the commodity and oil prices rise significantly. Official intervention can be effective in managing economics (Taylor & Sarno, 2001). Although the energy consumption in the U.S. maintains increasing, the strength of monetary policies exceeds the expectation of consumers, thus resulting in a negative statistical effect of energy consumption on inflation expectations during 1995–1997. Another driver of the negative linkage between energy consumption and inflation expectations is the new deficit reduction since 1994, which imposed higher tax to the wealthy but lower tax to the middle class. The welfare reform in 1996 further boosted consumers' expenditures including energy consumption.

Another causality running from energy consumption to inflation expectations appear during November 2011–June 2012, when the U.S. economy is constrained by the Z.L.B. and no significant climate policy change. Ever since the 2008 financial crisis, the nominal interest rate in the U.S. is hardly able to rise adequately and immediately to offset anabatic inflation expectations. Even so, a positive relationship between energy consumption and inflation expectations still exists. The disappearance of the positive causality from energy consumption to inflation expectations can be explained by the stimulation of quantitative easing policies in the U.S. after the 2008 financial crisis. Three rounds of quantitative easing in the U.S. flooded financial markets with money, leading to soaring inflation expectations. Such shocks affect consumers' inflation expectations far more than that of energy consumption. Climate policy appears to contribute little to changes in the effect of energy consumption on inflation expectations.

The rolling-window bootstrap Granger causality tests produce additional evidence to the relationship between inflation expectations and energy consumption in the U.S. Our results suggest that the relationship between inflation expectations and energy consumption is not always consistent with the intertemporal substitution effect which argues that higher inflation expectations induce lower future energy consumption (Weber et al., 2015), but agrees with some other studies (Bachmann et al., 2015).

This empirical work fits into a growing literature studying energy consumption in the context of significant climate policy changes. Local authorities can plan and implement many measures to boost the energy system towards a low-carbon future, such like energy-saving initiatives in public buildings and lighting, carbon trading, and renewable energy pilot projects. Nevertheless, will current high inflation expectations result in increased energy consumption in the future? By contrast, under the background of carbon reduction, how energy consumption affect inflation expectations? The empirical findings in this study show that the causal relationship between inflation expectations and energy consumption is not stable, particularly in periods with dramatic economic policy shocks. The findings, at least to a certain extent, suggest that the intertemporal substitution effect is not likely to be convincing and policies aiming at generating lower inflation expectations may not be a threat in stimulating future energy consumption. Meanwhile, given that the positive causality running from energy consumption to inflation expectations disappears since 2012, climate policy changes aiming at carbon reduction may have little effect on inflation expectations.

6. Conclusions

This article re-estimates the intertemporal substitution effect with particular focus on the causal relationship between inflation expectations and energy consumption in the U.S. under the background of frequent climate policy changes. Through a bootstrap full-sample Granger causality test, we find no significant causality between inflation expectations and energy consumption. However, when considering possible structural changes, we demonstrate long- and short-term parameter instabilities, thus showing that relationships between inflation expectations and energy consumption are unstable, thereby indicating that the full-sample results can be inaccurate. We proceed to estimate the causalities though sub-sample rolling window methods and report bidirectional causal relationships in certain periods. Specifically, inflation expectations affect energy consumption positively during November 2001–July 2005, but has no such effect during the rest of the sample period. Therefore, we conclude that the intertemporal substitute effect that a higher inflation expectation stimulates agents to consume now rather than in the future does not work for energy consumption for most periods. By contrast, energy consumption can exert positive or negative effects on inflation expectations in certain periods.

The results in this article taken together show weak evidence supporting the conventional wisdom that higher inflation expectations may stimulate current energy spendings (Eggertson, 2006; Ichiue & Nishiguchi, 2015). The importance of inflation expectations has been stressed in a growing literature showing the close relationship between policies and inflation expectations (Christiano et al., 2011; Eggertsson, 2011; Woodford, 2011). Considering that a higher inflation expectation is viewed as a sign of incertitude on the part of policymakers and its implicit tax effect (Aruoba & Schorfheide, 2011; Wiederholt, 2012), the significant causality running from energy consumption to inflation expectations tells a cautionary tale about climate policies aiming at engineering lower carbon emissions. By contrast, in the context of carbon neutrality target, current high level of inflation appears to pose no threat to carbon reductions because inflation expectations are no longer a causation of increased future energy consumption for many years. However, this study has some limitations. For example, the results are based on the practice of the U.S., which may not apply to other economies such as China and the European Union which have large carbon trading markets. Therefore, further research on other economies can provide further useful information on the trade-off between economic growth and carbon reduction, particularly for countries which are subject to emission limits.

Notes

1. The window size should include more than 20 observations. Furthermore, we estimated bootstrap rolling-window causality tests using 36- and 48-window sizes. The coefficients and p-values of bidirectional causalities between inflation expectations and energy

consumption are estimated. The results maintain approximately the same, thus showing that the causality tests based on a 60-month window size are robust. Therefore, we report the results of it in this article, but the details of the results based on other window sizes are available upon request.

Disclosure statement

All authors declare that they have no conflict of interest.

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Data availability statement

The data used in this study are available from the University of Michigan (https://data.sca.isr.umich.edu) and the U.S. Energy Information Administration (https://www.eia.gov/).

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