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The Economic Consequences of Effective Carbon Taxes

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Abstract

This paper studies the economic consequences of carbon taxes at the macroeconomic and sectoral level. I propose a novel monthly measure of effective carbon tax rates, which, in contrast to the measures used by the existing literature, accounts for the time-varying emission coverage of taxes that are both explicitly and implicitly levied on greenhouse gas-emitting goods. Employing the new measure for four Nordic countries, I find that effective carbon taxes reduce emissions as expected but also decrease macroeconomic and sectoral activity - though there is some heterogeneity in the effects within and across the Nordic countries.

JEL-codes: H23, Q54, Q58

Keywords: carbon tax, carbon pricing, climate policy, emissions, macroeconomy, economic sectors

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1 Introduction

As the world takes action to limit global warming, an increasing number of countries rely on carbon taxation to reduce the emission of greenhouse gases (GHG). The mechanism of a carbon tax works primarily through shifting relative prices, making GHG-emitting goods more expensive relative to non-emitting goods, and thereby incentivising consumers to move away from GHG-emitting goods and reduce emissions. A key finding of the existing literature is that carbon taxes reduce emissions (Green, 2021) without impacting GDP (Metcalf, 2019; Metcalf and Stock, 2020; Bernard and Kichian, 2021). However, these studies focus solely on *explicit* carbon taxes, which are levied on GHG-emitting goods with the explicit objective of reducing emissions. There exist alternative *implicit* carbon taxes such as energy taxes on gasoline, diesel or coal, which are also specifically levied on GHG-emitting goods - although their original objective is typically to raise funds for the government and not to reduce emissions.[1] Despite their different objectives, explicit and implicit carbon taxes operate through similar mechanisms, increasing the price of GHG-emitting goods and thereby providing price incentives to reduce emissions. Hence, explicit and implicit carbon taxes are essentially indistinguishable for consumers, implying that their aggregate, the *effective* carbon tax, is crucial for their consumption decision. Moreover, governments usually change explicit and implicit carbon taxes simultaneously, often with different magnitudes or even signs. The indistinguishability and simultaneous determination of these taxes suggest that estimates of the economic impact of explicit carbon taxes might be biased if the estimation does not account for implicit carbon taxes.

In this paper, I propose novel measures for effective carbon tax rates to study their sectoral and macroeconomic consequences in and across the four Nordic countries Denmark, Finland, Norway and Sweden. I find effective carbon taxes reduce emissions as expected but also dampen macroeconomic and sectoral activity. These findings suggest that existing studies may underestimate the economic consequences of taxes on carbon-emitting goods by excluding implicit carbon taxes from their analysis.

I focus on the four Nordic countries since they offer detailed publicly available tax ac-

[1] I follow the naming convention of Harding et al. (2014) and Sen and Vollebergh (2018) regarding explicit and implicit carbon taxes.

counts and were the first to introduce explicit carbon taxes alongside existing implicit carbon taxes with economically significant rates and emission coverages. Hence, these countries provide long time series for implicit and explicit carbon taxes with sufficient variation.

This study contributes to the literature in three ways. First, I create a measure for effective carbon tax rates that considers both explicit and implicit carbon taxes, which addresses their indistinguishability and simultaneous determination. Furthermore, the effective carbon tax rates account for the carbon taxes' time-varying coverage of emissions, solving another concern of reduced taxes for a part of the tax base (Sen and Vollebergh, 2018). The measure is close in spirit to the "effective carbon rates" of OECD (2016, 2018, 2021), but differs in terms of objective and methodology. While OECD (2016, 2018, 2021) developed cross-sectional measures of effectively charged carbon rates in OECD countries for the three years 2012, 2015 and 2018, I develop monthly time series of effective carbon tax rates in the Nordics, which facilitates both dynamic panel and country-specific analyses.

Second, I contribute to the literature by estimating the macroeconomic consequences of carbon tax rates. So far, empirical studies on this matter are rather scarce, which is surprising given that carbon taxation plays a vital role in many countries for the transition to a low-carbon economy. The small existing literature has primarily focused on the consequences of *explicit* carbon taxes for GDP, employment and consumer prices in Sweden, Canada and a panel of European countries (Yamazaki, 2017; Andersson, 2019; Metcalf, 2019; Metcalf and Stock, 2020; Bernard and Kichian, 2021; Konradt and di Mauro, 2022). I contribute towards this literature by focusing on the impact of *effective* carbon taxes and by providing a broader macroeconomic picture through the consideration of a range of outcome variables: gasoline prices, GHG emissions, GDP, the unemployment rate, consumer prices, the interest rate and the exchange rate. In addition, I extend the scope of this literature by estimating the macroeconomic effects for the panel of the four Nordic countries and for each country separately. To the best of my knowledge, this is the first study to examine the macroeconomic consequences of *effective* carbon taxes and to explore the heterogeneity of these consequences across countries.

Third, I contribute by examining the heterogeneity in the impact of effective carbon taxes on output across different sectors of the Nordic economies. To date, Yamazaki (2017) is the only study that explores empirically the sectoral dimension by evaluating the impact of explicit carbon taxes on sectoral employment within Canada.

To analyse the sectoral and macroeconomic impact of carbon tax rates, I make use of the modified local projections of Metcalf and Stock (2020). They feature the evaluation of a permanent change in the tax rate, bypassing the issue of the classical local projections of Jordà (2005) that the tax rate changes throughout the horizon of the impulse response. The added feature mimics how governments set tax rates in practice, which provides a more realistic evaluation of the effects of a carbon tax.

The results from the analysis are presented in three stages. In the first stage, I inspect the mechanism of effective carbon taxes by examining their impact on the price of gasoline, one of the most commonly used GHG-emitting goods, and on GHG emissions. I find that an increase in the effective carbon tax rate increases the gasoline price and decreases emissions, as expected. More specifically, an increase in the effective rate by one Euro decreases emissions by 0.54% across the Nordics, which is within the range of the literature (see Green, 2021 for an overview). In a more direct comparison, Sen and Vollebergh (2018) find that emissions are slightly stronger affected by effective carbon taxes when using the cross-sectional dataset of OECD (2013).

In the second stage, I show that effective carbon taxes also have unintended consequences: An increase in the effective carbon tax rate by one Euro decreases GDP by 0.17% and temporarily increases the unemployment rate by 0.02 percentage points across the Nordics. Hence, reducing emissions with a carbon tax leads to the unintended consequence of lower economic activity, which leaves policymakers with a trade-off between environmental and economic objectives. However, as Bernard and Kichian (2021) suggest in their analysis of explicit carbon taxation in British Columbia, adverse macroeconomic consequences might be avoided if the revenues from carbon taxes were used to cut other taxes. The prices for goods, capital and currencies are only partly affected by effective carbon tax rates. While consumer prices might be expected to increase after a raise in the effective carbon tax, I find they are unaffected. This might be due to the slowdown in economic activity that is usually associated with lower consumer prices (see, for example, Galí, 2015). In contrast, the nominal interbank interest rate and the exchange rate are both affected by carbon taxes.

An increase in the effective carbon tax rate by one Euro leads to a temporary decrease of 0.05 percentage points in the interest rate and a permanent depreciation of 0.38% in the real effective exchange rate. Examining each country independently, I find that the macroeconomic effects are heterogeneous across the four countries. While Sweden is usually most adversely affected by effective carbon tax rates, followed by Finland and Norway, Denmark is essentially unaffected.

In the third and last stage, I investigate the heterogeneity in the impact of effective carbon taxes on output in different sectors. I find that a sector is more adversely affected by effective carbon taxes if it emits a large amount of GHG, is not exempted from carbon taxation, and uses many GHG-emitting goods. For example, the manufacturing and construction sectors are usually strongly adversely affected by carbon taxes as they produce and use many GHG-emitting goods, whereas the agricultural sector is unaffected as it is mostly exempted from carbon taxation.

The rest of the paper is structured as follows: The next section explains how effective carbon tax rates are measured. Section 3 discusses the local projections method and its modification. Section 4 presents the sectoral and macroeconomic effects of effective carbon taxes and several robustness tests. Finally, section 5 concludes.

2 Measuring effective carbon tax rates

Explicit and implicit carbon taxes are difficult to tell apart, especially for consumers. Both increase the relative price of GHG-emitting goods despite their different objectives (Sen and Vollebergh, 2018; OECD, 2019; Flues and Van Dender, 2020; OECD, 2021), are typically levied in the same way and provide the same incentives. For example, both taxes raise the price paid per litre of gasoline at filling stations, thereby incentivising to reduce gasoline consumption. Consequently, both explicit and implicit carbon taxes reduce emissions (Sen and Vollebergh, 2018; Andersson, 2019; Green, 2021).

Moreover, governments often change explicit and implicit (carbon tax) rates simultaneously (see Appendix B). These changes can be substitutes or complements. For example, explicit and implicit rates both increase with inflation adjustments or if governments generally want to increase taxes on energy. Conversely, governments can also shift the two kinds of taxes against each other, which was the case in Sweden between 2001 and 2004, when increases in the explicit rate were largely offset by decreases in the implicit rate (Hammar and Åkerfeldt, 2011). The switching correlation of the simultaneous adjustments of explicit and implicit carbon tax rates drastically complicates disentangling their effects and might lead to incorrect estimates in econometric models even if both tax rates were included in the model. For these similarity and simultaneity reasons, I focus on the sum of explicit and implicit carbon tax rates when estimating the economic impact of carbon taxes. This stands in contrast to previous studies that focused only on explicit carbon taxes (Yamazaki, 2017; Metcalf, 2019; Metcalf and Stock, 2020; Bernard and Kichian, 2021; Konradt and di Mauro, 2022).

Another concern is the time-varying emission coverage of carbon tax rates. For example, governments commonly grant exemptions from carbon taxation to various sectors due to the concern that higher input prices might disadvantage domestic companies against their foreign competitors. These exemptions, which vary over time, reduce the average tax rate that is effectively paid per ton of GHG emissions in a country. Therefore, carbon tax rates that have not been adjusted for their coverage may not accurately reflect the true economic burden induced by carbon pricing and lead to biases in the estimation of effects (Sen and Vollebergh, 2018). In this sense, the carbon tax rates adjusted for their coverage, which I propose, differ from their unadjusted counterparts that are mostly used in existing studies.

I solve the issue of time-varying emission coverage by calculating average carbon tax rates as in Nordic Statistical Offices (2003): First, I collect the annual revenues of all explicit and implicit carbon taxes from the national statistical bureaus or the national tax authorities. While the definition of explicit carbon taxes is apparent due to their defined objective, I define *implicit carbon taxes* as taxes which change the price of GHG-emitting goods relative to non-emitting goods. This definition includes energy taxes such as taxes on gasoline, diesel, natural gas, coal and peat, but also potentially other taxes such as energy security and oil damages duties. Appendix A lists the considered taxes for each country. The selection of explicit and implicit carbon taxes that I use is similar to the selection underlying the "effective carbon rates" of OECD (2021). However, note that I do not consider carbon prices from emission trading systems, the alternative carbon pricing scheme to carbon taxes. After collecting a country's annual revenues of explicit and implicit carbon taxes, I divide them by the country's total amount of GHG emissions, which provides the average explicit and implicit carbon tax rate paid per ton of GHG emissions in a given country and year. The sum of the coverage-adjusted explicit and implicit rate, the *effective* carbon tax rate, then indicates the effective burden from direct and indirect carbon taxation in an economy.

A potential shortcoming of this method is the short annual data sample of explicit and implicit carbon tax rates. I overcome this issue by exploiting a timing feature of the tax systems to create monthly time series of carbon tax rates: Tax rates or tax coverages in the Nordics are adjusted by governments on 1 January in about nine out of ten cases (see Appendix B), which means that tax rates are typically constant throughout the rest of the year. Thus, I assign all changes in the tax rate and coverage to January and keep the rates constant throughout the remainder of the year. While this induces a small measurement error when tax rates or coverages change in other months than January, it increases the number of observations drastically and provides a solid approximation to the general behaviour of policymakers. From an econometric perspective, the measurement errors might lead to slightly more lagged effects and more estimation uncertainty.[2] In return, the high number of monthly observations allows country-specific analyses and a more detailed resolution of the dynamic effects of carbon tax rates.

Figure 1 exemplifies the timing feature and the importance of adjusting the tax rate for its emission coverage. The dashed black line denotes the coverage-unadjusted (marginal) explicit carbon tax rate in Denmark provided by the frequently used database of World Bank (2021), while the grey line shows the coverage-adjusted (average or effectively paid) explicit carbon tax rate, which I propose, along with major policy events that changed the rate or coverage. Both displayed rates are denoted in Danish kroner and deflated with the consumer price index with the base year 2015. The coverage-adjusted (average) rate would be equivalent to the unadjusted (marginal) rate if the considered tax covered all emissions.

[2]More specifically, I expect an attenuation bias in the shorter horizon of the impulse responses and a bias that magnifies the effects in the longer horizon since the measurement error assigns a change in the tax rate earlier than it actually occurs. Approximating adjustments of tax rate changes that occur within the year would not be credible as they would entail inaccuracy and subjectivity.

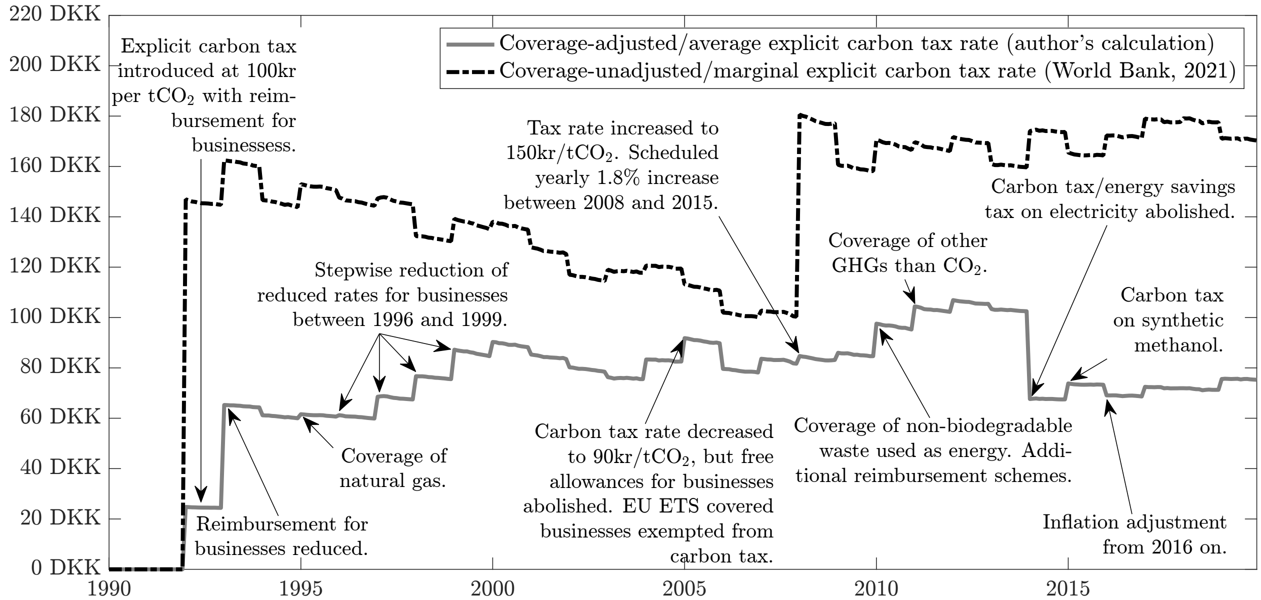

Figure 1: Emission coverage-adjusted and unadjusted explicit carbon tax rates for Denmark in real 2015-Danish kroner. Source of events: Skat (Danish Customs and Tax Administration), Retsinformation (Danish Legal Information) and Skatteministeriet (Danish Ministry of Taxation).

The Danish explicit carbon tax was introduced on 15 May 1992, an example for incorrectly assigning a change in the tax rate to January. However, note that this event is not included in the following analysis as the sample for Denmark begins only in February 1995 due to the availability of other data. All further annotated major policy events in Figure 1 occurred on 1 January and are, therefore, correctly assigned. The figure also highlights the importance of adjusting the rates for their emission coverage. For example, the coverage-unadjusted tax rate declined between 1993 and 2007, but as the grey line shows, various coverage adjustments actually increased the effectively paid tax rate in this period - still, it did not reach the level of the unadjusted tax rate, suggesting that the carbon tax did not cover all emissions. Hence, coverage-unadjusted carbon tax rates can differ substantially from effectively paid (coverage-adjusted) carbon tax rates. This speaks directly to the concern raised by Sen and Vollebergh (2018) that carbon tax rates might not reflect the true incentive to reduce emissions and the true economic burden if they are not adjusted for their emission coverage.

Figure 2 shows the coverage-adjusted real explicit, implicit and effective carbon tax rate paid on average per ton of CO2 (equivalent) emissions in the four Nordic countries. The four graphs show that real effective carbon tax rates increased substantially but not necessarily smoothly throughout the available sample period. In Denmark and Finland, implicit

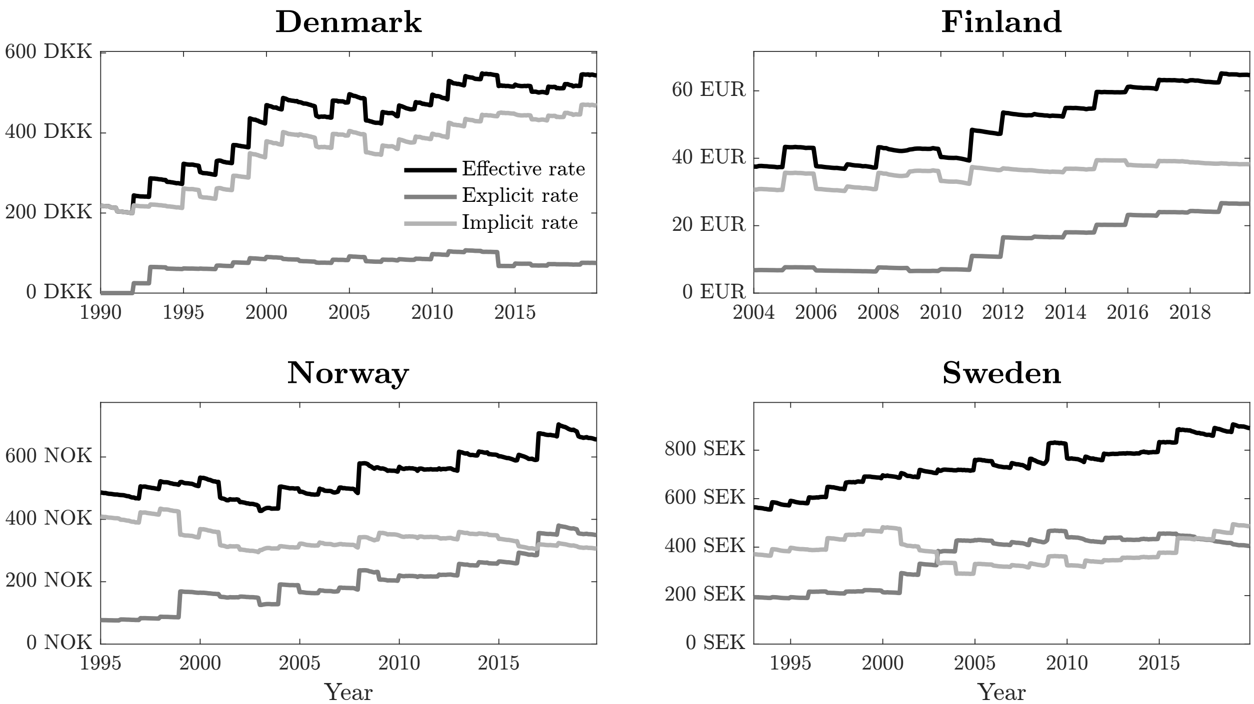

Figure 2: Real explicit, implicit and effective carbon tax rates in the four Nordic countries. All tax rates are denoted in local currencies and deflated with the country's consumer price index with the base year 2015. The different starting dates of the samples are determined by the data availability of tax revenues and GHG emissions.

rates were considerably higher than explicit rates throughout the whole sample, whereas, in Norway and Sweden, explicit rates even surpassed implicit rates in some parts of the sample. As alluded to previously, increases in explicit rates co-occur with increases or decreases in implicit rates (or vice versa), which was the case, for example, in 1999 in Norway and between 2001 and 2004 in Sweden. Moreover, the magnitude of changes in explicit and implicit carbon tax rates can differ substantially even if they go in the same direction.

3 Empirical method

To evaluate the dynamic impact of the real effective carbon tax rate $\tau_{i,t}$ in country i at time t on the k-th variable of interest $y_{k,i,t}$, I utilise the local projections method of Jordà (2005) and Jordà et al. (2013). The impulse response $\beta_{k,h}$ of variable k, h-months after an unexpected increase in the carbon tax rate by one Euro is given by the difference of the expected change in the variable of interest with and without the change in the tax rate, that is,

$$\beta_{k,h} = E(\Delta y_{k,i,t+h} \mid \Delta\tau_{i,t} = 1; \mathbf{x}_{i,t}) - E(\Delta y_{k,i,t+h} \mid \Delta\tau_{i,t} = 0; \mathbf{x}_{i,t}),$$

where $\Delta y_{k,i,t+h} = y_{k,i,t+h} - y_{k,i,t+h-1}$ is the h-month lead of the first difference of variable k and $\mathbf{x}_{i,t}$ is a vector of control variables. To estimate the impulse response $\beta_{k,h}$, I run independent OLS projections for each variable k at each horizon $h = 0, ..., H$:

$$\Delta y_{k,i,t+h} = \beta_{k,h}\Delta\tau_{i,t} + \mathbf{x}_{i,t}\boldsymbol{\gamma}_{k,h} + u_{k,i,t,h}, \tag{1}$$

where $\boldsymbol{\gamma}_{k,h}$ is a vector of coefficients for the control variables and $u_{k,i,t,h}$ is the error of the projection. The vector $\mathbf{x}_{i,t}$ contains a constant, country fixed effects as well as twelve lags of $\Delta\tau_{i,t}$ and twelve lags of all K variables of interest to allow for a reasonable degree of persistence. In addition, the variables are specified in first differences to avoid potential trending issues in the regression.

Similar to Metcalf and Stock (2020), I assume that the (first-differenced) tax rate is not affected by anything other than the control variables $\mathbf{x}_{i,t}$, which allows to interpret the impact of the tax rate $\beta_{k,h}$ on the first-differenced variable k as causal. This assumption implies the absence of simultaneity issues, that is, the tax rate $\Delta\tau_{i,t}$ is not contemporaneously affected by any of the other K variables - often a critical and contestable assumption in time series models. However, contemporaneous feedback effects of the K variables of interest on the tax rate should not be a concern in this case since governments set tax rates in advance and do not change them within the same month due to any current economic or political developments - though the model setup allows that governments adjust tax rates based on past developments.

Another potential concern is the anticipation of tax rates since they are known before their implementation. However, it is questionable whether the average household and firm know when carbon taxes are increased and how much it raises the price of gasoline before they experience the markup at the gas filling station. Note also that the empirical model allows to capture inflation adjustments and repetitive increases of carbon tax rates by controlling for the lags of inflation and the lags of $\Delta\tau_{i,t}$. To address any remaining concerns regarding potential anticipation, I conduct a robustness test in section 4.4 by controlling for real stock price changes. Firm valuations should reflect anticipated changes in the effective carbon tax rate as it impairs the firms' future profits due to increasing production costs.

One shortcoming of conventional local projections is their rather implausible treatment of the future tax rate path after an unexpected increase. For example, if the tax rate is modelled to increase unexpectedly by one Euro at horizon $h = 0$, the change in the tax rate at the horizons $h = 1, ..., H$ is not equal to zero but changes according to the tax rate's impulse response $\beta_{\tau,h}$ given by the projection

$$\Delta\tau_{i,t+h} = \beta_{\tau,h}\Delta\tau_{i,t} + \mathbf{x}_{i,t}\boldsymbol{\gamma}_{\tau,h} + u_{\tau,i,t,h}. \tag{2}$$

This is at odds with the observation that policymakers commonly keep the carbon tax rate constant after a change. To accommodate such a feature in the local projections model, I follow Metcalf and Stock (2020) and implement a zero-change in the tax rate at the horizons $h = 1, ..., H$ by taking the difference in the expected change of the variable of interest given that the tax rate changes only at horizon zero and given that it does not change at all:

$$\begin{aligned}\Theta_{k,h} = E(\Delta y_{k,i,t+h} \mid \Delta\tau_{i,t} = 1, \Delta\tau_{i,t+1} = ... = \Delta\tau_{i,t+h} = 0; \mathbf{x}_t)\\ - E(\Delta y_{k,i,t+h} \mid \Delta\tau_{i,t} = ... = \Delta\tau_{i,t+h} = 0; \mathbf{x}_t).\end{aligned}$$

In practice, a shock ε_h is introduced at each horizon h, which sets the desired change in the tax rate to $\Delta\tau^*_h = 1$ when $h = 0$ and $\Delta\tau^*_h = 0$ when $h > 0$, and which considers the repercussions of the previous shocks captured by the matrix $\boldsymbol{B}_\tau$. The series of shocks $\boldsymbol{\varepsilon}$ can then be obtained through $\boldsymbol{\varepsilon} = \boldsymbol{B}_\tau^{-1}\Delta\boldsymbol{\tau}^*$, where

$$\Delta\boldsymbol{\tau}^* = \begin{pmatrix} \Delta\tau_0^* \\ \Delta\tau_1^* \\ \vdots \\ \Delta\tau_H^* \end{pmatrix}, \quad \boldsymbol{B}_\tau = \begin{pmatrix} 1 & 0 & \cdots & 0 \\ \beta_{\tau,1} & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \beta_{\tau,H} & \beta_{\tau,H-1} & \cdots & 1 \end{pmatrix}, \quad \boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_0 \\ \varepsilon_1 \\ \vdots \\ \varepsilon_H \end{pmatrix}.$$

With the shock series $\boldsymbol{\varepsilon}$ at hand, the impulse responses $\boldsymbol{\Theta}_k$ of the change in variable k can be obtained through $\boldsymbol{\Theta}_k = \boldsymbol{\Lambda}\boldsymbol{\beta}_k$, where

$$\boldsymbol{\Theta}_k = \begin{pmatrix} \Theta_{k,0} \\ \Theta_{k,1} \\ \vdots \\ \Theta_{k,H} \end{pmatrix}, \quad \boldsymbol{\Lambda} = \begin{pmatrix} \varepsilon_0 & 0 & \cdots & 0 \\ \varepsilon_1 & \varepsilon_0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \varepsilon_H & \varepsilon_{H-1} & \cdots & \varepsilon_0 \end{pmatrix}, \quad \boldsymbol{\beta}_k = \begin{pmatrix} \beta_{k,0} \\ \beta_{k,1} \\ \vdots \\ \beta_{k,H} \end{pmatrix}.$$

I then cumulate the impulse responses through $\boldsymbol{CIR}_k = \boldsymbol{L}\boldsymbol{\Theta}_k$, where $\boldsymbol{L}$ is a lower triangular matrix with ones. The cumulated responses allow for the convenient interpretation as the deviation of the level of variable k from its counterfactual, that is, when the effective carbon tax rate would remain unchanged.

Montiel Olea and Plagborg-Møller (2021) show that heteroscedasticity robust standard errors are sufficient for lag-augmented local projections and that an adjustment for potential serial correlation in the error terms is not required. Hence, I obtain the standard errors $\boldsymbol{SE}_k$ of the cumulated impulse responses $\boldsymbol{CIR}_k$ through $\boldsymbol{SE}_k = \sqrt{diag(\boldsymbol{L}\boldsymbol{\Lambda}\boldsymbol{V}_{\boldsymbol{\beta_k}}\boldsymbol{\Lambda}'\boldsymbol{L}')}$, where $\boldsymbol{V}_{\boldsymbol{\beta_k}}$ is the heteroscedasticity adjusted variance-covariance matrix of the vector of coefficients $\boldsymbol{\beta}_k$ as in Metcalf and Stock (2020) (see Appendix C for its derivation).

4 The consequences of effective carbon taxes

In this section, I estimate the causal impact of increasing the real effective carbon tax rate by one Euro. Note that the effective (carbon tax) rate implies a full coverage of emissions in a country. To provide a broad overview of the economic consequences of effective rates, I evaluate the responses of $K = 7$ monthly variables: (1) real pump price of gasoline, (2) log of GHG emissions, (3) log of real GDP,[3] (4) unemployment rate, (5) log of CPI for all items, (6) nominal 3-month interbank interest rate and (7) log of the real effective exchange rate. The first two variables are included to illustrate the mechanism of carbon taxes, while the last five are commonly used indicators for macroeconomic performance. Apart from the interest, exchange and carbon tax rates, all variables are seasonally adjusted. Moreover, all variables are used in first differences in the estimations, as indicated in the section above. Rather than focusing on a specific period across all countries, I make use of the maximum quantity of available data in each country by beginning the sample in February 1993 for Sweden, in February 1995 for Denmark and Norway and in February 2004 for Finland, and ending the sample in December 2019 for all countries.

All monetary variables are denoted in local currencies to prevent distorting effects of exchange rates in the analysis. However, this poses an issue for the panel local projections since the monetary variables are not comparable across the four countries. Taking a pragmatic approach to solve this issue (and to enable a direct comparison of the panel and country-specific results later on), I rescale the monetary variables, carbon tax rates and gasoline prices, by the average exchange rate of the local currency to the Euro across the sample.[4] A detailed description, including sources and plots of all variables used in this paper, can be found in Appendix D and E.

4.1 Macroeconomic consequences of carbon tax rates

I begin by discussing the impact of the real effective carbon tax rate on the macroeconomies of the Nordic panel. Recall that an increase in the carbon tax rate should raise the price of GHG-emitting goods, and thus, emissions should decline. The first column of Figure

[3]As GHG emissions are only available at an annual frequency and GDP at a quarterly frequency, I follow Känzig (2021) and temporally disaggregate low-frequency variables to monthly variables using the Chow-Lin method provided by the code package of Quilis (2021). In essence, the low-frequency variation of the disaggregated monthly variable is still determined by the quarterly or annual variable, while its high-frequency variation, within a quarter or year, is determined by selected monthly indicators. For GHG emissions, the industrial production index, the unemployment rate and the real price of gasoline serve as monthly indicators. For GDP, the first two variables, the CPI for all items, the nominal interest rate and the exchange rate serve as monthly indicators.

[4]One Euro equals 7.44 Danish kroner, 8.35 Norwegian kroner and 9.26 Swedish kroner. Note that the rescaling is not necessary for log-transformed monetary variables since the first difference removes any time-invariant rescaling.

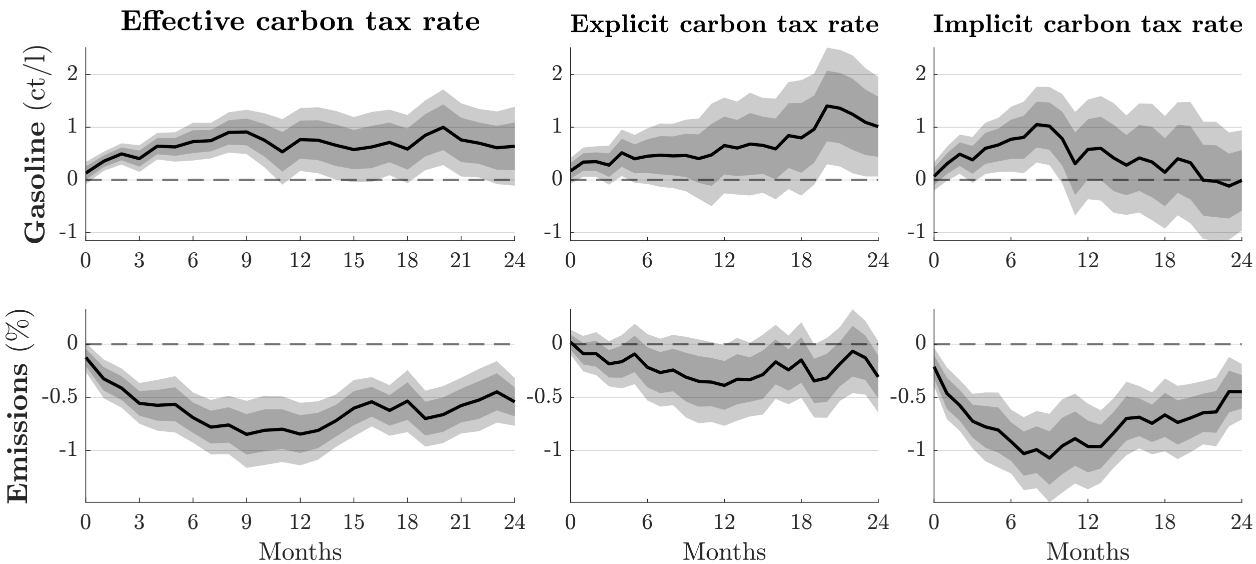

Figure 3: Cumulated impulse responses of the gasoline price (first row) and greenhouse gas emissions (second row) after an increase in the effective, explicit or implicit carbon tax rate (sorted by column) by one Euro. The dark and light grey areas indicate the 68% and 90% confidence bands.

3 confirms the presumed mechanism. It shows the cumulated impulse response with the 68% and 90% confidence interval of the gasoline price and GHG emissions in the 24 months following an increase in the effective carbon tax rate. To be specific, the price of gasoline, one of the most commonly used GHG-emitting goods, increases by 0.64 ct/l and emissions decrease by 0.54% in the two years after an increase in the effective rate by one Euro.

For comparison, I re-estimate the model with the explicit or implicit rate instead of the effective rate. After an increase in the explicit rate (second column), the gasoline price increases strongly, but emissions do not decline significantly. Vice versa, after an increase in the implicit rate (third column), the gasoline price does not increase in the medium and long run, but emissions decline strongly. While the responses of the effective rate perfectly align with the expected mechanism, the responses of the explicit and implicit rates demonstrate inconsistencies. This suggests that focusing purely on explicit carbon taxes would understate the true effects of taxing GHG-emitting goods.

The first column of Figure 4 presents the macroeconomic impact of effective rates. An increase in the carbon tax rate increases production costs for firms and fuel prices for consumers. Accordingly, economic activity should decrease as it is difficult to substitute many of the taxed GHG-emitting goods perfectly. This intuition is supported by the first impulse

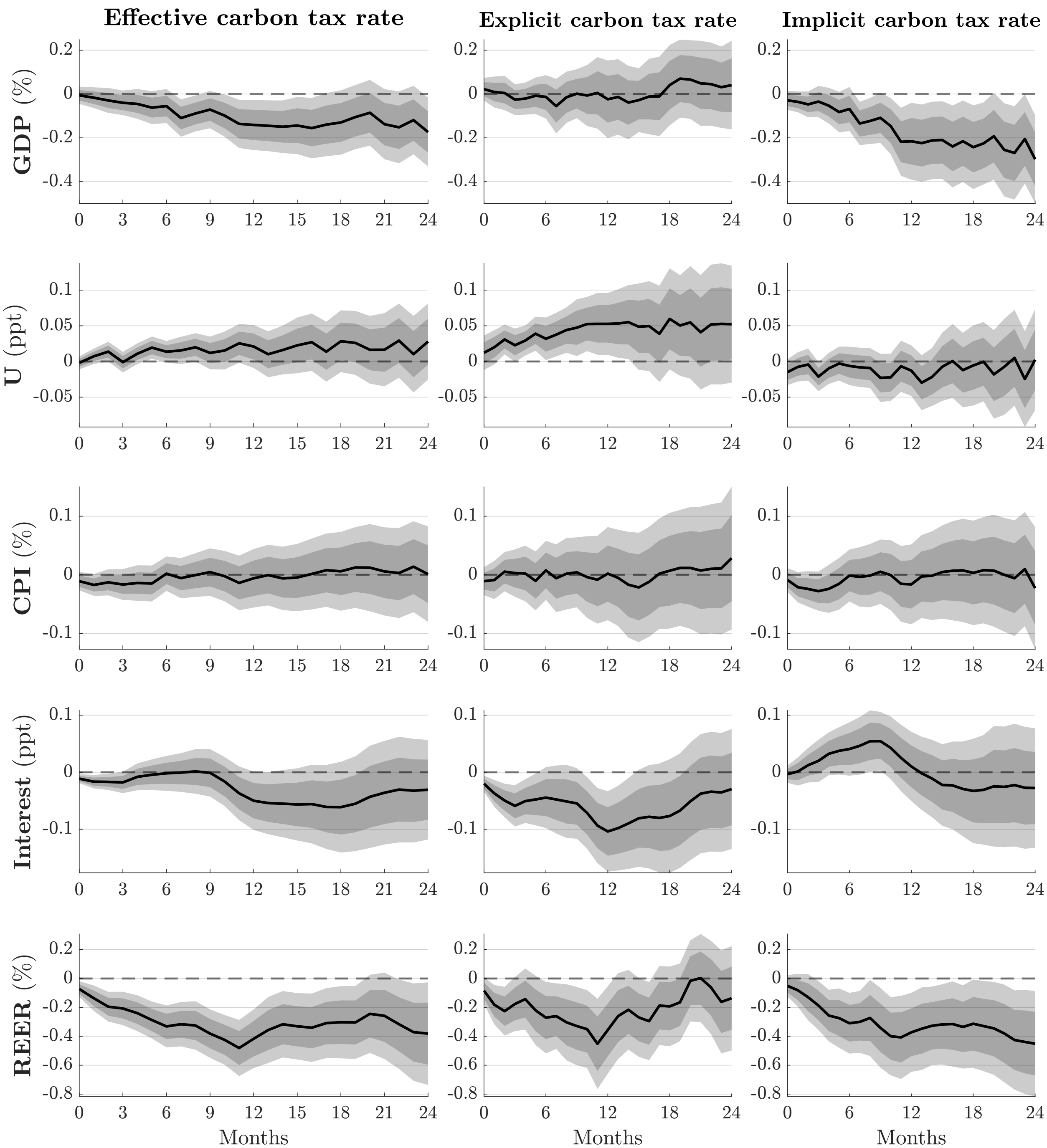

Figure 4: Cumulated impulse responses of macroeconomic indicators (by row) after an increase in the effective, explicit or implicit carbon tax rate (sorted by column) by one Euro. The dark and light grey areas indicate the 68% and 90% confidence bands.

response shown in Figure 4. In particular, an increase in the effective rate by one Euro leads to a 0.17% reduction in GDP after two years. The result also speaks to the finding of Känzig (2021) that carbon pricing under the EU emission trading system (the alternative carbon pricing tool) leads to a decline in industrial production. Hence, reducing emissions with carbon taxes leads to an unintended decline in economic activity, which might leave policymakers with a trade-off between emission reductions and economic growth. However, using the revenue of carbon taxes to reduce other kinds of taxes could be a possibility to avoid the adverse macroeconomic impacts of a carbon tax (Nordhaus, 1993; Gaskins and Weyant, 1993; Bernard and Kichian, 2021). This potential solution to the trade-off for policymakers and its theoretical and empirical support are discussed further below. Although GDP declines after an increase in the effective rate, the unemployment rate only increases significantly in the short run, but not in the long run, as Figure 4 displays.

McKibbin et al. (2020) argue that, depending on a central bank's objective, the trade-off between stabilising higher consumer prices and preserving economic activity following an increase in the carbon tax could be answered either with lower or higher interest rates. Though, the expected sign of the response of consumer prices following an increase in the carbon tax rate is ambiguous. On the one hand, consumer prices are expected to increase since the price of GHG-emitting goods increases. On the other hand, a decline in economic activity is typically associated with a decrease in consumer prices (see, for example, Galí, 2015). However, the two effects can only be surmised since the third row of Figure 4 suggests that the consumer price index (CPI) does not respond significantly to an increase in the effective rate. The lack of response is also in line with the finding of Konradt and di Mauro (2022) that explicit carbon tax rates do not change the CPI. Hence, central banks do not appear to face the classical trade-off and could focus on preserving economic activity. Indeed, Figure 4 suggests nominal interbank interest rates decline temporarily after an increase in the effective rate, which might point towards a potential supportive intervention of monetary policy. Finally, the increase in the effective carbon tax rate permanently decreases the real effective exchange rate (REER) by 0.38%, possibly due to the decline in economic activity.

The second and third column of Figure 4 shows the responses of the macroeconomic performance indicators when the model is re-estimated with the explicit or implicit rate instead of the effective rate. The results differ in several cases. Most notably, GDP does not change after an increase in the explicit rate, just as Metcalf (2019), Metcalf and Stock (2020), and Bernard and Kichian (2021) find. However, GDP declines strongly after an increase in the implicit rate. This puzzling discrepancy in the responses could have three explanations.

First, explicit and implicit rates are often set simultaneously by governments. As Figure 2 suggests, in some instances, the two rates increase coincidently; in other instances, they diverge. These irregular simultaneous changes could lead to wrong estimates (see discussion in section 2), which might also be reflected in the inconsistencies of the mechanisms of the explicit and implicit rate, as suggested by Figure 3.

Second, monetary policy might have played a role. Interbank interest rates increase after a raise in the implicit rate but decrease after a raise in the explicit rate. Possibly central banks supported (intentionally or unintentionally) the green transition but not increases in energy taxes. However, this potential explanation is questionable as central banks do not possess mandates to differentiate between different taxes. Moreover, the different interest rate responses might also result from the indistinguishability and simultaneity issues of the explicit and implicit carbon taxes.

Third, it might matter how the revenue of carbon taxes is used. Early on, the theoretical literature highlighted that it is crucial for the macroeconomic consequences how revenues from explicit carbon taxes are used (Nordhaus, 1993; Gaskins and Weyant, 1993) and also today, the idea is still at the heart of theoretical studies (see, for example, Goulder et al., 2019). While the revenue of implicit carbon taxes is commonly used as funds for the government in the Nordics (Nordic Statistical Offices, 2003), the revenue of explicit carbon taxes is partially recycled, that is, used to cut other taxes to reduce the burden on the economy. Carl and Fedor (2016) estimate that 30-50% of the revenue from *explicit* carbon taxes was recycled in the Nordics until 2014. However, they also note that there is not always a "direct link" between increases in carbon taxes and decreases in other taxes. Theory studies suggest that compared to inefficient government spending, revenue recycling can at least partially offset GDP losses from a carbon tax since other distorting taxes are cut (Gaskins and Weyant, 1993). Metcalf (2019), Metcalf and Stock (2020), and Bernard and Kichian (2021) also consider revenue recycling as a likely reason for not finding any adverse impact of explicit carbon taxes on GDP in British Columbia and a panel of European countries. However, while British Columbia fully (or even more than fully) recycled revenue from the carbon tax, the revenue recycling rate averaged across the European countries, based on the estimations of Carl and Fedor (2016), is only 27%. Hence, the revenue-neutral design of the carbon tax in British Columbia might provide a reasonable explanation for not affecting GDP. However, it is questionable whether the low revenue recycling rate in European countries can fully explain the lack of a response in GDP after an increase in the explicit carbon tax.

In the following sections, I continue to focus on the effective rate as it solves the simultaneity issue and provides the most credible mechanism.

4.2 Heterogeneity in the macroeconomic consequences

The economic consequences of carbon taxes depend on many factors, such as the elasticity of substitution of GHG-emitting goods and the GHG emissions level. As these factors differ across countries, analysing the effects of carbon taxes separately for each country might provide additional insights. To uncover the heterogeneity in the effects across the Nordics, I re-estimate the local projections described in section 3 for each country separately, leaving out the country fixed effects in $\mathbf{x}_{i,t}$ and dropping all the subscripts i.

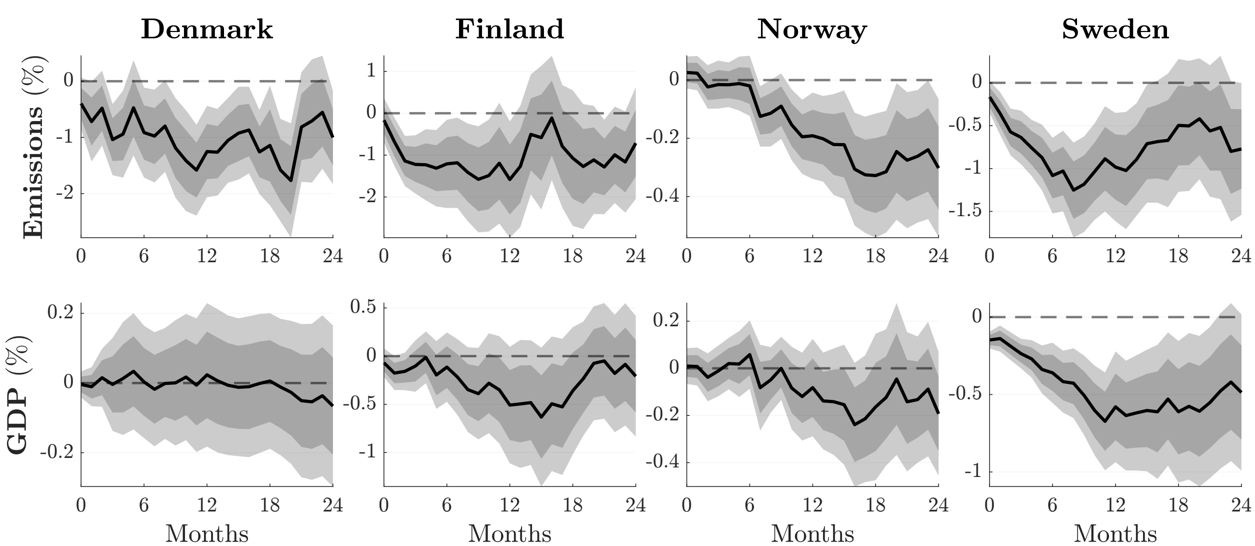

Figure 5: Cumulated impulse responses of GHG emissions and GDP after an increase in the real effective carbon tax rate by one Euro. The dark and light grey areas indicate the 68% and 90% confidence bands.

Figure 5 summarises the two most important results by showing how an increase in the real effective carbon tax rate by one Euro impacts emissions and GDP in the four Nordic countries. Complementary impulse responses of the other five variables can be found in

Appendix G. Naturally, the country-specific impulse responses are more noisy and uncertain than the responses of the Nordic panel due to the drastic reduction in the number of observations. Still, the impulse responses of the four countries clearly indicate a decrease in emissions that ranges between 0.3% and 1% two years after an increase in the effective rate. Therefore, carbon taxes can be considered an effective policy tool to decrease emissions in the Nordics. Moreover, Figure 5 uncovers some heterogeneity in the impact on economic activity. While GDP in Denmark is not affected at all, GDP in Sweden declines strongly after an increase in the effective rate. In Finland and Norway, GDP also tends to be adversely affected, but the significance of the impulse response does not allow for a clear interpretation.

4.3 Heterogeneity in the effects across sectors

The results above revealed some heterogeneity in the responses of macroeconomic activity across the Nordic countries. Similarly, there might also be heterogeneity in the effects across sectors within a country, especially since the emission intensity of production strongly differs across sectors.

	Denmark		**Finland**		**Norway**		**Sweden**	
(NACE code) Sector	**GVA**	**GHG**	**GVA**	**GHG**	**GVA**	**GHG**	**GVA**	**GHG**
(A) Agric., forestry, fishing	1,3	14,9	2,7	13,9	1,7	8,6	1,7	17,9
(B) Mining etc.	2,4	2,3	0,4	0,7	21,7	26,1	0,6	1,9
(C) Manufacturing	13,9	7,0	18,1	24,0	7,6	20,0	15,5	30,4
(D) Electricity etc.	1,5	17,4	2,2	32,7	2,2	3,0	2,7	14,8
(E) Water, waste	0,8	2,9	0,9	4,7	0,6	2,8	0,6	3,8
(F) Construction	5,1	1,8	6,8	2,3	5,9	3,0	6,1	3,8
(G) Wholesale & retail trade	12,8	1,5	9,5	1,0	7,7	1,8	10,8	3,5
(H) Transportation etc.	5,4	50,2	4,9	17,4	5,3	32,6	5,4	18,7
(I) Accommodation etc.	1,5	0,2	1,7	0,4	1,3	0,2	1,6	0,2
(J-U) All other sectors	55,2	1,9	52,8	2,9	45,9	1,8	55	5,1

Table 1: Averages of the sectoral share of GHG emissions and the gross value added (GVA) across the years 2008 to 2018. Data source: Eurostat.

Table 1 provides an overview of the average share of total GHG emissions and gross value added (GVA) for each sector in the four countries across the years 2008 to 2018, the period for which detailed data was available. Virtually all emissions in the four countries are produced by the goods sectors (A-F) and the transportation sector. Generally, agriculture, forestry and fishing, manufacturing and transportation are large emitters in all four countries. In addition, the electricity sector is a considerable emitter in Denmark, Finland and Sweden, whereas, in Norway, the mining sector is a large emitter. Apart from the transport sector, the service sectors (G-U) generally emit only a negligible fraction of all GHGs, but they account for the majority of GVA.

To evaluate the impact of an increase in the effective carbon tax rate on economic activity in a specific sector, I re-estimate the local projections with the sector's real and seasonally adjusted GVA[5] as an additional variable, such that $K = 8$. In principle, the more emission-intense a sector, the more adversely affected it should be by carbon taxes. In practice, partial or even full tax exemptions may complicate the picture since they reduce the sector's economic burden. Thus, each sector technically possesses its own effective carbon tax rate, but unfortunately, the availability of data on sectoral revenue from implicit and explicit carbon taxes is too limited to provide meaningful sector-specific carbon tax measures. Therefore, the impact of the effective carbon tax rate on the GVA of a sector reflects its emission intensity of production, its exemptions from carbon taxation, its ease of substituting GHG-emitting with non-emitting inputs, and potential spillovers from other sectors.

The first row of Figure 6 shows that GVA of the agriculture, fishing and forestry sector is essentially unaffected by an increase in the effective carbon tax rate. The lack of response is not unexpected, as most of the GHG emissions in this sector are exempted from carbon taxation. For example, emissions from livestock and soil and manure management are exempted in Norway (Norwegian Ministry of Climate and Environment, 2020). Nonetheless, the GVA of this sector declines temporarily in Finland and Sweden.

The aggregated GVA of the mining, electricity, water and waste sectors[6] declines temporarily for Finland and Sweden, where, according to Table 1, the aggregated GVA is dominated by the electricity sector. In contrast, the responses are entirely insignificant for Denmark and Norway, where the aggregated GVA is dominated by the mining (petroleum) sector

[5] Like GDP, GVA is only available on a quarterly frequency. Hence, the series is temporally disaggregated in the same way as GDP, following Känzig (2021) by using the Chow-Lin method provided by the code package of Quilis (2021).

[6] A more detailed resolution of the data for GVA is not available for the considered sample period. The same is the case for the combined GVA of the sectors (G, H, I) and (J-U), which is used further below.

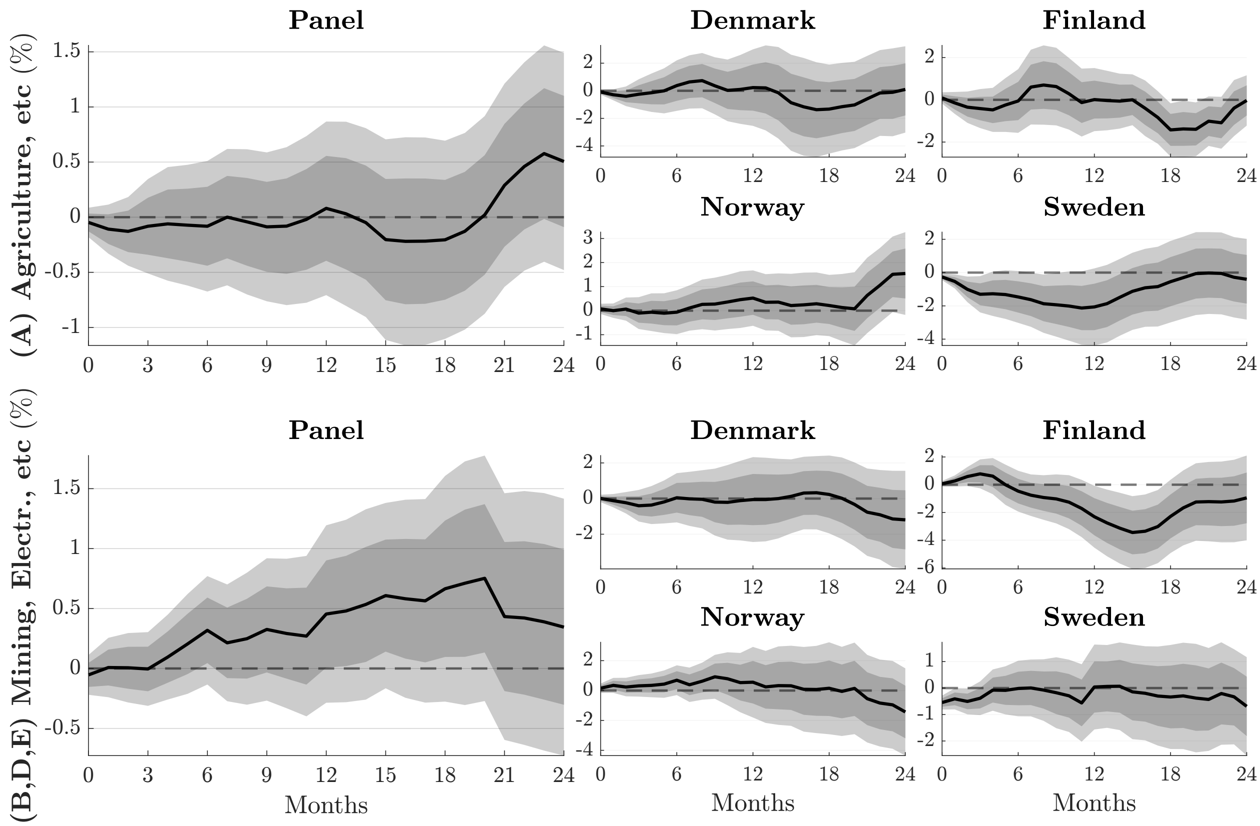

Figure 6: Cumulated impulse responses of GVA in the agriculture, fishing and forestry sector and the aggregate of the sectors mining, electricity, water and waste after an increase in the real effective carbon tax rate by one Euro. The dark and light grey areas indicate the 68% and 90% confidence bands.

and where electricity generation produces either little emissions or is barely taxed (Nordic Statistical Offices, 2003). On the one hand, this is somewhat surprising since the petroleum sector in Norway faces a high carbon tax rate, and thus, a decline in GVA would be expected. On the other hand, the "green paradox" theory proposed by Sinn (2008) suggests that fossil fuel production could even increase after the implementation of a climate policy that becomes increasingly stringent over time (see also Edenhofer and Kalkuhl, 2011, and Barnett, 2020). However, my results do not directly support either of the two presumptions since none of the two opposing effects dominates the responses of GVA for Denmark and Norway.

As the first row in Figure 7 shows, the GVA of the manufacturing sector is strongly decreasing, at least temporarily, which confirms the general presumptions of a heavy impact on this industry given its high share of emissions. The only exception is Denmark, where, if anything, GVA even increases. Two potential explanations for this exception might be

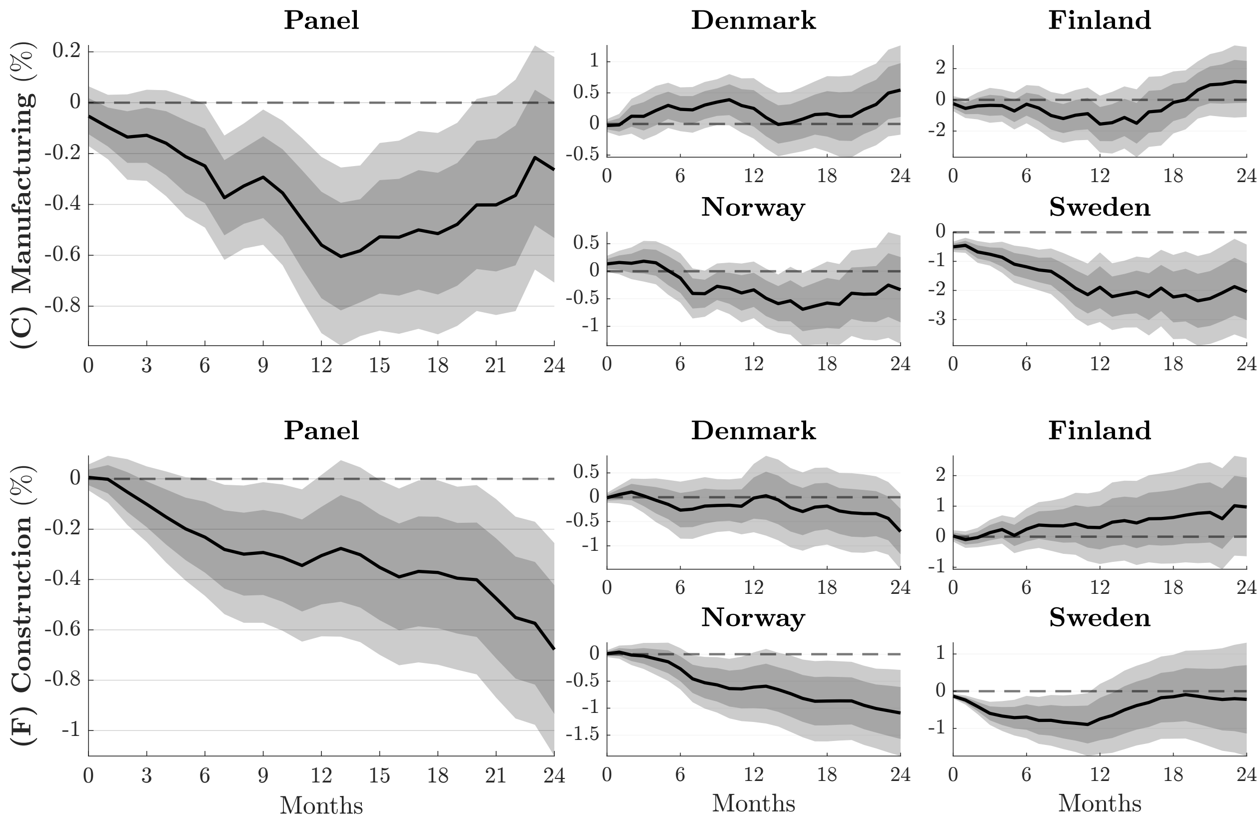

Figure 7: Cumulated impulse responses of GVA in the manufacturing sector and the construction sector after an increase in the real effective carbon tax rate by one Euro. The dark and light grey areas indicate the 68% and 90% confidence bands.

the low emission intensity of the Danish manufacturing sector and the emerging wind power industry, which might profit from carbon taxation as it incentivises companies to switch from fossil fuel-based energy to renewable energy.

The GVA of the construction sector is declining in all cases but Finland. Even though the sector emits only a small share of the total emissions in the Nordic countries, it uses many GHG-intensive materials such as cement and steel. Thus, spillovers from other sectors, especially from the manufacturing sector, might play an important role.

Figure 8 shows that the aggregated GVA of the trade, transportation and accommodation sectors strongly declines in all cases, at least temporarily. Though, the significance of this result is limited for Denmark and Finland. A strong impact on the transportation sector is generally expected due to its high emission intensity.

The aggregated GVA of all other service sectors slightly declines - merely Denmark is the exception once more. As emissions are negligible in these service sectors, the adverse

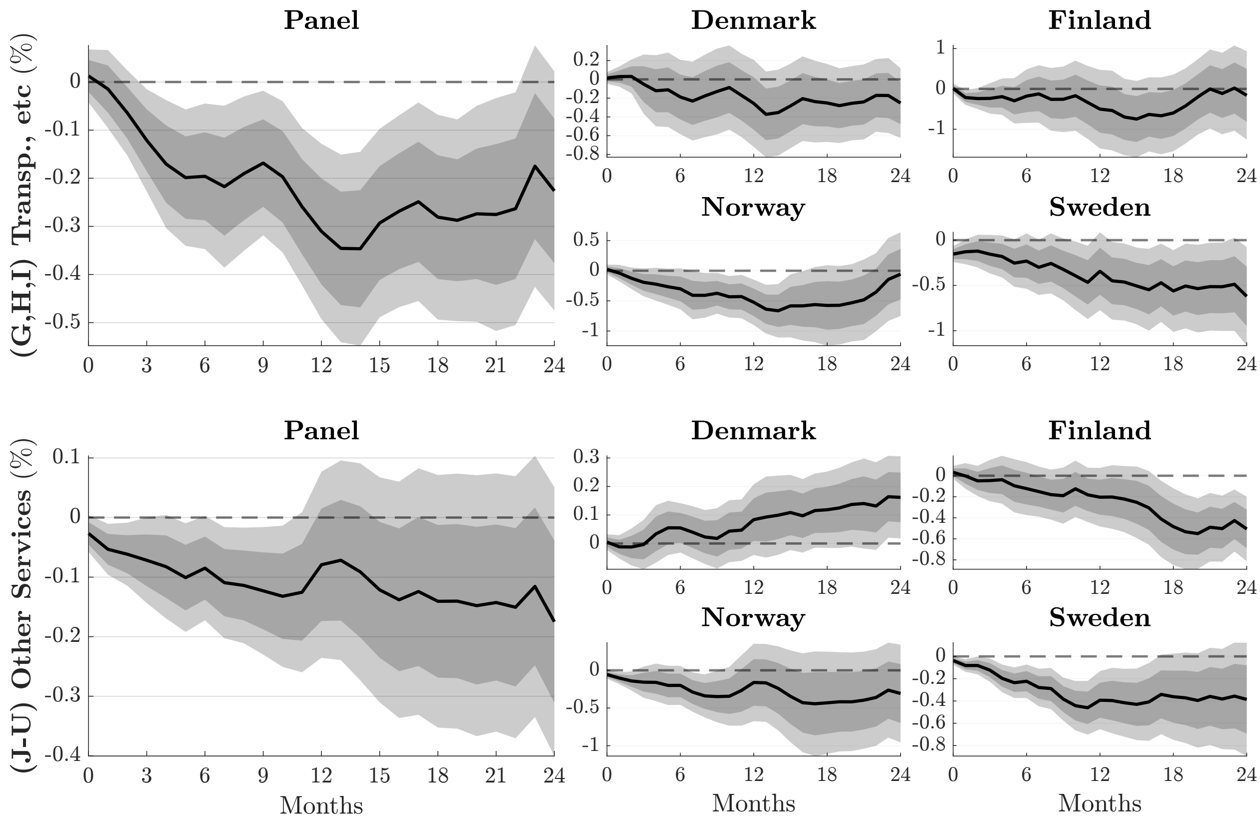

Figure 8: Cumulated impulse responses of the GVA of the aggregate of the wholesale and retail trade sector, the transportation sector, and the accommodation sector, and the aggregate of all other service sectors after an increase in the real effective carbon tax rate by one Euro. The dark and light grey areas indicate the 68% and 90% confidence bands.

impact might result from the high and commonly full coverage of carbon taxation for this sector and from spillovers of other sectors.

To summarise, sectors emitting much GHGs or using many GHG-intense goods, such as manufacturing, construction and transport, tend to be more adversely affected by carbon taxation. Exceptions to this rule are usually sectors that are mostly exempted from carbon taxation, such as the agricultural, forestry and fishing sector. However, even sectors that emit only little GHGs, such as the majority of service sectors, can be negatively affected by carbon taxation, which might be due to adverse spillover effects from other sectors. The observations align well across the Nordics, except for Denmark. This poses the question of how Denmark achieved emission reductions through carbon taxation without adversely impacting its economic activity. A potential explanation might be the build-up of a large wind power industry, which could explain why especially Denmark's manufacturing and "other" service sectors are, if anything, positively affected.

4.4 Robustness

To conclude the empirical analysis, I conduct a series of robustness tests to alleviate potential concerns about systematic biases in the estimated effects. I begin with checking the potential concern that the alternative carbon pricing system, the European Union emission trading system (EU ETS), might influence the carbon tax rate measures and their estimated effects. In the first robustness test, I add the contemporaneous value and twelve lags of the real one-month future price of emission allowances, addressing the concern that carbon tax rates might co-vary with the carbon price of the EU ETS. In the second robustness test, I add a dummy variable which takes the value zero before the introduction of the EU ETS and the value one afterwards. The dummy variable might capture the constant reduction of emission growth due to the EU ETS. However, the results found in section 4 are robust and do not appear to be systematically influenced by the EU ETS, as Figures 14-19 in Appendix H show.

In addition, I conduct robustness tests regarding further potentially confounding variables. In each test, the contemporaneous value and twelve lags of a potentially confounding first-differenced variable are added to the models used in section 4. Hence, the robustness tests are rather conservative and restrictive since they allow the carbon tax rate to react contemporaneously on the potentially confounding variable. The following four checks are conducted: (i) The potential anticipation of carbon tax rates is checked by adding the log of real stock prices. (ii) To check if increases in carbon taxes co-occur with increases in the general tax burden for the economy, the total tax revenue as a share of GDP is added. (iii) As tax rates on electricity are often changed simultaneously with implicit and explicit carbon tax rates, a potential bias is investigated by adding the average real electricity tax rate. (iv) To investigate if policymakers decrease carbon taxes when the economy is burdened with high commodity prices, the log of the country-specific commodity terms of trade (net export) index, constructed by Gruss and Kebhaj (2019), is added. As Figures 20-31 in Appendix H show, the results found in section 4 are generally robust, and the drawn conclusions remain.

Lastly, I investigate the sensitivity of the results to potential issues from seasonality or a trend in the first-differenced variables. The first is checked by controlling for monthly dummies in the model, while the latter is checked by adding a linear time trend. The results are robust, and the conclusions remain, as Figures 32-37 in Appendix H demonstrate.

5 Conclusion

Throughout the past three decades, many countries have implemented taxes with the explicit objective of reducing greenhouse gas emissions. In essence, these explicit carbon taxes increase the relative price of greenhouse gas-emitting goods and, thereby, incentivise reducing emissions. However, there also exist implicit carbon taxes with other objectives, which are essentially indistinguishable from explicit carbon taxes as they work in the same way. Moreover, both kinds of taxes are often determined simultaneously by governments. Consequently, the impact of explicit carbon taxes on emissions and economic activity might be biased if the estimation does not account for implicit carbon taxes.

This paper breaks new ground by examining the sectoral and macroeconomic consequences of effective carbon taxes within and across four Nordic countries. I begin with creating new monthly measures for effective carbon tax rates by considering explicit and implicit carbon taxes as well as their time-varying coverage of emissions. Employing these effective carbon tax rates in a local projections setting, I find that they are an effective policy tool to decrease emissions. However, they also dampen macroeconomic activity, which is reflected in the decline of GDP. Hence, policymakers might face a difficult trade-off between emission reductions through carbon taxation and economic growth. As previous studies suggest, a potential solution to this trade-off might be using the revenue of carbon taxes to cut other kinds of distorting taxes, which could prevent the adverse effects on GDP. Against the common presumption, I do not find that effective carbon taxes increase consumer prices, but they decrease the interest rate temporarily and the exchange rate permanently.

I also uncover heterogeneity in these effects across the Nordic countries. While the Swedish macroeconomy is most adversely affected by effective carbon tax rates, followed by the Finnish and Norwegian macroeconomy, the Danish macroeconomy appears to be unaffected. Finally, I explore heterogeneity in the consequences of effective carbon taxes rates on sectoral output. I find that emission-intense sectors are generally more adversely affected unless they are exempted from carbon taxation. Nevertheless, sectors which do not produce emission-intensely can also be negatively affected through spillovers from other sectors.

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Appendix A Data sources of the carbon taxes

Country	**Denmark**	**Finland**	**Norway**	**Sweden**
Source	Statistics Denmark (Danmarks Statistik)	Finnish Tax Administration (Vero Skatt)	Statistics Norway (Statistisk sentralbyrå)	Statistics Sweden (Statistiska centralbyrån)
Table name (Table Nr.)	SKAT: Taxation total, divided into rates and dues by type	Excise duty	Environmental taxes, by type of tax (10645)	Total environmental taxes in Sweden 1993–2020
Explicit carbon taxes	(a) Duty on carbon dioxide (CO2)	(a) Carbon dioxide tax on liquid fuels (b) Carbon dioxide tax on certain fuels	(a) Tax on CO2 emissions (b) Tax on CO2 emissions in the petroleum sector (c) Motor vehicle registration tax - imputed CO2 component (d) Tax on greenhouse gases HFC and PFC	(a) Carbon dioxide tax
Implicit carbon taxes	(a) Duty on petrol (b) Duty on certain oil products (c) Duty on natural gas (d) Duty on gas (e) Duty on coal, etc.	(a) Energy content tax on liquid fuels (b) Supply security fee of liquid fuels (c) Energy content tax on certain fuels (d) Energy taxation on certain fuels (e) Supply security fee of certain fuels (f) Oil waste duty (g) Oil damage duty	(a) Petrol tax (b) Diesel tax (c) Road tax on natural gas and LPG (d) Tax on lubricating oils (e) Tax on mineral oils	(a) Energy tax on fuels (b) Tax on diesel oil

Table 2: Excise taxes for the construction of explicit and implicit carbon tax rates and their sources.

Appendix B Carbon tax histories

	Implicit carbon taxes in Denmark			Explicit carbon taxes in Denmark
Date	**Energy tax on mineral oil products (Energiafgifter af mineralolieprodukter mv.)**	**Energy tax on coal and heat from waste (Energiafgift af kul og affaldsvarme)**	**Energy tax on natural gas (Energiafgift af naturgas og bygas)**	**Carbon dioxide tax (Kuldioxid-afgift)**
15 May 1992				introduction
01 Jan 1993				coverage
01 Jan 1996			price, coverage	price, coverage
01 Jan 1997				coverage
01 Jan 1998				coverage
01 Jan 1999				coverage
01 July 1999			coverage	coverage
01 Jan 2001			coverage	
01 Jan 2005				price
01 Jan 2006			price, coverage	
01 Jan 2007	price	price	price	
01 Jan 2008	price	price	price	price, coverage
01 Jan 2009	price	price	price	price
01 Jan 2010	price	price, coverage	price, coverage	price, coverage
01 Jan 2011	price	price	price	price, coverage
01 Jul 2011		price		
01 Jan 2012	price	price	price	price
01 Jul 2012	price		price	
01 Jan 2013	price	price, coverage	price	price, coverage
01 Feb 2013	price	price	price	
01 Jan 2014	price	price	price	price, coverage
01 Jan 2015	price	price, coverage	price	price, coverage
01 Jan 2016	price	price	price	price
01 Jan 2017	price	price	price	price
01 Jan 2018	price	price	price	price
01 Jan 2019	price	price	price	price

Table 3: Changes in price and coverage of *explicit and implicit* carbon taxes in Denmark. Data is collected to the author's best understanding of the tax histories provided in local language. Changes in price and coverage are incomplete towards the mid and beginning of the sample due to availability of information from official administration sources. Note that distinctions into changes in prices and changes in coverage can be ambiguous. Source: Skat (Danish Customs and Tax Administration).

Date	Explicit and implicit carbon taxes in Finland	Implicit carbon taxes in Finland	
	Energy content and carbon dioxide tax	Strategic stockpile fees	Oil pollution fees
01 Jan 2005			price
01 Jul 2005	coverage		
01 Jan 2008	price, coverage		
01 Jan 2010			price
01 Jan 2011	price, coverage		
01 Jan 2012	price		
01 Jan 2013	price		
01 Jan 2014	price		
01 Jan 2015	price		
01 Jan 2016	price, coverage	coverage	
01 Mar 2016	price		
01 Jan 2017	price		
01 Jan 2018	price		
01 Jan 2019	price		

Table 4: Price changes and some changes in coverage of *explicit and implicit* carbon taxes in Finland. Data is collected to the author's best understanding of the available tax histories. Information about changes in the coverage by the taxes are not available from official administration sources. Source: Statistics Finland.

	Explicit carbon taxes in Norway				
Date	**Avgift på mineralolje**	**Avgift på kull og koks mv.**	**CO2-avgift på mineralske produkter**	**Engangsavgift - beregnet CO2-komponent**	**Miljøavgift på klimagassene hydrofluorkarboner og perfluorkarboner**
01 Jan 1995	price, coverage	price			
01 Jan 1996	price	price			
01 Jan 1997	price, coverage	price, coverage			
01 Jan 1998	price	price			
01 Jan 1999	abolished	abolished	introduction		
01 Jan 2000			price, coverage		
01 Jan 2001			price, coverage		
01 Jan 2002			price		
01 Jan 2003			price, coverage		introduction
01 Jan 2004			price		price
01 Jan 2005			price		price
01 Jan 2006			price		price
01 Jan 2007			price	introduction	price
01 May 2007				coverage	
01 Jan 2008			price	price	price
01 Jan 2009			price, coverage	price, coverage	price
01 Jan 2010			price	price, coverage	price
01 Sep 2010			coverage		
01 Jan 2011			price, coverage	price, coverage	price
01 Jan 2012			price, coverage	price	price, coverage
01 Jan 2013			price	price, coverage	price
01 Jan 2014			price, coverage	price, coverage	price
01 Jan 2015			price	coverage	price
01 Jul 2015			price, coverage		
01 Jan 2016			price	price, coverage	price
01 Jan 2017			price	price, coverage	price
01 Jul 2017				coverage	
01 Jan 2018			price, coverage	price, coverage	price
01 Jan 2019			price	price	price
01 Jul 2019				coverage	

Table 5: Changes in price and coverage of *explicit* carbon taxes in Norway. Data is collected to the author's best understanding of the tax histories provided in local language. Note that distinctions into changes in prices and changes in coverage can be ambiguous. Source: Skatteetaten (Norwegian Tax Authorities).

Date	Implicit carbon taxes in Norway Veibruksavgift på drivstoff	Veibruksavgift på bensin	Veibruksavgift på autodiesel	Avgift på smøreolje mv.	Grunnavgift på mineralolje mv.
01 Jan 1995		price, coverage	price		
01 Jan 1996		price	price	price	
01 Jan 1997		price	price, coverage	price, coverage	
01 Jan 1998		price	price, coverage	price	
01 Jan 1999		price, coverage	price, coverage	price, coverage	
01 Jan 2000		price, coverage	price, coverage	price, coverage	introduced
01 Jul 2000		price	coverage		
01 Jan 2001		price	price	price	price
01 Jul 2001		price	price		
01 Jan 2002		price	price	price	price
01 Jan 2003		price	price	price	price
01 Jan 2004		price	price	price	price
01 Jan 2005		price	price	price	price
01 Jan 2006		price, coverage	price	price	price
01 Jan 2007		price	price	price	price
01 Jan 2008		price	price	price	price
01 Jul 2008		price	price		
01 Jan 2009		price	price	price	price
01 Jan 2010		price	price, coverage	price, coverage	price
01 Jul 2010					coverage
01 Jan 2011	introduced	abolished	abolished	price	price
01 Jan 2012	price			price	price
01 Jan 2013	price			price	price
01 Jan 2014	price			price, coverage	price, coverage
01 Jan 2015				price	price
01 Jul 2015	price				
01 Jan 2016	price, coverage			price	price
01 Jul 2016	coverage				
01 Jan 2017	price			price	price
01 Jan 2018	price			price	price
01 Jan 2019	price			price	price

Table 6: Changes in price and coverage of *implicit* carbon taxes in Norway. Data is collected to the author's best understanding of the tax histories provided in local language. Note that distinctions into changes in prices and changes in coverage can be ambiguous. Source: Skatteetaten (Norwegian Tax Authorities).

	Implicit carbon taxes in Sweden		Explicit carbon taxes in Sweden
Date	**Dieseloljeskatt**	**Energiskatt bränslen**	**Koldioxidskatt**
01 Jan 1993			price
01 Oct 1993		price	
01 Jan 1994		price	price
01 Jul 1994	price	price	
01 Jan 1995	abolished	price	price
01 Jan 1996		price	price
01 Sep 1996		price	
01 Jan 1997			price
01 Jul 1997		price	price
01 Jan 1999		price	price
01 Jan 2000		price	price
01 Jan 2001		price	price
01 Jan 2002		price	price
15 Nov 2002		price	
01 Jan 2003		price	price
01 Jan 2004		price	price
01 Jan 2005		price	price
01 Jan 2006		price	price
01 Jan 2007		price	price
01 Jan 2008		price	price
01 Jan 2009		price	price
01 Jan 2010		price	price
01 Jan 2011		price	price
01 Jan 2012		price	price
01 Jan 2013		price	price
01 Jan 2014		price	price
01 Jan 2015		price	price
01 Jan 2016		price	price
01 Jan 2017		price	price
01 Jan 2018		price	price
01 Jul 2018		price	price
01 Jan 2019		price	price
01 Jul 2019		price	

Table 7: Changes in price and coverage of *explicit and implicit* carbon taxes in Sweden. Data is collected to the author's best understanding of the tax histories provided in local language. Information about changes in the coverage of the taxes are not available from official administration sources. Source: Skatteverket (Swedish Tax Agency).

Appendix C Variance-covariance matrix

I follow Metcalf and Stock (2020) in obtaining the variance-covariance matrix $\boldsymbol{V}_{\boldsymbol{\beta_k}}$ of the vector $\boldsymbol{\beta}_k$. To simplify notation and provide more intuition, the Frisch-Waugh theorem is applied to equation (1). At first, project a single variable of interest $\Delta y_{k,i,t+h}$ and the tax rate $\Delta \tau_{i,t,h}$ on all control variables $\mathbf{x}_{i,t}$ to obtain their error terms $\Delta y^{\perp}_{k,i,t,h}$ and $\eta_{i,t,h}$, so

$$\Delta y_{k,i,t+h} = \mathbf{x}_{i,t}\mathbf{d}_{k,h} + \Delta y^{\perp}_{k,i,t,h}, \tag{3}$$

and

$$\Delta \tau_{i,t,h} = \mathbf{x}_{i,t}\mathbf{d}_{\tau,h} + \eta_{i,t,h}. \tag{4}$$

Afterwards, project $\Delta y^{\perp}_{k,i,t,h}$ on $\eta_{i,t,h}$ to obtain the coefficient $\beta_{k,h}$ and the error term $u_{k,i,t,h}$ from equation (1), that is,

$$\Delta y^{\perp}_{k,i,t,h} = \beta_{k,h}\eta_{i,t,h} + u_{k,i,t,h}.$$

As the number of observations differs at the various horizons, the variance-covariance matrix $V_{\boldsymbol{\beta}_k}$ is computed manually through

$$V_{\boldsymbol{\beta}_{k,lj}} = \left(\eta'_{i,t,l}\eta_{i,t,l}\right)^{-1} \left(\eta_{i,t,l} \circ u_{k,i,t,l}\right)' \sqrt{\frac{n_l}{n_l - q_l}} \sqrt{\frac{n_j}{n_j - q_j}} \left(\eta_{i,t,j} \circ u_{k,i,t,j}\right) \left(\eta'_{i,t,j}\eta_{i,t,j}\right)^{-1},$$

where $V_{\boldsymbol{\beta}_{k,lj}}$ denotes the l-th row and j-th column of $\boldsymbol{V}_{\boldsymbol{\beta_k}}$ and $\circ$ is the Hadamard product. $\eta_{i,t,l}$, $\eta_{i,t,j}$, $u_{k,i,t,l}$ and $u_{k,i,t,j}$ are the error terms of equation (3) and (4) at horizon $l = 1, ..., H$ and $j = 1, ..., H$, and n_l and n_j are the number of observations, and q_l and q_j are the number of regressors used in these regressions.

Appendix D All data sources and transformations

Variable	Source	Frequency	Conversion and use	Sample
Explicit and implicit carbon tax revenue; LCU	see Table 2	annual	Converted to monthly explicit, implicit and effective carbon tax rates.	DK: 1990M01-2019M12 FI: 2004M01-2019M12 NO: 1995M01-2019M12 SE: 1993M01-2019M12
Coverage-unadjusted real explicit carbon tax rate	World Bank (2021)	annual	Converted to local currencies with nominal exchange rates. Deflated with CPI.	All: 1990M01-2019M12
(Consumer) Pump price for gasoline (95 Octane) including taxes	Drivkraft Danmark, Statistics Finland, Statistics Norway, Macrobond	monthly	Seasonally adjusted with X11-X13 method in JDemetra+. Deflated with CPI.	All: 1990M01-2019M12
Greenhouse gas emissions without LULUCF	UNFCCC Annex I	annual	Temporally disaggregated to monthly levels with Chow-Lin method.	All: 1990M01-2019M12
Consumer price index for all items, 2015=100	OECD - Main Economic Indicators	monthly	Seasonally adjusted with X11-X13 method in JDemetra+.	All: 1990M01-2019M12
GDP (output based) and gross value added by various sectors (NACE Level 1 classification); LCU; current prices; seasonally and calendar adjusted	Eurostat	quarterly	Temporally disaggregated to monthly levels with Chow-Lin method.	DK: 1995M01-2019M12 FI: 1990M01-2019M12 NO: 1990M01-2019M12 SE: 1993M01-2019M12
GDP deflator; 2015=100; LCU; seasonally and calendar adjusted	Eurostat	quarterly	Used to deflate GDP and gross value added before the temporal disaggregation.	DK: 1995M01-2019M12 FI and NO: 1990M01-2019M12 SE: 1993M01-2019M12
Unemployment rate; all persons; seasonally adjusted	OECD - Key Short Term Economic Indicators	monthly	-	All: 1990M01-2019M12
Interbank interest rate yield, 3-month maturity	OECD - Key Short Term Economic Indicators	monthly	Missing value for Sweden in 2001M11 was replaced with previous month's value.	All: 1990M01-2019M12
Real effective exchange rate index, 2015=100	OECD - Main Economic Indicators	monthly	-	All: 1990M01-2019M12

Table 8: Data description of variables used in the main analysis.

Variable	Source	Frequency	Conversion and use	Sample
Nominal exchange rates	Eurostat, Bank for International Settlements	monthly	Used to rescale or convert monetary variables to other currencies.	All: 1990M01-2019M12
Settlement price of futures on carbon price from EU ETS, in Euro	Datastream (Ticker: LEXC.01), same as in Känzig (2021)	monthly	Price before implementation of EU ETS is set to zero. Converted to local currencies.	All: 2005M04-2019M12
Real electricity tax rates in LCU	Statistics Denmark, Finish Tax Administration, Statistics Norway, Statistics Sweden, Eurostat	annual	Electricity tax revenues are divided by electricity consumption to obtain average electricity tax rates paid. Deflated and disaggregated to monthly data in the same way as effective carbon tax rates using the timing feature.	DK: 1990M01-2019M12 FI: 2004M01-2019M12 NO: 1995M01-2019M12 SE: 1993M01-2019M12
Commodity terms of trade net export price index	Gruss and Kebhaj (2019)	monthly	-	All: 1990M01-2019M12
Industrial production (excluding construction), 2015=100, seasonally adjusted	OECD - Main Economic Indicators	monthly	Used as indicator to temporally disaggregate GDP, GVA and GHG emissions with the Chow-Lin method.	All: 1990M01-2019M12
Share price index, 2015=100	OECD - Monthly Monetary and Financial Statistics (MEI)	monthly	Deflated with CPI.	All: 1990M01-2019M12
Total tax revenue as a share of GDP, in percent	OECD - Revenue Statistics OECD countries	annual	Disaggregated to monthly data in the same way as effective carbon tax rates assuming the same timing feature.	All: 1990-2019
Greenhouse gas emissions by sector (NACE Level 1 classification)	Eurostat	annual	Average across sample used in Table 1.	All: 2008-2018
Gross value added by sector (NACE Level 1 classification); current prices	Eurostat	annual	Average across sample used in Table 1.	All: 2008-2018

Table 9: Data description of variables used in robustness checks, in tables and for the construction of other variables.

Appendix E Plots of variables

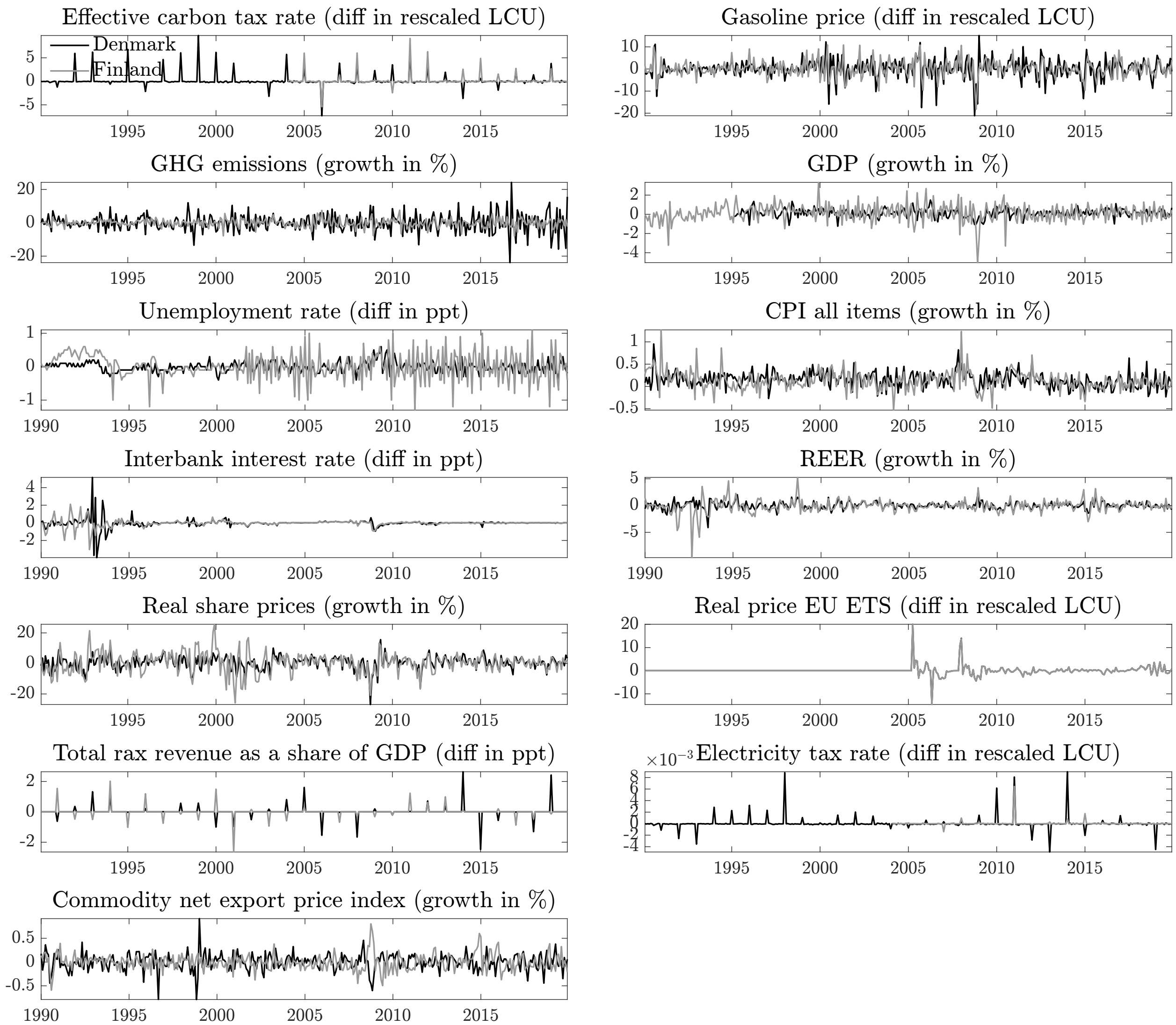

Figure 9: Plots displaying the employed variables for Denmark and Finland.

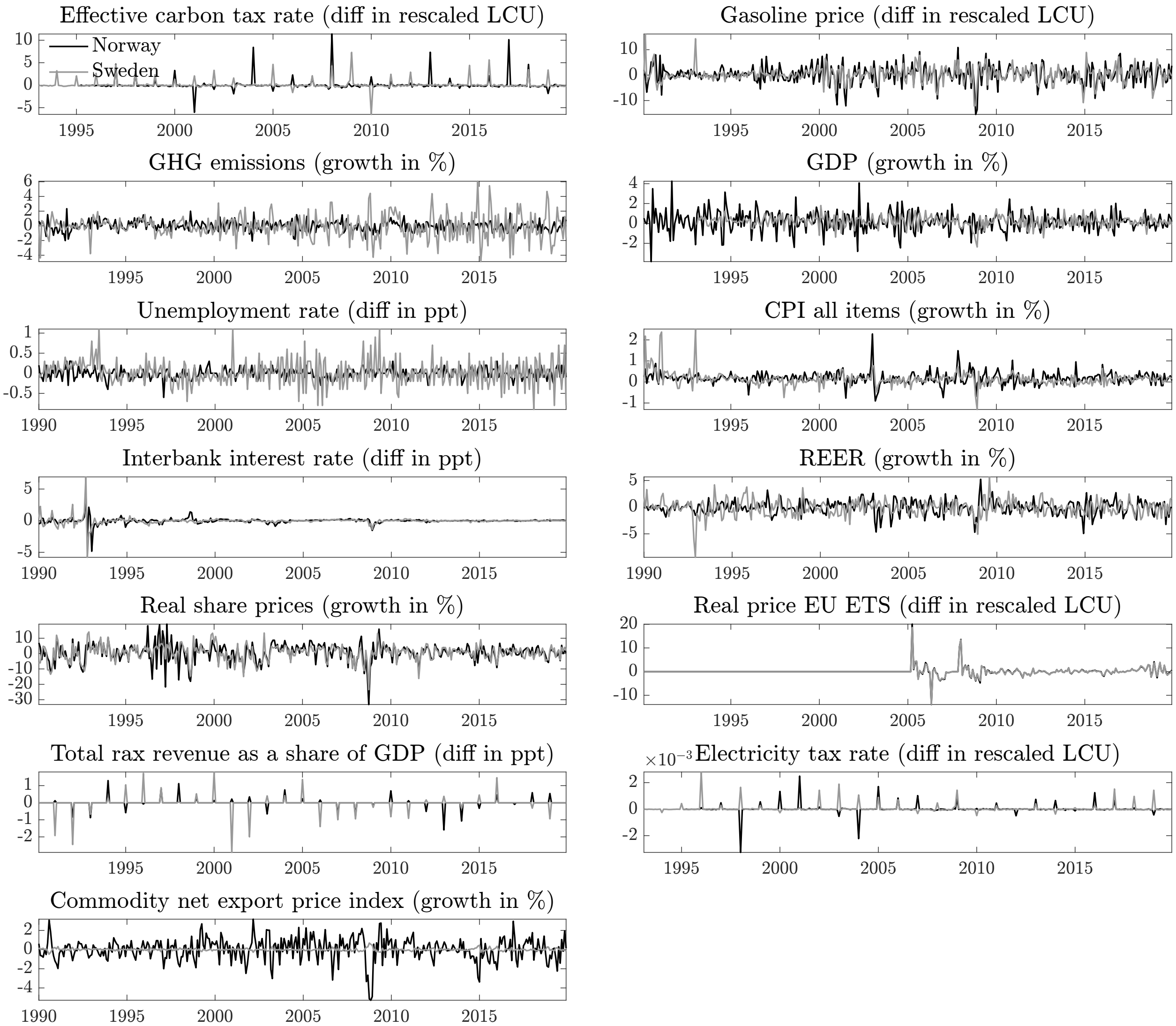

Figure 10: Plots displaying the employed variables for Norway and Sweden.

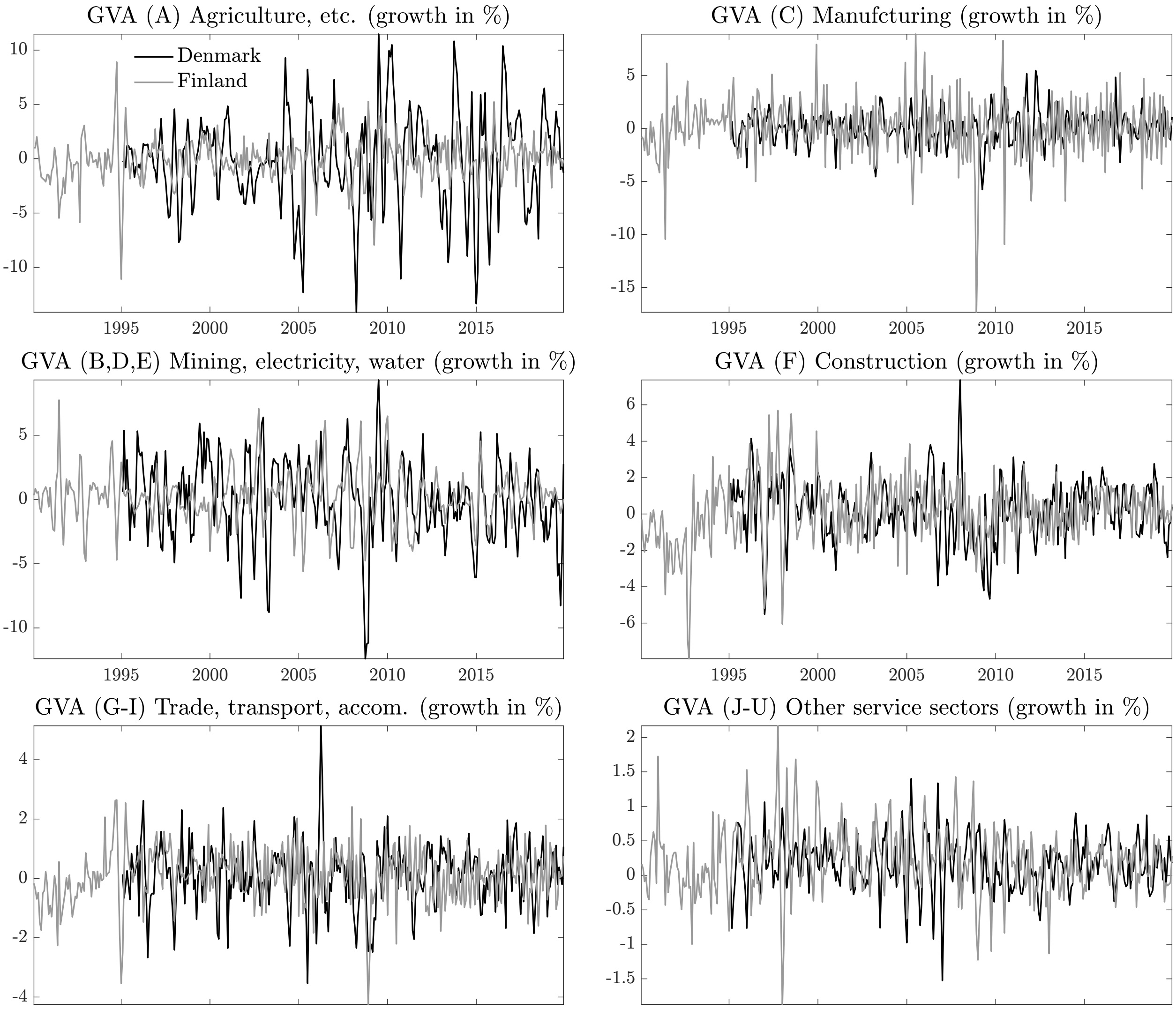

Figure 11: Plots displaying gross value added (GVA) for various sectors in Denmark and Finland.

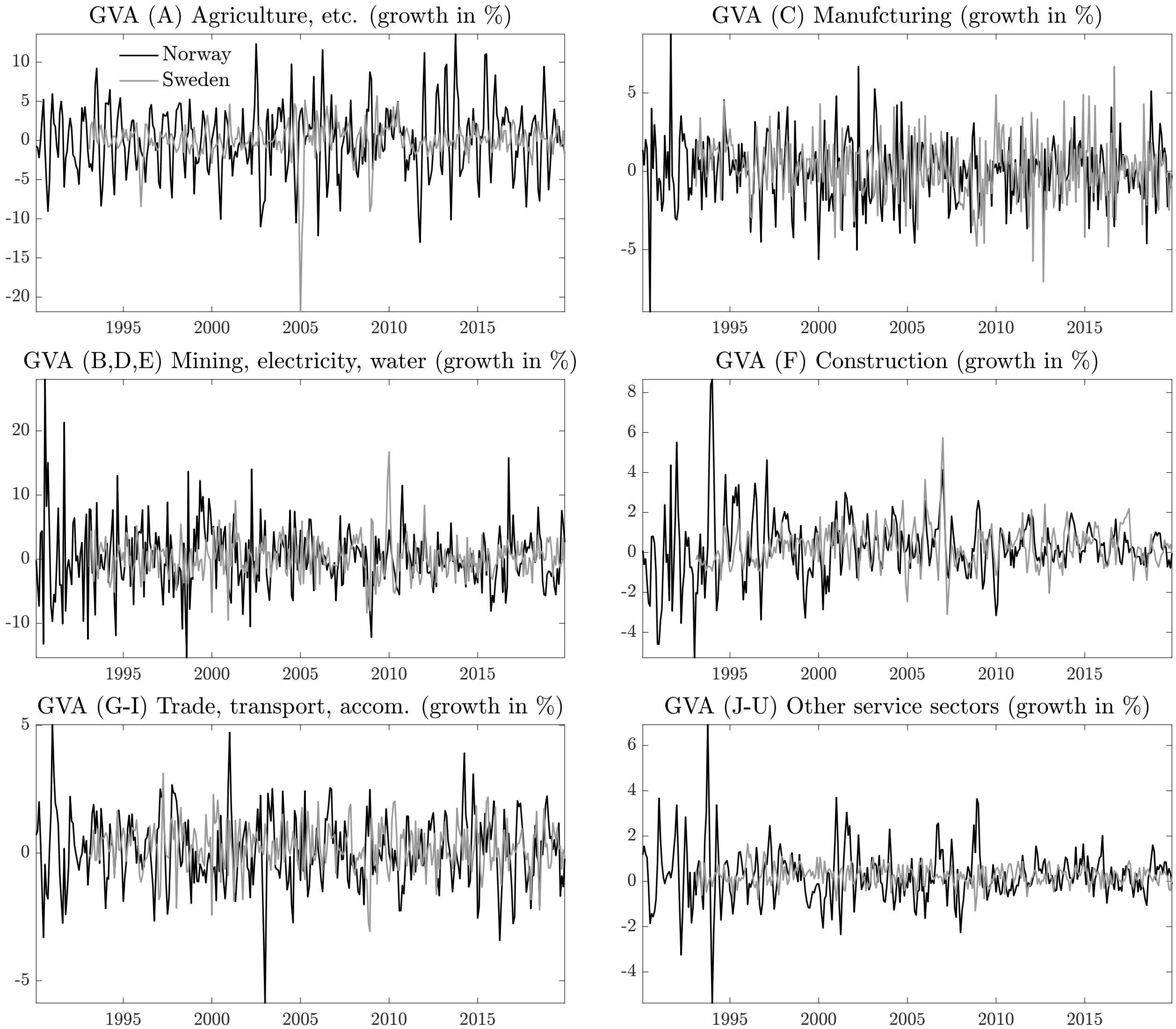

Figure 12: Plots displaying gross value added (GVA) for various sectors in Norway and Sweden.

Appendix F GVA and GHG emissions by sector

	Denmark		Finland		Norway		Sweden	
Sector	**GVA**	**GHG**	**GVA**	**GHG**	**GVA**	**GHG**	**GVA**	**GHG**
(A) Agriculture, forestry and fishing	3,1	12,6	4,8	8,3	5,3	5,4	6,3	9,2
(B) Mining and quarrying	5,4	1,9	0,7	0,4	67,7	16,3	2,2	1,0
(C) Manufacturing	31,6	5,9	32,2	14,3	23,7	12,5	58	15,7
(D) Electricity, gas, steam	3,5	14,8	3,9	19,5	6,9	1,9	9,9	7,7
(E) Water supply and waste	1,8	2,4	1,6	2,8	1,9	1,8	2,4	2,0
(F) Construction	11,5	1,5	12,1	1,4	18,5	1,9	22,8	2,0
(G) Wholesale, retail and repair	29,2	1,2	16,9	0,6	23,9	1,1	40,3	1,8
(H) Transportation and storage	12,4	42,6	8,8	10,4	16,6	20,4	20,3	9,7
(I) Accommodation, food service	3,5	0,2	3,0	0,2	4,2	0,1	6,1	0,1
(J) Information, communication	10,5	0,1	9,6	0,0	12,4	0,0	27,6	0,1
(K) Finance and insurance act.	13,6	0,1	5,5	0,2	14,5	0,0	16,2	0,1
(L) Real estate act.	23,1	0,1	21,3	0,1	22,3	0,1	31,8	0,2
(M) Prof., scientific and techn. act.	13,0	0,2	8,8	0,0	13,8	0,0	27,6	0,5
(N) Admin. and support serv. act.	6,7	0,2	5,9	0,3	8,3	0,0	12,8	0,5
(O) Public admin., social security	12,2	0,4	10,7	0,5	19,0	0,4	18,2	0,4
(P) Education	14,5	0,1	9,8	0,1	15,4	0,0	20,5	0,1
(Q) Human health, social work act.	24,7	0,2	16,9	0,2	31,6	0,1	40,0	0,5
(R) Arts, entertainment, recreation	3,5	0,1	2,3	0,1	3,0	0,0	4,9	0,2
(S) Other service activities	3,5	0,1	3,0	0,1	3,0	0,4	5,9	0,1
(T) Act. of households as employers	0,6	0,0	0,3	0,0	0,0	0,0	0,2	0,0
(U) Extraterritorial organisations	0,0	0,0	N/A	0,0	0,0	0,0	0,0	0,0
Total	227,8	84,8	178,3	59,7	312,1	62,6	373,9	51,7

Table 10: Averages of GHG emissions in million tCO_2e and gross value added (GVA) in billion Euro in various sectors across the years 2008 to 2018. GVA is defined as output minus intermediate consumption. Data source: Eurostat.

Appendix G Additional Results

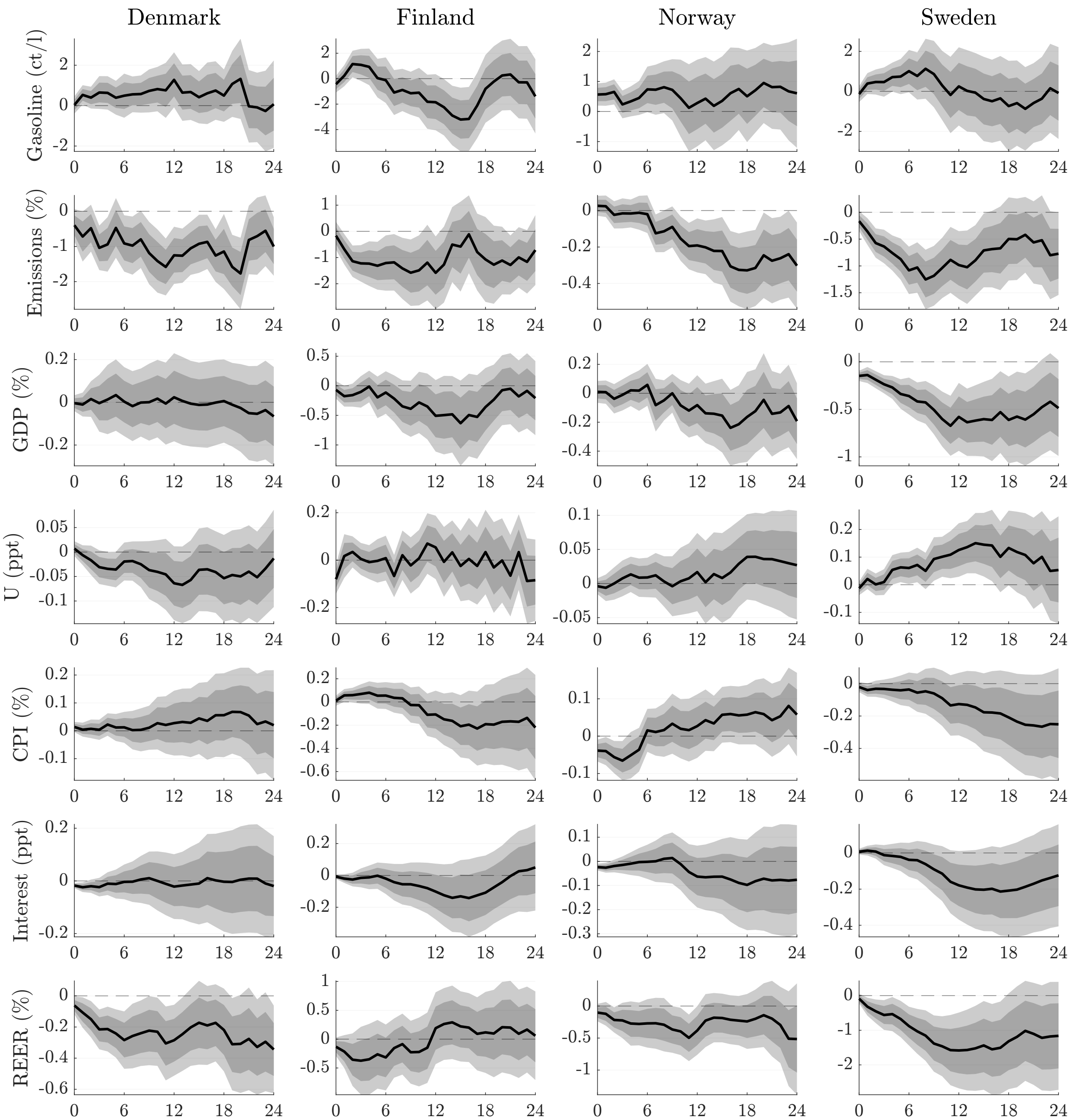

Figure 13: Cumulated impulse responses of gasoline prices, emissions and macroeconomic indicators (by row) in the 24 months after an increase in the effective carbon tax rate by one Euro in the Nordics. The dark and light grey areas indicate the 68% and 90% confidence bands.

Appendix H Robustness tests

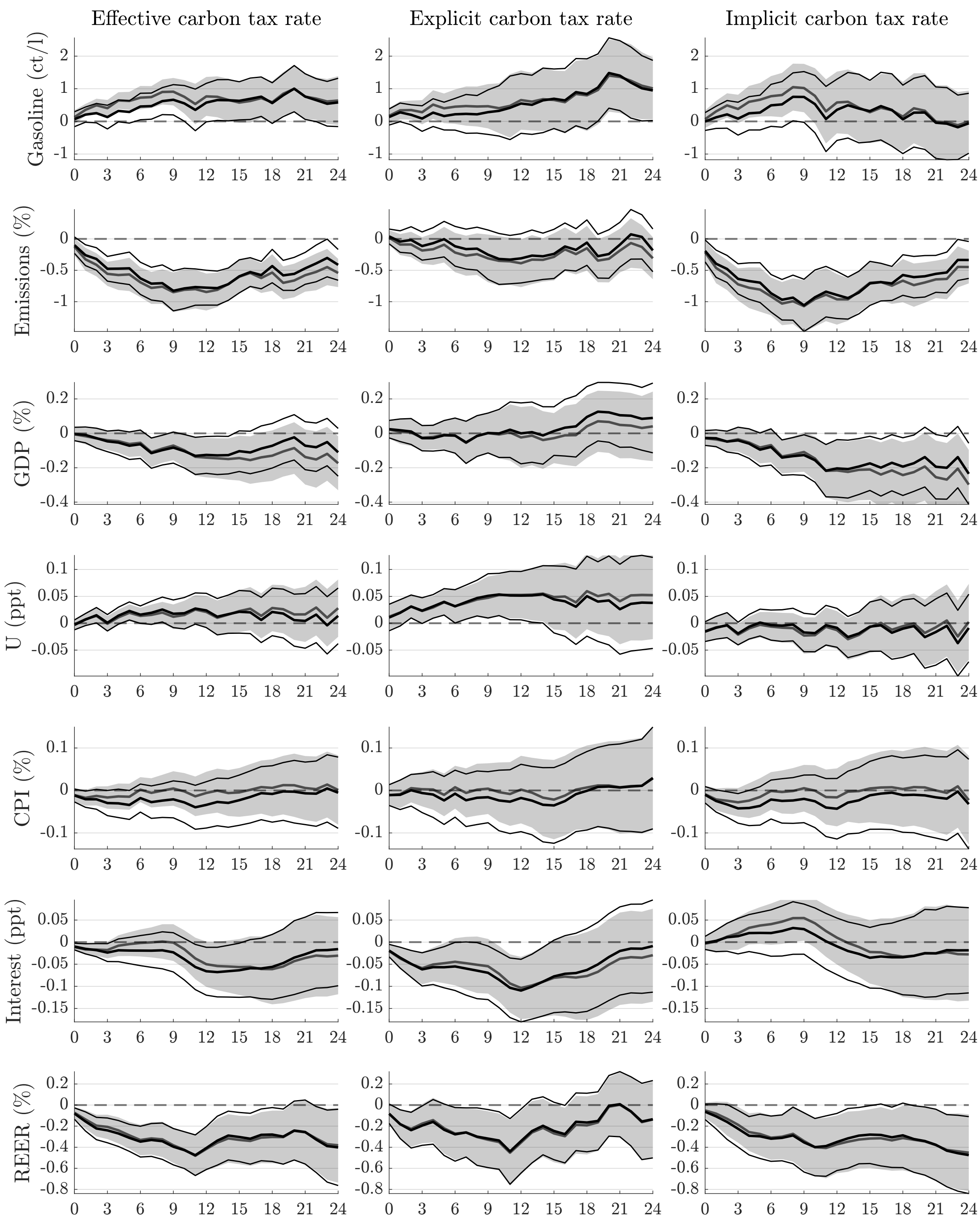

Figure 14: Results from section 4.1 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with the emission permit price of the European Union Emissions Trading System (thick black line, area between thin black lines indicates 90% confidence interval).

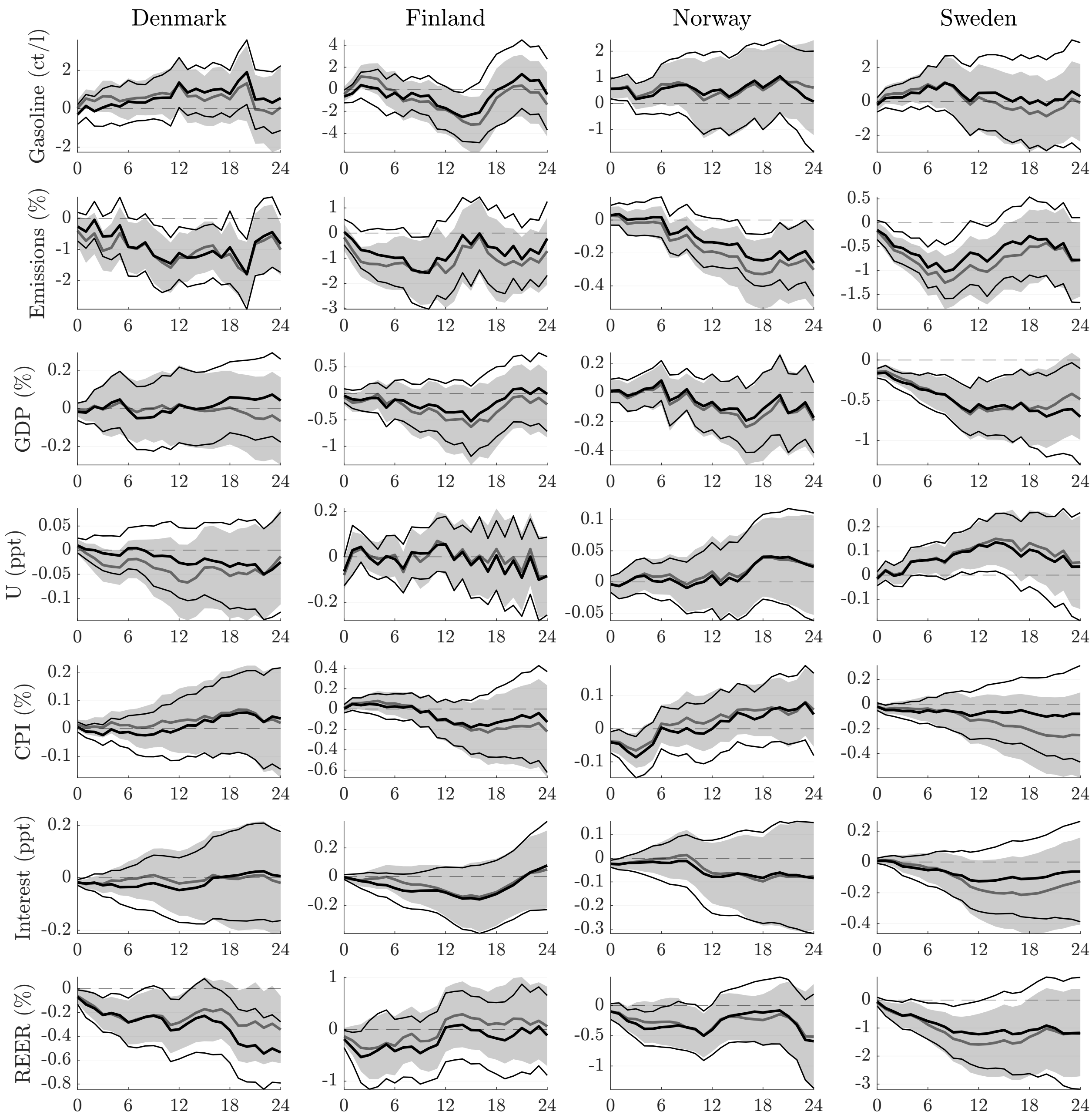

Figure 15: Results from section 4.2 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with the emission permit price of the European Union Emissions Trading System (thick black line, area between thin black lines indicates 90% confidence interval).

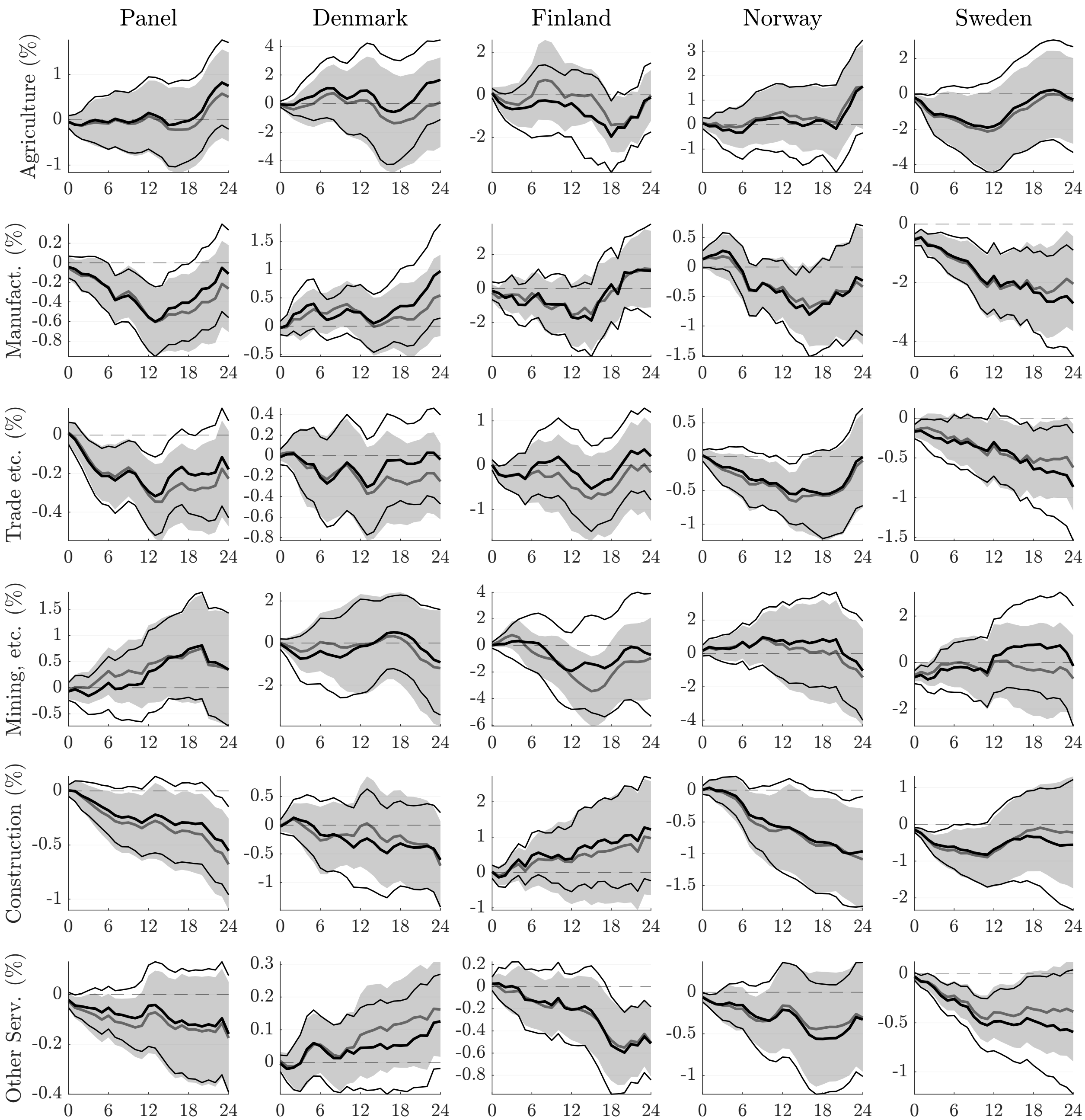

Figure 16: Results from section 4.3 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with the emission permit price of the European Union Emissions Trading System (thick black line, area between thin black lines indicates 90% confidence interval).

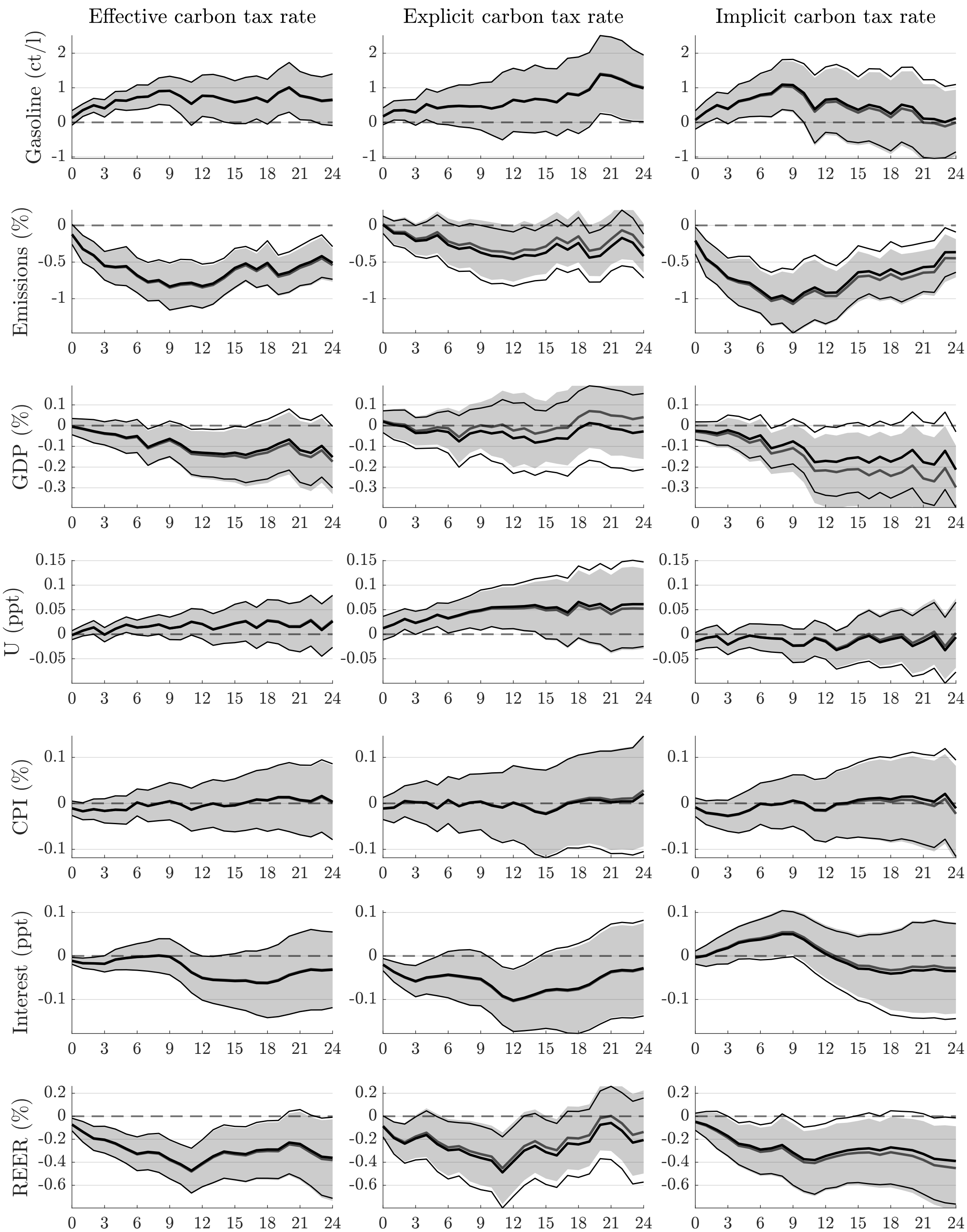

Figure 17: Results from section 4.1 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with a dummy for the European Union Emissions Trading System from 2005-2019 (thick black line, area between thin black lines indicates 90% confidence interval).

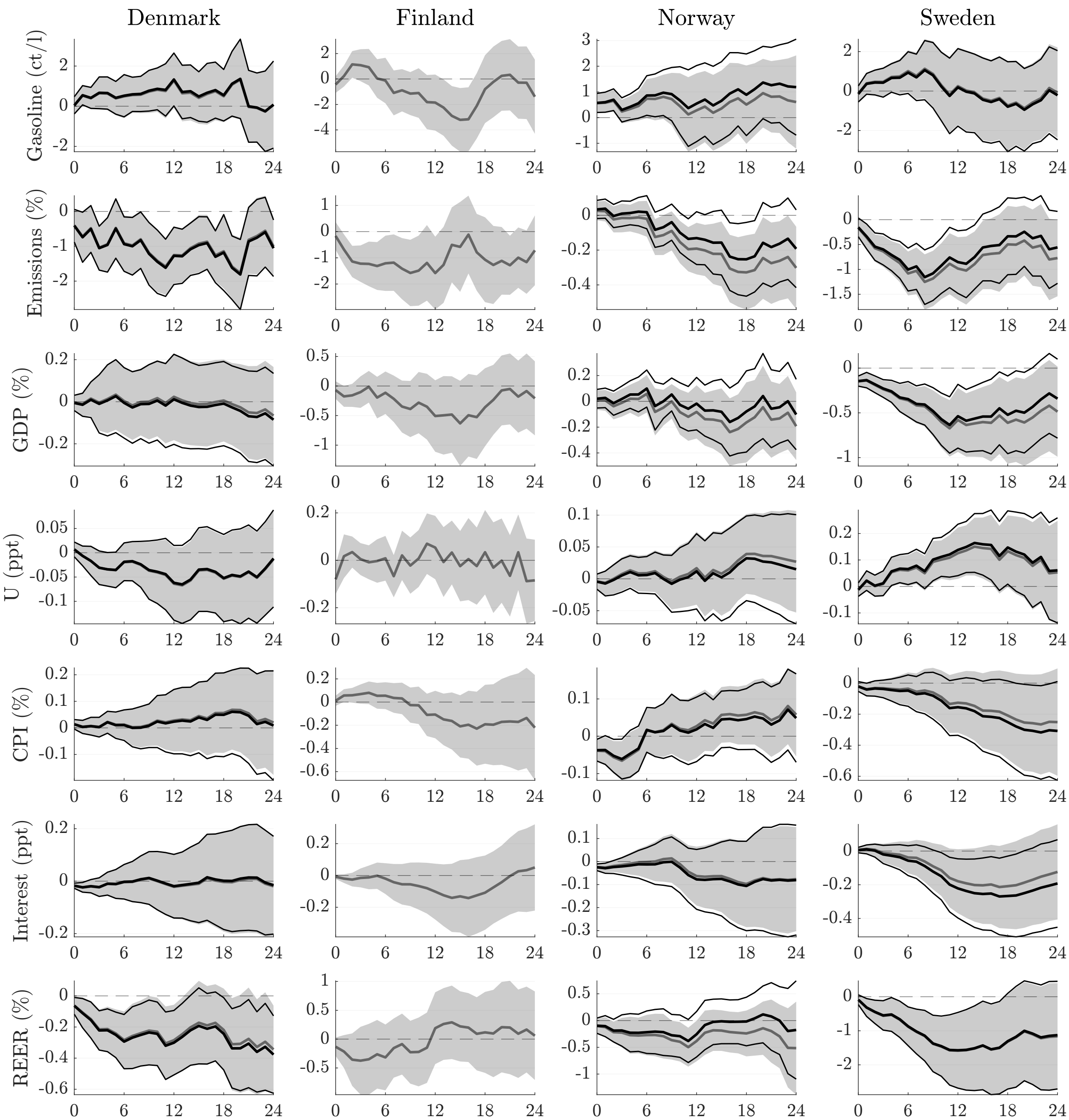

Figure 18: Results from section 4.2 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with a dummy for the European Union Emissions Trading System from 2005-2019 (thick black line, area between thin black lines indicates 90% confidence interval). Note that robustness checks for Finland cannot be conducted as its effective sample only starts in 2005.

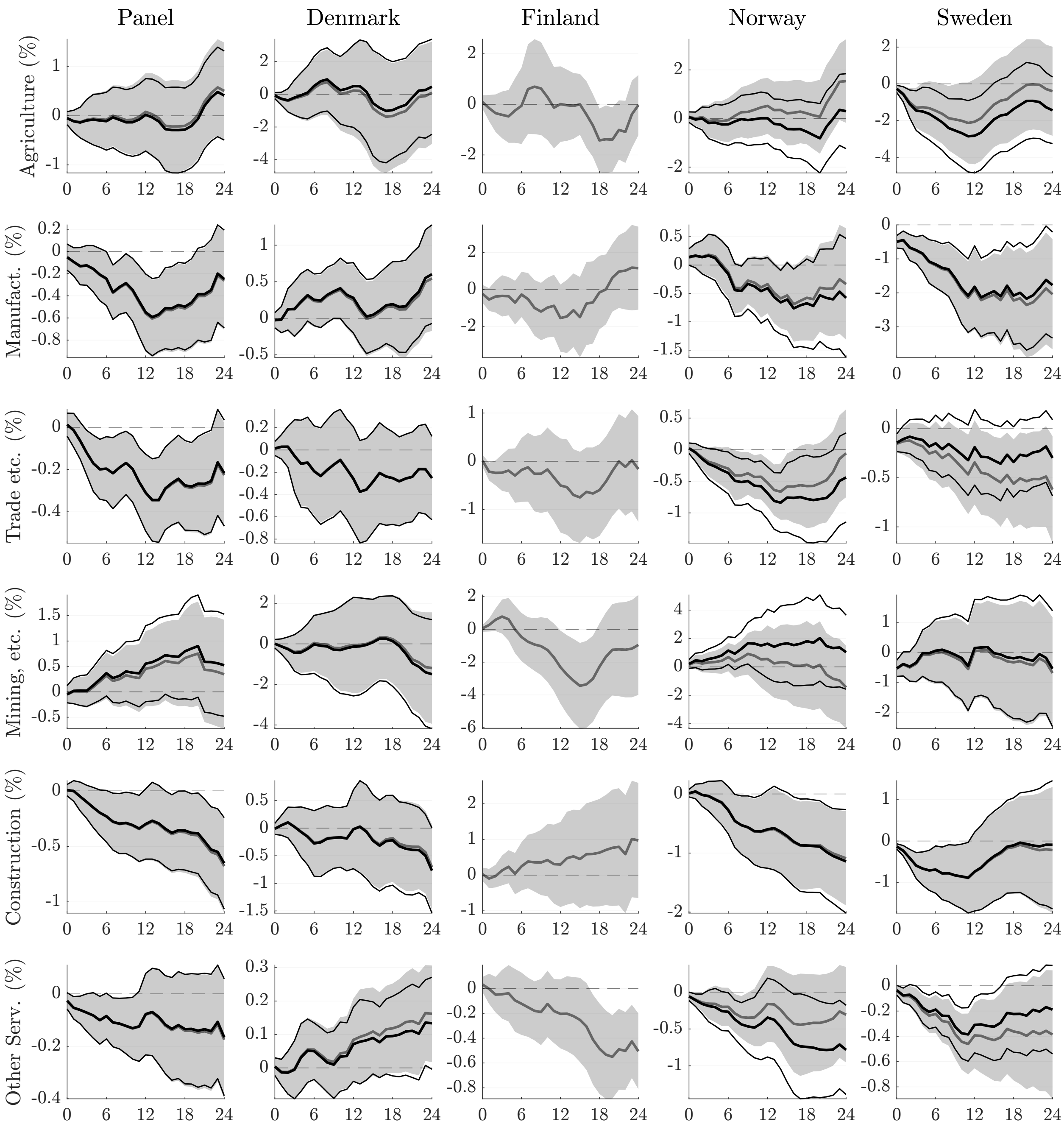

Figure 19: Results from section 4.3 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with a dummy for the European Union Emissions Trading System from 2005-2019 (thick black line, area between thin black lines indicates 90% confidence interval). Note that robustness checks for Finland cannot be conducted as its effective sample only starts in 2005.

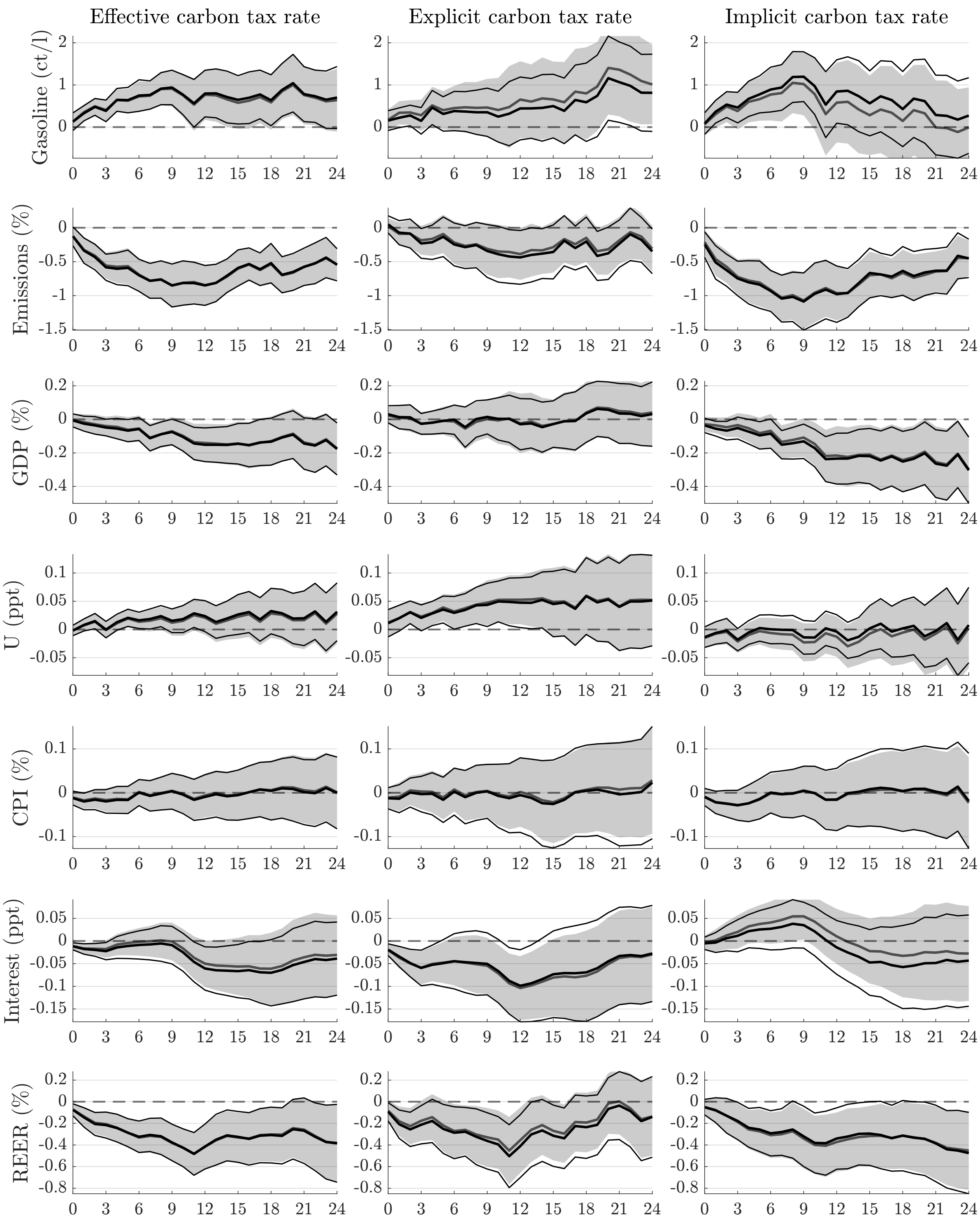

Figure 20: Checking the results from section 4.1 (dark grey line, shaded area indicates 90% confidence interval) for the anticipation of carbon tax rate changes by adding the real log of the stock price index as additional variable in the system ordered above the tax rate (thick black line, area between thin black lines indicates 90% confidence interval).

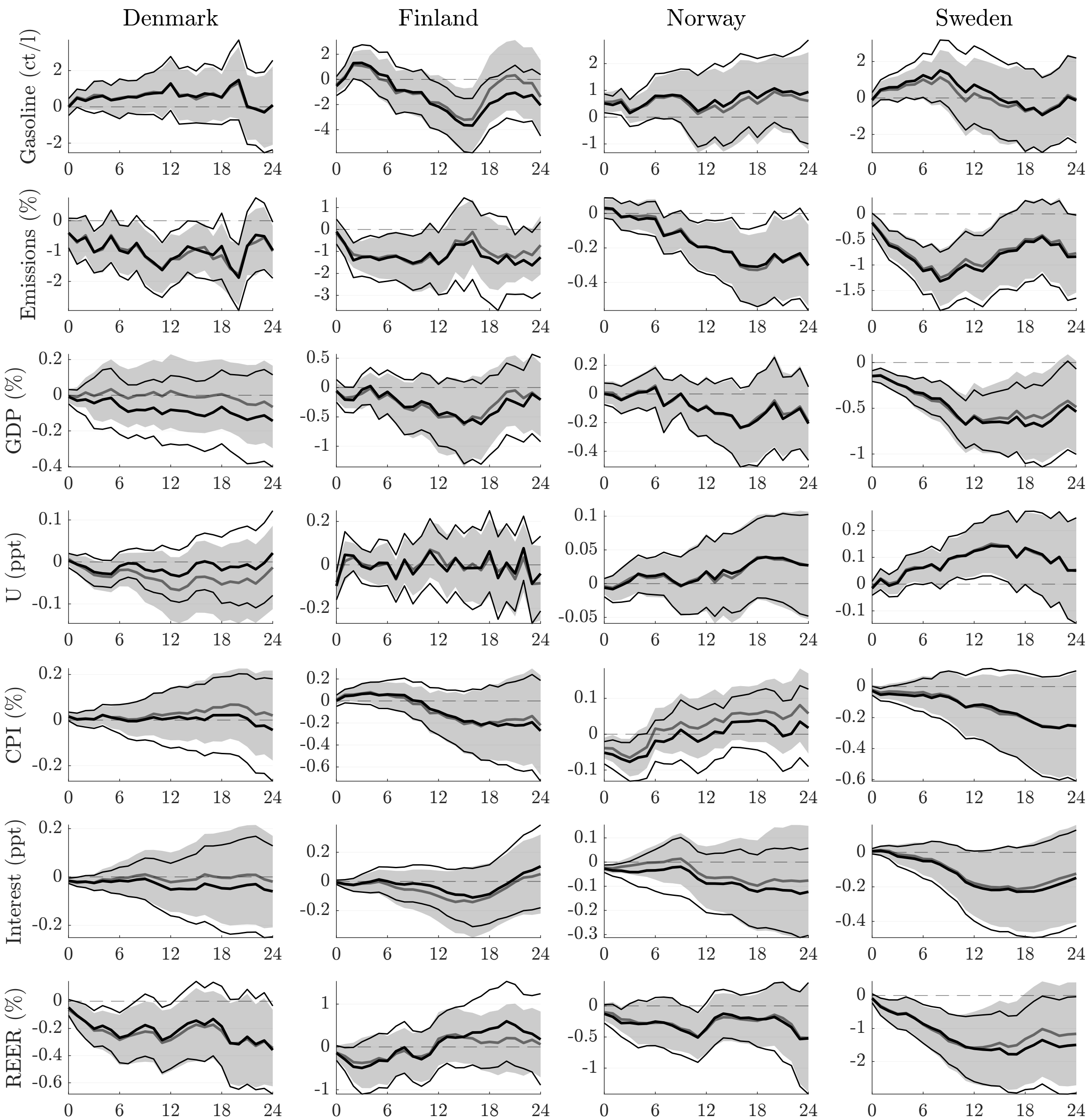

Figure 21: Checking the results from section 4.2 (dark grey line, shaded area indicates 90% confidence interval) for the anticipation of carbon tax rate changes by adding the log of stock price index as additional variable in the system ordered above the tax rate (thick black line, area between thin black lines indicates 90% confidence interval).

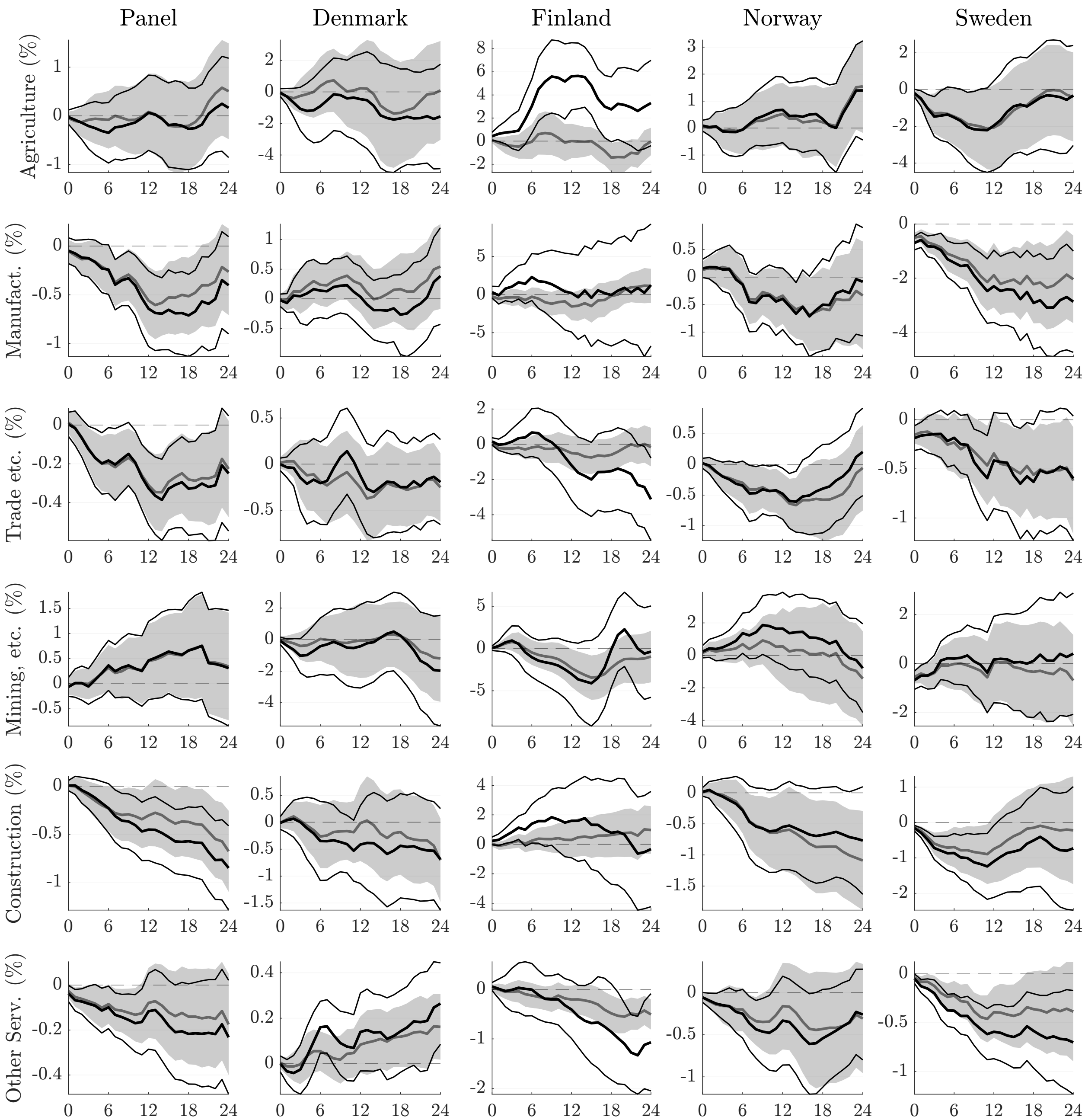

Figure 22: Checking the results from section 4.3 (dark grey line, shaded area indicates 90% confidence interval) for the anticipation of carbon tax rate changes by adding the log of stock price index as additional variable in the system ordered above the tax rate (thick black line, area between thin black lines indicates 90% confidence interval).

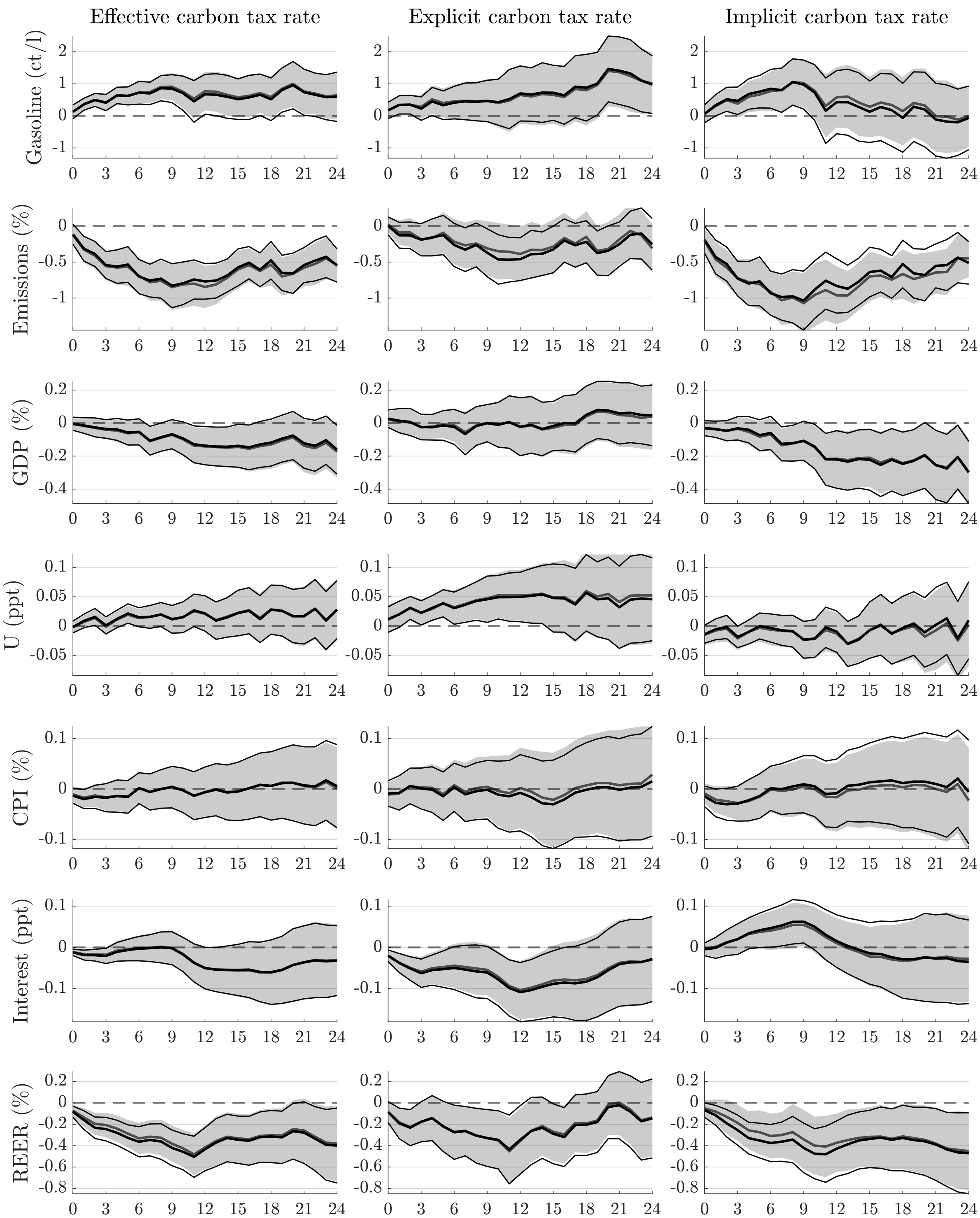

Figure 23: Results from section 4.1 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with the total tax revenue as a share of GDP (thick black line, area between thin black lines indicates 90% confidence interval).

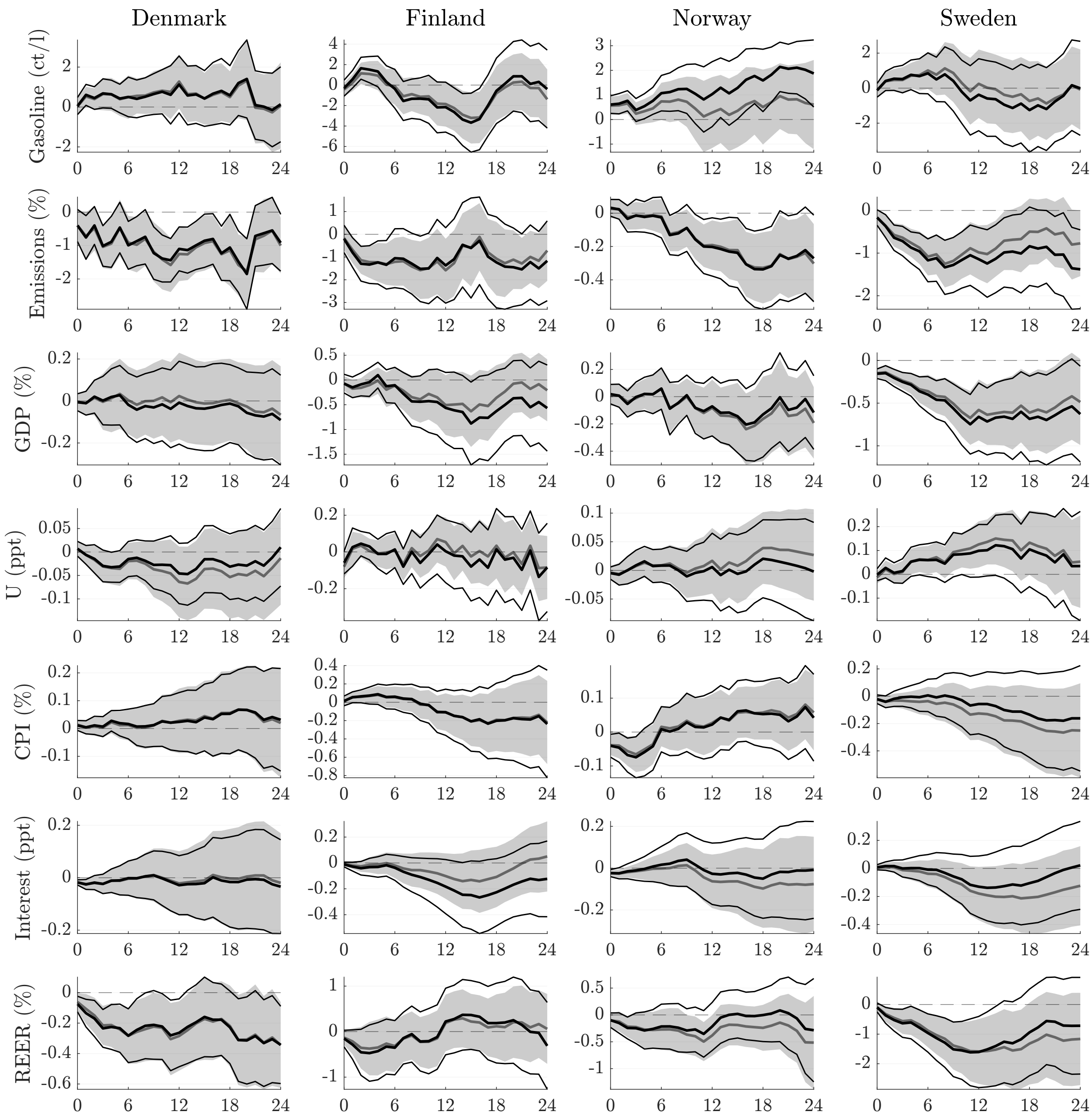

Figure 24: Results from section 4.2 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with the total tax revenue as a share of GDP (thick black line, area between thin black lines indicates 90% confidence interval).

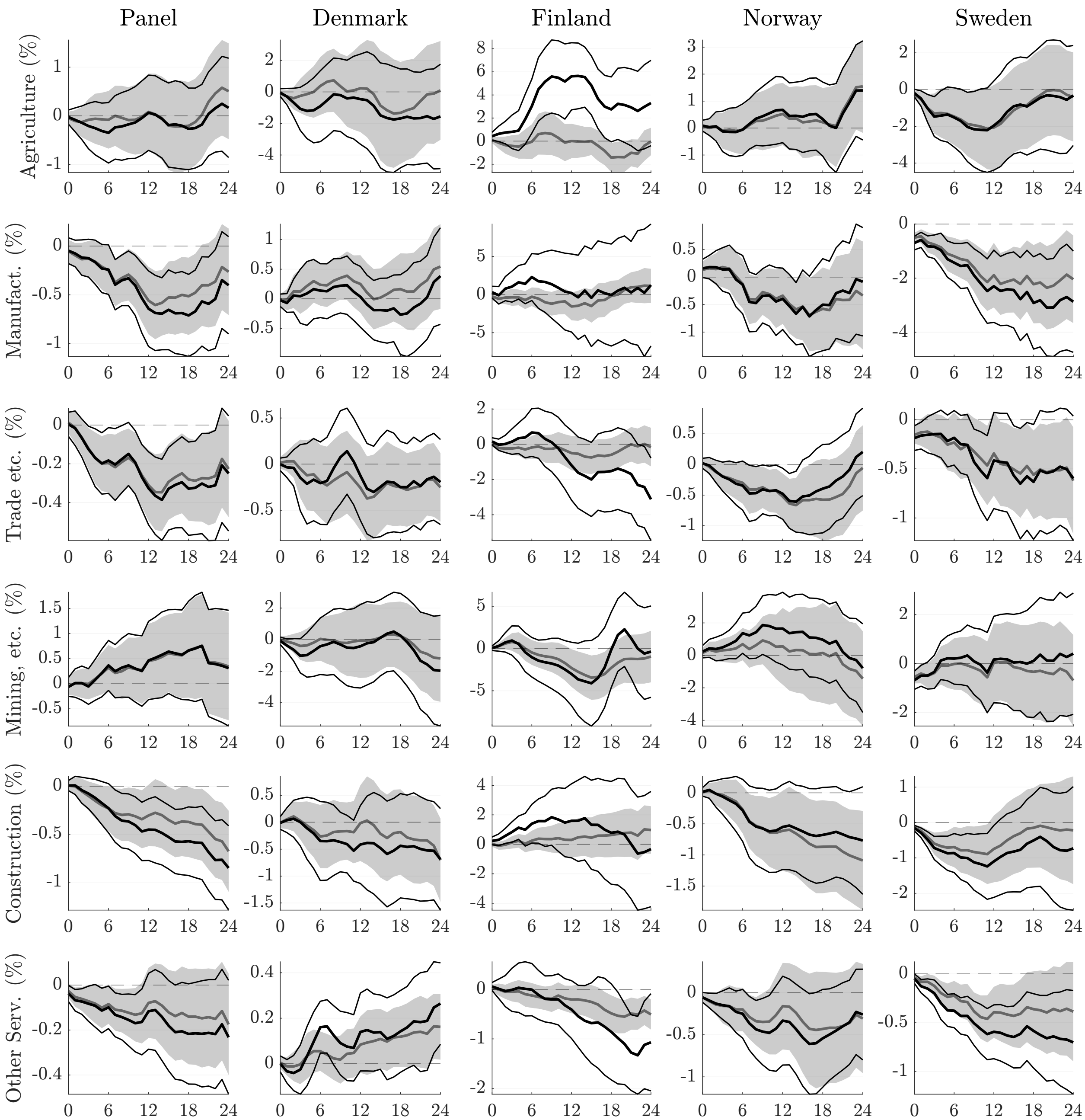

Figure 25: Results from section 4.3 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with the total tax revenue as a share of GDP (thick black line, area between thin black lines indicates 90% confidence interval).

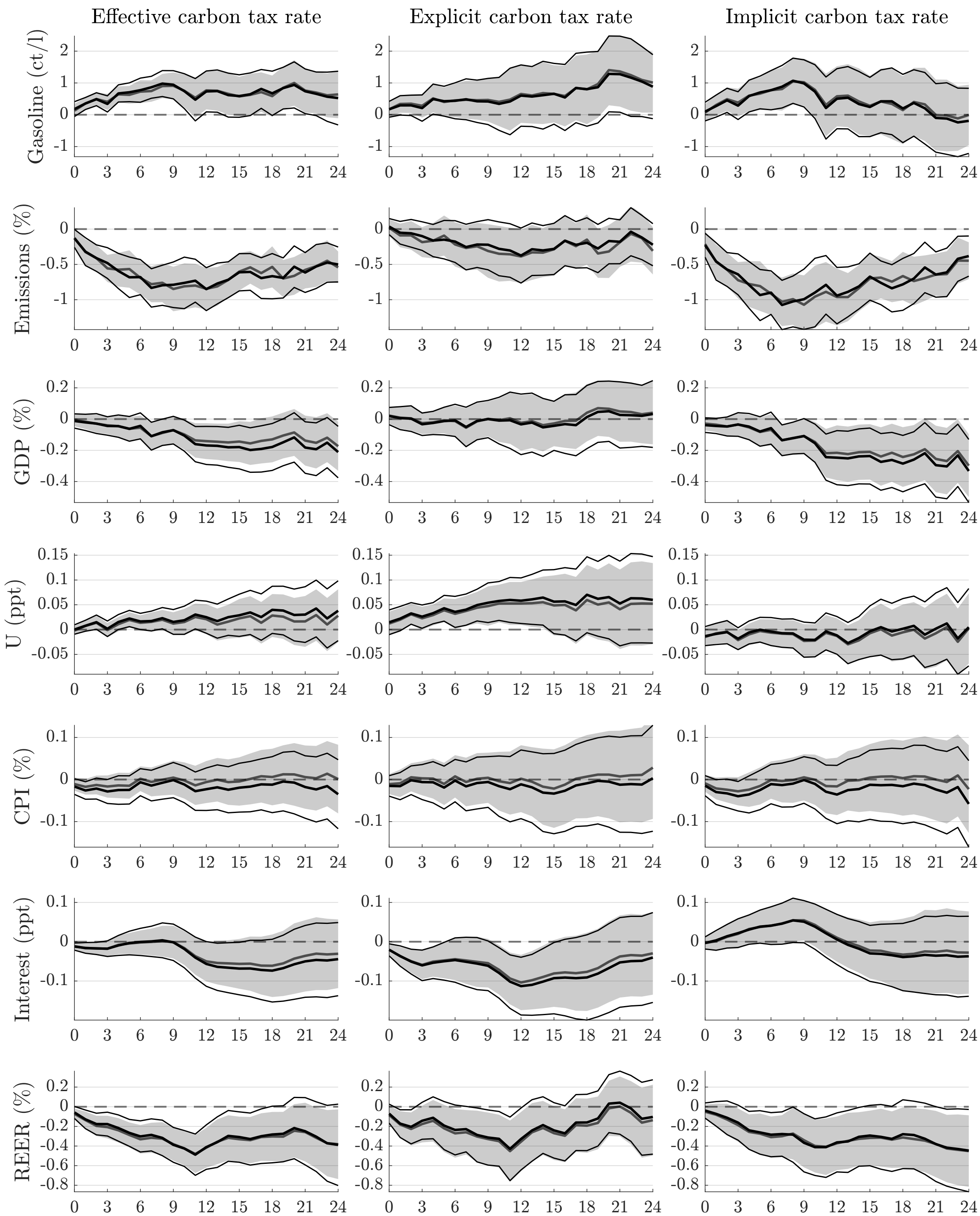

Figure 26: Results from section 4.1 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with average tax rates on electricity (thick black line, area between thin black lines indicates 90% confidence interval).

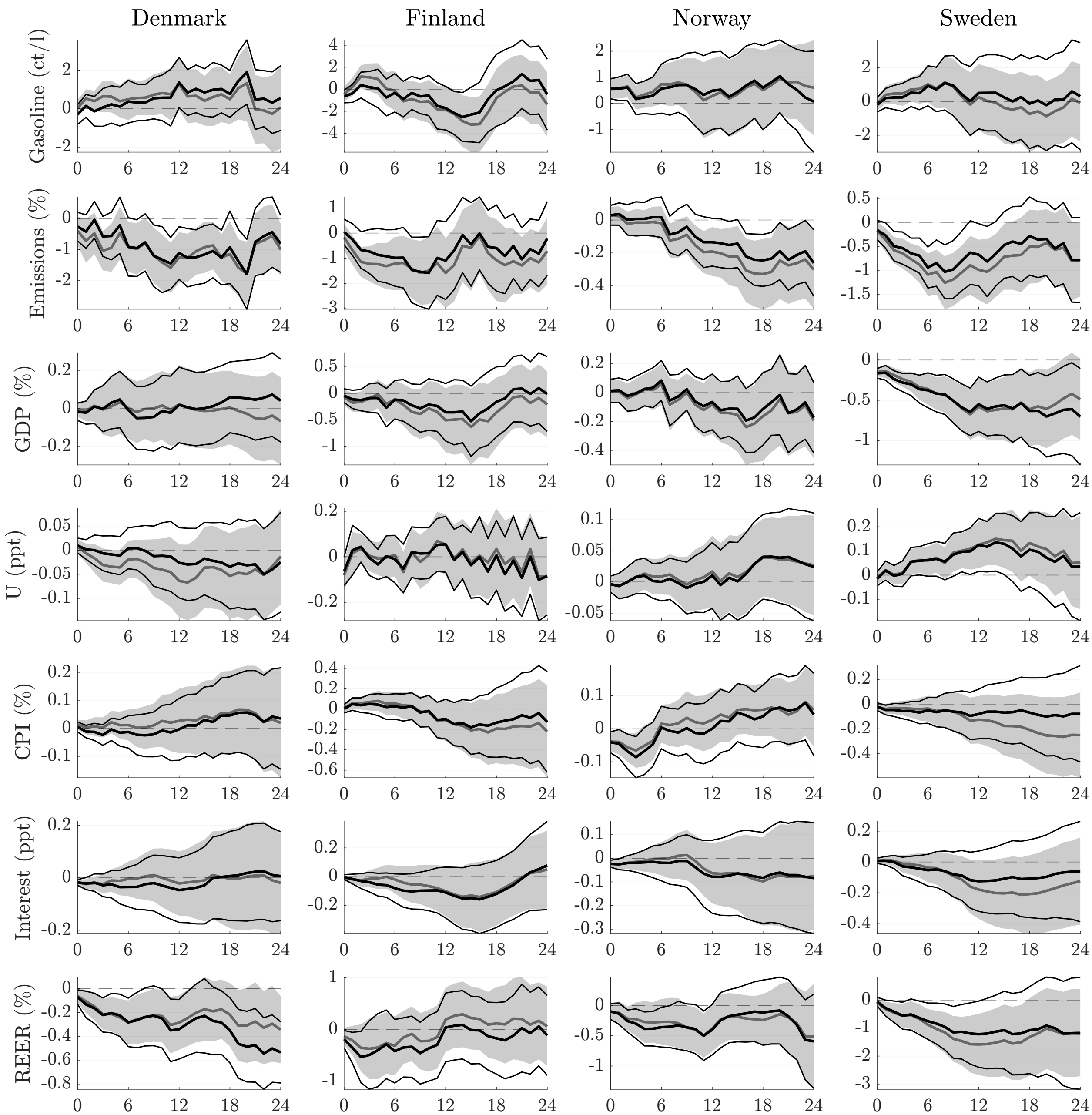

Figure 27: Results from section 4.2 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with average tax rates on electricity (thick black line, area between thin black lines indicates 90% confidence interval).

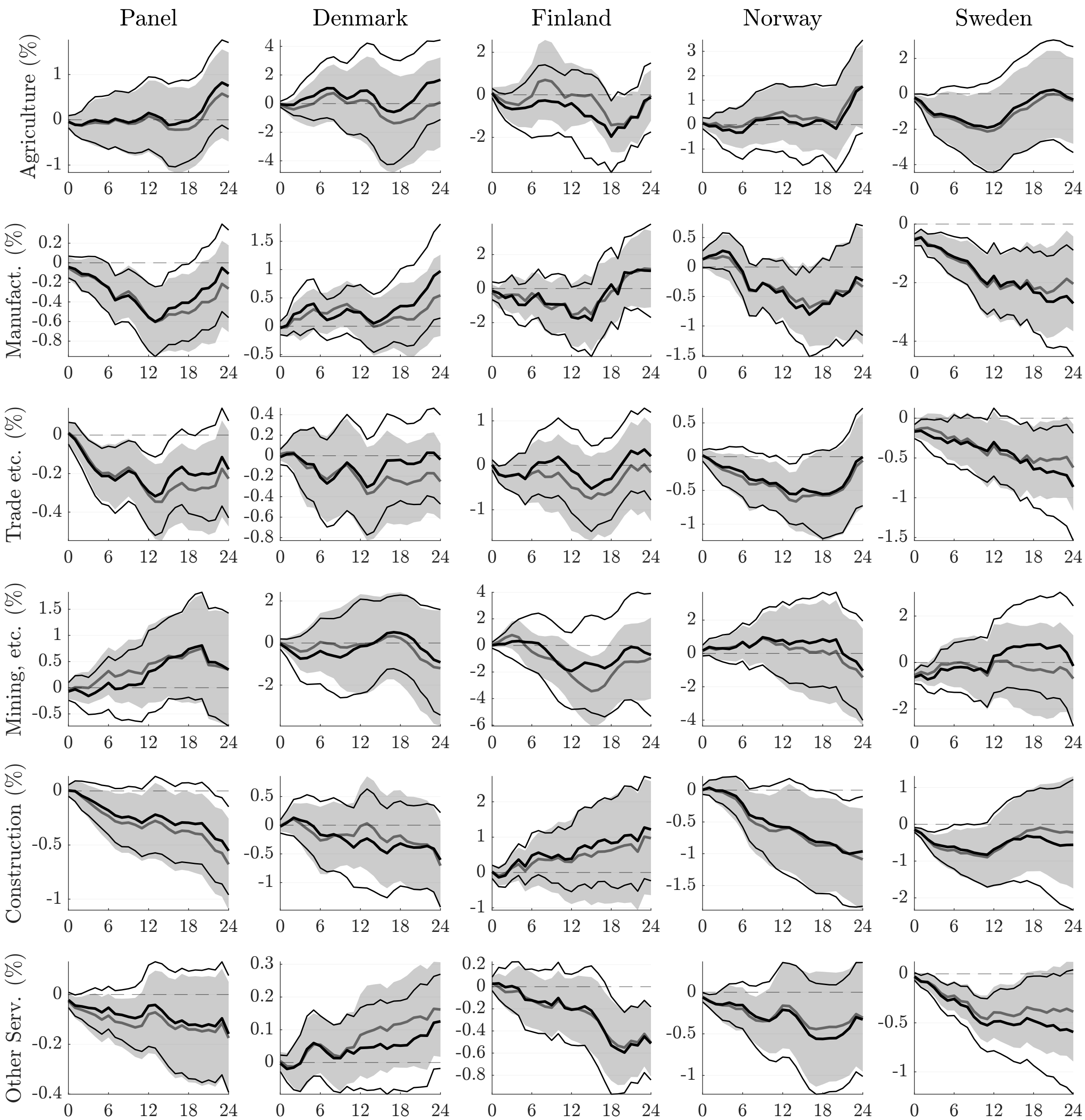

Figure 28: Results from section 4.3 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with average tax rates on electricity (thick black line, area between thin black lines indicates 90% confidence interval).

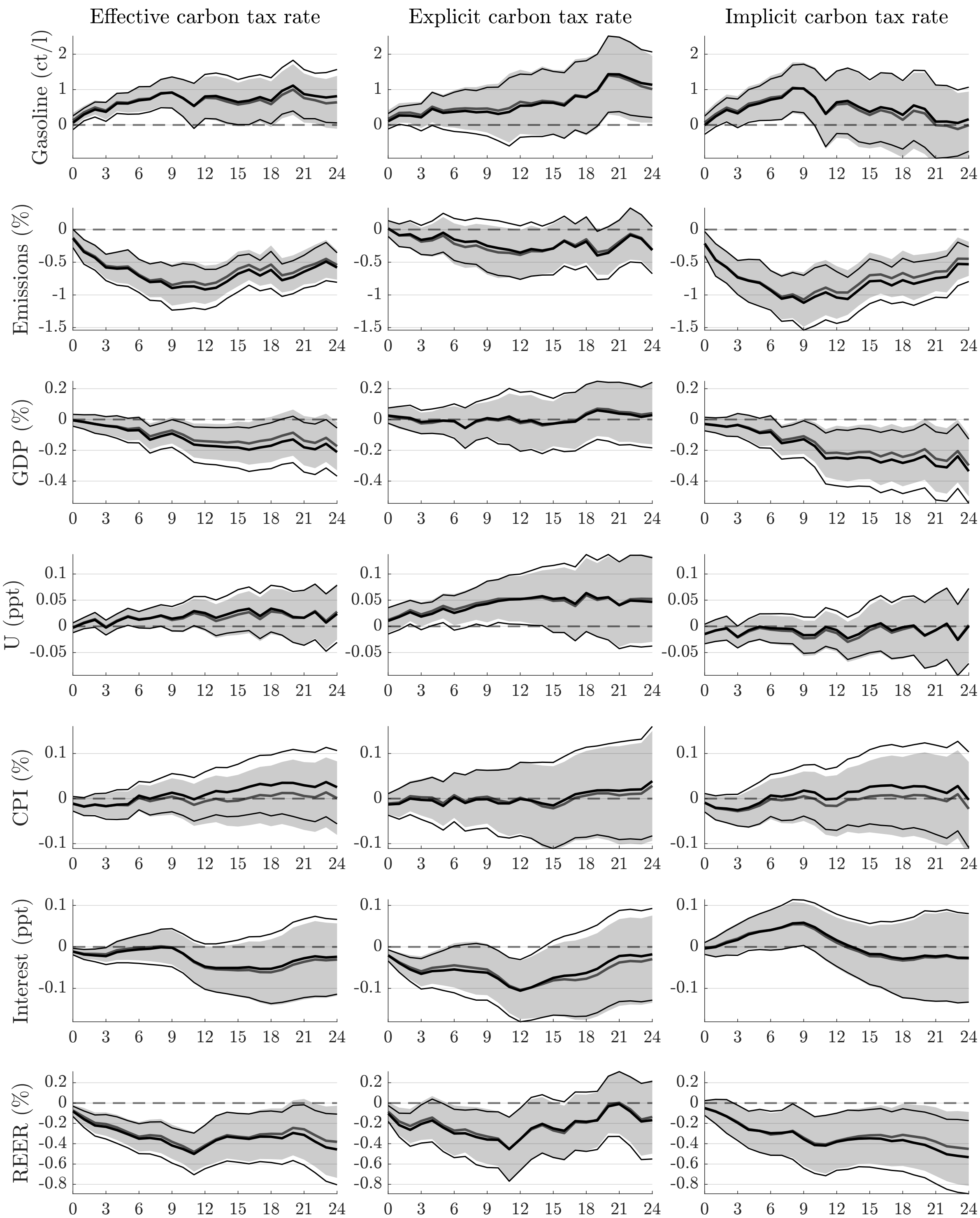

Figure 29: Results from section 4.1 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with the commodity terms of trade net export price index (thick black line, area between thin black lines indicates 90% confidence interval).

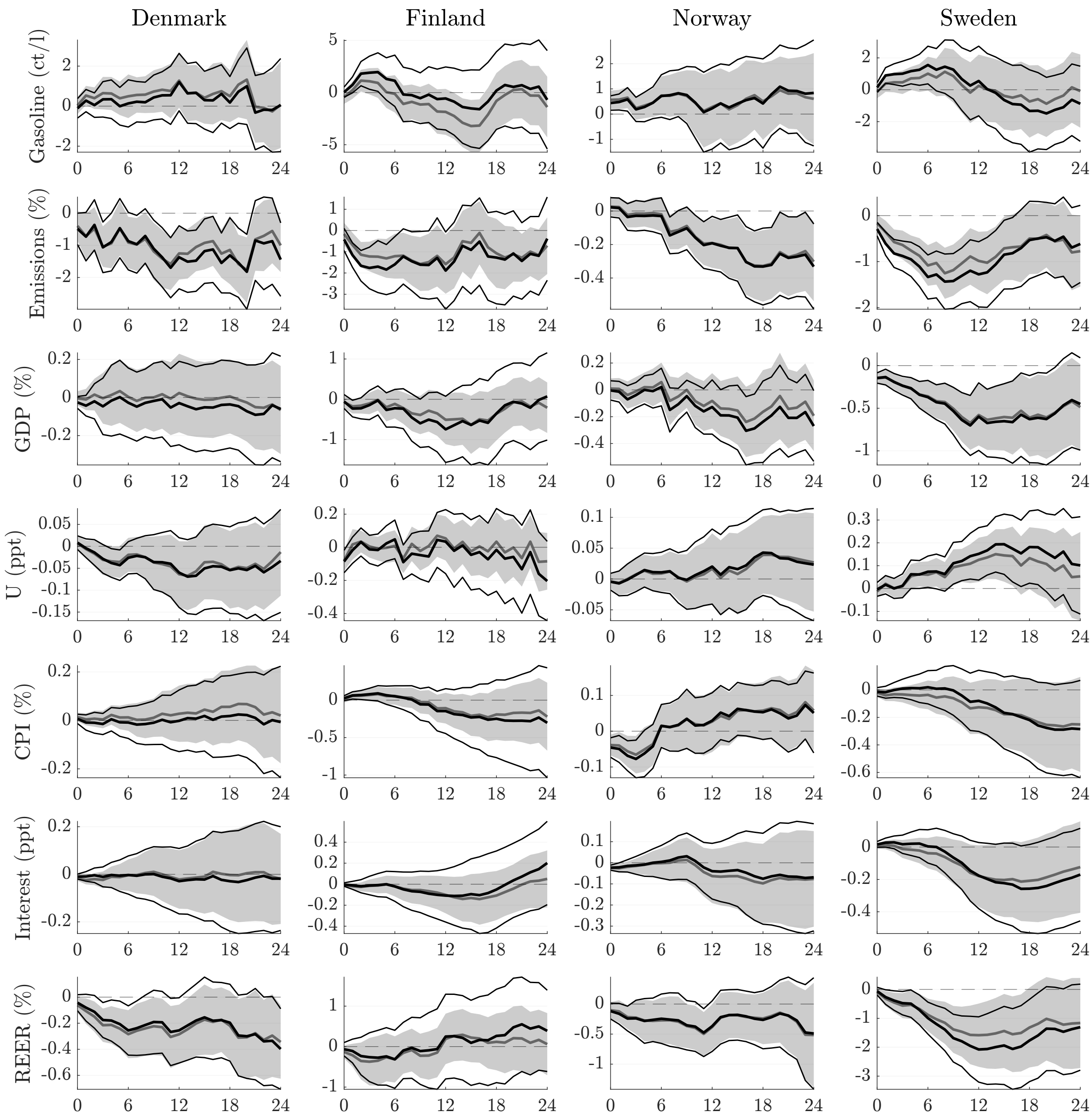

Figure 30: Results from section 4.2 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with the commodity terms of trade net export price index (thick black line, area between thin black lines indicates 90% confidence interval).

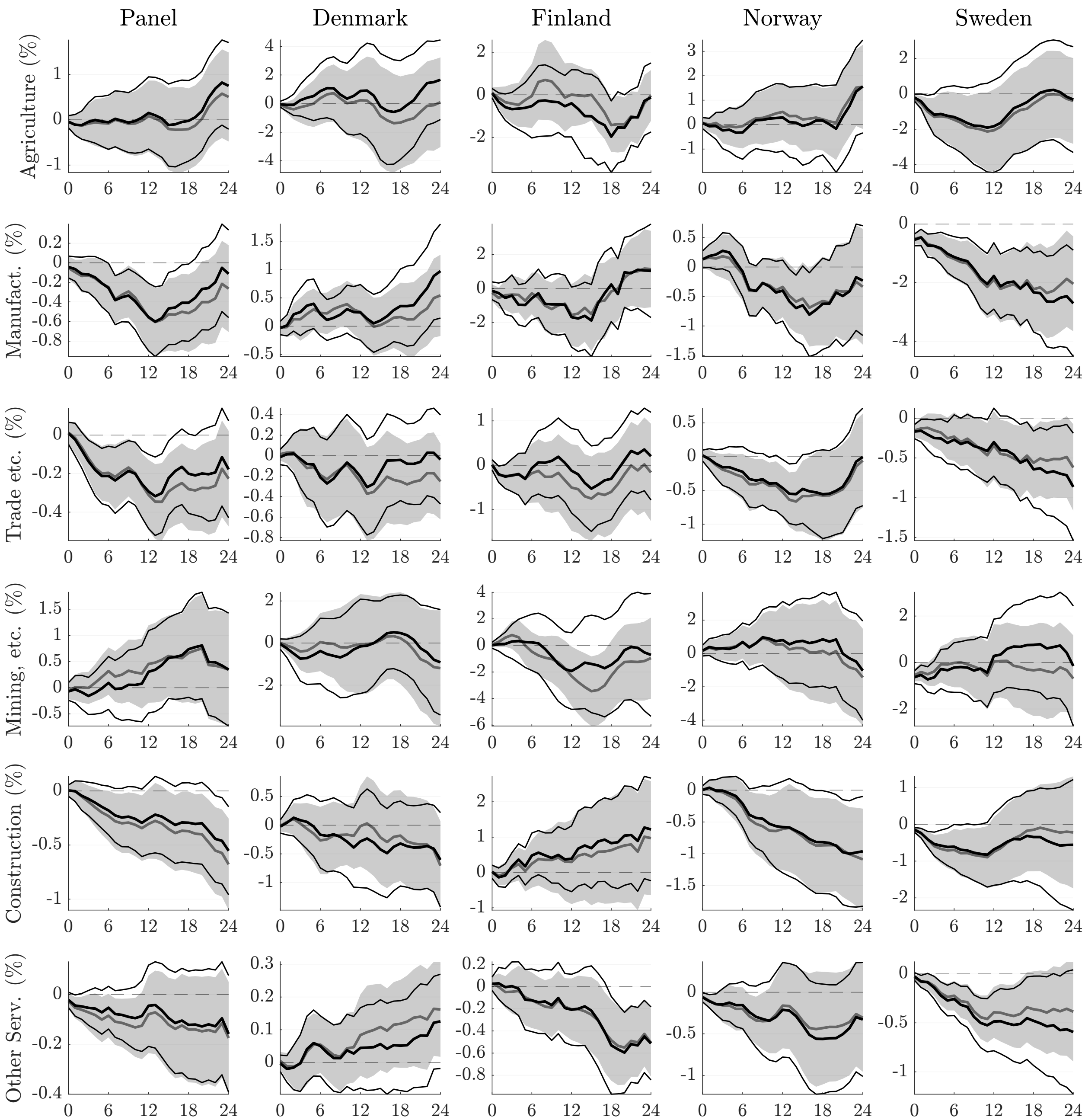

Figure 31: Results from section 4.3 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with the commodity terms of trade net export price index (thick black line, area between thin black lines indicates 90% confidence interval).

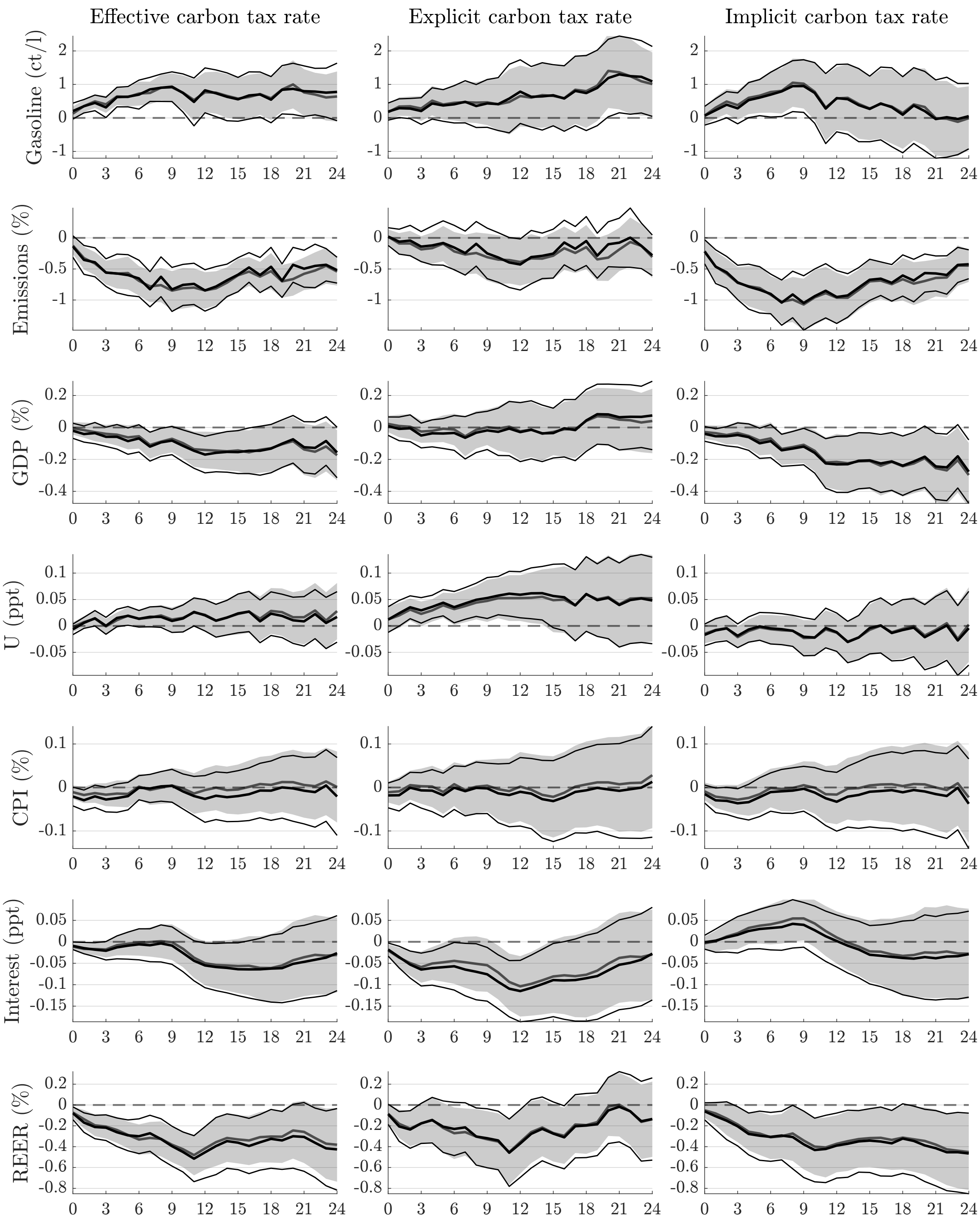

Figure 32: Results from section 4.1 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with monthly dummies to check for seasonality (thick black line, area between thin black lines indicates 90% confidence interval).

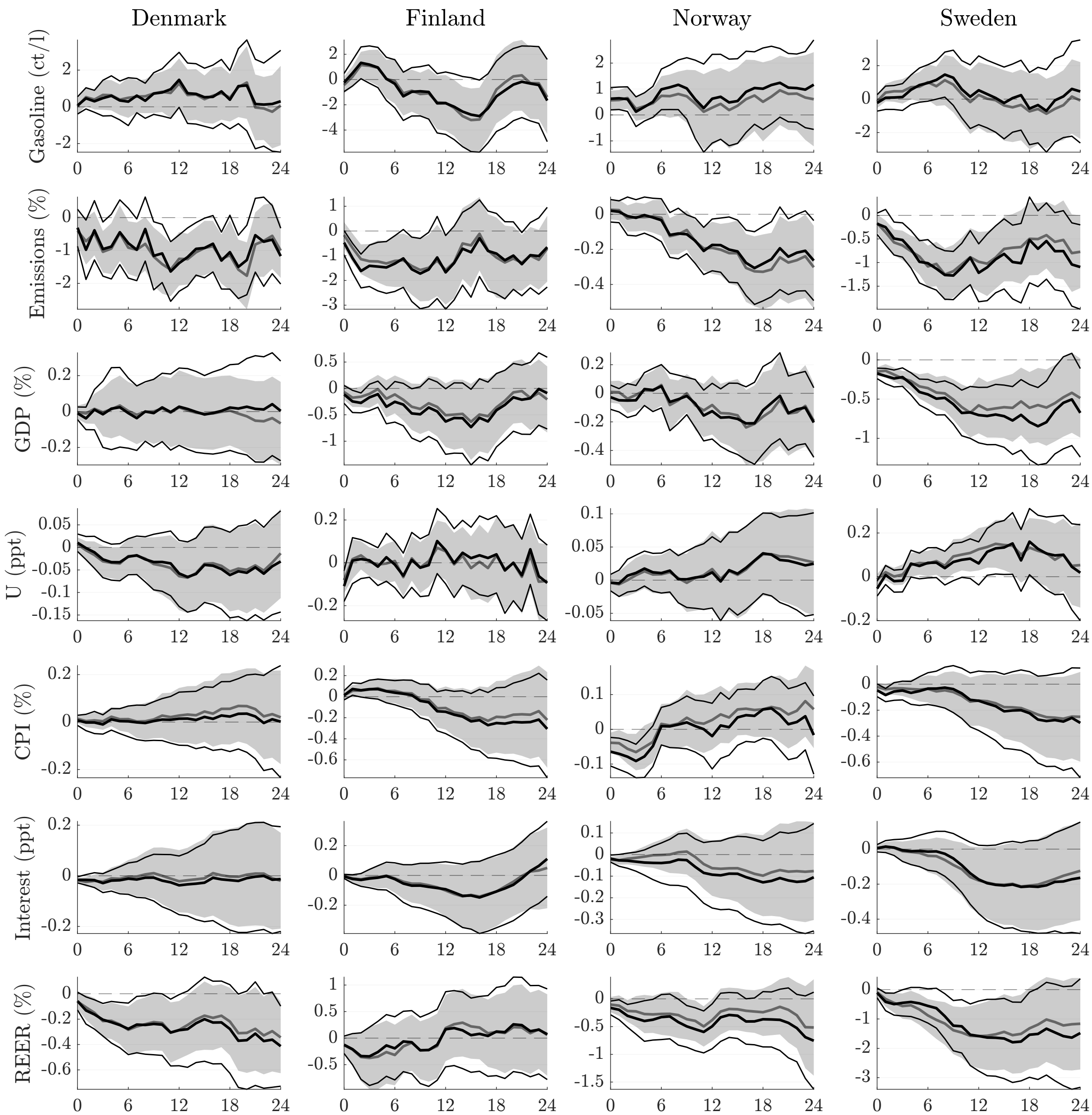

Figure 33: Results from section 4.2 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with monthly dummies to check for seasonality (thick black line, area between thin black lines indicates 90% confidence interval).

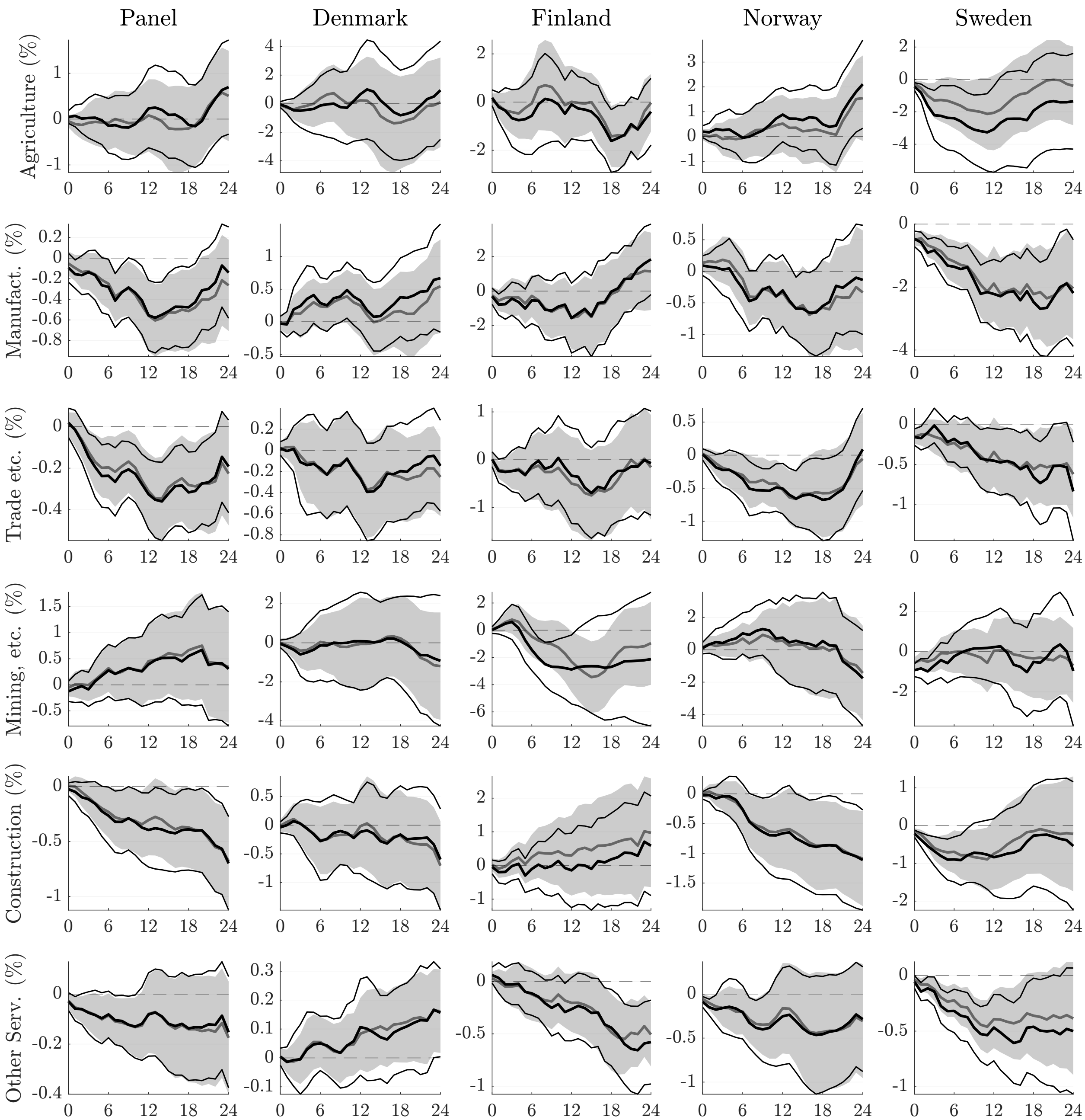

Figure 34: Results from section 4.3 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with monthly dummies to check for seasonality (thick black line, area between thin black lines indicates 90% confidence interval).

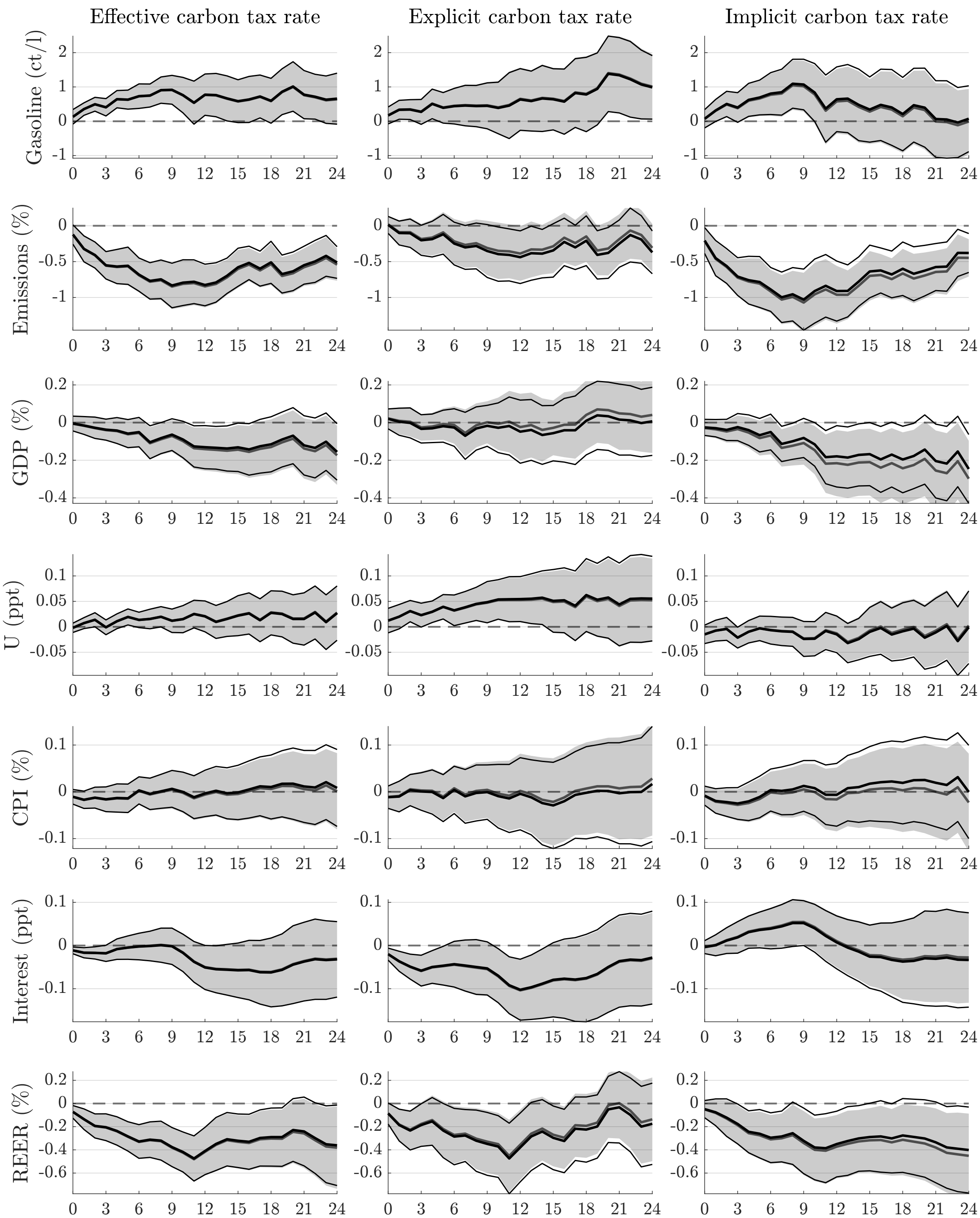

Figure 35: Results from section 4.1 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with a trend (thick black line, area between thin black lines indicates 90% confidence interval).

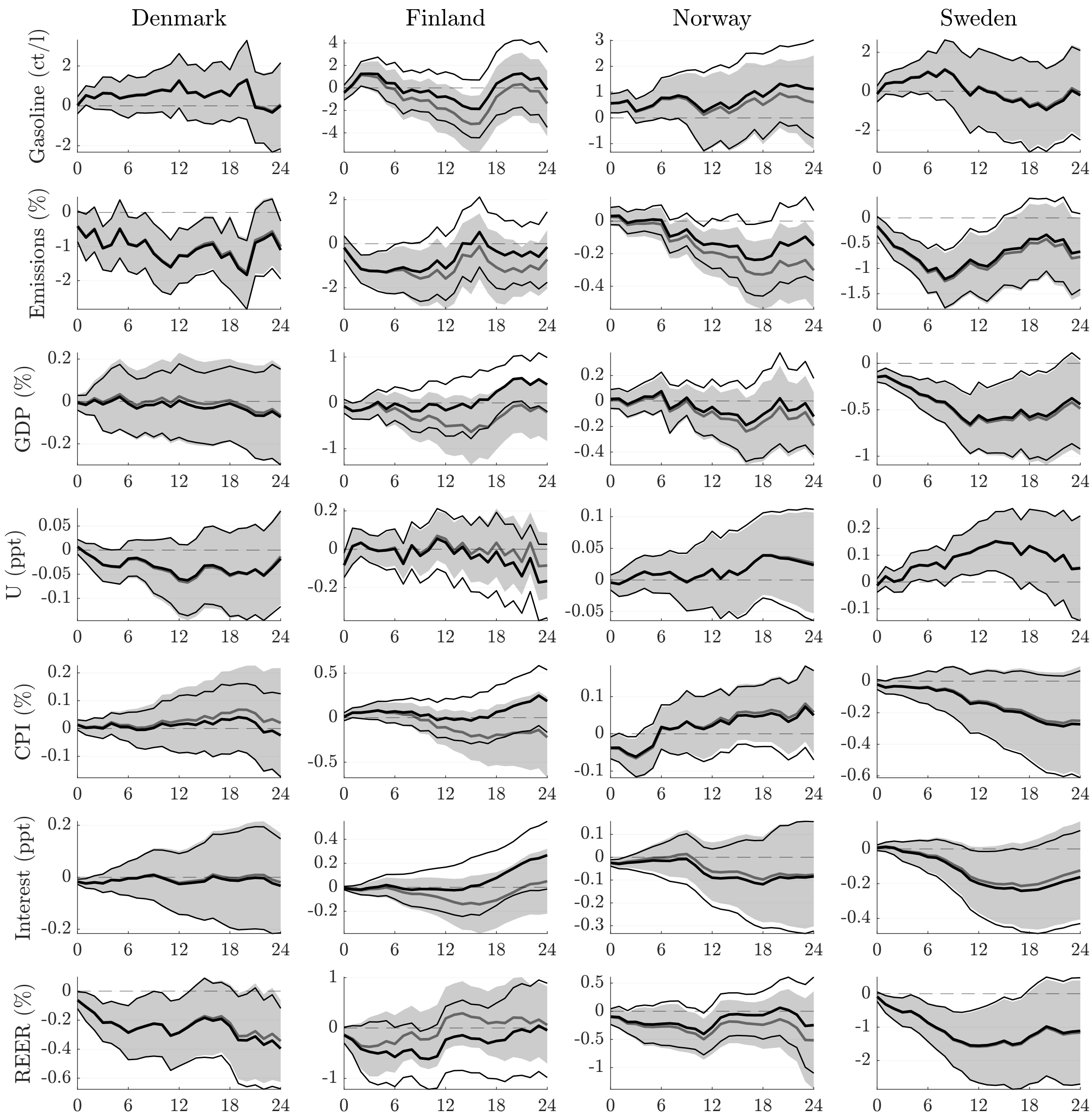

Figure 36: Results from section 4.2 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with a trend (thick black line, area between thin black lines indicates 90% confidence interval).

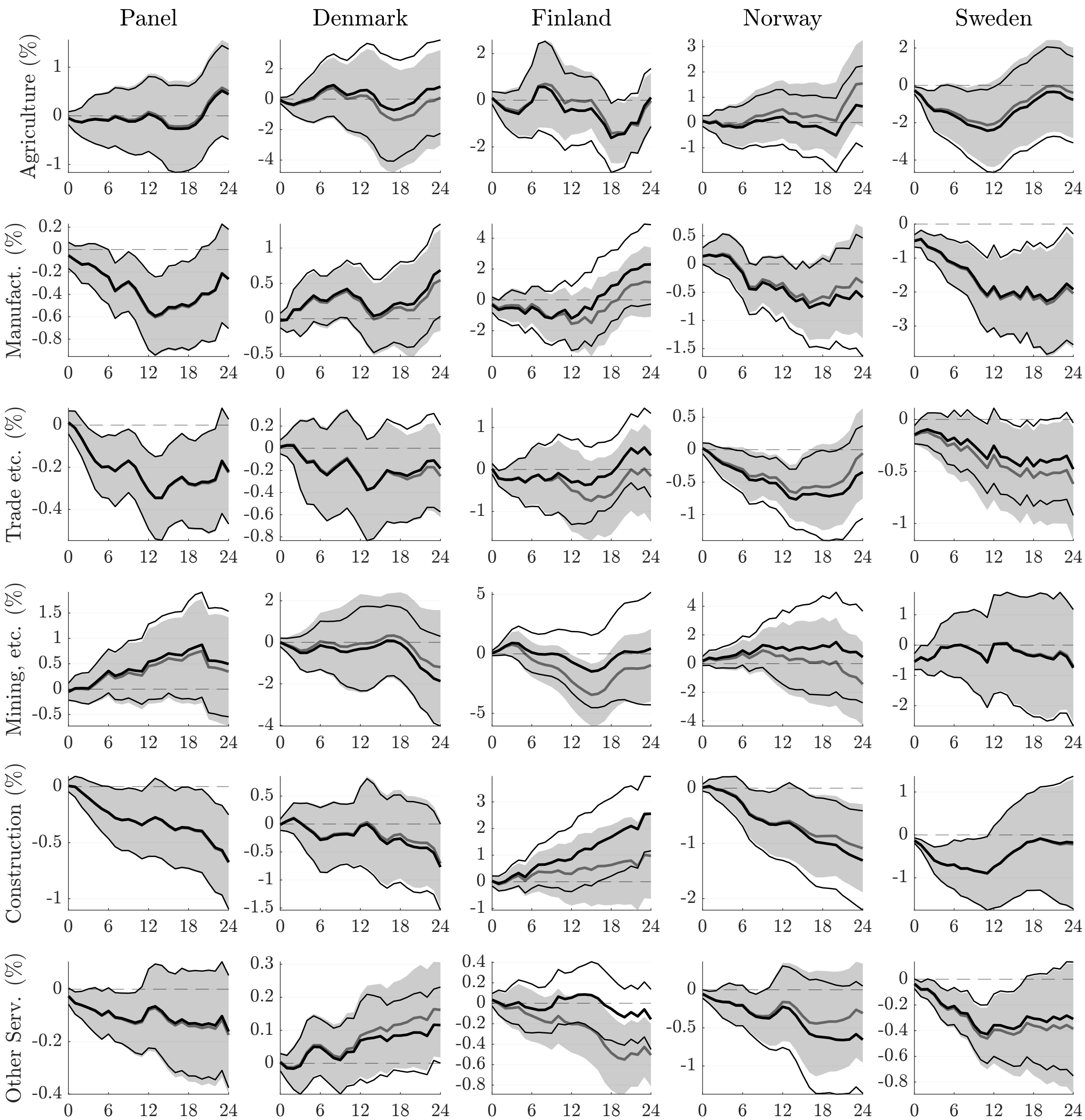

Figure 37: Results from section 4.3 (dark grey line, shaded area indicates 90% confidence interval) and their robustness to augmenting the model with a trend (thick black line, area between thin black lines indicates 90% confidence interval).

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