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Claudia Kettner
Daniela Kletzan-Slamanig
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Internal review: Simon Loretz, Margit Schratzenstaller

Research assistance: Katharina Köberl-Schmid, Susanne Markytan

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While the EU-wide carbon price has already been adopted for the buildings and transport sectors with ETS 2, detailed analyses of the macroeconomic and distributional effects (both within and between countries) are scarce. We use the macroeconomic model ADAGIO to estimate the effects of EU-wide carbon pricing. For two case study countries (Austria and Poland), which differ considerably in terms of the structure of their energy systems and economies, results are discussed in greater detail. We focus on the macroeconomic and greenhouse gas effects of the introduction of a carbon price under various revenue recycling options. Moreover, the distributional effects of the policy scenarios are investigated. The introduction of carbon pricing leads to negative macroeconomic effects for the EU 27, which vary in level depending on the recycling option as well as the assumed model closure and exchange rates; for Austria and Poland, slightly positive macroeconomic effects are found in some simulations. Additionally, our analysis confirms the efficiency-equity trade-off in the context of carbon pricing with respect to different revenue recycling options.

E-Mail: claudia.kettner@wifo.ac.at, daniela.kletzan-slamanig@wifo.ac.at, mark.sommer@wifo.ac.at, gerhard.streicher@wifo.ac.at

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Abstract

While the EU-wide carbon price has already been adopted for the buildings and transport sectors with ETS 2, detailed analyses of the macroeconomic and distributional effects (both within and between countries) are scarce. We use the macroeconomic model ADAGIO to estimate the effects of EU-wide carbon pricing. For two case study countries (Austria and Poland), which differ considerably in terms of the structure of their energy systems and economies, results are discussed along with the EU 27. We focus on the macroeconomic and GHG effects of the introduction of a carbon price under various revenue recycling options. Moreover, the distributional effects of the policy scenarios are investigated. The introduction of carbon pricing leads to negative macroeconomic effects for the EU 27, which vary in level depending on the recycling option as well as the assumed model closure and exchange rates. For Austria and Poland, slightly positive macroeconomic effects are found in some simulations. Additionally, our analysis confirms the efficiency-equity trade-off in the context of carbon pricing with respect to different revenue recycling options.

Keywords: carbon pricing, revenue recycling, macroeconomic effects, distributional impacts, multi-regional Input-Output modelling

JEL codes: Q54, Q58, H23, C67, D57

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1. Introduction

With the European Climate law adopted in 2021, the European Union has legally determined to become climate-neutral by 2050, thus recognizing the need to ambitiously combat anthropogenic climate change. The law also contains the intermediate target of reducing greenhouse gas emissions by 55% by 2030 compared to 1990 levels. Although EU-wide emissions have been decreasing for the past three decades, declining by 31% between 1990 and 2022, reaching the ambitious long-term decarbonization objective will require further efforts. Significant emission reductions will therefore have to be achieved in all areas of the economy, particularly in the buildings and transport sectors.

The 'Fit for 55' package launched in 2021 intends to establish the regulatory framework that ensures the climate targets to be reached in a fair and cost-effective way in the EU member states. Therefore, EU climate and energy policies have been amended and new instruments have been introduced. Almost all of the package's legislative proposals have been adopted by now[1].

For large emitters in industry and energy generation the European Emission Trading System (EU ETS) was established in 2005, which covers about 45% of total GHG emissions in the EU. For these sectors an EU-wide GHG reduction target of 62% compared to 2005 levels has been defined for 2030. In addition, the system is being extended to include also international maritime transport. In contrast, emissions from other sources, most notably from buildings and transport, so far have been regulated at Member State level. For the non-ETS sectors the 2030 objective is an emission reduction of 40%, with differentiated reduction targets defined for the individual Member States (Effort Sharing Regulation). Up to now, for the Effort Sharing sectors, national energy and carbon taxes have been key instruments for reducing GHG emissions. However, from 2027 on a separate, EU-wide emission trading system (ETS 2) will become operational for emissions from road transport, buildings and other sectors (mainly small, non-ETS industry). Emission allowances in the ETS 2 will entirely be auctioned, with revenues being partly used to endow the Social Climate Fund (SCF). This Fund has been created to accompany the new emission trading system to mitigate negative impacts in the regulated sectors, provide support for vulnerable households, transport users and micro-enterprises, starting in 2026. The SCF, together with the Just Transition Fund supporting the regions most affected by the transition, serves the purpose of easing the transition effects for vulnerable groups such as households affected by energy and transport poverty.

The introduction of these new funds underlines the increasing emphasis that is put on social and fairness considerations in climate policy making. Especially the developments in recent years with stark energy price increases following the war in Ukraine show the importance of compensation measures that need to be implemented to particularly safeguard (vulnerable) household groups against price increases which may occur in relation to the transition towards climate neutrality. This regards energy cost increases as well as investment needs for improving

[1] Currently, only the revision of the energy taxation directive is still pending agreement. The unanimity requirement in taxation issues has proven to be a major obstacle for reforming energy taxation in the EU for decades. Not least due to the resistance of some Member States (notably Poland), progress towards an agreement is currently not in sight.

a dwelling's thermal quality or a change of the heating system. In addition, different needs and possibilities for a change towards decarbonized consumption and production patterns in various groups and regions must be considered. On the one hand, the status quo regarding energy supply, infrastructure and technical equipment may differ considerably. On the other hand, the feasibility of mitigation and adaptation options and their affordability may be distributed unevenly. Thus, ideally, compensation measures for carbon pricing should be designed in a way that they account for such differences and primarily target those households and businesses most affected. Economic literature on ecological tax reforms and carbon pricing in particular has discussed various forms of revenue recycling like the reduction of distortionary taxes (e.g. on labor or fees for renewable electricity), lump-sum transfers to households or financing of R&D and specific green investments (Bach et al., 2019; Bovenberg, 1999; Kaestner et al., 2023; Köppl and Schratzenstaller, 2023; Kosonen, 2012). The implementation of CO_2 pricing has in practice largely focused on revenue recycling via the reduction of taxes or social security contributions or via lump-sum transfers as in the case of the (regionally differentiated) Austrian climate bonus (Kettner et al., 2021).

While the EU-wide carbon price has already been adopted for the buildings and transport sectors with ETS 2, detailed analyses of the macroeconomic and distributional effects (both within and between countries) are scarce. So far, the analysis has focused on the EU as a whole (e.g. Chevallier, 2011; Metcalf and Stock, 2020; European Commission, 2021; Green, 2021; Fragkos and Fragkiadakis, 2022; Känzig, 2023; Känzig and Konradt, 2023), without considering the particularities of individual Member States, such as differences in energy systems or income levels[2].

Table 1 provides an overview of cross-country studies on EU-wide carbon pricing and energy taxation, detailing different countries or regions. It includes studies that focus exclusively on macroeconomic effects, studies that only consider distributional effects, and studies that include an integrated analysis. With respect to macroeconomic impacts, the evidence is not clearcut[3]. Applying a Computable General Equilibrium (CGE) model, Lutz and Meyer (2010) find positive employment impacts of carbon pricing in combination with labor tax reductions for almost all EU countries, and negative to neutral impacts on GDP. Without compensation, the CGE analysis by Cunha Montenegro et al. (2019) points at decreasing GDP for all countries/regions distinguished. Another CGE study by Orrechia and Parrado (2014) indicates varying GDP effects of carbon pricing without compensation mechanism between Member States, with stronger negative impacts for Eastern European Member States. An ex post study of national carbon pricing approaches in Europe (Metcalf and Stock, 2023) finds neutral impacts on employment and neutral to modestly positive impacts on GDP.

With respect to the distributional impacts, most studies point at regressive results of carbon pricing at the household level without revenue recycling, implying a higher burden of carbon pricing on low-income households (Büchs et al., 2021; Cunha Montenegro et al., 2019; Rüb, 2024;

[2] For a detailed analysis of the framework conditions in two case study countries – i.e., Austria and Poland – see Kletzan-Slamanig and Kettner (2024).

[3] However, there are numerous studies examining the double-dividend hypothesis in individual countries, see Freire-González (2018) for a meta-analysis.

Symons et al., 2002). Landis (2019), however, finds progressive to neutral outcomes for carbon pricing for most countries, even in absence of revenue recycling, Rüb (2024) shows considerable differences between countries and the largest burden for middle-income households. The analysis by Feindt et al. (2021) indicates that carbon pricing leads to mainly neutral, sometimes progressive outcomes at the national level. At an aggregate EU level, however, carbon pricing would be regressive since some low-income countries would be more strongly affected. The authors conclude that while national redistribution could achieve a progressive EU-wide incidence, an EU-wide redistribution would be more effective to compensate the most vulnerable households, since regressivity on the EU level is driven by between-country effects.

Table 1. Overview of cross-country studies on EU carbon pricing

Source	Country(ies)	Target year	Tax design	Carbon price level	Tax coverage	Compensation measures	CO_2 impacts	Macroeconomic impacts	Distributional impacts
Agostini et al. (1992)	OECD Europe countries	NA	CO_2 tax	\$ 5 (€ 4)/t CO_2 \$ 50 (€ 7)/t CO_2 \$ 100 (€ 75)/ t CO_2	Economy-wide	No compensation	\$ 5/t CO_2: -0.3% vs BL \$ 50/t CO_2: -2.08% vs BL \$ 100/ t CO_2: -3.79% vs BL	NA	NA
Birkelund et al. (1993)	Western European countries	2000	CO_2 tax/ Energy tax	\$ 5 (€ 4)/barrel (50% CO_2 tax, 50% energy tax) \$ 10 (€ 8)/barrel toe (100% CO_2 tax)	Economy-wide	No compensation	-12% to -14% vs BL	NA	NA
Symons et al. (2002)	FR, IT, ES, DE, UK	NA	CO_2 tax/ Energy tax	€ 100/t CO_2 Energy tax same revenue	Economy-wide	No compensation	NA	NA	Household level Regressive, energy taxes slightly more than CO_2 Regressive: FR, ES; Neutral: IT; Progressive: UK (except for the highest income group)
Padilla & Roca (2004)	EU - OECD countries	NA	CO_2 tax/ Energy tax	CO_2: € 50/t CO_2 CO_2: € 25/t CO_2 plus € 58.44/toe CO_2: € 38.5/t CO_2 + nuclear taxes	Economy-wide	National lump-sum	NA	NA	Country level: Mildly regressive (smaller in the nuclear tax design) Progressive with revenue recycling to countries per capita
Lutz & Meyer (2010)	EU 27 countries	2020	ETS	€ 18-184/t CO_2	Economy-wide	Combination of reductions in employers' social security contributions, income tax	-20% vs BL	GDP vs BL: 0 to -2.1% Labor vs BL: +0.02% to +0.77% (effects vary between scenarios and countries)	NA
Orecchia & Parrado (2014)	Western Europe Eastern Europe	2020	CO_2 tax/ GHG tax	Implicit € 18.8-49.1/t CO_2[3]	Economy-wide	No compensation	-20% vs 1990 -30% vs 1990	GDP vs BL Western Europe: -0.28% to -0.71% Eastern Europe: -0.87% to -2.07%	NA

Cunha Montene-gro et al. (2019)	EU 27 countries	2050	ETS/Non ETS	Indirect – re-sulting from GHG reduction target[2]	ETS/Economy-wide	No compensation	-62% ETS -83% vs 2005: -95% vs 1990	GDP vs BL: +2% to -13% – varies be-tween scenario and country Higher emission tar-get leads to lower growth	Household level: Regressive w/o recycling
Büchs et al. (2021)	EU 27 countries	NA	CO_2 tax	€ 80/t CO_2	Heating, Transport	<u>Compensation scenarios:</u> No compensation Equal per capita Provision of universal green vouchers for renewable electricity and public transport Voucher only - no CO_2 tax	Tax: -1.21% heating, -1.56% transport Tax&rebate: -0.33% heating, -0.71% transport Tax&voucher: -13.6% heating, -23.8% transport Voucher only: -12.2% heating, -22.3% transport	NA	Household level: Regressive, compensation schemes ben-efit low-income HH. Voucher only is more redistributive and generates the highest gains for low-in-come HH. Taxes on heating more regressive than on transport fuels.
Feindt et al. (2021)	23 EU countries + EU	NA	CO_2 tax	€ 25/t CO_2	Economy-wide	<u>Compensation scenarios:</u> National lump-sum European lump-sum Targeted transfers High-intensity con-sumers	NA	NA	Household level: EU level regressive – low-income coun-tries strongly affected, esp. HH in BG, PL, RO EU-wide redistribution more effective National level neutral to progressive
Landis et al. (2021)	EU 27 countries	NA	ETS/ CO_2 tax	Harmonizing CO_2 price across EU 27: ETS + national tax ETS + trade among non ETS Full ETS	Economy-wide	<u>Compensation scenarios:</u> National lump-sum European lump-sum More revenues to lower-income coun-tries	NA	NA	Country level: Varies between countries and depends on redistribution Household level: Progressive or neutral for most countries w/o recycling, Strongly progressive with recycling per capita
Charlier et al. (2023)	16 EU countries	NA	CO_2 tax	€ 20/t CO_2	Heating	Redistribution be-tween countries to equalize share in GDP	-0.6% to -1.3% vs 2017 depending on country	NA	Country level: Redistribution main beneficiaries: PL, BE - main burden: DK, LU Redistribution compensates the poorest and coldest countries (CZ, PL)
Metcalf & Stock (2023)	EU 27 plus EU ETS countries	six years after	CO_2 tax	€ 40/t CO_2	30% emis-sions (Non-ETS Sectors)	No compensation	-4% to -6% after six years of imple-mentation	GDP: Zero to modest positive, Labor: zero	NA

		imple-menta-tion							
Abrell et al. (2024)	EU 27 countries	2030	ETS	€ 130-286/ t CO_2 for ETS € 175-360/t CO_2 for ETS2	Economy-wide	No compensation	-55% vs 1990	NA	NA
Rüb (2024)	DE, FR, ES, PL, FI, HU, IE	NA	CO_2 tax	€ 100/t CO_2	Heating, Transport	<u>Compensation scenarios:</u> National lump-sum EU-wide lump-sum	NA	NA	Household level Increased inequality, compensation reduces inequality Inequality effects of the two fuel types vary greatly between countries Middle-income HH bear most of the burden

[1]Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden and United Kingdom. [2]REF scenario: -62% ETS; 4 policy scenarios: Coalition: -83% vs 2005 + Non ETS, Local Solution: -83% vs 2005 + Non ETS, EU alone: -95% vs 1990, Paris Agreement: -95% vs 1990. [3]2 emission targets (-20% & -30%), 2 tax scenarios: CO_2 tax, GHG tax.

In this paper we intend to contribute to the research on the potential of a uniform EU-wide carbon price in the non-ETS sectors under different revenue recycling options in the EU 27. Specifically, we focus on the following three research question:

1. What are the effects of carbon pricing policies for the non-ETS sectors on CO_2 emissions?
2. What are the macroeconomic impacts of these carbon pricing policies?
3. What are the distributional effects of these carbon pricing policies across household income quintiles and regions?

To answer these questions, a model-based analysis with the 'ADAGIO' model (Kratena et al., 2017) is carried out. For two case study countries (Austria and Poland), that differ considerably in terms of the structure of their energy systems and economies (Kletzan-Slamanig and Kettner, 2024), results are discussed along with the EU 27.

We focus on the macroeconomic and GHG effects of the introduction of a carbon price under various revenue recycling options (i.e., increases in public consumption, lump-sum transfers for households, reductions in income taxes, reductions in workers' social security contributions, reductions in non-wage labor costs, and reductions in the value added tax rate). In addition, the distributional effects of the policy scenarios for 15 different household types (income quintiles x three different areas of residence) are investigated, thereby also addressing one important dimension of horizontal distribution.

Hence, key contributions of our paper lie in

1. the in-depth analysis of a broad range of different revenue recycling options and the resulting trade-offs between equity and efficiency;
2. the detailed presentation of results for two EU Member States that differ considerably in terms of their energy systems and economic performance; and
3. a comprehensive set of sensitivity analyses, highlighting in particular the importance of technical modelling assumptions in shaping the simulation outcomes (and the importance of clearly describing these assumptions).

The paper is structured in the following sections: We start by describing the key assumptions for the scenario analyses in section 2. This regards the development of tax rates over time, the increase of CO_2 prices compared to the status quo in those Member States that have already introduced a national carbon price, as well as different revenue recycling options. Moreover, we include a short description of the model, the simulation setup and the most important impact channels driving the results. Modelling results are presented in section 3, followed by a discussion in section 4. The final section 5 provides conclusions and policy recommendations.

2. Material and Methods

2.1 Policy Scenarios

In the following, the key assumptions for the policy scenarios are described. These scenarios are compared to a baseline where no carbon price for the non-ETS sectors will be introduced.

In the policy scenarios an EU-wide carbon price is implemented from 2027 on for current non-ETS sectors (Table 2). In our main carbon pricing scenario, the initial price of € 45 per t CO_2 remains constant until 2036, which is the target price for ETS 2 until 2030[4]. In addition, we perform sensitivity analyses involving higher carbon prices in the non-ETS sectors: In Sensitivity Scenario A, the price increases linearly from € 45 to € 180 per t CO_2. By contrast, a constant CO_2 price of € 180 per t CO_2 over the whole simulation period is assumed in Sensitivity Scenario B. Finally, in Sensitivity Scenario C, the starting price is already € 80 per t CO_2 and linearly increases to € 300 in 2036[5]. For those EU member states that have already implemented a national CO_2 price, the price paths are converted into country-specific mark-ups with the respective changes in carbon prices depending on the 2019 carbon price level in the countries. While carbon taxes in Sweden, Finland and France are at a level not requiring any adaptation in the main scenario, Sensitivity Scenario A entails a rise in tax rates from 2032 in Sweden and from 2028 in Finland and France, respectively. For the other countries with domestic CO_2 prices (Ireland, Denmark, Portugal, Slovenia, Estonia, Lithuania, Poland), carbon prices already increase in the main scenario (see Table A. 2 to Table A. 5 in Appendix A).

For sectors covered by the EU ETS, we assume that the carbon price increases from € 60 per t CO_2 in 2027 to € 120 per t CO_2 in 2036 in all scenarios[6].

Table 2: CO_2 price developments in the model scenarios (€/t CO_2)

€/t CO_2	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Non-ETS sectors											
Baseline	0	0	0	0	0	0	0	0	0	0	0
Main: € 45 constant	0	45	45	45	45	45	45	45	45	45	45
Sensitivity A: € 180 increasing	0	45	60	75	90	105	120	135	150	165	180
Sensitivity B: € 180 constant	0	180	180	180	180	180	180	180	180	180	180
Sensitivity C: € 300 increasing	0	80	104	129	153	178	202	227	251	276	300
EU ETS sectors											
All Scenarios	60	60	68	75	83	90	98	105	113	120	120

In addition to assumptions regarding the CO_2 price paths, six options for revenue recycling and mitigating adverse macroeconomic and distributional impacts are investigated:

[4] When the average allowance price in ETS 2 exceeds € 45 per t CO_2 for two consecutive months, allowances from the market stability reserve shall be released (Directive 2003/87/EC, Art 30h).

[5] These higher prices were obtained in a survey among Austrian energy and climate policy experts for the SoMBI project (https://sombi.wifo.ac.at/).

[6] The value for 2026 was set at the observed EU ETS price in 2022. To this price, we apply the growth rate of the MIX-CP scenario in the Impact Assessment to the EU's 'Fit for 55'-Package (European Commission, 2021) to obtain the price path until 2030.

4. **PCI**: Revenues are used for public consumption. This is the 'default option' in the model, which is closed via endogenous public consumption given a pre-defined budget deficit (see below). Ceteris paribus[7], public consumption will increase.
5. **CDP**: Recycling of carbon tax revenues via lump-sum transfers to households, i.e., climate dividend payments. The payments are distributed on a per capita basis, with children up to 14 years obtaining a reduced amount of 40%.
6. **LCR**: Non-wage labor costs are reduced by lowering employers' social security contributions. This is the only option with positive direct impacts on competitiveness.
7. **SSCw**: Reductions in workers' social security contributions. Contrary to the LCR option, it has no direct (positive) impact on competitiveness.
8. **ITR**: Reduction in workers' income taxes. This is similar to the SSCw option. Like CDP and SSCw, it implies a c.p. increase in disposable income.
9. **VTR**: Reduction of the standard value added tax rate on goods and services, except for energy goods. Indirectly, via reduced inflation, this option influences the wage rate and thus competitiveness.

For all options it is assumed that the introduction of the carbon price is revenue-neutral, i.e., the total volume of the compensation measures corresponds to the revenues generated by the CO_2 pricing mechanism in the respective member state.

2.2 Modelling Approach

ADAGIO is a dynamic global input-output model belonging to a family of regional models sharing a 'Dynamic New Keynesian' philosophy (see Kratena et al., 2017, for a detailed description). While not a traditional general equilibrium model, ADAGIO exhibits equilibrium-like behavior in the goods and labor markets; determinants of financial markets (interest and exchange rates as the most important ones), however, are exogenous. The 'New Keynesian' element is represented by the presence of a long-run full employment equilibrium, which is unattainable in the short run due to institutional rigidities. These include liquidity constraints for consumers[8], wage bargaining[9], and imperfect competition.

As an input-output model, ADAGIO is inherently demand-driven. However, compared to traditional static input-output models it shows several advancements: First, it introduces a unit-cost price system. Thereby, it links the price and quantity sides of the model, allowing demand to react to prices and labor prices to respond to demand via labor scarcity. Second, unlike models with uniform prices, ADAGIO incorporates user-specific prices reflecting different margins, taxes and subsidies, as well as import shares[10]. Third, the main components of final demand

[7] Ceteris paribus, because a strong contracting effect of the carbon price on the economy could lead to an overall net decrease in public consumption. It is exactly this possibility that will be investigated via our model simulations.

[8] I.e., deviation from the Permanent Income hypothesis.

[9] I.e., deviation from the competitive labor market. Wages are derived from into account sectoral productivity, the general price level, and the unemployment rate.

[10] For international trade, a consistent cif/fob correction is applied to account for international trade and transport margins as well as for country-and-commodity-specific import (or export) taxes.

(consumption, investment, and exports) are endogenous, determined by consumer behavior, regional import demand, and producer behavior. Fourth, aggregated input factor bundles are endogenous and explained by production models, rather than being exogenous.

While sharing similarities with Computable General Equilibrium (CGE) models, ADAGIO diverges in crucial aspects. Output is demand-driven, and the supply side is represented by a cost function including total factor productivity (TFP), which is the primary long-term supply-side force. Almost all prices are endogenous, derived from output prices through a Translog cost function considering capital, labor, energy, domestically produced intermediates, and imported intermediates ($KLEM_mM_d$ model). Although derived from the Translog block, a capacity-utilization-related markup adjusts output prices to account for capacity constraints, dampening demand. Labor demand, determined in the production function, is distributed across three skill levels based on relative wages and wages by skill level are then mapped to households by income group.

International trade is demand-driven, with import shares determined in a nested two-step structure: first, the overall import share for each user-commodity-pair is determined from its import and domestic price in an Armington-type equation; then, imports are distributed to the trading partners based on their relative cif-prices[11]. Exports are the mirror image of imports (after conversion to fob), exports to the Rest-of-the-World depend on a country's export price.

Household consumption is modeled for five income groups, with different structures and elasticities. The groups receive income from wages, a share of profits, and social transfers; they pay income taxes and social security contributions as well as wealth taxes. For each group, consumption is split into durables and non-durables. Durables are modelled in a stock-flow-model, non-durables in an AIDS-type model. Sectoral investment is based on the profit-share in value added as modelled by the Translog-production function. The model incorporates a consistent representation of government, household, and enterprise flows, treating the public sector as an active economic player, allowing, e.g., for simulations with exogenous public deficit.

Capital spending (investment) is endogenous and, thus, differs between simulations. What is not different, however, is the 'quality' of the investment: (energy) efficiency (of new capital) is not endogenous and will remain constant around a deterministic trend – technical change is exogenous. The energy price increase, therefore, will not endogenously lead to the development of more efficient capital goods. We argue that this is a minor drawback: for one, the 'efficiency elasticity' of capital goods with respect to energy costs is extremely difficult to determine; also, it would bear on new capital goods only, not the (much larger) existing capital stock. Third, the regional ('only' EU 27) as well as temporal dimensions (a mid-term period of around a decade) are probably not large enough to initiate such major breakthroughs in energy efficiency anyway. Instead, the mix of capital, labor, and material inputs used in the production processes will vary between simulations, reflecting the development of relative prices. Implicitly, and depending on the sector, this can and will lead to energy-saving increases in capital spending and/or labor (or, probably, outsourcing via intermediate inputs).

[11] Taking into account exchange rates, which are exogenous.

For the analysis, ADAGIO was extended with features of its sister model DYNK (a single region model of Austria, focusing on macroeconomic energy and environmental analyses[12]); these extensions consist of specific modules of energy demand for industry sectors (shares of energy carriers) and private households (energy demand for mobility, heating and appliances). The production module has been augmented to account for inter-fuel substitution.

The model builds on Supply-Use tables from the WIFO database, modeling the economy in terms of commodity flows between sectors and users. The Supply-Use tables are based on the set of regions included in the WIOD project (Timmer et al., 2015) and encompass 43 Countries plus a Rest-of-the-World. As this database is no longer updated, the current version of ADAGIO is based on Supply-Use-Tables adapted from EUROSTAT (for the EU 27/8) and OECD (for the remaining countries) with the base year 2017/18.

2.3 Simulation Set Up

For the simulations, we choose the following assumptions about government revenue and expenditure: Unemployment benefits are endogenously determined based on the number of unemployed, which is calculated as the difference between total employment and labor supply, and the wage rate. Other transfer payments, such as pensions and family benefits, are assumed to remain constant in real terms, adjusting to inflation. This assumption reflects common practice and is more realistic than maintaining nominal values.

Public consumption is endogenously determined to maintain a predefined deficit path. The deficit is calculated as the difference between government revenue (primarily from taxes and social security contributions) and expenditure (most notably unemployment benefits and public consumption). This approach leads to pronounced effects, as public consumption directly responds to changes in both revenue and spending[13]. By closing the model through endogenous public consumption, the model captures the government's role in influencing economic outcomes.

The most important exogenous variables are financial: apart from interest rates, the exchange rate is assumed to be exogenous – and fixed. The fixed exchange rate has major implications for the model results: in the real world, deteriorating terms-of-trade could be compensated by intervening in the currency market; in fact, some changes in the exchange rate will be brought about by normal market forces, when capital flows react to changes in prices and growth. Our simulations abstract from such adjustments. Consequently, the carbon price effects on exports are more pronounced than they probably would be in reality (and in other model applications). We demonstrate the effect of (changes in) the exchange rate in a sensitivity analysis.

2.4 Main Impact Channels

The carbon price primarily influences the economy through its effect on output prices. By increasing the price of energy inputs, it raises sectoral output prices, leading to higher domestic

[12] For details see e.g. Kirchner et al. (2019), Sommer and Kratena (2020), or Kettner et al. (2024).

[13] While maintaining a constant deficit might seem restrictive, it serves two purposes: to highlight the potential impact of policy changes and to simplify the model by avoiding complex and arbitrary transition paths.

purchaser prices. This results in a deterioration of the terms of trade, reducing export competitiveness and stimulating import demand, ultimately exerting a contraction on the economy. While the impact on output prices is moderate for lower carbon prices[14], particularly in energy-intensive sectors it becomes more pronounced at higher levels.

The different revenue recycling schemes should mitigate the negative impacts of carbon pricing on households or the macro-economy:

- The fallback option, spending the revenues of carbon pricing on public consumption, acts as an 'anti-cyclical' policy mitigating the negative macroeconomic effects of higher energy costs.
- Transferring carbon pricing revenues to households via climate dividend payments increases disposable income, thus stimulating private consumption.
- Similarly, decreasing social security contributions or income taxes for workers primarily affects disposable income, although a smaller share of the population benefit than under climate dividend payments, due to differing participation in the labor market.
- A reduction in non-energy VAT, by lowering consumer prices, relieves wage pressure[15], therefore indirectly reducing labor costs. We assume that this reduction in VAT is fully passed on to the consumers.
- Finally, reductions of employers' social security contributions directly reduce non-wage labor costs, stimulating employment and mitigating inflationary pressures, and exert a more pronounced impact on basic prices.

3. Results

In this section, we present the simulation results for our main carbon price scenario (Main) and the various recycling options, starting with the effects on total CO_2 emissions.

3.1 Impacts on CO_2 Emissions

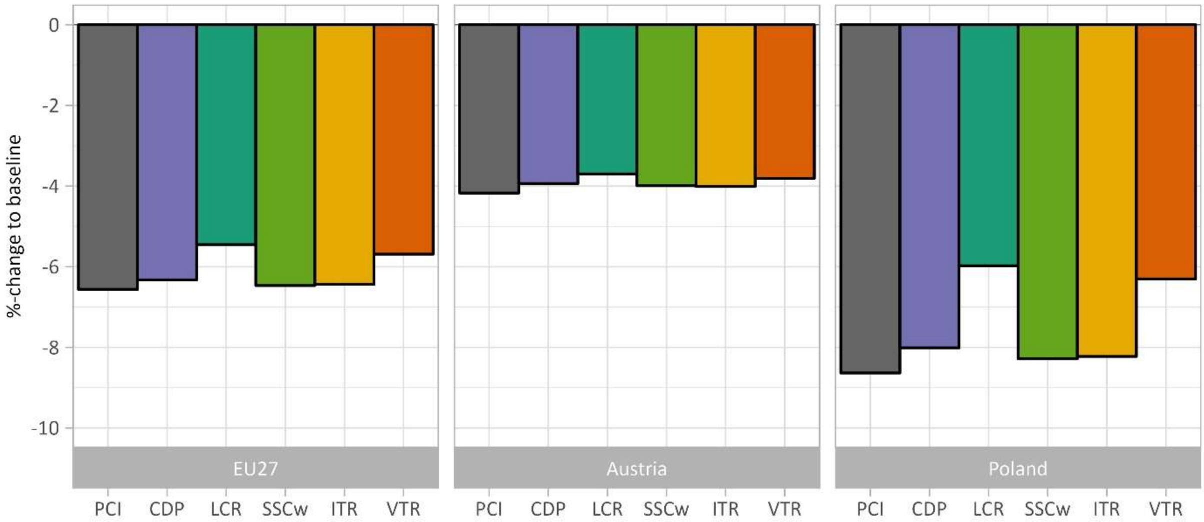
For the EU total, ten years after the introduction of the carbon price CO_2 emission reductions range between 6% and 7% compared to the baseline. This regards emissions from all sectors not only the non-ETS sectors. In Austria reductions reach around 4%, in Poland emissions are reduced by 6% to 9% (Figure 1), depending on the recycling option. ADAGIO exhibits a rapid decline in emissions following the implementation of the carbon price. This behavior is primarily attributed to the abrupt adjustment of final energy consumption by households, contrasting

[14] The share of energy in the inputs of sectors not covered by the EU ETS is rather low: In the respective low-tech sectors energy inputs account for approximately 2% of turnover; in the medium-high to high-tech sectors the share is lower, in most sectors below 1%). Service sectors exhibit varying energy intensities: Whereas in most business and market services energy costs account for less than half a percent of turnover, their share is around 2% in trade and tourism sectors, and 3% to 4% in public sectors like administration, education, and health. Naturally, the share of energy costs is considerably higher in the transport sector, ranging between 10% and 14% of turnover.

[15] Wage bargaining is modeled as a function of unemployment rate (negative impact), productivity, and consumer price index (positive impacts). A VAT reduction indirectly decreases wages by lowering consumer prices, resulting in more competitive labor costs.

with the more gradual response of intermediate energy consumption (see Figure B. 1 and Figure B. 2 in Appendix B). The underlying cause is the model's production function, which allows for gradual factor demand adjustments, unlike the immediate response of household energy demand to price changes. This discrepancy reflects the challenges in econometrically modeling household behavior, particularly regarding capital investment decisions. Unlike firms, households often face longer replacement cycles for energy-intensive assets, such as heating systems, and may lack control over energy efficiency upgrades in rental properties.

Figure 1. Changes in total CO_2 emissions in the main carbon pricing scenario by recycling option compared to the reference scenario in 2036



3.2 Macroeconomic Impacts

Figure 2 shows the effects of a carbon price of € 45 per t CO_2 under various recycling options on real GDP. In addition to the six recycling options outlined above, here we also include a scenario assuming no recycling. This implausible 'no-recycling' assumption yields notably extreme outcomes, especially in the short run. ADAGIO estimates an 8.9% decline in Poland's real GDP and a 0.8% decrease in Austria's relatively carbon-efficient economy[16]. At the EU 27 level,

[16] In Austria, the no-recycling option leads to better results than some recycling options. However, this is somewhat misleading: In the first eight years, the effects of "no recycling" are decidedly negative – at its height, after around 4 years, real GDP is more than 2.5% lower than in the reference scenario, double the percentage of the next-worst option (in Poland, the maximum drop is 20%, since public consumption has to be reduced by four fifths in order to adhere to the pre-determined deficit path). After the maximum impact, GDP quickly recovers; in Poland as well as the EU27, this leads to a moderate improvement. In Austria, however, recovery is more pronounced, leading to this seemingly "neutral" effect of the no-recycling option.

GDP would decline by more than 5%. Given these drastic results, this scenario is excluded from further analysis[17].

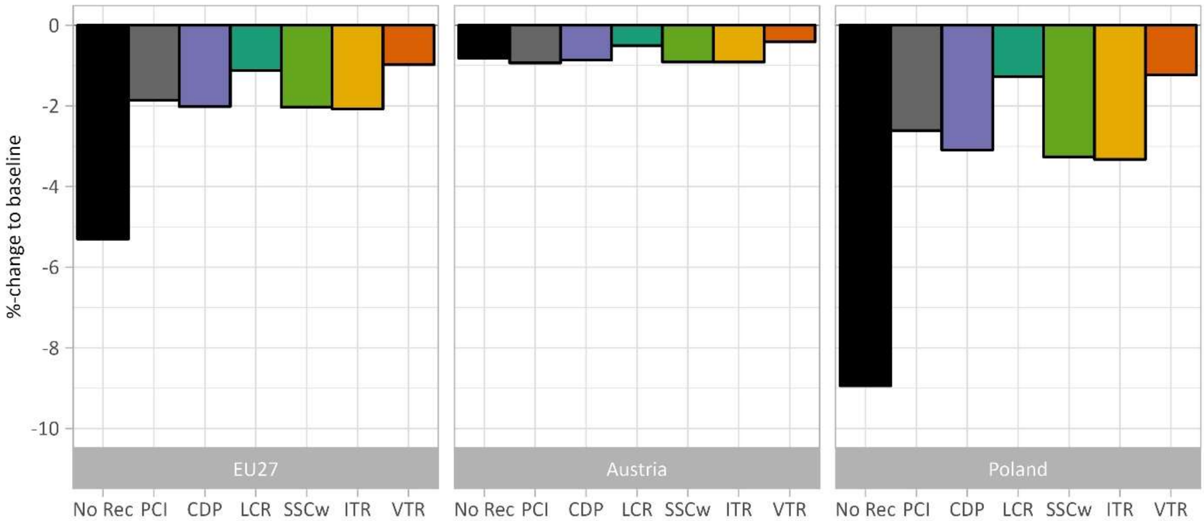
Revenues from carbon pricing are significant: at a carbon price of € 45, ten years post-implementation, Austria generates approximately € 1.6 billion in revenue, Poland € 6.7 billion, and the EU 27 around € 77 billion that are used for financing compensation measures in the other scenarios. Even under these more realistic policy scenarios, the carbon price exerts substantial negative macroeconomic effects. At the EU level, real GDP decreases by 1.0% to 2.1%, with Austria experiencing a 0.4% to 0.9% decline and Poland facing a negative effect of 1.2% to 3.3%, depending on the recycling option chosen.

Reductions in non-wage labor costs as well as the reduction in VAT deliver the most favorable outcome in terms of real GDP. A reduction in non-wage labor costs directly (and in a dampening way) impacts output prices, thus counteracting the carbon price-induced price increases. In the second option, VAT reduction, the impact is indirect via its inflation-reducing effect (lower inflation means less wage increases, again implying a reduction in output prices, albeit to a lesser extent than the non-wage-cost option). Additionally, however, it has an expansionary effect on consumption, which the former option lacks. For certain countries, such as Poland, the reduction in employers' social security contributions results in an initial increase in GDP before the negative price effects dominate. This phenomenon stems from model dynamics, as the dampening effect of reduced social security costs is realized more rapidly than the delayed responses of other price variables, particularly wage rates.

The drop in real GDP results from (and is followed by) sizable inflation. Some of the recycling options, however, can significantly mitigate the inflationary pressure (see Figure C. 1 in Appendix C). While climate dividend payments or increased government spending tend to spur inflation, a reduction in non-wage labor costs and particularly cuts in non-energy VAT can effectively curb consumer price inflation. While the dampening effect on consumer prices is less pronounced, reducing employers' social security contributions positively impacts real export performance (see Figure C. 2). However, this outcome varies somewhat across countries. In Austria (as well as in the EU), the VAT reduction (via its dampening effect on inflation and, thus, wages – see above) leads to a better export performance than non-wage labor cost reductions, while in Poland, the two scenarios are very similar with respect to exports. These differences arise from the different ratios of carbon revenues to employers' social security contributions in the individual countries: While in Austria carbon pricing revenues amount to less than 8% of total employers' social security contributions, in Poland they correspond to more than 25%, resulting in more substantial output price reductions.

[17] These extreme results are a consequence of the closure rule, i.e., the assumption of a constant budget deficit: To keep to the pre-defined deficit path, and without the possibility to spend the carbon price revenues, public consumption in Poland has to be drastically reduced, exacerbating the regressive impact of the carbon price. This leads to a downward spiral since public consumption as a counter-cyclical stabilizer is completely missing under this closure – in fact, the model must reduce public consumption by more than 80% to keep the budget deficit at the necessary level.

Figure 2. Changes in real GDP in the main carbon pricing scenario by recycling option compared to the reference scenario in 2036



Counterintuitively, the more regressive redistribution of carbon price revenues via income tax reductions yields only marginally worse macroeconomic outcomes than the redistribution via lump-sum climate dividend payments. Given the higher marginal propensity to consume of lower-income households (approximately 100% versus 60% for higher-income households), one might expect a more pronounced positive impact from lump-sum payments. However, distinct consumption patterns among income groups attenuate this effect. Lower-income households spend a greater share of their incomes on food and rent, while spending on recreation and touristic services is lower, as is the share of imputed rents. Food exhibits a relatively high import content, while recreation is a domestically provided service. Consequently, lower-income households, characterized by a higher propensity to consume food, allocate a larger proportion of their disposable income to imports compared to higher-income households[18]. This pattern is reinforced by the relatively high import content of energy goods which also constitute an above-average share of lower-income groups' consumption expenditure.

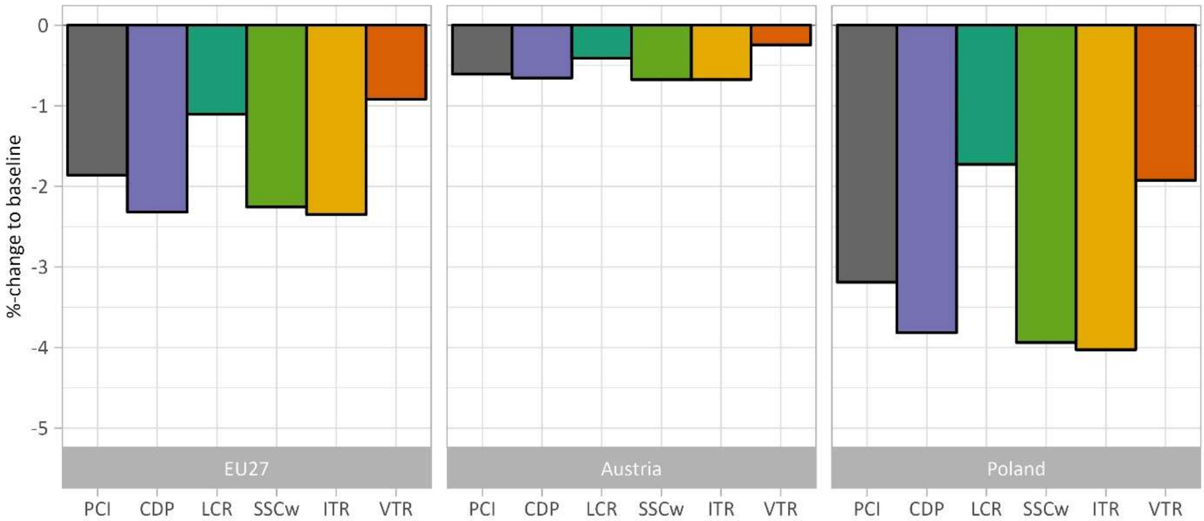
Unlike food consumption, housing, which is domestic by definition, exhibits a less expansionary impact. Most rental income accrues to higher-income households with lower consumption propensities, effectively redistributing income from high- to low-spending households and dampening overall consumption growth.

The reductions in value added taxes (VTR) and employers' social security contributions (LCR) deliver the most favorable impacts on employment, given their positive effect on prices, exports and, accordingly, GDP. Conversely, the public consumption recycling option exhibits the most adverse outcomes (Figure 3). This disparity is likely attributable to the comparatively higher

[18] International tourism, a significant component of consumption, is inadequately represented in official input-output tables, limiting the model's ability to capture cross-border tourist flows. This constitutes a key limitation of ADAGIO's multiregional framework.

wage levels prevalent in public sector industries such as administration, education, and healthcare. Only the LCR and VTR recycling options effectively contain unemployment levels (see Figure C. 3). Poland even records a decline in unemployment, while the EU's unemployment rate remains relatively stable. In contrast, other scenarios, such as those involving increased public consumption or income tax reductions, lead to a doubling of unemployment in Poland. This surge cannot be offset by labor force reductions, which in 2036 reach 0.3% to 1.4% in Poland compared to roughly 0.2% to 0.6% in Austria and 0.3% to 0.7% in the EU (see Figure C. 4), depending on the recycling option.

Figure 3. Changes in employment in the main carbon pricing scenario by recycling option compared to the reference scenario in 2036



3.3 Distributional Impacts

A central focus of our analysis lies in the distributional impacts of the carbon pricing under the various revenue recycling options. The model distinguishes between five household income quintiles, each exhibiting distinct characteristics, particularly the lowest quintile (Q1).

First, income composition varies significantly across quintiles. The poorest quintile derives less than 20% of income from wages, profits or wealth, compared to over 95% for the richest income quintile. By contrast, social transfers constitute the primary income source for the poorest quintile (over 80%) but less than 5% for the richest one. Consequently, poorer households experience relatively smaller income losses due to the carbon price, as social transfers, including pensions, family benefits, and unemployment benefits are less sensitive to economic fluctuations. The full indexation of transfers in the simulations further shields poorer households from economic downturns.

Second, consumption propensities differ markedly across quintiles. The poorest quintile exhibits near-complete income consumption, while the richest quintile often saves over one third. In addition, consumption structures vary, with energy consumption being relatively homogenous across quintiles (around 10% in Austria and 16% in Poland) but differing by use type: electricity and heating are more important for poorer households, private transport for richer ones. Poorer households tend to allocate a larger share of income to energy consumption, rendering them more vulnerable to price increases. Additionally, lower-income households exhibit higher consumption shares of food and housing, and lower shares of recreation and services, which bears implications for the revenue recycling mechanisms.

It is important to note that household income and its structure are not static. Households can transition between income quintiles over time, complicating the analysis of distributional impacts. A dynamic microsimulation model would be required to accurately capture the effects on individual households.

Except for the recycling via employers' social security contributions, poorer households generally experience smaller declines in disposable income compared to richer households. This is primarily due to the indexation of transfers, which provides a degree of protection against inflationary periods. In some cases, this mechanism may even lead to net gains during the initial stages of the simulation period.

Under most recycling options, real disposable income of lower-income quintiles remains relatively stable. Climate dividend payments even imply a slight increase for these groups. In Austria, similar patterns emerge within income brackets, with quintiles Q4 and Q5, as well as Q2 and Q3, exhibiting comparable changes in real disposable income. Poland deviates from this pattern, as losses escalate with income due to the country's more pronounced economic downturn as a consequence of carbon pricing. Reductions in employers' social security contributions yield the most homogeneous impact across income quintiles and regions.

Table 3. Changes in real disposable income in the main carbon pricing scenario by recycling option and household type compared to the reference scenario in 2036

	Austria						Poland						EU 27					
	Q1	Q2	Q3	Q4	Q5	**Total**	Q1	Q2	Q3	Q4	Q5	**Total**	Q1	Q2	Q3	Q4	Q5	**Total**
PCI	-0.2	-0.8	-1.2	-1.6	-1.5	**-1.3**	-1.0	-2.0	-3.2	-4.2	-4.7	**-3.9**	-0.2	-1.1	-1.8	-2.6	-2.7	**-2.2**
CDP	0.6	0.0	-0.6	-1.0	-1.2	**-0.8**	3.5	1.7	-0.5	-2.4	-4.3	**-2.3**	1.8	0.5	-0.8	-1.9	-2.5	**-1.5**
LCR	-0.2	-0.4	-0.6	-0.8	-0.7	**-0.6**	-0.6	-0.9	-1.2	-1.6	-2.0	**-1.6**	-0.1	-0.6	-0.9	-1.3	-1.5	**-1.2**
SSCw	-0.2	-0.5	-0.7	-1.0	-0.9	**-0.8**	-0.7	-1.2	-1.9	-2.6	-3.3	**-2.6**	-0.1	-0.8	-1.3	-1.9	-2.1	**-1.6**
ITR	-0.2	-0.5	-0.9	-1.2	-0.8	**-0.8**	0.0	-0.6	-1.6	-2.6	-3.2	**-2.4**	-0.1	-0.6	-1.2	-1.9	-1.8	**-1.5**
VTR	-0.1	-0.3	-0.5	-0.6	-0.4	**-0.4**	-0.3	-0.7	-1.3	-1.8	-2.0	**-1.6**	0.0	-0.4	-0.7	-1.1	-1.1	**-0.9**

Figure 4 explores the impact of the various recycling options on income distribution across different regions and income quintiles in Austria and Poland. The national results were regionalized with the help of information from EU SILC. The region types describe the degree of urbanization, differentiated according to urban, suburban and peripheral.

The CDP scenario is unique in that it results in slight income gains for households in the two lowest income quintiles (Q1 and Q2) in both Austria and Poland. These gains are directly attributed to the climate dividend payments, which in Q1 are particularly beneficial for urban households. However, an exception is observed in Q2 and Q3, where the positive effects of climate dividend payments in urban areas are overcompensated by significant wage losses, leading to an overall income reduction.

For the scenarios PCI, LCR, SSCw, and VTR, in the lowest income quintile (Q1) the most adverse effects are observed in suburban regions. This is indicative of the heightened vulnerability of these areas to economic shifts. Income quintiles Q2 and Q3, however, experience the most severe impacts in urban areas, largely due to wage losses that represent a more important income component in urban areas. By contrast, income quintiles Q4 and Q5 in urban regions experience lower income losses than those in suburban and peripheral regions, benefiting substantially from reductions in taxes on various income sources.

For the reduction in income taxes, the results show a similar pattern. Against that, in Poland households in the lowest income quintile (Q1) residing in urban areas experience income gains. This reflects the larger benefits from increased transfers and reductions in wealth taxes, which are more pronounced in urban areas.

In addition to examining the regional differences with respect to changes in income, we also analyzed the regional differences regarding non-energy consumption using detailed information on household consumption expenditures from national household budget surveys (Figure 5). To keep the analysis/presentation concise, we focus exclusively on one recycling option, i.e. climate dividend payments. The consumption pattern we find is quite distinct from the income pattern: While all household quintiles face a reduction in their non-energy consumption possibilities, the decline in non-energy consumption is least pronounced for households residing in urban areas, irrespective of the income quintile and in both Austria and in Poland. This reflects mainly lower expenditures on propellants in urban areas due to a lower dependence on private cars. Moreover, the most emission-intensive fuels (heating oil in Austria, coal in Poland) are most prevalent in rural regions. These regional disparities in energy use and, consequently, emissions constituted a key topic in the political debate during the implementation of Austria's national carbon pricing scheme in 2022. This resulted in the introduction of regionally differentiated lump-sum ("climate bonus") payments, that should alleviate the burden of carbon pricing on rural households.

Figure 4. Changes in real disposable income in the main carbon pricing scenario by recycling option and household income and region compared to the reference scenario in 2036

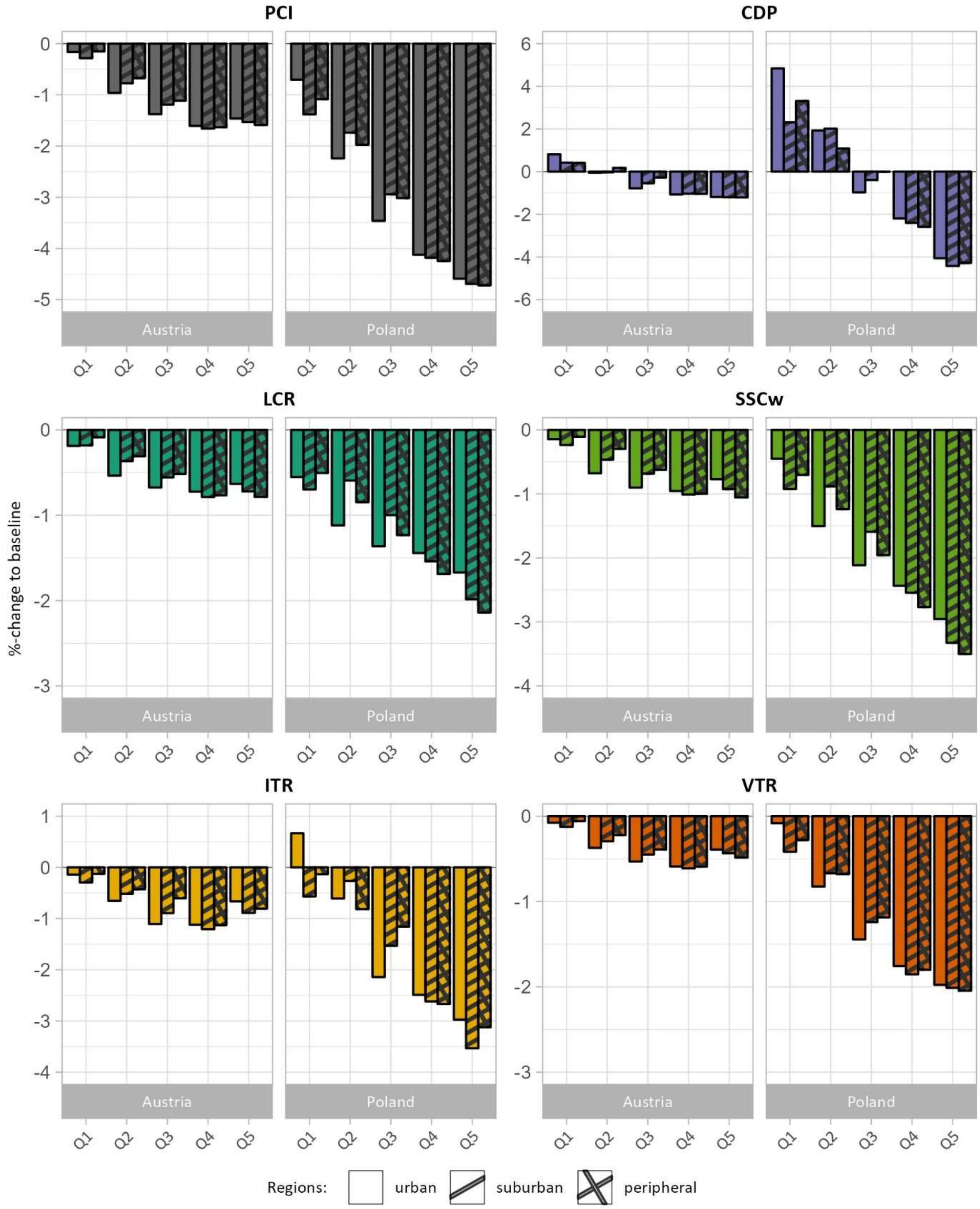
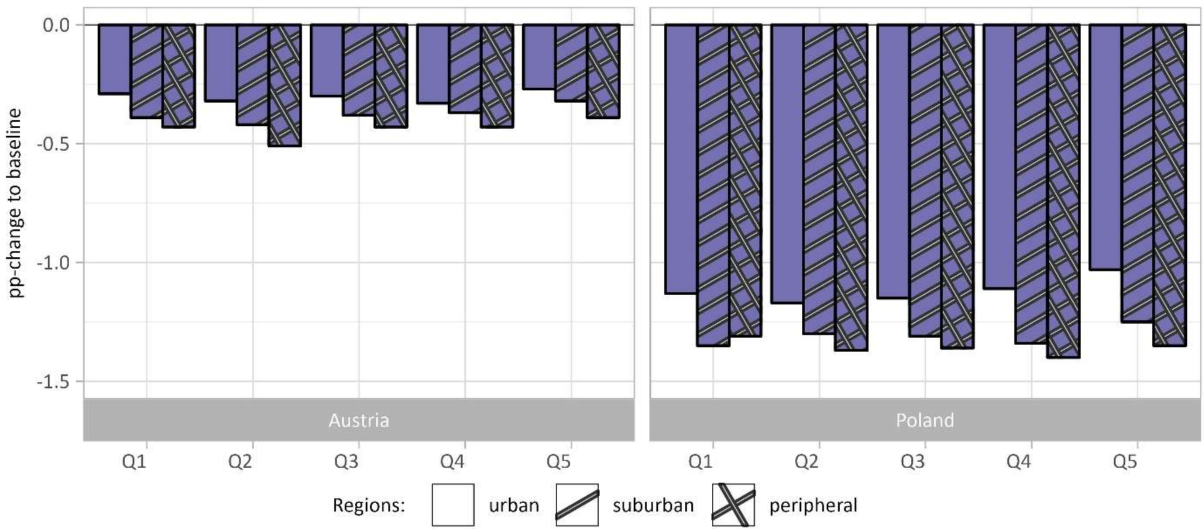


Figure 5. Changes in non-energy household consumption in the main carbon pricing scenario with climate dividend payments by household income and region compared to the reference scenario in 2036



3.4 Sensitivity Analyses

3.4.1 Sensitivity Analyses with Respect to the Carbon Price Level

We have analyzed the effects of carbon pricing assuming a very moderate price of € 45 per ton in the main scenario (€ 45 con). To assess the impact of higher carbon prices, three sensitivity scenarios are simulated: a scenario with € 180 per ton and a scenario with € 300 per ton (see Table 2). In the latter, Sensitivity Scenario C, the carbon price is phased in over eight years, with € 80 per ton in the first year. The € 180 per ton scenario is simulated under two conditions: a gradual phase-in over eight years, starting at € 45 per ton (Sensitivity Scenario A), and an immediate full implementation (Sensitivity Scenario B). While both scenario variants ultimately produce comparable maximum impacts, the trajectories diverge significantly. For recycling, it is assumed that all government revenue generated from the carbon price is transferred to households via climate dividend payments while maintaining predefined deficit paths.

The imposed carbon price of € 300 per ton (Sensitivity Scenario C) induces severe economic consequences. Poland's GDP drops by a fifth, while Austria exhibits greater resilience with a 6% decline in real GDP. The EU 27 in total shows an 11% reduction in real GDP. Both the gradual and immediate implementation of the € 180 per ton carbon price (Sensitivity Scenarios A and B) yield comparable ultimate impacts, at least for Austria and the EU total. Generally, the reduction in real GDP is more continuous and less abrupt with a phasing-in of the carbon price. In the final year real GDP losses for the EU are around 7% to 8%, for Austria 3% to 4%. For Poland, GDP declines by 12% (gradual implementation) to 15% (immediate implementation).

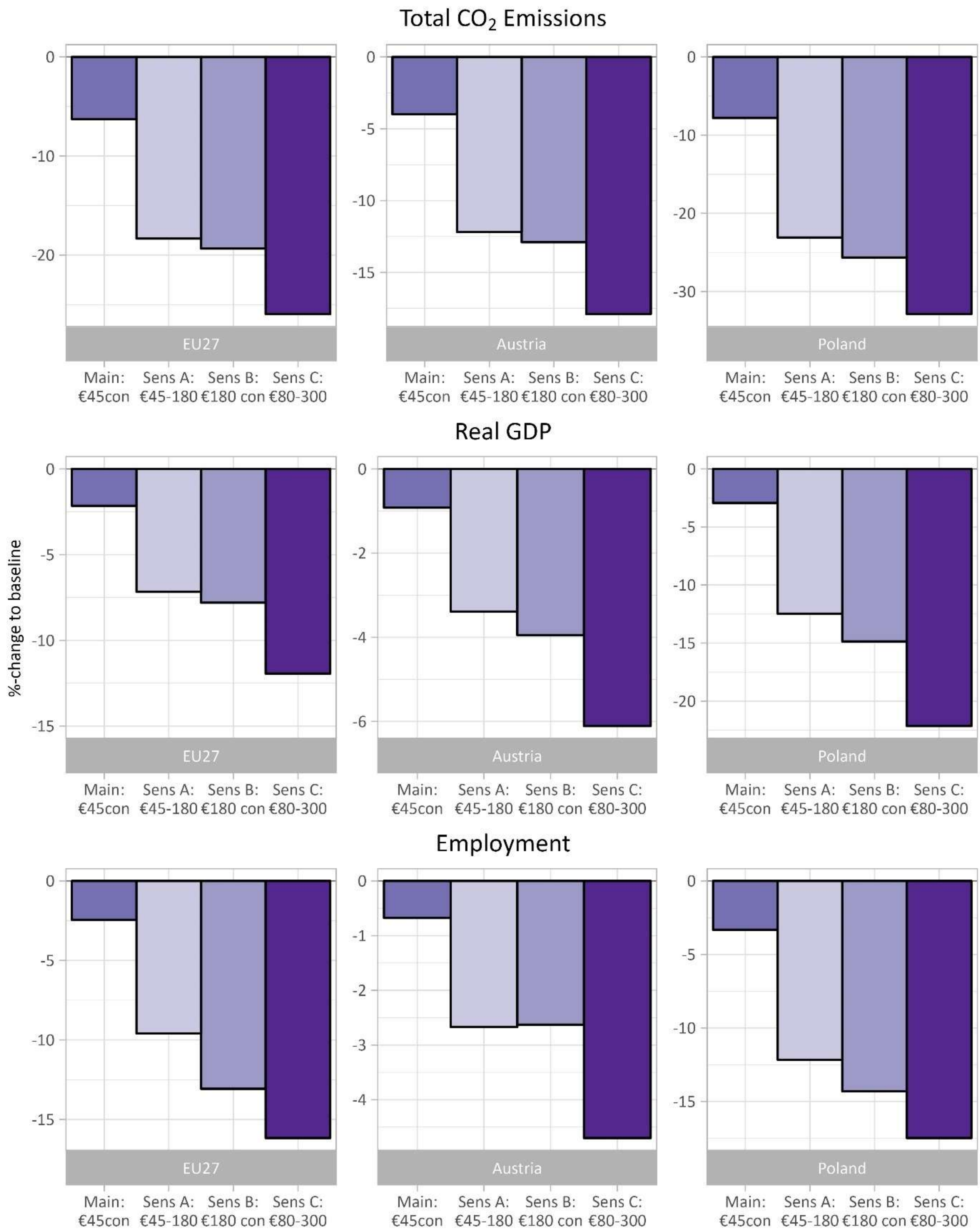
Also, effects on employment are rather significant. In Austria, it decreases by 3% (€ 180) to nearly 5% (€ 300) in 2036. In the EU 27, the employment effect is stronger and reaches between -6% and -11%. Poland is again hit hardest with employment reductions in the range of 12% to

16%. As with GDP impacts the immediate implementation of the € 180 carbon price leads to stronger negative effects in the medium term compared to the gradually rising price in the € 300 scenario.

The simulation results with ADAGIO indicate a substantial reduction in carbon emissions under the extreme € 300 per ton carbon price scenario, with emissions falling by over a quarter for the EU total, exceeding a third in Poland and reaching 18% in Austria. Final emission reductions are nearly identical for the two variants of the € 180 carbon price in Austria (16%) and the EU (21%). In Poland, final emissions decline by around a third. Note, however, that the path again is different for the two variants: in the first five years emission reductions are stronger for the immediate implementation of the € 180 carbon price than for the € 300. Only after 2032 the latter delivers higher emission reductions.

Overall, the sensitivity analyses with higher carbon prices do not indicate major non-linearities but merely show that higher carbon prices intensify effects. However, the reliability of these extreme results is questionable due to the unprecedented nature of such high carbon prices. The model's underlying elasticity assumptions, calibrated on historical data, may not accurately capture the behavioral responses to such extreme price shocks in energy consumption and production.

Figure 6. Sensitivity of changes in CO_2 emissions, real GDP, and employment under climate dividend recycling with respect to the carbon price path in 2036



3.4.2 Sensitivity Analyses with Respect to the Model Closure

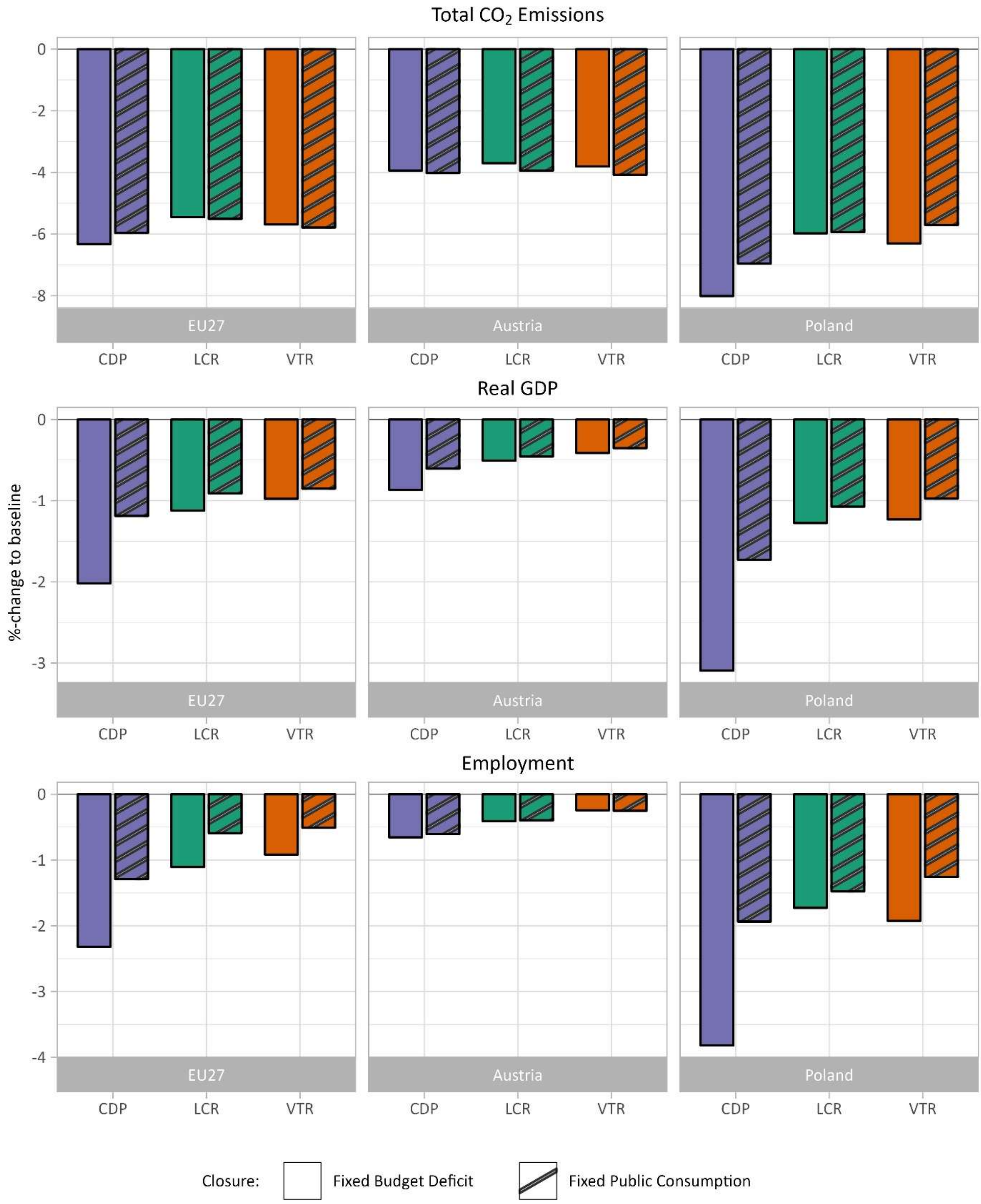
As noted above, the simulation results strongly depend on the model closure chosen. We therefore perform a second strand of sensitivity analyses, with a different closure that keeps public consumption at a fixed level and allows for changes in the budget deficit. The results of these simulations on CO_2 emissions, real GDP and employment as key macroeconomic indicators are presented in Figure 7. To facilitate comparability of both variants, we focus on the effects of the three recycling options showing the most pronounced differences, i.e., climate dividend payments (CDP), reductions in non-wage labor costs (LCR) and reductions in VAT (VTR).

In terms of macroeconomic effects, the variation in the closure rule delivers quite different results, with fixed public consumption typically leading to smaller effects. This is due to the fact, as discussed previously, that the endogenous public consumption given a fixed budget deficit tends to magnify the tendency inherent in the investigated policy, i.e. it increases both recessive as well as expansionary tendencies. This is true especially for the recycling option CDP, while there are only little differences for LCR and VTR. In general (irrespective of the closure rule applied), the recycling options LCR (reduction in non-wage labor costs) and VTR (VAT reductions) perform best, i.e., result in lowest decreases in real GDP. Under the assumption of a fixed budget deficit climate dividend payments (CDP) result in a more pronounced decline in GDP than under the assumption of fixed public consumption.

With respect to the employment effects, changing the closure entails varying effects for the three regions. For the EU 27 total, a fixed budget deficit results in higher declines in employment than fixed public consumption for all recycling options. The opposite is true for Austria. Finally, in Poland little difference is found for LCR, while employment declines more strongly in the case of climate dividend payments (CDP) and reductions in the value added tax (VTR) under a fixed budget deficit than under fixed public consumption.

Regarding the development of CO_2 emissions, both options for model closure deliver comparable results: the pattern between scenarios is very similar; in general, the reductions are somewhat smaller for the fixed public consumption closure, simply because the economic effects are more subdued. For the EU 27 total and Austria, fixed public consumption results in more pronounced declines in total CO_2 emissions for the LCR and VTR recycling options, while only little differences with respect to the closure are found for climate dividend payments (CDP). Conversely, for Poland, total CO_2 emission reductions are similar for reductions in non-wage labor cost and the value added tax rate under both closures, while for climate dividend payments they are higher under the assumption of a fixed budget deficit.

Figure 7. Sensitivity of changes in CO_2 emissions, real GDP, and employment with respect to the model closure in 2036



3.4.3 Sensitivity Analyses with Respect to the Exchange Rate

As noted above, in ADAGIO financial variables are exogenous, most notably the exchange rate. In international trade, however, the exchange rate is of major importance since it quite directly bears on competitiveness. The negative effects of the carbon price (via domestic producer prices) can be (partially) offset by a reduction of the currency 'price', i.e., by a devaluation. We therefore conduct a third range of sensitivity analyses where we compare the main results assuming fixed exchange rates with a uniform 1% devaluation of the EU 27's currencies[19]. The main effects of this devaluation are that exports become cheaper (for the EU's trading partners), and imports become more expensive. This should reduce the negative impacts on exports (and positive impacts on imports, thus re-balancing the trade balance), but at the expense of somewhat higher inflationary pressure (due to more expensive imports). Again, for the comparison we focus on the three recycling options that show the most pronounced differences: climate dividend payments (CDP), reductions in non-wage labor costs (LCR) and reductions in VAT (VTR).

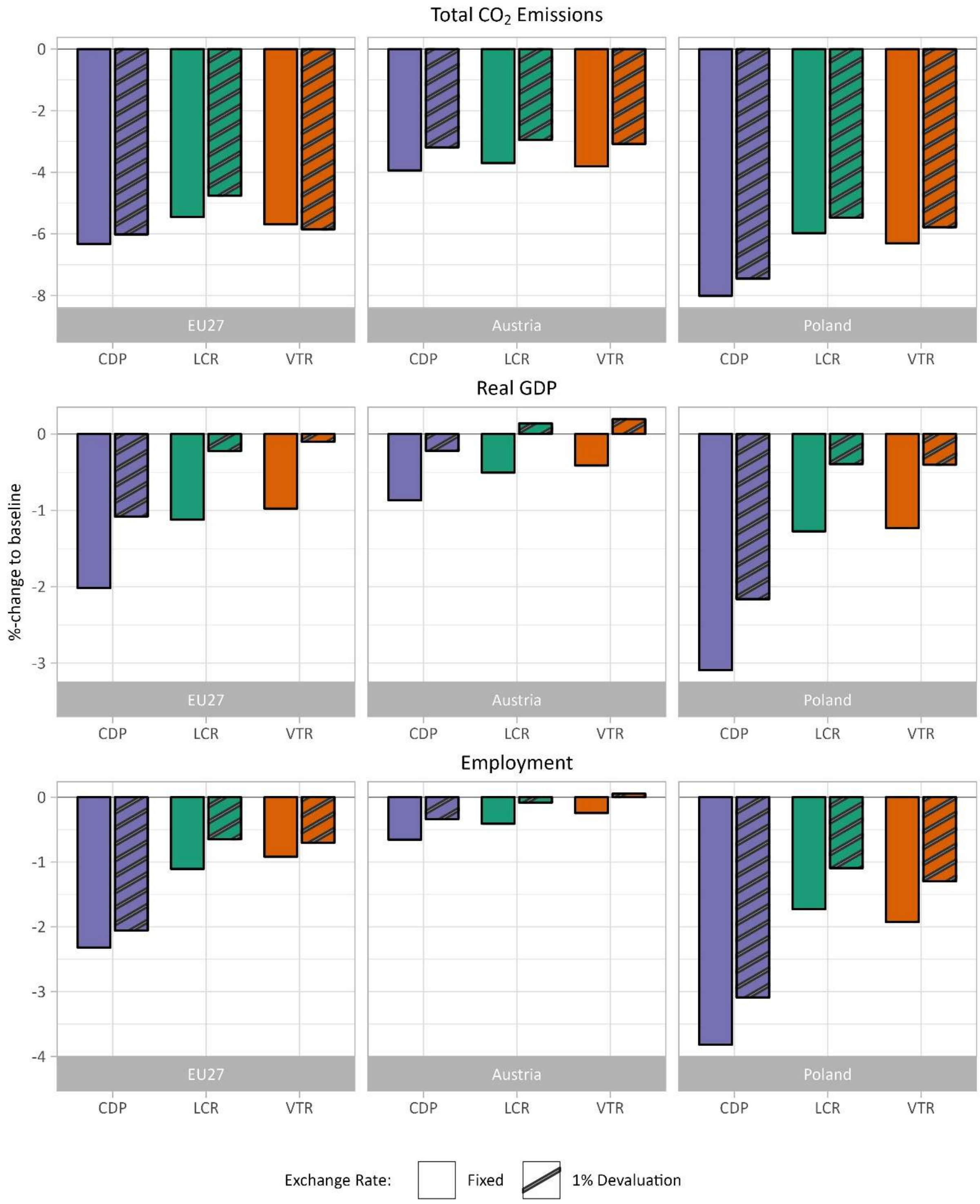
As the simulation results show, this 1% devaluation can reduce the negative impact of the carbon price in all regions; in Austria even positive effects on real GDP are found for the LCR and VTR scenario, and employment increases in the VTR scenario (see Figure 8)[20]. 1% devaluation is hence sufficient to offset the inflationary effects of the carbon price almost perfectly in Austria, and to markedly reduce its impact in Poland. The more favorable economic outcomes are accompanied by a lower reduction in total CO_2 emissions, resulting mainly from a weaker reduction in intermediate CO_2 emissions due to the less pronounced economic downturn.

The exogenous treatment of the exchange rate in our main simulations probably explains some of the differences to other model simulations (Kattelmann et al., 2021; Varga et al., 2022), which show less pronounced reactions in macroeconomic indicators for even higher carbon prices. However, the specific treatment of major exogenous variables as well as the model closure chosen is not addressed in the respective papers.

[19] Not only the Euro, but all non-Euro-Members' currencies as well; vis-à-vis each other, the currencies of the EU 27 retain their value.

[20] In addition, the reduction in non-wage labor costs results in lower unemployment compared to the baseline in both Austria and Poland.

Figure 8. Sensitivity of changes in CO_2 emissions, real GDP, and employment with respect to the exchange rate in 2036



4. Discussion

The most important assumptions, in our opinion, pertain to the model closure (the chosen option, holding the budget deficit constant, tends to lead to more pronounced results, both for expansionary as well as for contracting policies), the exchange rate (we assume this to be fixed) and the exogeneity of technological change. To assess the impact of the first two, we conducted a series of sensitivity analyses.

These analyses showed that, indeed, using a different closure (holding real government consumption constant instead of the budget deficit), leads to more moderate results over the medium term (although in the short term, the differences are much more pronounced). As for the exchange rate, the analysis clearly shows the quite large impact of this variable, although the model is likely to overstate its influence: on the world market, some goods (and many commodities, although in Poland, and much more so in Austria, export of commodities is of minor importance) are priced in dollars; for these, domestic price increases cannot be simply 'devalued away'. ADAGIO, however, cannot distinguish between goods priced in national currencies and those priced in dollars, thus overstating the exchange rates' influence.

The last assumption, the exogeneity of technological change, does not mean that technological change is absent; in fact, it is embedded in the equations describing the factor shares in the sectoral production processes. It is, however, identical between simulations. Though not completely satisfactory, we would argue that this feature is not overly critical due to the following aspects: for one, over the relatively short period investigated here, the potential of carbon prices to appreciably influence technological change is limited, as is the potential for the adoption of climate-friendly products – fossil-fuel powered cars purchased today will mostly be in use in ten years' time. Other technologies (such as buildings and heating systems) have even longer lifetimes. Also, endogenizing technological change is difficult, as it would necessitate some 'elasticity' of energy efficiency (directly, or indirectly via R&D, innovation, and investment) with respect to energy prices – but major progress (in energy efficiency as well as other characteristics) does not follow a linear path but takes a more haphazard development. Indeed, when factoring in technological progress, care has to be taken not to assume such breakthroughs prematurely – the 'hydrogen economy' or the 'bio-based economy' are two such buzzword that probably over-optimistically assume exactly such major breakthroughs.

5. Conclusions

The main conclusions from our analysis relate to four key points.

The first point concerns the use of macro models to analyze policy scenarios, such as carbon pricing policies. Our analysis demonstrates that the results of the simulations are not only contingent on the scenario assumptions (e.g., level of CO_2 price) but are also significantly influenced by the model assumptions (such as the closure applied). This highlights the importance of clear and transparent descriptions of model assumptions.

Secondly, our analysis confirms the efficiency-equity trade-off in the context of carbon pricing with respect to different revenue recycling options (see, e.g., Goulder et al., 2019; Kettner et al., 2024; Kirchner et al., 2019). Climate dividend payments are the only option that can avoid income losses for low-income households (first and second quintiles). However, in terms of macroeconomic effects, climate dividend payments perform much worse than reductions in non-wage labor costs or VAT rates. Probably a mix of various policies – for example, means-testing the climate dividend for households (or subjecting it to personal income tax) – would allow to devote part of the revenues from carbon pricing to other policy options, e.g., reducing non-wage labor costs as the most efficient recycling option from a macro-economic perspective, without completely foregoing the redistributive benefits of the climate dividend.

Thirdly, the results for Austria and Poland highlight that countries facing more severe socio-economic challenges related to decarbonization will need higher support. This is due to an above-average carbon intensity aggravated by weaker economic performance and a lag in industrial structural change. The EU's Just Transition Fund can contribute to mitigating adverse socio-economic impacts of the low-carbon transformation and preventing an intensification of inequalities within and between countries.

A last key aspect is that carbon pricing must be embedded in a broader policy mix to achieve greenhouse gas emission reduction targets: Though it is not directly evident from the modelling results (or, rather, because it is not directly evident, because endogenous technological change is absent from ADAGIO), technological innovation (energy efficiency, low-carbon technologies, green industry transformation) has to be supported, from creating optimal conditions for R&D to fostering the take up of new, more efficient appliances and machinery by industry and households alike, to ensure both ecological effectiveness as well as economic competitiveness.

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Appendix A: Carbon Price Mark-Up by Member State

Table A. 1. CO_2 Tax Rates in EU Member States 2019

	CO_2 tax rate in € 2019	Year of Implementation	Share of GHG covered in % 2019
Finland (Transport)	63	1990	37
Finland (Other)	54		
Poland	1	1990	4
Sweden	119	1991	40
Denmark	23	1992	40
Slovenia	17	1996	24
Ireland	20	2010	48
Estonia	2	2010	3
GB	21	2013	23
France	45	2014	35
Latvia	5	2014	15
Portugal	13	2015	29

Source: World Bank (2019).

Table A. 2. Carbon Price Mark-Ups in the Main Scenario: € 45 constant

	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Sweden	0	0	0	0	0	0	0	0	0	0	0
Finland	0	0	0	0	0	0	0	0	0	0	0
France	0	0	0	0	0	0	0	0	0	0	0
Ireland	0	25	25	25	25	25	25	25	25	25	25
Denmark	0	23	23	23	23	23	23	23	23	23	23
Portugal	0	33	33	33	33	33	33	33	33	33	33
Slovenia	0	29	29	29	29	29	29	29	29	29	29
Latvia	0	40	40	40	40	40	40	40	40	40	40
Estonia	0	43	43	43	43	43	43	43	43	43	43
Poland	0	44	44	44	44	44	44	44	44	44	44
Other MS	0	45	45	45	45	45	45	45	45	45	45

Table A. 3. Carbon Price Mark-Ups in Sensitivity Scenario A: € 180 increasing

	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Sweden	0	0	0	0	0	0	17	29	42	55	67
Finland	0	0	7	22	36	51	66	81	95	110	125
France	0	0	17	32	46	61	76	91	105	120	135
Ireland	0	25	40	55	70	85	100	115	130	145	160
Denmark	0	23	38	53	68	83	98	113	128	143	158
Portugal	0	33	48	63	78	93	108	123	138	153	168
Slovenia	0	29	44	59	74	89	104	119	134	149	164
Latvia	0	40	55	70	85	100	115	130	145	160	175
Estonia	0	43	58	73	88	103	118	133	148	163	178
Poland	0	44	59	74	89	104	119	134	149	164	179
Other MS	0	45	45	45	45	45	45	45	45	45	45

Table A. 4. Carbon Price Mark-Ups in Sensitivity Scenario B: € 180 constant

	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Sweden	0	67	67	67	67	67	67	67	67	67	67
Finland	0	125	125	125	125	125	125	125	125	125	125
France	0	135	135	135	135	135	135	135	135	135	135
Ireland	0	160	160	160	160	160	160	160	160	160	160
Denmark	0	158	158	158	158	158	158	158	158	158	158
Portugal	0	168	168	168	168	168	168	168	168	168	168
Slovenia	0	164	164	164	164	164	164	164	164	164	164
Latvia	0	175	175	175	175	175	175	175	175	175	175
Estonia	0	178	178	178	178	178	178	178	178	178	178
Poland	0	179	179	179	179	179	179	179	179	179	179
Other MS	0	180	180	180	180	180	180	180	180	180	180

Table A. 5. Carbon Price Mark-Ups in Sensitivity Scenario C: € 300 increasing

	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
Sweden	0	0	0	22	46	69	93	117	140	164	187
Finland	0	25	49	74	98	123	147	172	196	221	245
France	0	35	59	84	108	133	157	182	206	231	255
Ireland	0	60	84	109	133	158	182	207	231	256	280
Denmark	0	58	82	107	131	156	180	205	229	254	278
Portugal	0	68	93	117	141	166	190	215	239	264	288
Slovenia	0	64	88	113	137	162	186	211	235	259	284
Latvia	0	75	99	124	148	173	197	222	246	270	295
Estonia	0	78	103	127	152	176	201	225	249	274	298
Poland	0	79	104	128	153	177	201	226	250	275	299
Other MS	0	80	104	129	153	178	202	227	251	276	300

Appendix B: Additional Results on CO_2 Emissions for the Main Carbon Pricing Scenario

Figure B. 1. Changes in final emissions in the main scenario by recycling option compared to the reference scenario

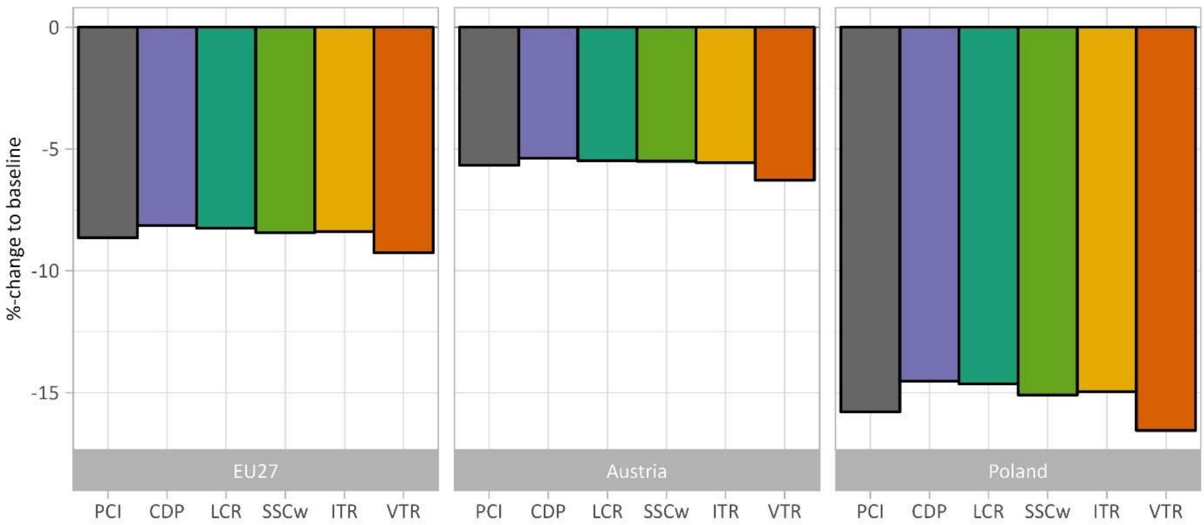
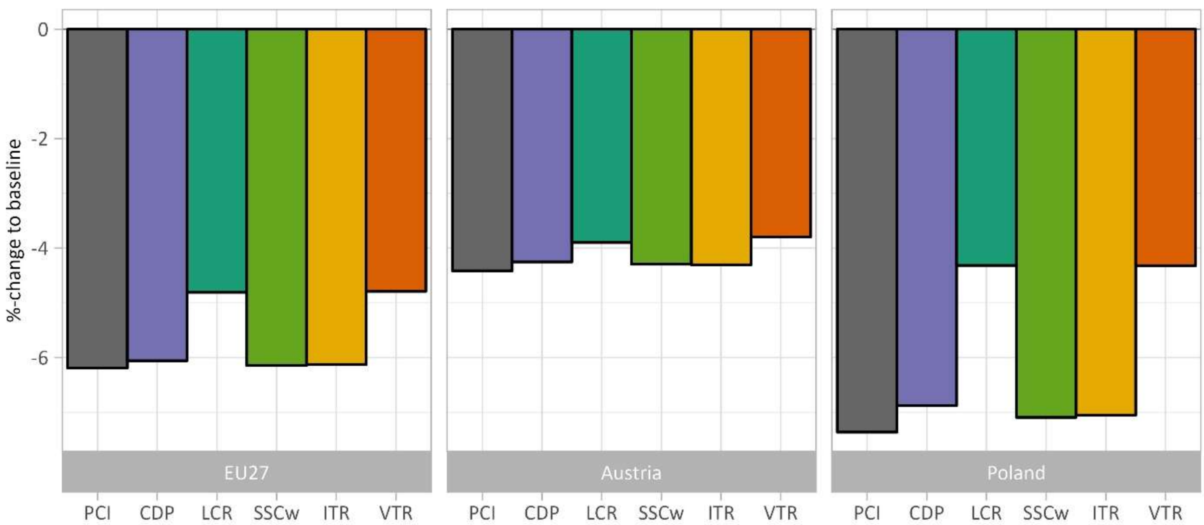


Figure B. 2. Changes in intermediate emissions in the main scenario by recycling option compared to the reference scenario



Appendix C: Additional Macroeconomic Results for the Main Carbon Pricing Scenario

Figure C. 1. Changes in the Consumer Price Index in the main scenario by recycling option compared to the reference scenario

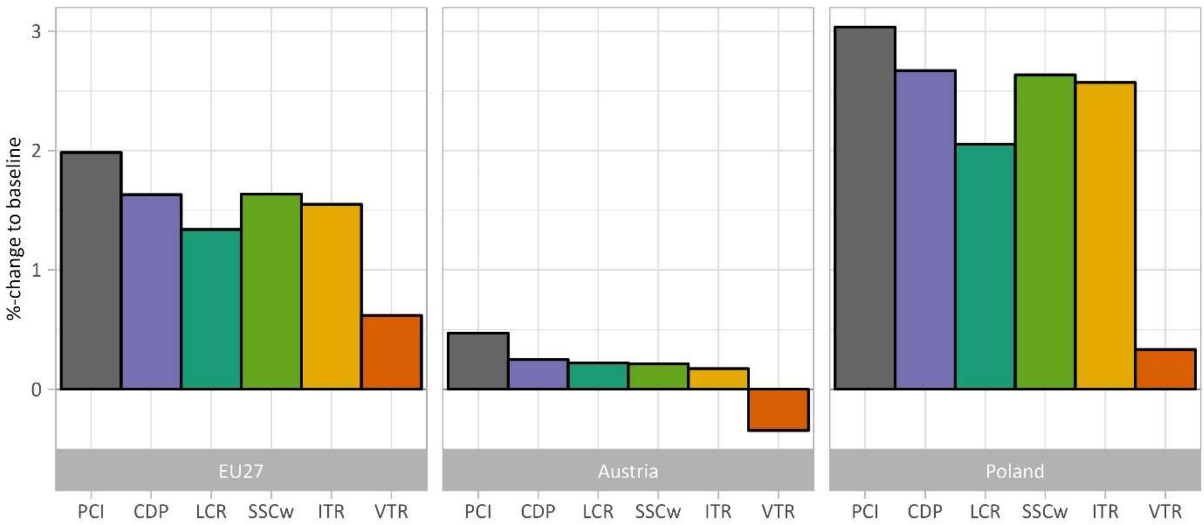


Figure C. 2. Changes in exports in the main scenario by recycling option compared to the reference scenario

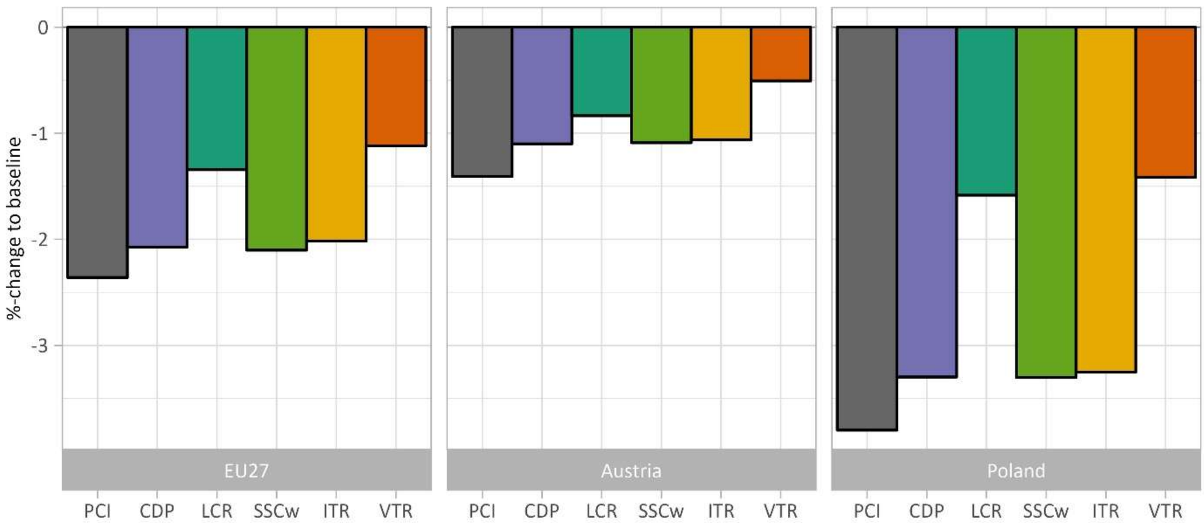


Figure C. 3. Changes in unemployment in the main scenario by recycling option compared to the reference scenario

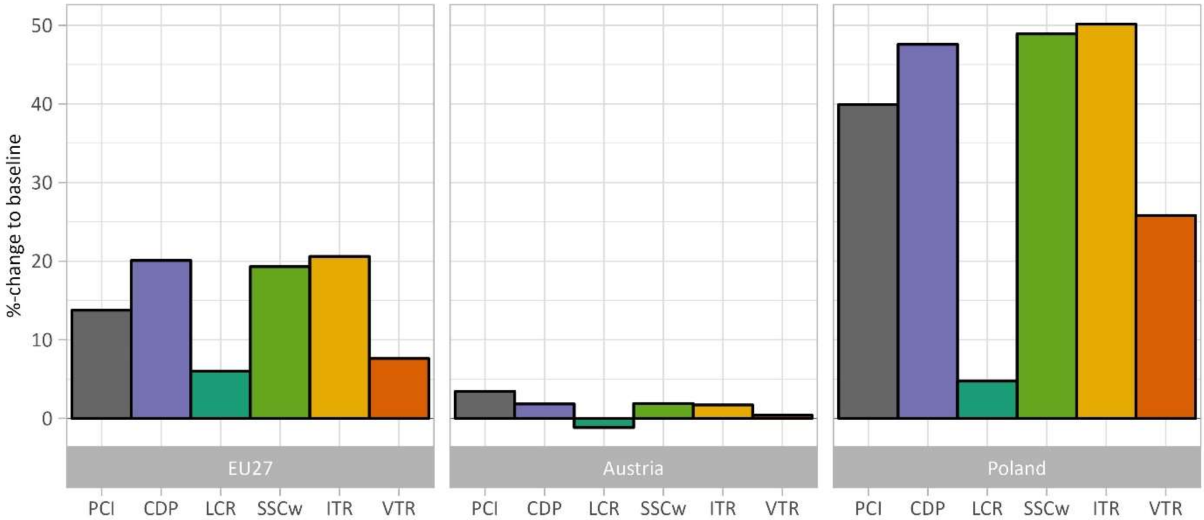


Figure C. 4. Changes in labor supply in the main scenario by recycling option compared to the reference scenario