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Abstract

Unilateral climate policy suffers from carbon leakage, i.e. the (partial) offset of the initial emission reduction by increases in other countries. Different than most typically discussed climate policies, degrowth not only aims at reducing the fossil fuel use in an economy, but rather at a reduction of all factor inputs, which may lead to different leakage implications. We conduct the first investigation of degrowth in a multi-country setting in order to (i) compare the leakage effects of national pure emission reduction policies to degrowth scenarios, (ii) identify underlying channels by decomposing the implied emission changes into scale, composition, and technique effects, and (iii) investigate which country characteristics determine degrowth's relative effectiveness to overcome the leakage problem. Using a structural gravity model, we find that degrowth indeed significantly reduces leakage by keeping the sectoral composition of the country more stable and reducing uncommitted countries' incentives to shift towards more energy-intensive production techniques. The higher effectiveness of degrowth in reducing carbon emissions is most pronounced for small and trade-open economies with comparatively clean production technologies.

JEL-Codes: F180, Q540, Q570.

Keywords: degrowth, climate policy, gravity model, carbon leakage.

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1 Introduction

The relationship between unilateral climate policy and international trade has been of major interest in the last years. The focus of attention has been on carbon leakage. Leakage occurs if emission reductions in one country are offset by emission increases elsewhere (Felder and Rutherford, 1993). It mainly works through two channels: First, stricter climate policy in one country will lead to higher carbon prices (e.g. through carbon certificates, taxes, or regulations). This will make carbon-intensive production relatively more expensive in that country. In response, production in strongly affected sectors may relocate to other countries with laxer climate policy and increase emissions there. Carbon-intensive goods can then be redistributed to the first country via international trade. Second, stricter climate policy in one country will lead to lower energy demand. This in turn leads to a fall of the price for energy on the world market. In response, other countries may use more energy in production relative to other factor inputs and hence increase emissions. In this case, climate policy leads to an adjustment of energy intensities via the international energy market (see e.g. McAusland and Najjar, 2015).

The obvious and ideal solution to overcome carbon leakage is a globally coordinated climate policy which involves all countries. The Paris Climate Agreement marks an important step in this direction. However, past negotiations have highlighted the difficulty to coordinate and enforce targets on a global level. The Paris Agreement relies on targets which are individually determined and not internationally enforceable. If some countries fail to submit or fulfil their targets, sub-global initiatives will prevail. Hence, a better understanding of unilateral action remains important.

Besides global climate policies, an instrument that may be capable of reducing carbon leakage is degrowth. Degrowth has been proposed by a growing group of authors as a policy alternative to more conventional measures such as pure emission targets.[1] As a climate policy, degrowth implies not only an emission reduction, but also the downscaling of the economy as a whole. In particular, degrowth is often assumed to restrict the quantity of available factor inputs (e.g. working time, natural resources and land). With restricted factor inputs, production will be reduced. Since degrowth additionally decreases income via lower total factor income and hence demand for products, the decline in carbon-intensive production due to stricter policy is less likely to be compensated by an increase in production abroad. Degrowth can therefore potentially limit leakage.

The interest in degrowth and related fields (such as steady-state economics, ecological macroeconomics, prosperity/managing without growth, and Postwachstum, sometimes jointly summarised as post-growth) has considerably grown during recent years. Contributions to these fields are diverse. There is no single account of what exactly degrowth means and what precise policies would follow from it (see e.g. van den Bergh, 2011).[2] Regarding climate policy, what is common to most authors is that they argue for at least a temporary downscaling or stabilisation of the economy as a whole. Due to the high degree of coupling between economic activity and environmental impact, degrowth is seen as a necessary measure to reduce and stabilise the economic impact on the environment (see e.g. Schneider,

[1]Some of the key contributions to the degrowth literature are e.g. Victor (2008); Jackson (2009); Paech (2012); Dietz and O'Neill (2013); D'Alisa, Demaria, and Kallis (2014). The current degrowth literature is strongly inspired by the seminal works of Daly (1972, 1996); Georgescu-Roegen (1971, 1977); Meadows, Meadows, Randers, and Behrens III (1972). For recent degrowth literature surveys, see e.g. Weiss and Cattaneo (2017); Hardt and O'Neill (2017); Urhammer and Røpke (2013); Kallis, Kerschner, and Martinez-Alier (2012); Martínez-Alier, Pascual, Vivien, and Zaccai (2010).

[2]Degrowth generally argues for a broader set of social and political goals based on a deeper transformation of the social and economic system as a whole. Some of the more common goals include the reduction of poverty, full employment, the reduction of wealth and income inequality, the promotion of international cooperation, and the development of new economic indicators of human well-being (see e.g. Victor, 2008; Jackson, 2009; Dietz and O'Neill, 2013; D'Alisa, Demaria, and Kallis, 2014).

Kallis, and Martinez-Alier, 2010; Kallis, 2011; Research & Degrowth, 2010).

A number of degrowth studies are based on the LowGrow model by Victor and Rosenbluth (2007) and Victor (2008, 2012), or the SIGMA and FALSTAFF models developed by Jackson, Drake, Victor, Kratena, and Sommer (2014), Naqvi (2015), Jackson and Victor (2015, 2016), and Jackson, Victor, and Naqvi (2016). LowGrow results suggest that degrowth can substantially decrease emissions for Canada and at the same time improve welfare in terms of poverty, inequality, adult literacy, and longevity when appropriately adjusting tax rates and public spending on health care and education. Similar results have been obtained when the model was applied to the German, French, and Swedish economy (see Gran (2017); Briens and Maïzi (2014a,b); and Malmaeus (2011), respectively). SIGMA- and FALSTAFF-based studies show that declining growth rates need not lead to higher inequality (Jackson and Victor, 2016) and that zero growth can be stable in the presence of interest-bearing debt (Jackson and Victor, 2015).

All of these studies rely on a single-economy model. We therefore take a complementary approach to previous studies by investigating degrowth scenarios in a multi-country general equilibrium framework. Specifically, we use the extended version of the structural gravity model developed by Larch and Wanner (2015).[3] This model incorporates a sectoral production structure with varying energy-intensities. A trade model with such a sectoral structure is well suited to capture the first, trade-driven leakage channel. The additional inclusion of a separate energy sector in which prices can adjust endogenously and which uses an internationally tradable energy resource (such as oil or other kinds of fossil fuels) allows to take into account the second, energy-market, leakage channel. Different from classical quantitative trade gravity models,[4] this model also includes two

[3]Note that we actually use an updated draft of Larch and Wanner (2015) which is currently under review and available from the authors upon request.

[4]See Eaton and Kortum (2002) and Anderson and van Wincoop (2003) for seminal contri-

economy-environment feedback channels. One channel works through the production structure which uses energy as an input factor and generates emission as a side output. The other channel works through the utility function in which higher global emission levels negatively affect welfare. While we hold this model structure to be well suited to consider the trade and leakage effects of degrowth policies, it restrains us from considering a number of other interesting questions related to degrowth, such as distributional consequences within countries, alternative welfare indicators, or questions related to the monetary system.

The goal of this paper is to investigate how the embedding of a country into the world economy affects the consequences of national degrowth policies. To this aim, we compare a pure emission reduction policy in which the policy country only reduces its energy use to degrowth scenarios in which it also reduces other factor usages. We investigate the emission effects in both the policy country and all other countries, additionally making use of a decomposition of emission effects into scale, composition, and technique effects. Further, we try to identify the driving factors that determine in which macroeconomic circumstances the differences between pure energy reduction scenarios and degrowth policies are particularly pronounced.

Our main result is that degrowth can substantially limit leakage compared to pure energy reduction policies. Reducing all national factors rather than only curbing energy use cuts the median leakage rate to about a quarter (6.67%) of the energy reduction scenario median leakage rate (25.87%). When additionally reducing the supply of energy resources to the international market, degrowth implies even negative median leakage rates (−9.59%), i.e. the reduction in carbon emissions achieved in the policy country is reinforced by other countries' reactions to the policy. Degrowth in terms of national production factors mainly works by limiting the large compositional changes that go in hand with pure energy reduc-

butions in the field and Head and Mayer (2014) for a survey.

tion policies, i.e. degrowth eliminates the shift towards imports of dirty products in the policy country. When including a reduction of the energy resource supply to the world market, degrowth additionally acts strongly via the technique effect. As the world supply of energy resources is shortened, non-policy countries no longer face the incentive to increase the energy-intensity of their production. Regarding the macroeconomic context of climate policy, we find that degrowth reduces leakage in almost all countries, but can be most effective compared to the pure energy reduction scenario when implemented in small, trade-open and clean countries. However, the reduction in leakage rates comes at the cost of substantially larger welfare losses in our model structure.

The remainder of this paper is organised as follows. Section 2 introduces the structural gravity model with energy production by Larch and Wanner (2015) and the decomposition of the total emission effect and demonstrates how the different emission reduction and degrowth scenarios can be implemented in this framework. Section 3 describes the data set. Section 4 discusses the results of the counterfactual analysis. Section 5 concludes.

2 Structural Gravity with Energy Production

This section introduces the multi-country, multi-sector, multi-factor structural gravity model by Larch and Wanner (2015). Specifically, we use the extended version of the model which incorporates energy production in order to allow for leakage effects via the international energy market.

2.1 Supply Side

On the supply side, the model incorporates one non-tradable goods sector S, a set $\mathcal{L}$ of L tradable goods sectors and a separate energy sector in each of the

N countries. Input factors are skilled and unskilled labour, capital, land, natural resources, jointly summarised in set $\mathcal{F}$, energy E, and international energy resource R. Sectoral production is modelled by Cobb-Douglas production functions:

$$q_l^i = A_l^i (E_l^i)^{\alpha_{lE}^i} \prod_{f \in \mathcal{F}} (V_{lf}^i)^{\alpha_{lf}^i}, \tag{1}$$

$$q_S^i = A_S^i (E_S^i)^{\alpha_{SE}^i} \prod_{f \in \mathcal{F}} (V_{Sf}^i)^{\alpha_{Sf}^i}. \tag{2}$$

The energy sector is neither part of the non-tradable nor tradable goods sectors. It has a separate production function given by:

$$E^i = A_E^i (R^i)^{\xi_R^i} \prod_{f \in \mathcal{F}} (V_{Ef}^i)^{\xi_f^i}. \tag{3}$$

Here and throughout this paper, model variables and parameters are country-, sector- and factor-specific. Let countries be denoted by superscript i, sectors by subscript S, l and E, and factors by subscript f, E and R.[5] For example, q_l^i denotes output in sector l in country i. V_{lf}^i denotes the use of factor $f \in \mathcal{F}$ in sector l in country i. Similarly, A_l^i is a sector- and country-specific productivity parameter. R^i is the use of the internationally freely tradable energy resource with exogenous global supply R^W as in Egger and Nigai (2015). E^i denotes the total energy output, while E_l^i denotes the sector specific energy input. Note that energy and emissions are denoted by the same variable. Given the very high correlation between energy use and emissions (cf. e.g. Egger and Nigai, 2015), they are assumed to be directly proportional. According to the Cobb-Douglas structure, the α and ξ parameters denote factor cost shares in production, with $\alpha_{lE}^i + \sum_{f \in \mathcal{F}} \alpha_{lf}^i = 1$, $\alpha_{SE}^i + \sum_{f \in \mathcal{F}} \alpha_{Sf}^i = 1$, and $\xi_R^i + \sum_{f \in \mathcal{F}} \xi_f^i = 1$.

[5] Whenever necessary, additional superscripts j and k are used for countries, subscript m for tradable sectors, and subscript g for factors.

All factors except R^i are national factors. They are assumed to be internationally immobile between countries, but perfectly mobile between sectors in the same country. By contrast, R^i is an international factor and perfectly mobile between countries. All factor prices adjust endogenously. Cost minimization together with factor market clearing then leads to the following expressions for prices of products (p_l^i), factors (v_l^i), energy (e^i), and the international energy resource (r), respectively:

$$p_l^i = \frac{c_l^i(e^i, v_f^i, \bar{q}_l^i)}{\bar{q}_l^i} = \frac{1}{A_l^i}\left(\frac{e^i}{\alpha_{lE}^i}\right)^{\alpha_{lE}^i} \prod_{f \in \mathcal{F}} \left(\frac{v_f^i}{\alpha_{lf}^i}\right)^{\alpha_{lf}^i}, \tag{4}$$

$$v_f^i = \frac{(\alpha_{Sf}^i + \xi_f^i \alpha_{SE}^i) Y_S^i + \sum_{l \in \mathcal{L}} (\alpha_{lf}^i + \xi_f^i \alpha_{lE}^i) Y_l^i}{V_f^i}, \tag{5}$$

$$e^i = \frac{1}{A_l^i}\left(\frac{r}{\xi_R^i}\right)^{\xi_R^i} \prod_{f \in \mathcal{F}} \left(\frac{v_f^i}{\xi_f^i}\right)^{\xi_f^i} = \frac{\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i}{E^i}, \tag{6}$$

$$r = \frac{1}{R^W} \sum_{i=1}^{N} \xi_R^i \left(\alpha_{SE}^i Y_S^i + \sum_{l \in \mathcal{L}} \alpha_{lE}^i Y_l^i\right), \tag{7}$$

where $Y_l^i \equiv p_l^i q_l^i$ and $Y_S^i \equiv p_S^i q_S^i$ denote the sectoral values of production.

2.2 Demand Side

Consumers are assumed to obtain utility according to the following utility function:

$$U^j = (U_S^j)^{\gamma_S^j} \left[\prod_{l \in \mathcal{L}} (U_l^j)^{\gamma_l^j}\right] \left[\frac{1}{1 + (\frac{1}{\mu^j} \sum_{i=1}^{N} E^i)^2}\right], \tag{8}$$

with

$$U_l^j = \left[\sum_{i=1}^{N} (\beta_l^i)^{\frac{1-\sigma_l}{\sigma_l}} (q_l^{ij})^{\frac{\sigma_l - 1}{\sigma_l}} \right]^{\frac{\sigma_l}{\sigma_l - 1}}, \tag{9}$$

which combines (i) upper-tier Cobb-Douglas utility across sectors, (ii) linear utility from non-tradable consumption, (iii) CES utility from tradable consumption (with sectoral elasticity of substitution σ_l), and (iv) multiplicative damages from carbon emissions. The latter follows the specification of Shapiro (2016) as to ensure an almost constant social cost of carbon and is assumed to be a pure externality as in Shapiro and Walker (2015), implying that consumers do not take into account the social costs of carbon when making consumption choices.[6]

Consumers earn income from factor inputs including the country's international energy resource supply. Total income in country j is given by:

$$Y^j = \sum_{f \in \mathcal{F}} v_f^j V_f^j + \omega^j r R^W, \tag{10}$$

where ω^j is the share in the world resource endowment of country j. Due to the homothetic utility function, the consumers' maximization problem can be expressed in terms of a representative consumer who maximises U^j in (8) subject to a budget constraint given by:

$$Y^j = p_S^j q_S^j + \sum_{l \in \mathcal{L}} \sum_{i=1}^{N} p_l^{ij} q_l^{ij}. \tag{11}$$

[6]This model integrates only one feedback channel from the environment to the economy via dis-utility from global emissions. A more complete approach would also take into account feedback from the environment on production. For example, higher emission may negatively affect productivity and factor endowments and ultimately income potentials (see e.g. Nordhaus and Boyer, 2000; Tol, 2009). In the degrowth literature, see e.g. Naqvi (2015), Taylor, Rezai, and Foley (2016), and Dafermos, Nikolaidi, and Galanis (2017), where rising emission levels decrease labour productivity and destroy capital stocks due to a damage function.

The budget constraint ensures that total expenditure in country j, $\mathfrak{X}^j$, is equal to the total spending on varieties from all sectors and countries, including j, at delivered consumer prices, p_l^{ij}.

Demand in country j for goods from country i in tradable sector l is then given by:

$$q_l^{ij} = \left(\frac{\beta_l^i p_l^{ij}}{P_l^j} \right)^{-\sigma_l} \left(\frac{\beta_l^i \mathfrak{X}_l^j}{P_l^j} \right), \tag{12}$$

where $\mathfrak{X}_l^j \equiv \gamma_l^j \mathfrak{X}^j$ denotes sectoral expenditure and P_l^j is the sectoral price index defined as:

$$P_l^j = \left[\sum_{i=1}^{N} (\beta_l^i p_l^{ij})^{1-\sigma_l} \right]^{\frac{1}{1-\sigma_l}}. \tag{13}$$

2.3 Trade Flows

Bringing supply and demand together, we can derive a gravity equation for bilateral trade flows. Introducing iceberg trade costs (with $T_l^{ij} = T_l^{ji} \geq 1$ and $T_l^{ii} = 1$), the value of exports from i to j in sector l can be obtained from (12) as

$$X_l^{ij} = p_l^i q_l^{ij} T_l^{ij} = \left(\frac{\beta_l^i p_l^i T_l^{ij}}{P_l^j} \right)^{1-\sigma_l} \mathfrak{X}_l^j. \tag{14}$$

Assuming market clearing and multilaterally balanced trade, additionally defining world income as $Y^W = \sum_{i=1}^{N} Y^j$ and world income and production shares as $\theta^j = Y^j / Y^W$ and $\theta_l^j = Y_l^j / Y^W$, respectively, bilateral trade flows are given by

$$X_l^{ij} = \frac{\gamma_l^j Y^j Y_l^i}{Y^W} \left(\frac{T_l^{ij}}{\Pi_l^i P_l^j} \right)^{1-\sigma_l}, \tag{15}$$

where

$$(\Pi_l^i)^{1-\sigma_l} = \sum_{j=1}^{N} \left(\frac{T_l^{ij}}{P_l^j} \right)^{1-\sigma_l} \gamma_l^j \theta^j, \tag{16}$$

$$(P_l^j)^{1-\sigma_l} = \sum_{i=1}^{N} \left(\frac{T_l^{ij}}{\Pi_l^i} \right)^{1-\sigma_l} \theta_l^i. \tag{17}$$

The structural terms Π_l^j and P_l^j, coined by Anderson and van Wincoop (2003) as outward and inward multilateral resistance terms, are theoretical constructs and not directly observable. However, any theory-consistent gravity estimation takes these terms into account. They capture the idea that in a multi-country setting, bilateral trade flows are affected not simply by absolute bilateral trade barriers, but by an aggregate trade resistance that each country faces with all its trading partners.[7]

2.4 Solving the Baseline Model

The baseline serves as a benchmark for comparison with the counterfactual policy scenarios. Baseline values are calculated by fitting the model as closely as possible to the given data. To solve the baseline, factory-gate prices have to be obtained first. All other values of interest can then be calculated. Let the additional subscripts b and c denote the baseline and counterfactual case, respectively. There is no need to solve for the preference parameter β_l^i. We can simply define scaled equilibrium prices as $\psi_{l,b}^i = (\beta_l^i p_{l,b}^i)^{1-\sigma_l}$. Rewriting the market clearing condition for each tradable sector $Y_{l,b}^i = \sum_{j=1}^{N} X_{l,b}^{ij}$ in the baseline, inserting exports (14) and the sectoral price index (13) gives the following expression for sectoral baseline

[7]For an extensive discussion of the concept of multilateral resistance, see e.g. Yotov, Piermartini, Monteiro, and Larch (2016)

income:

$$Y_{l,b}^i = \psi_{l,b}^i \sum_{j=1}^N \frac{(\hat{T}_l^{ij})^{1-\sigma_l}}{\sum_{k=1}^N \psi_{l,b}^k (\hat{T}_l^{kj})^{1-\sigma_l}} \gamma^j Y_b^j. \tag{18}$$

Given data for income and production and values for the expenditure shares and sectoral elasticities of substitution, we only need to estimate trade costs to be able to solve for scaled equilibrium prices.[8]

To estimate trade costs, we use the gravity equation derived above, approximating trade costs as a function of observable characteristics $T_l^{ij} = \exp((\boldsymbol{z}^{ij})'\mathbf{b}_l)$, adding a multiplicative stochastic error term ε_l^{ij}, and pooling all exporter- and importer-specific variables ($n_l^i = Y_l^i (\Pi_l^i)^{\sigma_l - 1}$ and $m_l^j = \gamma_l^j Y^j (P_l^j)^{\sigma_l - 1}$, respectively):

$$X_l^{ij} = \frac{1}{Y^W} \exp((\boldsymbol{z}^{ij})'\boldsymbol{\delta}_l) n_l^i m_l^j \varepsilon_l^{ij}, \tag{19}$$

where $\boldsymbol{\delta}_l = \boldsymbol{b}_l(1 - \sigma_l)$. To estimate this expression, we use the Poisson Pseudo-Maximum-Likelihood estimator as proposed by Santos Silva and Tenreyro (2006) where n_l^i and m_l^j are captured by importer and exporter fixed effects.

2.5 Solving the Counterfactual Model

One important feature of structural gravity is that it allows to conduct counterfactual policy analysis. We evaluate three counterfactual policy scenarios: (i) a pure emission reduction target (henceforth referred to as the "pure scenario"), (ii) a degrowth scenario in which all national factors of production are reduced (henceforth "simple degrowth"), and (iii) a more comprehensive degrowth scenario in which

[8] Note that even with estimated trade costs, the system of equations is only solvable up to scalar. If $\psi_{l,b}^i$ is a solution, so is $\lambda\psi_{l,b}^i$. A unique solution requires normalisation for each sector by a numéraire country (Anderson and Yotov, 2016; Yotov, Piermartini, Monteiro, and Larch, 2016). By choice, we set scaled equilibrium prices in Albania equal to one in all tradable sectors. The choice of normalisation does not affect our reported results.

additionally the country's supply of energy resources to the international market is lowered (henceforth "full degrowth"). To make them more comparable, we choose the same hypothetical reduction rate of ten percent for all three scenarios. We simulate each policy for each of the 128 countries in our dataset, amounting to a total of $128 \times 3 = 384$ simulated scenarios. In each case, the policy is assumed to be implemented unilaterally in one of the countries without the participation of others. In the extended version of their model used in this paper, Larch and Wanner (2015) only consider counterfactual scenarios in which the only policy change is a tariff introduction. We therefore show how emission targets can be implemented in this framework and how this approach can be extended to allow for additional reductions of other production factors. When solving the counterfactual model, we need to distinguish between committed and uncommitted countries. While the committed country implements one of the three policy scenarios, all other uncommitted countries follow no climate policy and can endogenously adjust to the policy changes in the committed country.

2.5.1 Uncommitted Countries

Irrespective of the specific policy scenario chosen by the committed country, the system of equations for the uncommitted countries that has to be solved jointly with the equations corresponding to the policy country are the following five expressions for sectoral production values, the international resource price, national income, the change in scaled equilibrium prices, and national energy prices, respectively:[9]

$$Y^i_{l,c} = \psi^i_{l,c} \sum_{j=1}^{N} \frac{(\hat{T}^{ij}_l)^{1-\sigma_l}}{\sum_{k=1}^{N} \psi^k_{l,c} (\hat{T}^{kj}_l)^{1-\sigma_l}} \gamma^j_l Y^j_c, \tag{20}$$

$$r_c = \frac{1}{R^W_c} \sum_{i=1}^{N} \xi^i_R \left(\alpha^i_{SE} \gamma^i_S Y^i_c + \sum_{l \in \mathcal{L}} \alpha^i_{lE} Y^i_{l,c} \right), \tag{21}$$

$$\begin{aligned} Y^i_c = & \sum_{f \in \mathcal{F}} \left[(\alpha^i_{Sf} + \xi^i_f \alpha^i_{SE}) \gamma^i_S Y^i_c + \sum_{l \in \mathcal{L}} (\alpha^i_{lf} + \xi^i_f \alpha^i_{lE}) Y^i_{l,c} \right] \\ & + \omega^i_c \sum_{j=1}^{N} \xi^j_R \left(\alpha^j_{SE} \gamma^j_S Y^j_c + \sum_{l \in \mathcal{L}} \alpha^j_{lE} Y^j_{l,c} \right), \end{aligned} \tag{22}$$

$$\begin{aligned} \left(\frac{\psi^i_{l,c}}{\psi^i_{l,b}} \right)^{\frac{1}{\sigma_l - 1}} = & \left(\frac{e^i_b}{e^i_c} \right)^{\alpha^i_{lE}} \times \\ & \prod_{f \in \mathcal{F}} \left(\frac{(\alpha^i_{Sf} + \xi^i_f \alpha^i_{SE}) Y^i_{S,b} + \sum_{m \in \mathcal{L}} (\alpha^i_{mf} + \xi^i_f \alpha^i_{mE}) Y^i_{m,b}}{(\alpha^i_{Sf} + \xi^i_f \alpha^i_{SE}) \gamma^i_S Y^i_c + \sum_{m \in \mathcal{L}} (\alpha^i_{mf} + \xi^i_f \alpha^i_{mE}) Y^i_{m,c}} \right)^{\alpha^i_{lf}}, \end{aligned} \tag{23}$$

$$e^i_c = e^i_b \left(\frac{r_c}{r_b} \right)^{\xi^i_R} \prod_{f \in \mathcal{F}} \left[\frac{(\alpha^i_{Sf} + \xi^i_f \alpha^i_{SE}) \gamma^i_S Y^i_c + \sum_{l \in \mathcal{L}} (\alpha^i_{lf} + \xi^i_f \alpha^i_{lE}) Y^i_{l,c}}{(\alpha^i_{Sf} + \xi^i_f \alpha^i_{SE}) Y^i_{S,b} + \sum_{l \in \mathcal{L}} (\alpha^i_{lf} + \xi^i_f \alpha^i_{lE}) Y^i_{l,b}} \right]^{\xi^i_f}. \tag{24}$$

2.5.2 The Committed Country

For the committed country, some of these equations change due to the policy restrictions. Let τ^i denote the reduction factor in country i. Given our hypothetical ten-percent target, $\tau^i = 0.9$ for the committed country.

Pure Emission Reduction Target. Since emissions are assumed to be perfectly correlated with the use of energy, the emission reduction target directly translates into an energy reduction. Energy usage is then no longer endogenous. Instead

[9]Note that the expressions for uncommitted countries are equivalent to those obtained by Larch and Wanner (2015). We therefore refer the interested reader to their work for details on the derivations.

of using (24), energy prices can therefore be obtained directly from solving the energy market clearing condition in the counterfactual:

$$e^i_c = \frac{\alpha^i_{SE}\gamma^i_S Y^i_c + \sum_{l\in\mathcal{L}} \alpha^i_{lE} Y^i_{l,c}}{\bar{E}^i_c}, \tag{25}$$

where the amount of energy, $\bar{E}^i_c = \tau^i E^i_b$, is now counterfactually constrained. For pure reduction target scenarios, we then jointly solve equations (20) to (23) for all countries, (25) for the committed country and (24) for uncommitted countries. International energy resource supplies stay constant, i.e. $\omega^i_c = \omega^i_b$ and $R^W_c = R^W_b$.

Simple Degrowth. Simple degrowth restricts emissions as well as the available quantity of the other national factors of production. Factor endowments are then no longer constant to the baseline but are instead counterfactually reduced, i.e. $V^i_{f,c} = \tau^i V^i_{f,b}$. This implies an additional change in the equation for scaled equilibrium prices (23), which for the committed country is then given by:

$$\begin{aligned}\left(\frac{\psi^i_{l,c}}{\psi^i_{l,b}}\right)^{\frac{1}{\sigma_l - 1}} &= \tau^i \left[\left(\frac{\alpha^i_{SE} Y^i_{S,b} + \sum_{l\in\mathcal{L}} \alpha^i_{lE} Y^i_{l,b}}{\alpha^i_{SE}\gamma^i_S Y^i_c + \sum_{l\in\mathcal{L}} \alpha^i_{lE} Y^i_{l,c}}\right)\right]^{\alpha^i_{lE}} \times \\ &\prod_{f\in\mathcal{F}} \left[\frac{(\alpha^i_{Sf} + \xi^i_f \alpha^i_{SE}) Y^i_{S,b} + \sum_{m\in\mathcal{L}} (\alpha^i_{mf} + \xi^i_f \alpha^i_{mE}) Y^i_{m,b}}{(\alpha^i_{Sf} + \xi^i_f \alpha^i_{SE})\gamma^i_S Y^i_c + \sum_{m\in\mathcal{L}} (\alpha^i_{mf} + \xi^i_f \alpha^i_{mE}) Y^i_{m,c}}\right]^{\alpha^i_{lf}}.\end{aligned} \tag{26}$$

As for the pure scenario, international energy resources remain constant ($\omega^i_c = \omega^i_b$ and $R^W_c = R^W_b$).

Full Degrowth. In addition to simple degrowth, full degrowth also restricts the committed country's international energy resource supply and hence reduces its world resource share, ω^i. This leads to two further changes. First, national energy resource shares are now given by

$$\omega_c^i = \frac{\tau^i \omega_b^i}{\sum_j^N \tau^j \omega_b^j}, \tag{27}$$

with $\tau^i = 1$ for all uncommitted countries. Second, the world energy resource supply reduces to:

$$R_c^W = \left(1 - (1 - \tau^{pol})\omega_b^{pol}\right) R_b^W, \tag{28}$$

where the *pol* subscript denotes the specific committed (i.e. policy) country.

2.5.3 Decomposition of the Emission Effects

One of the advantages of the model by Larch and Wanner (2015) is that it allows to decompose the emission changes. Defining the total nominal value of production as $\tilde{Y}^i \equiv Y_S^i + \sum_{l \in \mathcal{L}} Y_l^i$, sectoral production shares as $\kappa_S^i \equiv Y_S^i / \tilde{Y}^i$ and $\kappa_l^i \equiv Y_l^i / \tilde{Y}^i$, and the production-share-weighted average energy intensity as $\bar{\alpha}_E^i \equiv \alpha_{SE}^i \kappa_S^i + \sum_{l \in \mathcal{L}} \alpha_l^i \kappa_l^i$, total emissions can be expressed as follows:

$$E^i = \bar{\alpha}_E^i \frac{\tilde{Y}^i}{P^i} \left(\frac{e^i}{P^i}\right)^{-1}. \tag{29}$$

Taking the total differential yields the decomposition of emission changes into scale, composition, and technique effects:

$$dE^i = \underbrace{\frac{\bar{\alpha}_E^i}{e^i/P^i} \times d(\tilde{Y}^i/P^i) +}_{\text{scale effect}} \underbrace{\frac{\tilde{Y}^i}{e^i} \times d\bar{\alpha}_E^i}_{\text{composition effect}} + \underbrace{\frac{-\bar{\alpha}_E^i \tilde{Y}^i/P^i}{(e^i/P^i)^2} \times d(e^i/P^i)}_{\text{technique effect}}. \tag{30}$$

To obtain an index of the relative importance of each effect, we also refer to the shares of the absolute values of the three effects in the overall emission change (e.g.

the share of the scale effect (SE) is calculated as $|SE|/(|SE| + |CE| + |TE|)$.

This decomposition relies on total differentials and is therefore a linear approximation around the baseline values. This approximation may not be reasonable for large overall emission changes. In these cases, we follow Larch and Wanner (2015) and use their log-change decomposition.

3 Data

We rely on the data set constructed and used by Larch and Wanner (2015). The main source is the Global Trade Analysis Project (GTAP) 8 database (Narayanan, Aguiar, and McDougall, 2012). The database comprises data for $N = 128$ countries covering all countries in the world. This implies $128 \times 127 = 16,256$ bilateral country pairs for trade data excluding intra-national trade flows. The data is given for 57 sectors, which are aggregated to one non-tradable and $L = 14$ tradable sectors. As GTAP 8 uses 2007 as its most recent reference year, the whole data set is constructed as a cross-section for this year.

The GTAP data is combined with additional bilateral data on regional trade agreements (Egger and Larch, 2008) and geographic variables (Head, Mayer, and Ries, 2010) for the gravity estimation. Additional data for the calibration of the dis-utility parameter for carbon emissions is taken from the Interagency Working Group on the Social Cost of Carbon (2013), Nordhaus and Boyer (2000), and the Penn World Tables 9.0. Further details on the data set as well as descriptive statistics are given in Larch and Wanner (2015).

4 Results

4.1 Carbon Leakage

The most important result of our counterfactual analysis is the distribution of leakage rates, as shown in figure (1). Note that the text labels always denote the committed country associated with each result.[10] Table (1) additionally reports key summary statistics. Leakage is on average considerably lower in degrowth than in the pure scenario. Simple degrowth limits the mean leakage rate to about a third (10.76%) of the pure scenario rate (29.52%). The median leakage rate is even cut to a fourth (6.67%) of the pure scenario rate (25.87%). Full degrowth has on average even negative leakage rates (−26.56%), implying that the initial emission reductions are amplified by additional reductions in other countries. The median, which is less affected by the extreme outliers in full degrowth, is still below zero (−9.59%).

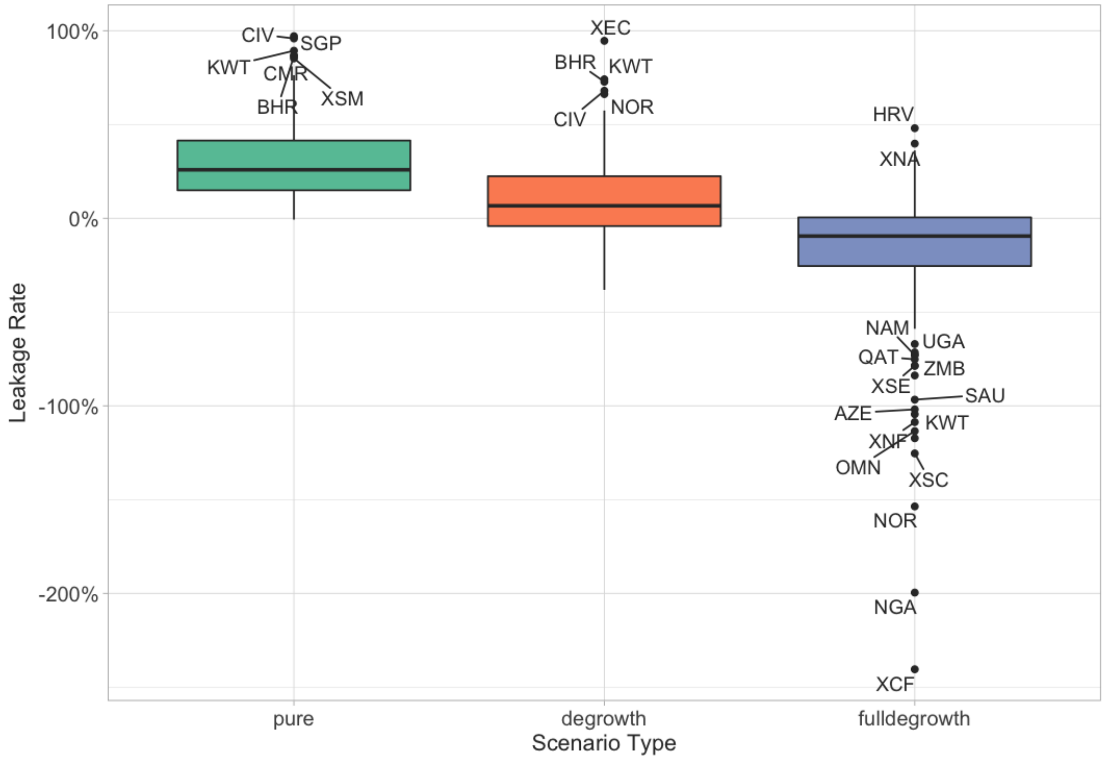
In sum, degrowth can on average substantially reduce leakage compared to the pure emission target. However, the results show huge variation. Pure emission reduction scenarios lead to leakage rates between −0.69% and 97.11%.[11,12] In simple degrowth, leakage rates range from −38.16% to 94.63%, in full degrowth from −578.89% to 48.04%. Even when ignoring extreme outliers, leakage rates still vary by up to 100 percentage points within each policy scenario.

[10]The GTAP country codes are used. These typically coincide with usual ISO3 country codes, except for the aggregated regions in the data.

[11]Note that previous literature identifying leakage rates based on CGE model assessments (e.g. Babiker, 2005; Böhringer, Bye, Fæhn, and Rosendahl, 2012), structural gravity (e.g. Egger and Nigai, 2015; Larch and Wanner, 2015), or empirical ex-post studies of e.g. the Kyoto Protocol (e.g. Aichele and Felbermayr, 2012, 2015) also find huge variation in leakage rates, ranging from very low to more than "full" (i.e. 100%) leakage.

[12]The pure scenario has negative leakage rates in two cases, Namibia (−0.62%) and Panama (−0.69%). One explanation is that these countries have very different distributions of sectoral energy intensities compared to their trading partners. The sectoral shift in production due to climate policy can then lead to a decline in energy use both for the committed and uncommitted countries.

Figure 1: Leakage Rates across Scenario Types



Notes: Each boxplot describes the distribution of leakage rates of the 128 simulated scenarios for each policy type. The extreme outlier South Central Africa (XAC) (−578.89%) in the full degrowth scenario is not shown. Text labels denote the committed country.

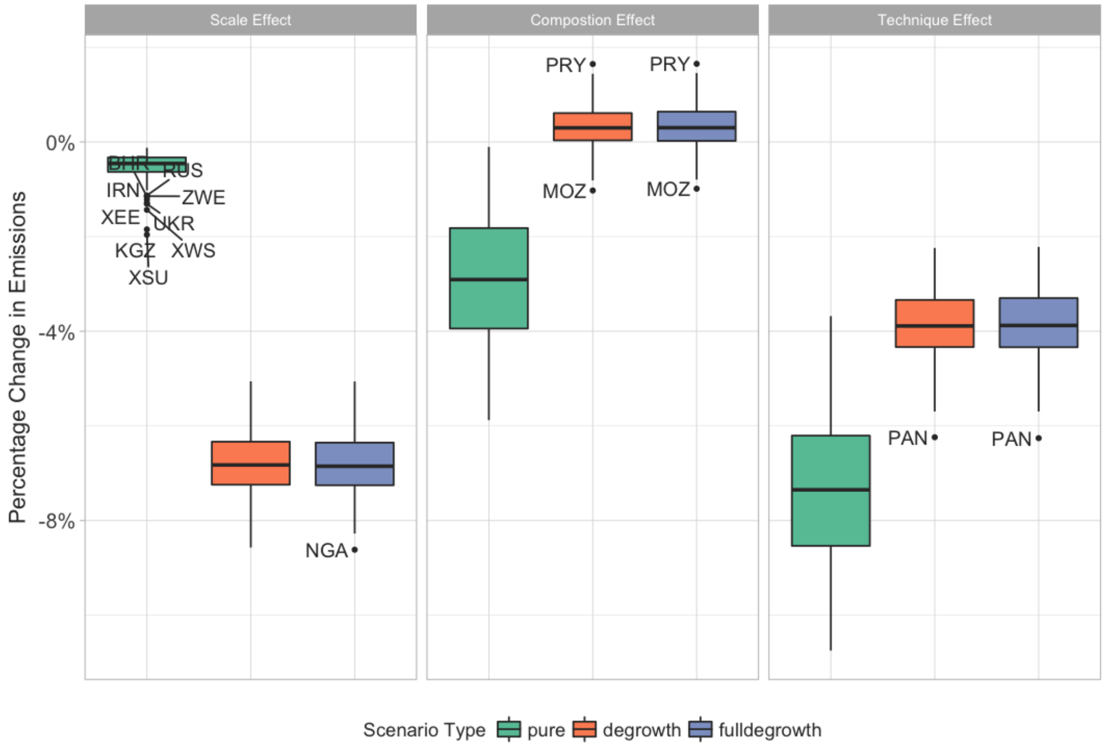
Table 1: Leakage Rates

	Min	1st Qu	Median	Mean	3rd Qu	Max	S.D.
pure	−0.69	14.94	25.87	29.52	41.47	97.11	22.39
degrowth	−38.16	−4.15	6.67	10.76	22.44	94.63	22.10
full degrowth	−578.89	−26.18	−9.59	−26.56	0.38	48.04	65.05

4.2 Decomposition of the Emission Effects

Figures (2) and (3) show the decomposition of emission changes into scale, composition, and technique effects for committed and uncommitted countries, respectively. Note first that for committed countries all three partial effects should add up to the ten-percent reduction target. Given the approximation errors of the

Figure 2: Decomposition of Emission Effects for Committed Countries

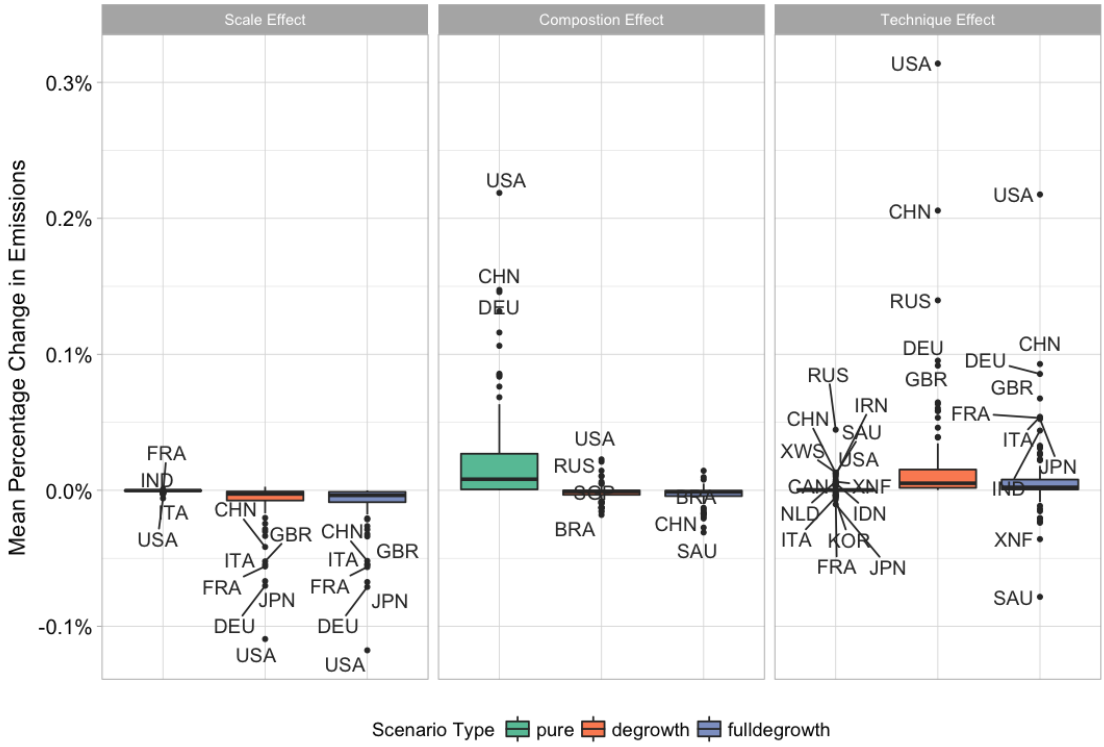


Notes: Each boxplot describes the distribution of the percentage change in emissions of the 128 committed countries for each policy type.

total differential decomposition, we also report the log-change decomposition for committed countries in figure (4). While the log-change decomposition is more exact, it only gives relative values. The sum of the partial effects is now 100 % rather than the ten-percent reduction target. Also note that we could in principle analyse results for 127 uncommitted countries for each scenario. However, this would require the depiction of 127 × 128 values. We therefore only present the mean effects for uncommitted countries.

In order to better understand the variation in leakage rates, we will discuss each partial effect in detail. The left panel of figures (2) and (3) shows the scale effect. The scale effect captures the reduction in emissions due to an overall reduction in output. As expected, it is negative for all policy scenarios for the committed

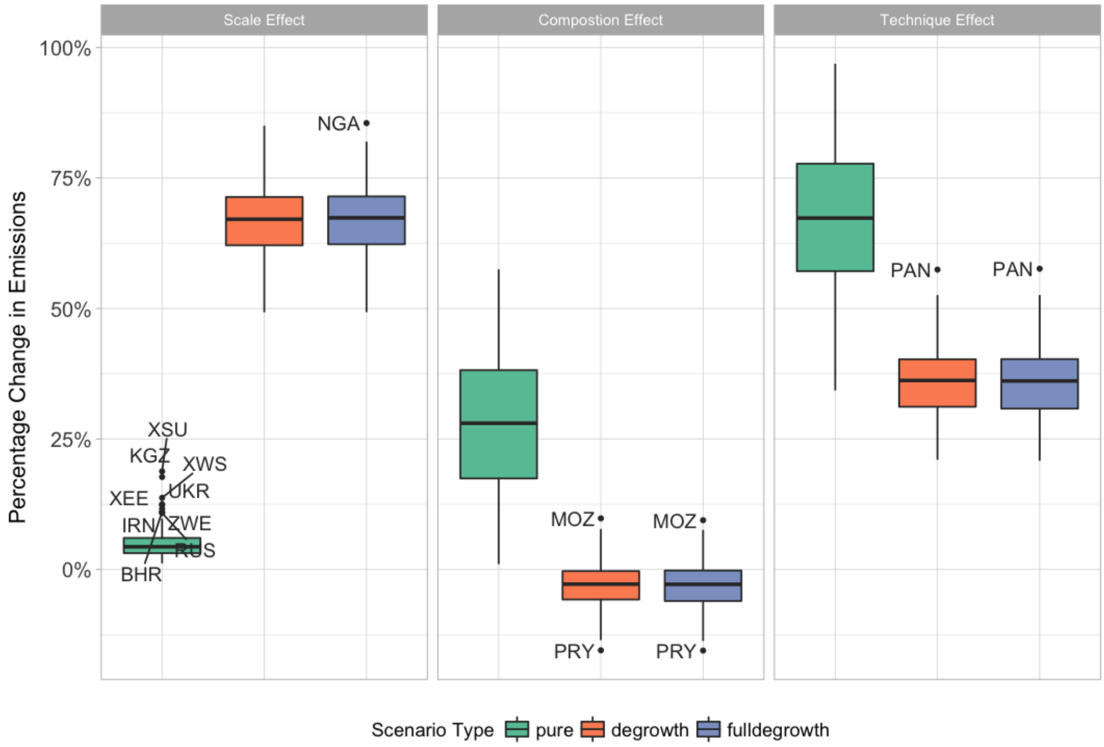
Figure 3: Decomposition of Emission Effects for Uncommitted Countries



Notes: Each boxplot describes the distribution of the partial emission effects. The data points represents the simple mean of the emission effect of the 127 uncommitted countries for each policy scenario. Text labels denote the committed country.

country. In other words, countries partly achieve the reduction target by downscaling overall output. However, the scale effect strongly differs in magnitude. Both degrowth scenarios lead to much stronger effects. While it accounts in relative log-change terms for between one and 20 % of the total reduction in the pure scenario, it varies between 49 and 86 % in both degrowth scenarios, as shown in figure (4). Note that this result is generally consistent with findings by Victor (2012) who also reports that most of the emission reduction comes from the reduction in overall economic size. The stronger scale effects can partly be explained by the additional restriction that degrowth imposes on other factor inputs. This directly reduces output and hence emissions. It is also attributable to the fact

Figure 4: Log-Change Decomposition of Emission Effects for Committed Countries



Notes: Each boxplot describes the distribution of the log-change effects for the 128 committed countries for each policy type. Log-change effects give the relative values of the total effect, i.e. for each scenario all three effects sum up to 100 %.

that production can relatively easily adjust to the pure scenario by shifting into less energy-intensive sectors, without incurring sizeable losses of overall output. This sectoral shift will be reflected in the composition effect, as discussed below. It can also be seen by looking at the extreme values, which show the effect most clearly. The negative outliers for the pure scenario in figure (2) include the Rest of Former Soviet Union (XSU), Kyrgyzstan (KGZ), Rest of Western Asia (XEE), Ukraine (UKR), Russia (RUS) and Iran (IRN), all of which are among the most energy-intensive economies in the world, as measured by $\bar{\alpha}^i_E$. Unsurprisingly, the sectoral adjustment will be harder for these countries, as they generally use higher energy intensities in production. To achieve the policy target, they therefore have to restrict overall output more strongly.

For uncommitted countries, the mean scale effect is negative, too. This is intuitive as the introduction of climate policy in one of their trading partners implies a reduction of demand for their products. Consequently, they reduce their overall output and hence emissions. Note that the scale effect works in the same direction for both committed and uncommitted countries. The stronger scale effects then partly explain why degrowth can reduce leakage compared to the pure scenario.

The middle panel of figures (2) and (3) shows the composition effect. The composition effect captures the change in emissions due to a shift in production into more or less energy-intensive sectors. As expected, in the pure scenario, it has a negative sign for the committed countries and a positive sign for the uncommitted countries. This is because the introduction of the pure emission target makes energy relatively more expensive, which leads to a shift of production into less energy-intensive industries. In response, other countries move production into more energy-intensive sectors to compensate the shortfall in supply of energy-intensive products. Degrowth eliminates these composition effects, i.e. it closes down the first leakage channel which works via a shift of emission-intensive production to uncommitted countries. The composition effect in these cases is close to zero both for the committed and the uncommitted countries.

The right panel of figures (2) and (3) shows the technique effect. The technique effect captures changes in emissions within sectors due to changes in factor usage driven by energy price changes. In the pure scenario, the technique effect accounts for the largest part of the emission reductions of the committed countries (66.67 % in relative log-change terms). In both degrowth scenarios, the importance of the technique effect is reduced as the scale effect now accounts for the majority of the emission reduction.

For the uncommitted countries, the mean technique effect in the pure emission reduction scenario tends to be weak. This is intuitive as the decline in demand for the international energy resource due to the pure emission target in a single country is unlikely to have a strong effect on the world-market price for energy resources. The mean technique effect only becomes positive when the pure scenario is implemented in large, energy and resource intensive (in terms of ξ_R^i) countries.

In the case of simple degrowth, the technique effect for uncommitted countries is positive. Simple degrowth works through downscaling not just energy but all available national factor inputs, while keeping the international resource supply constant. This has the effect that the committed country continues to supply its resources to the world market, but at the same time reduces its own demand. The resulting fall in the world market price pushes uncommitted countries towards higher energy intensities and hence higher emissions.

Full degrowth on the other hand also restricts the supply of the energy resource. This counteracts the fall in the world resource price experienced in the simple degrowth scenario and hence lowers uncommitted countries' incentives to shift towards generally more energy-intensive production. Hence, different from simple degrowth, full degrowth also works against the second (energy-market) leakage channel.

The specific technique effects of uncommitted countries are strongly linked to the variation in the committed country's resource richness. Resource richness is here understood as the ratio of a country's international resource endowment share, ω_b^i, to its economic size, Y_b^i. For resource-rich countries, the reduction in supply outweighs the reduction in demand, which in turn leads to an increase in the world-market price for energy resources. In response, uncommitted countries switch to lower energy intensities and thus decrease emissions. Note that the effect will be stronger the resource-richer the committed country. This mechanism

Table 2: Welfare Effects for Committed Countries

	Min	1st Qu	Median	Mean	3rd Qu	Max	S.D.
pure	−1.84	−0.56	−0.42	−0.48	−0.31	−0.12	0.27
degrowth	−8.11	−7.02	−6.61	−6.62	−6.26	−5.03	0.60
fulldegrowth	−8.73	−7.28	−6.90	−6.83	−6.41	−5.07	0.66

can also explain the (partly strongly) negative leakage rates observed when full degrowth is implemented in particularly resource-rich countries.

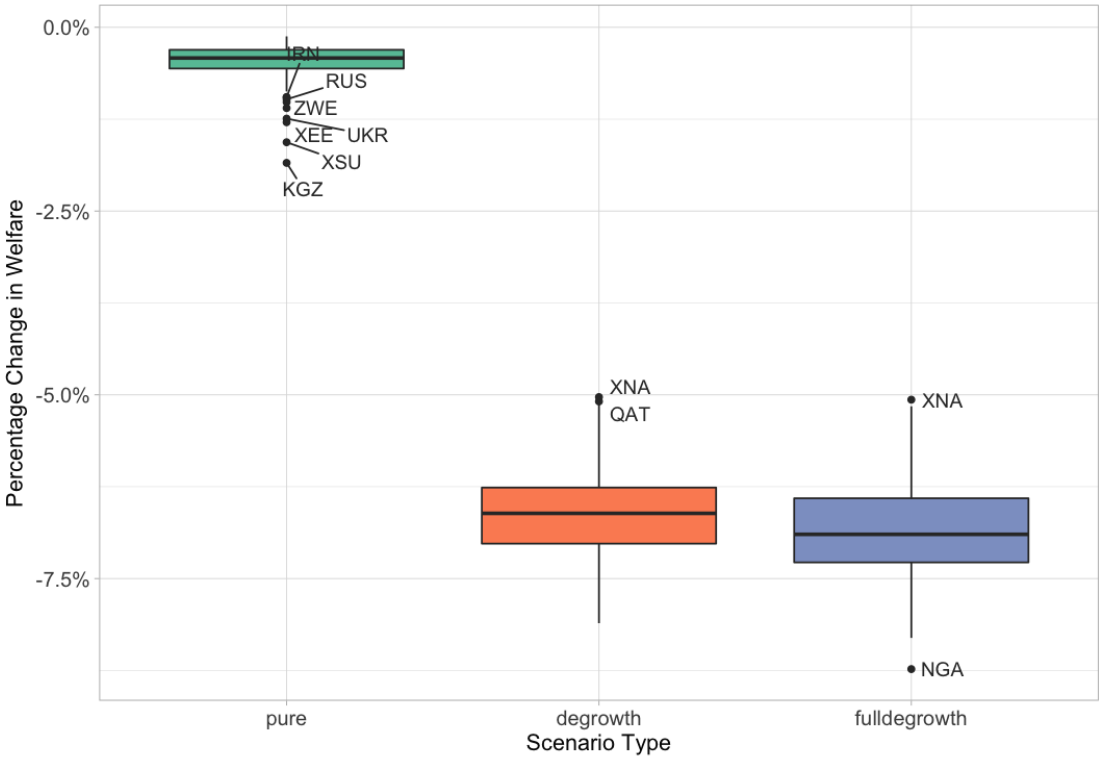
4.3 Welfare Effects

Table (2) reports summary statistics for the welfare effects of the committed country. Figure (5) additionally shows the distribution of welfare effects. Note first that all welfare results are negative. No country gains unilaterally from the introduction of climate policy. The magnitude however differs strongly between degrowth and the pure scenario. The introduction of simple degrowth implies considerable welfare losses, ranging from −8.11 to −5.03 %. As expected, full degrowth leads to even larger losses, varying between −8.73 and −5.07 % as countries additionally forego revenues from selling the energy resource. The pure scenario in contrast leads to relatively small welfare losses, ranging from −1.84 to −0.12 %.

These welfare effects in the committed country are almost entirely driven by changes in real income because the welfare gains from a reduction in world emissions due to unilateral climate policy in a single country cannot significantly compensate its own loss of real income. This can also explain why the welfare losses are substantially larger for degrowth compared to the pure scenario, despite lower leakage rates, since the additional reduction of factor inputs in degrowth implies larger real income losses.

The welfare reductions can be considered as the cost of the specific climate policy at hand. It then becomes apparent that degrowth is a very expensive

Figure 5: Welfare Effects for Committed Countries



Notes: Each boxplot describes the distribution of the percentage change in welfare of the 128 committed countries.

climate policy in our model structure. For example in the case of full degrowth, median world emission reductions are 2.4 times higher than in the pure energy reduction scenario, but at the same time median welfare losses for the committed country are more than 16 times higher. Hence, countries appear to pay a high price for the increased environmental effectiveness of their policy.

While our result is generally in line with findings by Naqvi (2015) who also reports that degrowth leads to a relatively large loss of real income, it stands in contrast to several studies which show that degrowth can actually be welfare enhancing (e.g. Bilancini and D'Alessandro, 2012; Victor, 2012; Andreoni and Galmarini, 2014; Heikkinen, 2015). There are several factors explaining this discrepancy. First, we follow the trade literature in defining utility (and hence welfare) narrowly with a clear focus on consumption. This implies that potentially beneficial effects of degrowth (other than reduced emissions), such as more leisure, reduced land use, or lower status competition, are not taken into account. Second, given our focus on international interactions, we model a multi-country world, abstracting from some country details. This restrains us among other things from considering alternative welfare indicators (such as poverty and adult literacy) or from looking at a shift from market to reciprocity work due to degrowth. Third, owing to our model structure, we cannot investigate different policies to implement degrowth, but rather just exogenously cut the factor supplies, even though different policies leading to degrowth may imply very different outcomes for a number of different welfare indicators.[13] To sum up, our assessment of the costs of degrowth focuses on real income. Future work may enhance our international perspective on degrowth by taking up additional welfare factors, which will potentially lead to a lower cost evaluation of degrowth.

4.4 Relationship with Country Characteristics

To explore the macroeconomic conditions in which degrowth is more effective in reducing leakage than the pure scenario, we consider the reduction in leakage from the pure scenario to degrowth. The reduction in leakage is calculated as the percentage-point difference between the pure scenario leakage rate and the respective degrowth rate. The discussion of our results will be guided by three hypotheses on the relationship between the reduction in leakage and key macroeconomic variables.

Hypothesis 1. The reduction of leakage from the pure emission reduction sce-

[13] E.g., Victor and Rosenbluth (2007) show how a no growth scenario with devastating welfare consequences can be turned into a desirable future path – still without economic growth – by applying a policy mix including active labour market programmes, strong redistribution policies and a shift from labour to capital taxation.

nario to the degrowth scenarios is larger the smaller the committed country in terms of economic size.

The intuition behind this hypothesis is that small countries face particularly high leakage rates in the pure scenario. This is because their compositional shifts towards cleaner production can particularly easily be compensated by other countries who then provide additional energy-intensive products. Therefore, small countries are expected to experience stronger leakage reductions once they take degrowth policies which tend to reduce emissions more via scale than via composition.

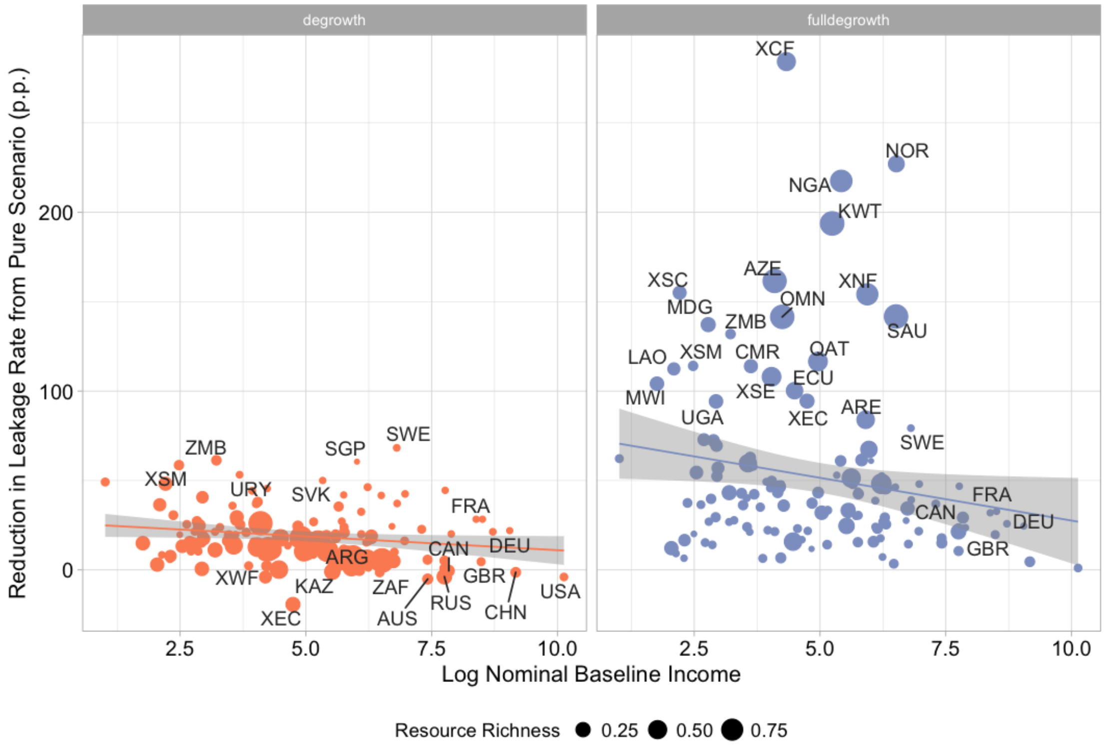
Figure (6) shows the change in leakage in relation to the committed country's economic size. Note first that simple degrowth leads to lower leakage in almost all cases, as indicated by the mostly positive values.[14] Full degrowth leads to lower leakage in all cases.

The result provides some evidence in support of the hypothesis. The linear regression line indicates a negative relationship between the change in leakage and economic size. In other words, degrowth tends to be more effective in reducing leakage the smaller the committed country. Comparing both degrowth scenarios, the relationship becomes stronger for full degrowth, but also the variation around the linear relationship becomes larger, as indicated by the widened 95-percent confidence bands around the regression line. In addition, the size of the data points reflects the committed country's resource richness. In line with previous results, the change from simple to full degrowth is largely driven by national variations in resource endowment shares relative to economic size.

Hypothesis 2. The reduction in the leakage rate from the pure scenario is larger the more trade-open the committed country.

[14] Most of the exceptions are among the largest economies in the world, including the United States (USA), China (CHN), Russia (RUS) and Australia (AUS). These countries suffer from very strong mean technique effects, as shown in figure (3).

Figure 6: Change in Leakage vs. Economic Size

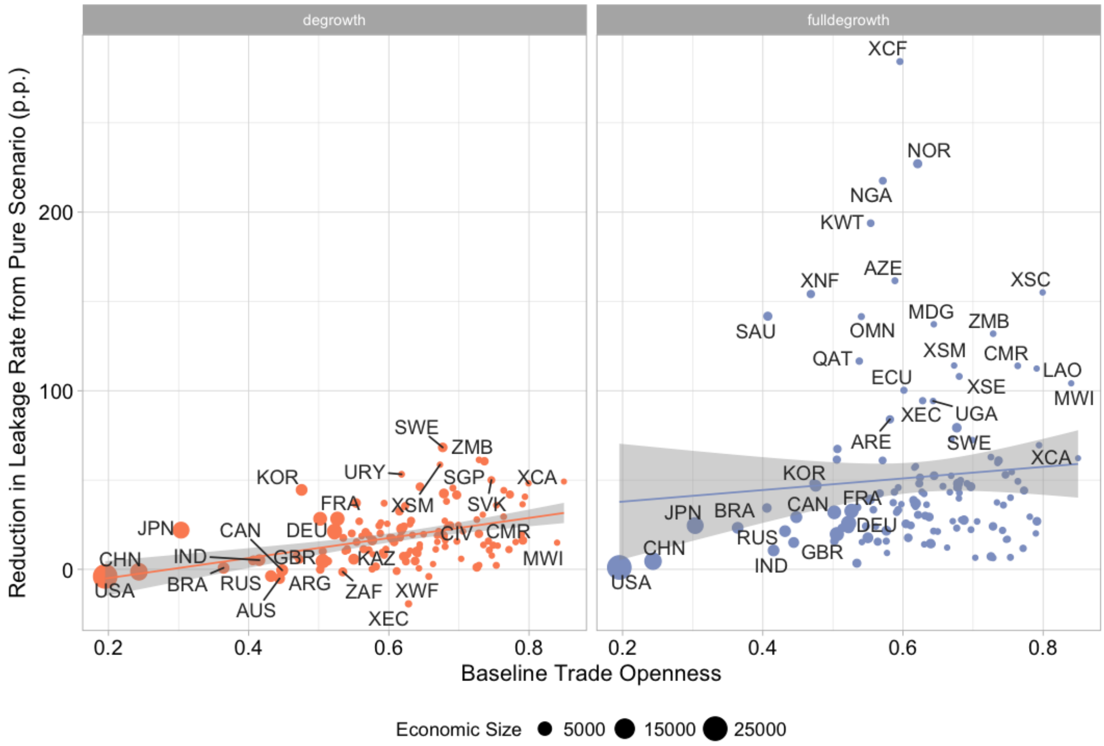


Notes: Log nominal baseline income is given by the natural logarithm of Y_b^i. Resource richness is calculated by first taking the ratio of international resource endowment share, ω_b^i to total income, Y_b^i, and then dividing all values with the maximum value to constrain the values on the [0, 1] range. The extreme outlier South Central Africa (XAC) is not shown.

A priori, one would expect leakage to be relatively high for more open economies in the pure scenario as energy-intensive production can more easily move abroad. This is reflected in strong composition effects, as discussed above. Degrowth in contrast is expected to lead to significantly lower leakage rates in more open economies. Since degrowth implies a sizeable reduction in income and hence demand without directly altering relative production costs, energy-intensive production is less likely to relocate to other countries than in the pure scenario. Consequently, one would expect degrowth to be more effective in more open countries. We measure trade openness as the ratio of a country's exports over its total income.

Figure (7) plots the change in leakage against trade openness. The results seem

Figure 7: Change in Leakage vs. Trade Openness



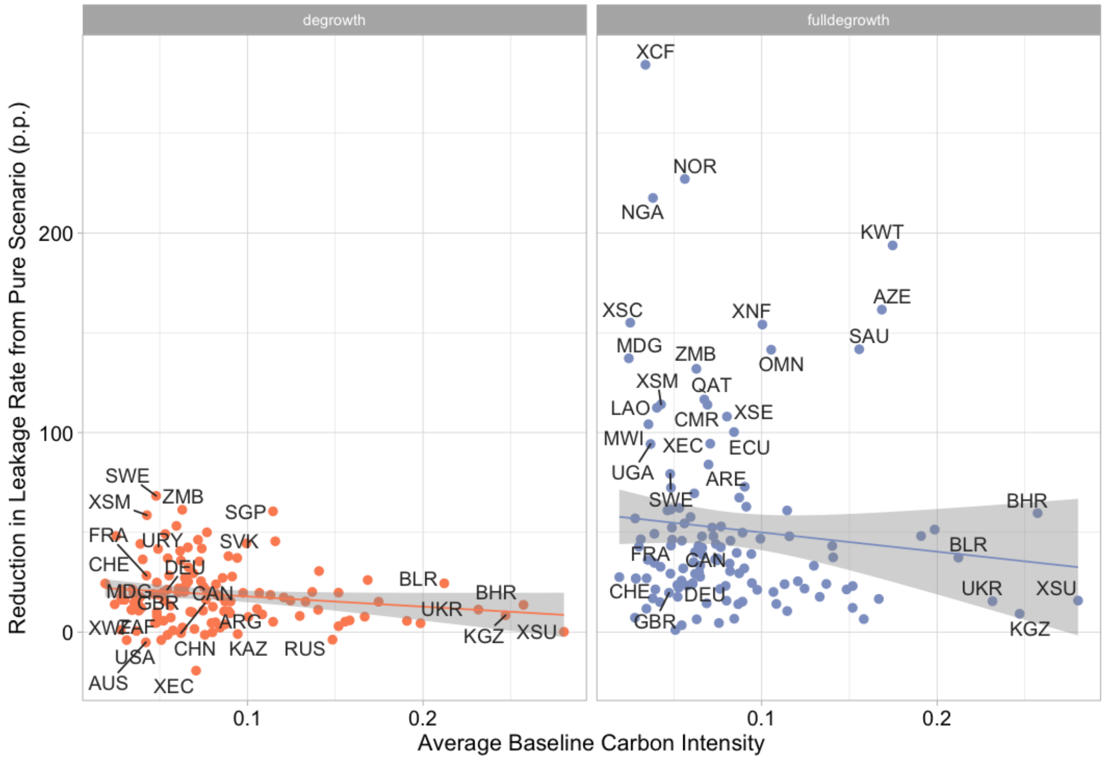
Notes: Baseline trade openness is given by the ratio of a country's exports to its total income. Economic size is given by Y_b^i in million US-\$. The extreme outlier XAC is again not shown.

to confirm the hypothesis. The regression line indicates a positive relationship between the change in leakage and trade openness. The relationship is similarly strong but again associated with more variation for full degrowth.

Hypothesis 3. The change in the leakage rate from the pure scenario is larger the less carbon-intensive the committed country, measured by $\bar{\alpha}_{E,b}^i$.

A priori, one would expect leakage in the pure scenario to be relatively high for cleaner countries, i.e. those countries with lower carbon intensities, as the pure scenario in already relatively clean countries will lead to a shift towards even cleaner industries. In response, other relatively dirty countries move production into even dirtier sectors. As these countries require more energy to produce the

Figure 8: Change in Leakage vs. Average Carbon Intensity



Notes: The average baseline carbon intensity is given by $\bar{\alpha}^i_E$. The extreme outlier XAC is again not shown.

same amount of goods, the initial emission reduction is likely to be offset by the resulting emission increases in these countries. As discussed, degrowth on the other hand is likely to limit this composition effect. Consequently, one would expect degrowth to be more effective in reducing leakage when implemented in cleaner countries relative to the pure scenario.

Figure (8) shows the change in leakage in relation to the initial carbon intensity. The result gives some evidence in support of the hypothesis. The regression line indicates a negative relationship between the change in leakage and average carbon intensity. The relationship becomes stronger for full degrowth. To sum up, degrowth reduces leakage in the large majority of cases. Our results suggest that degrowth is especially effective in reducing leakage in small, trade-open, and clean countries.

5 Conclusion

Unilateral climate policy is associated with the problem of carbon leakage. Using the quantitative trade model with energy production by Larch and Wanner (2015), we investigate whether and how degrowth can solve this leakage problem. We find that reducing all national production factors rather than only the energy input reduces leakage strongly by eliminating incentives of uncommitted countries for compositional shifts towards production of dirtier products. When additionally restricting the degrowth country's supply of energy resources to the international market, leakage is further reduced by preventing a fall in the world energy resource price and hence eliminating incentives for uncommitted countries to shift towards overall more energy-intensive production techniques. The higher environmental effectiveness of degrowth comes at the cost of strong real income losses for the country undertaking the policy. Relating our results to underlying country characteristics, we find that the potential of degrowth to reduce leakage compared to conventional energy-based climate policies is especially high in small, trade-open economies with clean production methods.

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