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Carbon pricing and its implications in input-output networks: the case of France

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Increasing ambitions in climate policy and corresponding rises in coverage and level of carbon prices raise the question of the economic impact these policies will have, especially in the face of strong cross-sector and cross-country heterogeneity of carbon intensity. In this *Focus*, we quantify the extent of cross-sector reallocations induced by the taxation of greenhouse emissions where they are produced.

To do so, we implement carbon taxation scenarios into a quantitative multi-country, multi-sector real model of input-output networks. Under the extreme assumption that the carbon tax does not affect the technology of production, heterogeneous tax rates induce substitution away from the most energy-intensive sectors.

We find that a carbon tax of $100/ton on domestic production and consumption emissions puts a limited tax burden on the French economy. Depending on the scenario we're looking at, such a tax would induce a domestic welfare impact between -0.0036% if the tax were only implemented in France and 0.0031% if the tax were implemented globally. Accounting for exposure along the entire value chain, we find that Air Transport and Minerals production is most strongly taxed at around 8%, with most sectors carrying a tax burden between 1.5 and 3%. Additionally taxing the consumption of Refined Petroleum at $100/ton puts a tax burden of 12.6% on the domestic consumption in this sector.

In line with this finding, our results indicate a limited overall reduction in domestic welfare in France of 0.0036% and a reduction in real wages by around 0.02%. Any adverse effects are strongly mitigated by the redistribution of the tax revenues back to consumers in a lump-sum transfer. The welfare reduction instead reaches 0.0154% if the carbon price is modeled as an iceberg cost that does not generate any tax revenues. The counterpart of the limited impact of the tax on the overall economy is that the impact on the volume of emissions is far from sufficient given carbon neutrality objectives. A $100/ton tax would indeed induce a reduction of 22 Mt in greenhouse gas yearly emissions in France. As a reminder, France is committing to attaining carbon neutrality by 2050, when Citepa (Centre interprofessionnel technique d'études de la pollution atmosphérique) estimated that CO_2 emissions should reach 408 Mt in 2022.

As expected, the consequences on sectoral output are strongly heterogeneous. Carbon-intensive sectors experience the strongest declines in output, with Refined Petroleum and Air Transport most affected, at minus 30%. Heavily emitting production sectors, such as Minerals and Mining also experience declines of 5-10%, with less carbon-intensive sectors expanding slightly.

Extending the coverage of carbon pricing to the global level has two opposing effects on domestic welfare. On the one hand, given the increase in prices, it decreases overall output and consumption, lowering domestic welfare worldwide. On the other hand, given the fixed labor supply, domestic real wage increases, thereby mitigating adverse effects for domestic welfare. Our results are robust to different specifications. Varying the elasticities of substitution only affects our results marginally, with more substitutability creating slightly larger adverse effects for the French economy.

The impacts of the carbon price in a model without technological change suggest that carbon neutrality is hardly achievable without reducing the emission intensity of production ("green growth"), and/or a shift in consumer preferences ("degrowth"). The results can be interpreted as additional support for the use of carbon taxation proceeds in a targeted manner, so as to support a technological transition in heavily emitting sectors.

Motivation and Background

In recent years, the issue of climate policy has taken centre stage in both national and global policy discussions. Policymakers react to the increasing pressure to reduce carbon emissions by implementing a wide range of policies, including subsidies, emission standards, public innovation funding, and carbon pricing. Whilst being complemented with the other policy options based on sector-specific considerations, a carbon pricing regime is often the cornerstone of national and international climate policy strategies. Since 2005, the share of global greenhouse gas emissions covered by a carbon pricing scheme has risen from 5% to almost 25% (World Bank 2023). As depicted in Figure 1, this is reflected in increasing geographical coverage, and additional carbon pricing systems are under consideration in major economies in Latin America and South-East Asia.

With the EU carbon price recently surging across the mark of € 100/ton, and other pricing schemes following this hike (World Bank 2023), questions arise about the shifts in global production and consumption such a tax scheme may induce. In addition to firms likely adjusting their production technology towards less carbon-intensive methods (Wagner et al. 2022), one of the intended effects is also to generate substitution away from heavily emitting sectors, both in terms of input use by industry and in final consumption.

Considering the strong heterogeneity of carbon intensity across sectors and countries, the introduction of carbon pricing, or any complementary environmental regulation, will have strongly diverging effects. Using a model of global input-output networks (Baqaee and Farhi 2019), which allows taking into account shifts along the entire value chain, the goal of this Focus is to quantify the substitution patterns resulting from varying environmental policies, especially considering the implications for the French industry and French consumers.[1,2] We provide a detailed description of the model in the Appendix. In the next sections, we describe the scenarios implemented for this Focus and provide an intuition for the resulting tax burden in France before discussing the results.

In addition to developing an understanding of the potential of carbon pricing to induce substitution away from heavily emitting sectors, this analysis will help to quantify the distribution of potentially resulting economic costs across industries and countries. Against a background of decreasing free allowance allocation in the EU Emissions Trading System (EU ETS), as well as high inflationary pressure on consumers, understanding which industries and which countries are likely most adversely affected as well as which consumer goods might be subject to the strongest price hikes is critical. This knowledge will help design targeted policy interventions to smooth any social consequences from potential economic perturbations due to carbon pricing, especially in the short term.

Scenario description

To develop an intuition about how emission-based regulation will reallocate production and consumption across sectors, we feed carbon tax scenarios into a quantitative multi-country, multi-sector real model based on Baqaee and Farhi (2019).[3] Details on the model and its calibration are provided in the Appendix. It represents a general-equilibrium multi-country economy with multiple industries linked to each other through input-output relationships. Primary factors are available in fixed supply. They are immobile across countries but freely mobile across sectors.[4] Carbon taxes affect the relative price of high-versus low-emission production and consumption, which generates a reallocation of the demand for final and intermediate consumption away from the most emitting sector*country pairs.

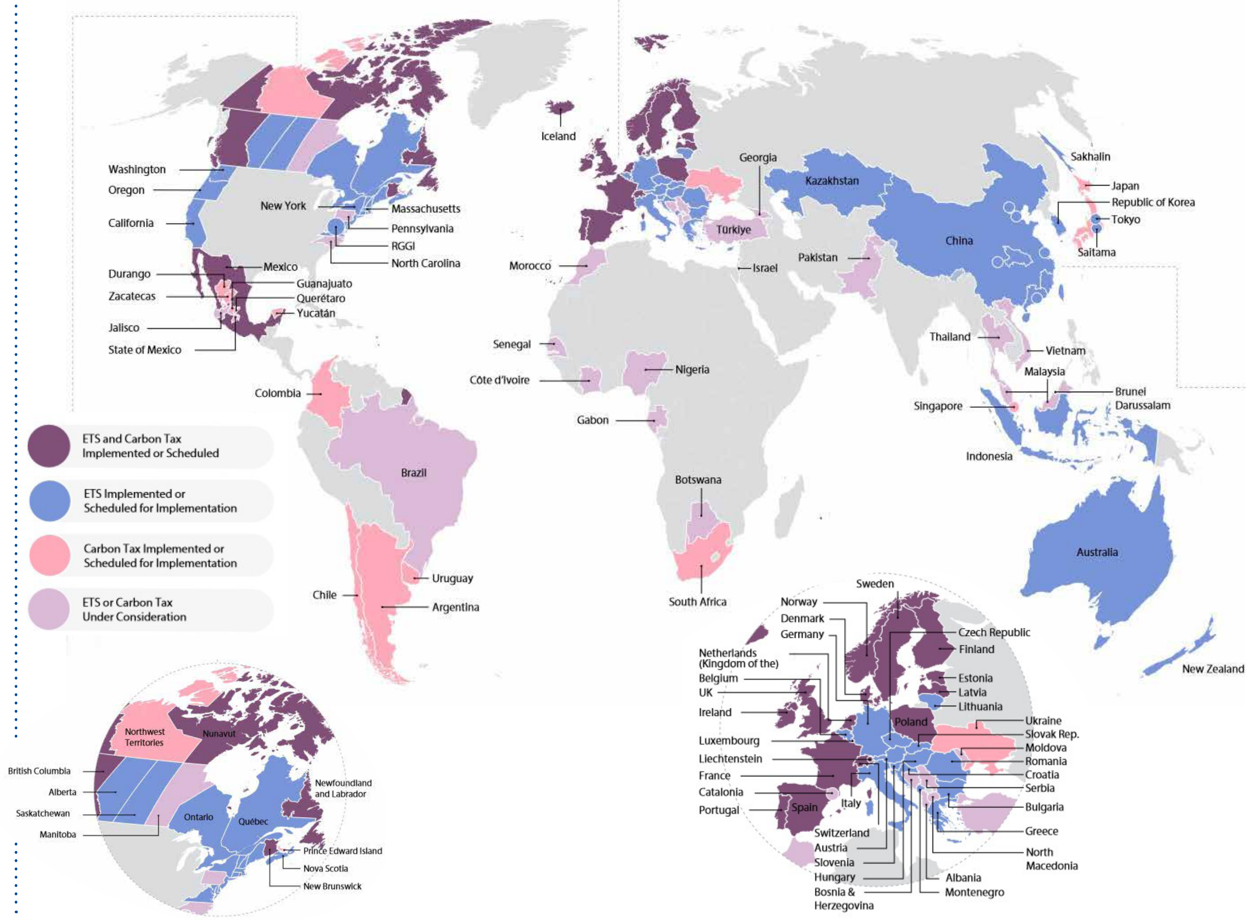
[1] Similar analyses are implemented in Devulder and Lisack (2020), Frankovic (2022), Campiglio, Massoni, and Trsek (2022) and Bellora and Fontagné (2023). Their results are broadly consistent with ours, although the exact numbers vary with the microeconomic assumptions surrounding the production structure and the values used to calibrate the various substitution elasticities.

[2] We also acknowledge CGE models with a more explicit formulation of the energy consumption patterns of consumers and industry, based on engineering-based bottom-up approaches. A prominent example is the ThreeME model, developed by the French Environment and Energy Management Agency (Reynes et al. 2021) and detailed in the associated note. Given our emphasis on the role of trade, input-output linkages, and indirect tax burdens along the supply chain, we opt for models with more comprehensive modelling of global production networks, perhaps omitting some intricacies of domestic substitution patterns. Extending this analysis, one can complement our results with simulations using bottom-up energy modelling to get a more granular perspective of the shifts in consumption patterns, with less focus on the shifts in global production networks.

[3] Throughout the analysis, the policy scenarios are described as "carbon taxes" and are modelled as a tax on output or consumption that is proportional to emissions generated by the activity of firms and consumers. Although the tax is closest to carbon tax policies, it must be kept in mind that any environmental policy whose objective is to reduce the quantity of production and consumption associated with high levels of emissions is expected to have similar redistributive consequences. From that point of view, the analysis should not be thought of as solely applying to carbon tax scenarios.

[4] A variant of the model also allows factors to be sector-specific. Sector-specific factors increase the overall cost of carbon taxes by reducing adjustment mechanisms through the reallocation of factors from high-to low-emitting sectors.

Figure 1. Map of global carbon pricing coverage (World Bank 2023)



In the baseline scenario, we model a carbon tax of $100/ton, that applies to emissions generated during production processes as well as at the final consumption stage. In the baseline scenario, the tax solely applies to France, but we later extend the geographical coverage. On the production side, a company in France is taxed when it sells a good whose production process involves the emission of greenhouse gases, regardless of whether the sales are in France or abroad, *i.e.*, there is no export rebate. The tax thereby creates a wedge between the price received by the French firm and the price paid by its domestic and foreign consumers, be they firms or final consumers. In turn, the price wedge has consequences for the relative competitiveness of French firms, in each market. On the consumption side, we impose a tax all consumers must pay when buying fuel, diesel, or heating oil for final consumption. The tax on energy consumption at the level of households is assumed to apply to all petroleum goods, whatever their origin. In both cases, the tax burden is set in proportion to the corresponding emissions.

To illustrate the incidence of carbon taxes, we can look at a specific example to see how this scenario translates into tax burdens for the economy in France. The carbon price on production acts equivalently to a percentage mark-up on marginal costs, that is proportional to the emissions generated in the corresponding production step. So, if a consumer buys a bike, the tax corresponds to the direct emissions generated from the ovens used to bake the carbon frame. This corresponds to what we call the “direct tax burden” for the remainder of this *Focus*. However, the emissions generated for producing any additional input, for example, required materials, are taxed when the bicycle manufacturer purchases them, thereby indirectly increasing the cost for the consumer. This corresponds to the “indirect tax burden”. We will refer to the sum of these tax burdens along the value chain as the “total tax burden”.

The case is different for the consumption tax, which applies to purchases of fossil fuels by final consumers. Here, for a consumer, in addition to the total tax burden on the various stages of production, there will be an additional tax on the emissions we assume will be generated when the purchased fuel is combusted for final consumption in a private car or heating system.

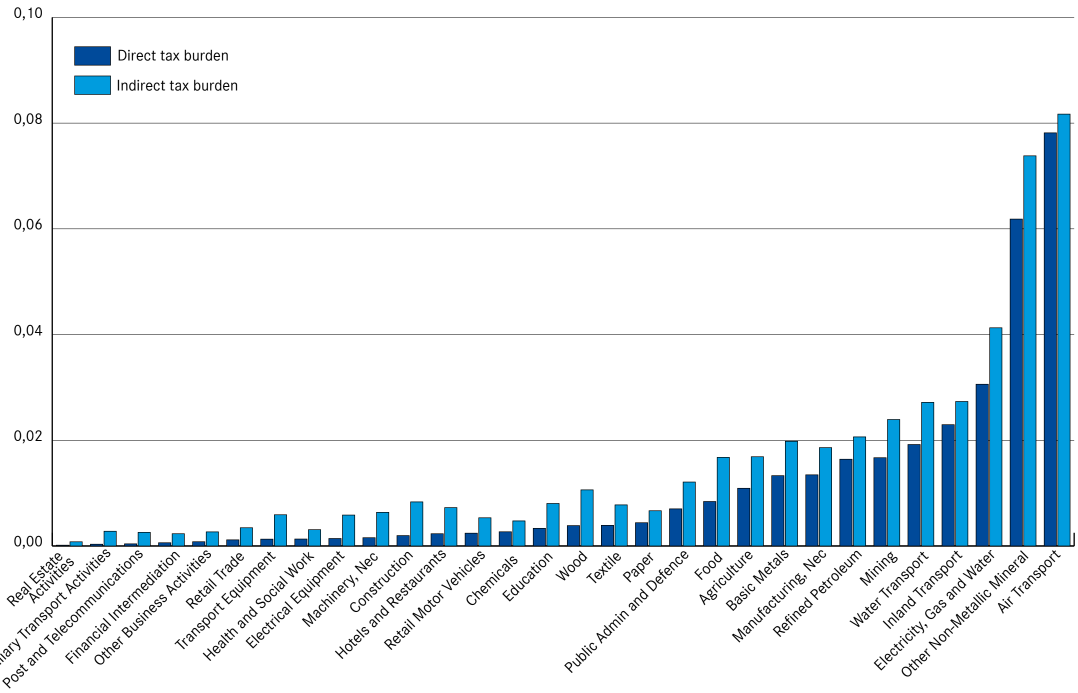
While the French carbon tax constitutes the baseline scenario, we will then extend the coverage of the taxation from France to the EU or globally, where all mechanisms apply equivalently. Increasing the geographic scope of the environmental policies has two consequences for French firms and consumers. On the one hand, their overall exposure to carbon taxes increases beyond domestic absorption. On the other hand, the distortive effect of the tax is reduced as French producers now compete with foreign firms that are themselves taxed on their emissions. In the scenario modeling a global carbon tax, any heterogeneity in tax burden arises from differences in the emission intensity of existing production technologies, industry focus, and consumption patterns.

Intuition for relevance and magnitude

To provide an intuition of the magnitude of the potential disruptions a carbon tax might cause, Figure 2 reports the tax burden resulting from the output taxes in a scenario of a $100/ton carbon tax in France. The figures are calculated in percentage relative to a situation without a carbon tax. The dark blue bars measure the direct tax burden, which is directly proportional to the emission intensity of the corresponding sector. The light blue bars add the indirect tax burden that firms incur through their production process, i.e., the increase in their marginal cost attributable to the price of their inputs being inflated by carbon taxes.[5] The difference between the dark blue and light blue bars thus interprets as the indirect tax burden, attributable to production using inputs that vary by their emission intensity.

As is evident, the tax burdens in our scenario correspond closely with common wisdom about carbon-intensive sectors, with Air Transport, Minerals, Energy, and Heavy industry sectors most strongly affected. At a carbon price of $100/ton, the tax burden remains limited to roughly 8% in the most emission-intensive sector. In the case of refined petroleum, the 2% tax on output is however inflated by a 12.6% consumption tax, for sectoral sales to final consumers.

Figure 2. Tax burden for the French industry (exluding consumer tax)



Note: The figure shows the impact of taxes on output at the sectoral level, in percentage of the producer price. The dark blue bars correspond to the direct tax, in percentage terms. The light blue bars add the indirect effect of the tax, i.e. the increased in sectoral marginal costs caused by inflated input prices. The indirect effect is approximated using the Leontief inverse calculated from the Input-Output tables used in the calibration.

Figure 2 also highlights the importance of input-output linkages in amplifying the consequences of carbon prices, as the true exposure of some sectors is hidden along the value chain. Considering the sector of Construction as an example, we see that the direct tax burden is rather limited. The emissions directly linked to construction are not especially large.

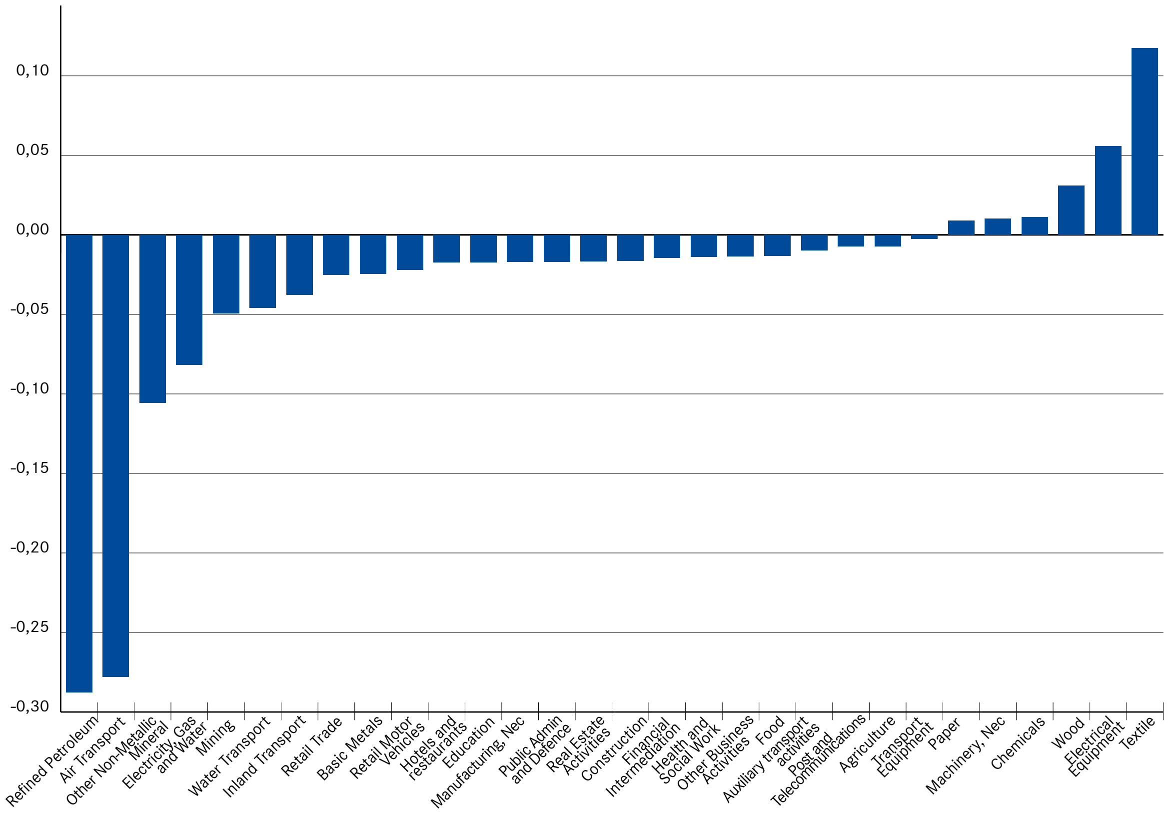
[5] In Figure 2, we go from the direct to the overall tax burden using the Leontief inverse associated with the baseline input-output matrix. The calculation implicitly assumes full pass-through of taxes onto prices and unitary elasticities of substitution along the production network. Whereas the overall tax burden is useful to recover intuition about the accumulation of taxes along production networks, our full quantification assumes lower elasticities of substitution. Throughout the analysis, we however maintain the assumption of full pass-through.

This means that for the French industry and consumers, purchasing goods from this sector comes with a relatively low direct tax burden. However, when considering the incidence of taxation further upstream, the tax burden increases by a factor of almost ten due to some of the main inputs of the sector, such as cement, being intensive in greenhouse gases. On the contrary, we see the difference between direct and indirect tax burden is very small for other sectors, such as Air Transport. Here, the bulk of the emissions is generated directly when producing the service, meaning only a very small share of the tax burden arises from taxation further up the value chain.

Results of the model

This section presents the results of introducing a $100/ton carbon tax on French firms and consumers into the global input-output model of Baqaee and Farhi (2019). We will discuss how these results change when extending the coverage of the carbon price to the EU and worldwide.

Figure 3. Impact of the French carbon tax on sectoral output



Note: The figure shows the impact of the French carbon tax (output + consumption) on the real output of each French sector, in relative terms with respect to real output in the baseline period.

We plot the percentage changes in real output for sectors in France in Figure 3. These arise from two margins of substitution: nationally, consumers and producers shift their consumption towards less carbon-intensive goods and inputs, and internationally, they reallocate consumption and input use away from French products towards the equivalent sector from countries without carbon taxation.[6]

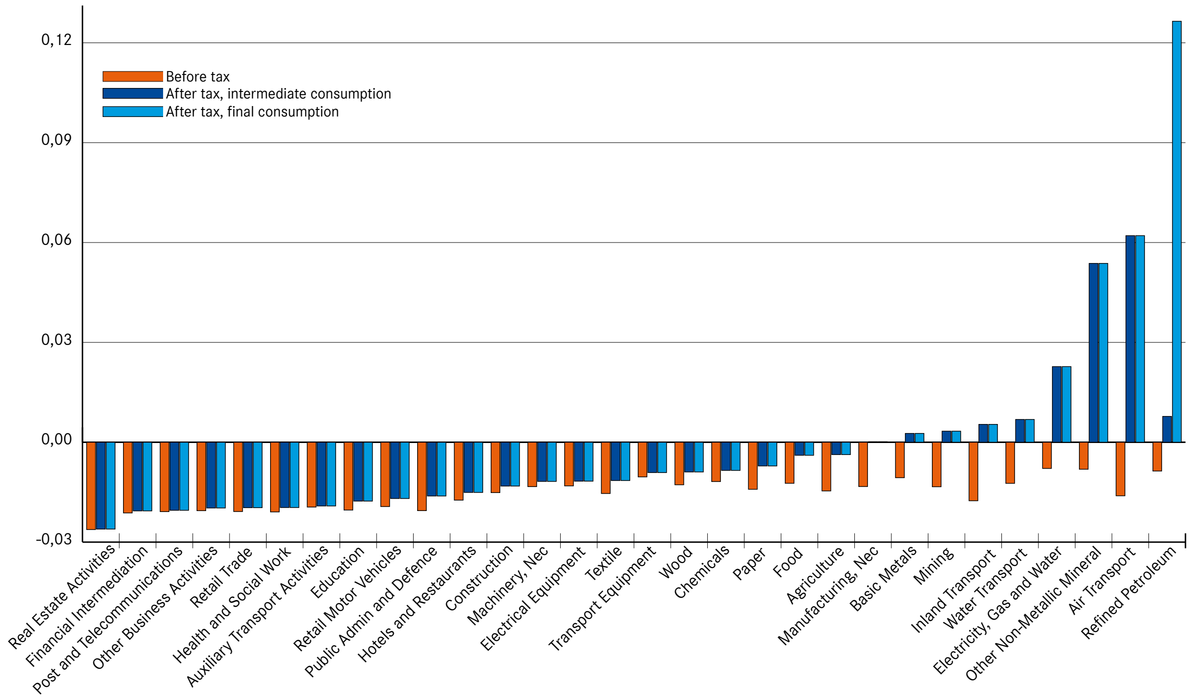
We find the strongest decline of output for refined petroleum, which in addition to what is implied by Figure 2, is the only sector subject to a consumption tax for final consumers. This makes that sector a special case, as the strong decrease in output stems from two sources. In this sector, real output contracts by a high 29%. The impact of the tax is almost as large, 28.8%, in the Air Transport industry, the most emitting sector in our data. The contraction in real output is an order

[6] Remember that the carbon tax only applies to France in this scenario. With elasticities of substitution across countries within a sector calibrated based on Caliendo and Parro (2015), firms and consumers can absorb the shock by substituting away from French products.

of magnitude lower, less than 10%, in the rest of the economy. Output even increases in a few manufacturing industries. The reason why the contraction of output for other non-metallic mineral products is an order of magnitude lower than in the air transport industry, despite similar tax burdens, is that mineral products are less traded than air transport services, which reduces the substitution away from heavily taxed French products.[7]

We dig deeper into the underlying mechanisms for the reallocation across sectors using the simulated evolution of production and consumption prices (Figure 4).

Figure 4. Price changes by sector in France



Note: The figure shows the impact of the French carbon tax (output + consumption) on the product prices of each French sector. The orange bars measure price adjustments at the factory gate, the dark blue bars add the tax burden of production taxes and the light blue bars further add the consumption tax, thus measuring the growth in consumption prices.

Even though every sector in France bears at least a small share of the tax burden, what is important is the exposure to a sector relative to the rest of the economy. The mechanisms for a French sector with below-average tax exposure are the following: it will experience substitution away from its products due to consumers and industry buyers switching towards international, untaxed competition. However, in France, domestic consumers and industry will also switch towards this sector, away from even heavier taxed sectors. In addition, taxation reduces the labor demand, especially in heavily taxed sectors. As factors in the model are mobile across sectors, and overall supply is fixed, this results in a decrease in factor costs for all sectors by around 2-2.5%. Thereby, in addition to benefitting from domestic substitution, some sectors even gain in international competitiveness. For sectors with a relatively low tax burden, these effects can dominate and increase the output, even though they are being exposed to a carbon tax.[8] This mechanism can be verified using the share of products of French origin in total final and intermediate consumption in France across sectors. Whereas the share of domestic products decreases in the most heavily taxed sectors, it instead increases in some sectors such as Electrical Equipment, Textile, or Wood Products, which can explain the unintuitive expansion of these sectors under the carbon tax scenario.

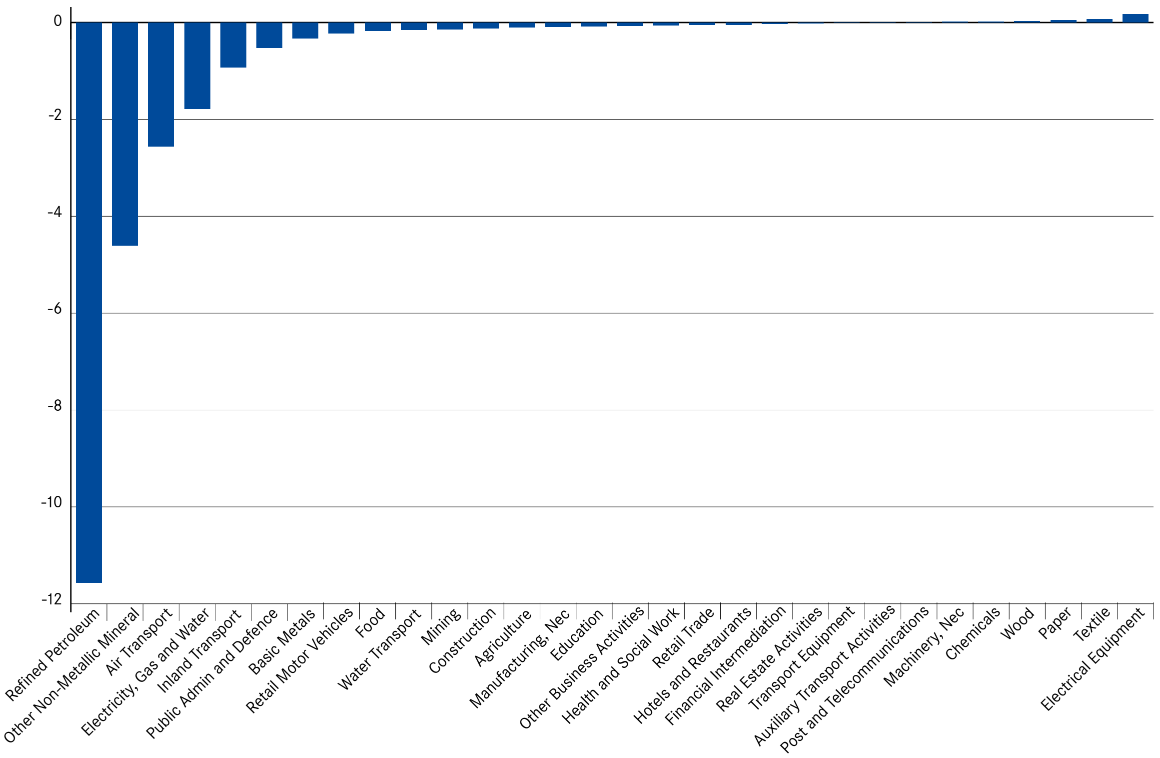
In summary, these shifts in allocation and prices, in combination with the fact that carbon tax revenues are rebated back to French consumers in a lump-sum transfer, means the reduction in welfare, measured in consumption by individual

[7] The share of domestic absorption in final consumption thus goes from 66.3 to 59.2% in air transport, to be compared with a decline from 79.5 to 76.5% in mineral products. The corresponding numbers for intermediate consumptions are declining from 25.3 to 20.0% for air transport services and 76.3 to 73.5% for mineral products.

[8] The model allows quantifying the disruptions the policy causes in the labor market. The baseline calibration assumes mobile factors across sectors, meaning each country has an exogenous endowment of capital and three types of labor, low, medium and high-skilled. By shifting the output decisions of firms across sectors, introducing a carbon tax also shifts the labor demand accordingly. Standard calibrations set a complementary relationship between value-added and intermediary input used for producing a good. Intuitively, this means that a decrease in intermediate consumption by a firm is accompanied by a less-than-proportional increase in labor demand. The opposite would be true for calibrating a substitutability relationship, where a decrease in intermediate input use could be more than compensated by increasing the labor input in production.

consumers, for a unilateral carbon price of $100/ton in France is only 0.0036%. Given the price adjustments, the changes in factor prices translate into a reduction in real wages of 1.2-1.5% for domestic workers, depending on the worker type.

Figure 5. Impact on emissions



Note: The figure shows the impact of the French carbon tax (output + consumption) on the emissions of each French sector.

A large share of this real wage reduction is mitigated by the distribution of the tax revenues back to consumers. Factoring out the tax rebates, meaning all tax revenue from the carbon tax is lost, would increase the loss in domestic welfare to 0.0154%.

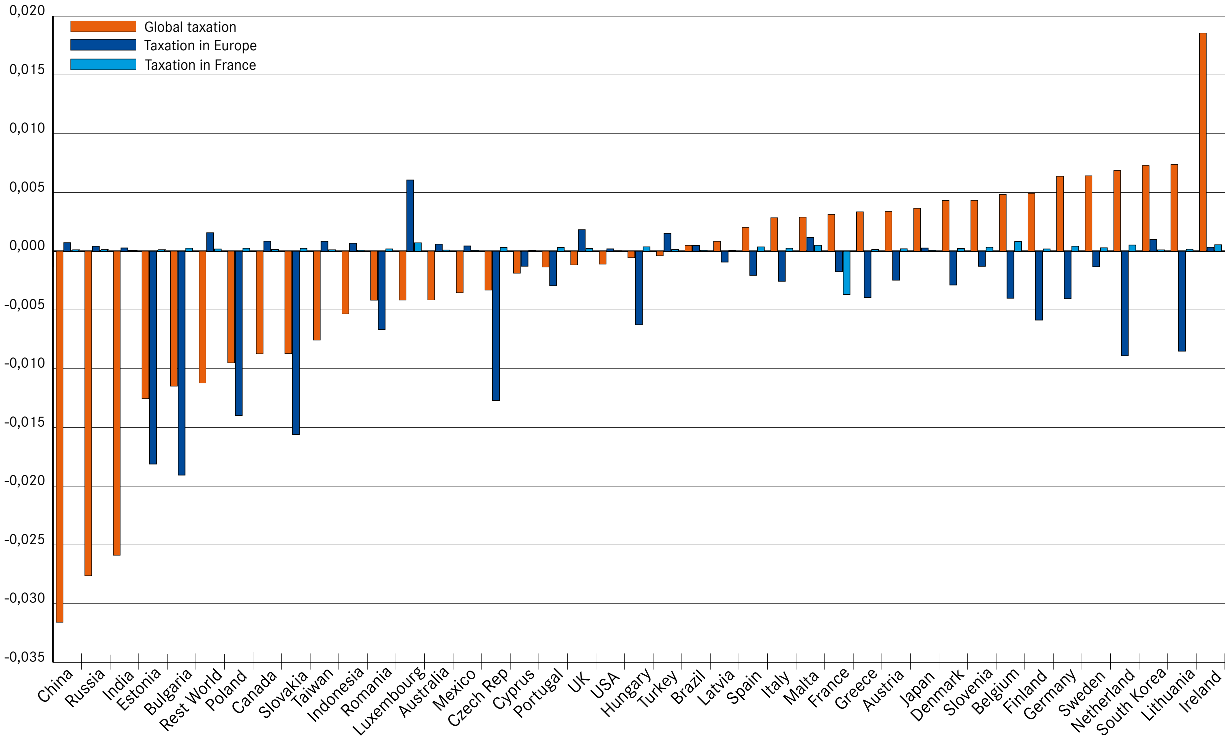
In addition to quantifying the impact on real output across sectors, Figure 5 shows the model's predictions regarding CO_2 emissions. As we assume constant technologies, the reductions in emissions correspond directly to the reductions in physical output. As the above is in percentage changes, one must multiply by the existing emission intensities to recover the total changes in emissions. For a $100 tax, we arrive at a reduction of around 22 Mt in GHG yearly emissions in France, which is around 5.9% of emissions in France in the baseline period.[9] It is important to note that these results emphasize the emission reduction achievable purely through substituting away from polluting sectors, notwithstanding any advances in technology. The results indicate that, given constant technologies, the potential of emission reduction through substitution is quite limited. This re-emphasizes that carbon neutrality is hardly achievable without reducing the emission intensity of production ("green growth"), and/or a shift in consumer preferences ("degrowth"). The results are consistent with the set-up of the model. If emission intensities of sectors do not change, it will be very hard to reach net zero, as at some point, contracting the polluting sectors by 60-75% would come at a huge cost along the entire supply chain, meaning it needs an extremely high carbon tax to trigger such a shift.

[9] Staying consistent with the original model by Baqaee and Farhi (2019), we follow their approach and calibrate the model with the WIOD 2013 release, using 2008 – one of the latest included years – as baseline for our calibration.

Alternative scenarios: EU and Worldwide carbon price

Given carbon pricing schemes are increasingly being deployed across the globe, we implemented additional scenarios where an equivalent carbon tax applies to all EU countries, or worldwide. In this section, we will discuss the main results from these scenarios.

Figure 6. Changes in welfare across countries



Note: The figure compares the impact of the varying carbon pricing scenarios on domestic absorption across countries.

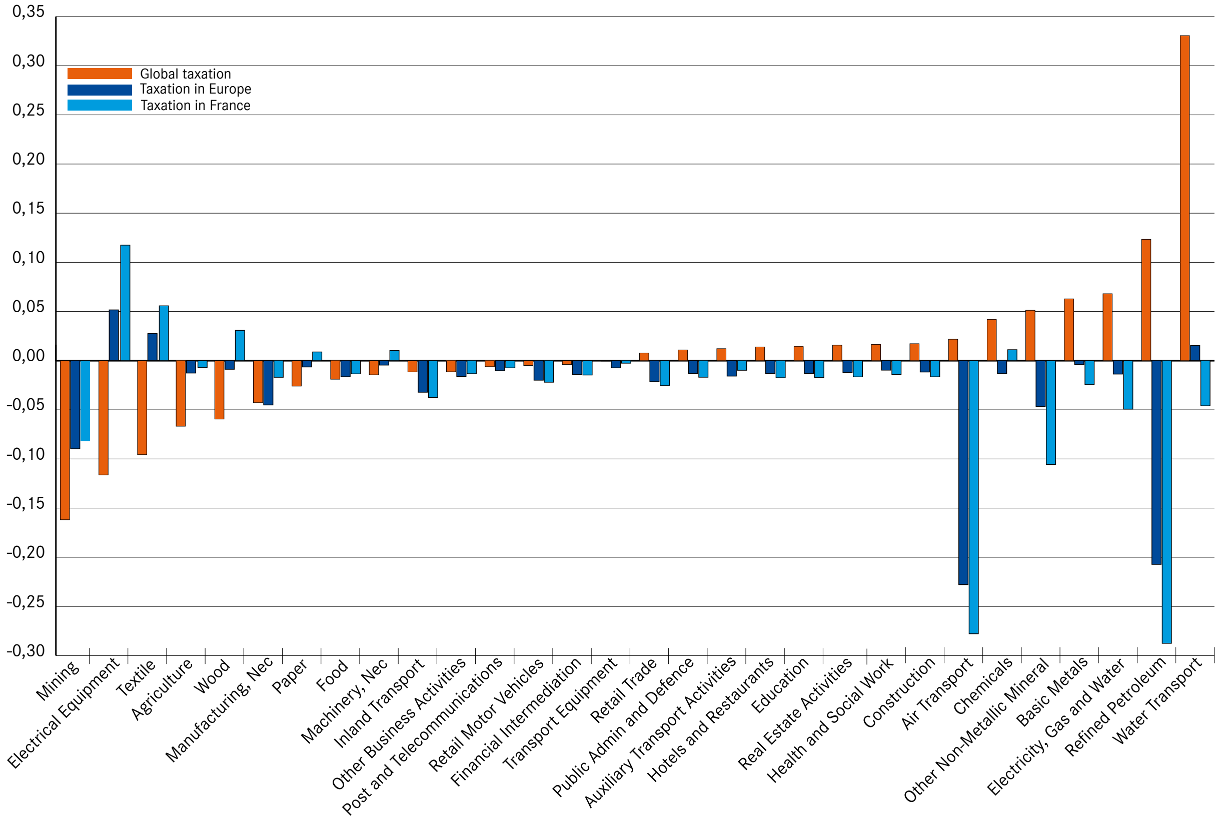
Plotting the welfare effects resulting from varying geographical coverage of a carbon price for EU countries in Figure 6 shows a strong heterogeneity across countries. Firstly, we see that taxation limited to France has almost negligible impacts on welfare in the global economy. Naturally, increasing the coverage and thus overall tax burden to the entire EU and globally increases those effects.

When introducing a European carbon tax, countries in Eastern Europe are most adversely affected. Here, there is traditionally an emission-intensive economic structure, with a large share of coal in the energy mix and a strong reliance on heavy industry. The case of Luxembourg highlights an interesting feature of the propagation of shocks through the value chain. Consumers in Luxembourg are positively affected by the introduction of a European carbon price. Remembering that domestic consumers are assumed to own local firms and factors, this can likely be explained by Luxembourg's strong reliance on financial intermediation and other service sectors. These are amongst the least carbon-intensive sectors. Given the introduction of a carbon price in all of Europe, consumers and industry are shifting their consumption to less carbon-intensive sectors, benefitting Luxembourg with its reliance on sectors with a low carbon intensity. This underlines that the impact of a carbon tax shock on a given country or sector is not only determined by the absolute size of the tax burden but more importantly by the relative magnitude as compared to other sectors and countries.

When taxing carbon emissions globally, China, India, and Russia are hit the strongest. Slightly benefitting from a carbon price in Europe, once domestic emissions are also taxed, domestic welfare decreases by around 0.03% in those economies. Once again, this may be explained by the structure of these countries' economy. It is also evident that the introduction of a global carbon tax as opposed to a European one seems to be beneficial for most EU countries. For a lot of them, the impact of such a tax is even positive.

Extending the coverage of carbon pricing has ambiguous consequences for the French economy. On the one hand, the competitive disadvantage for French sectors is reduced or, depending on relative emission intensities, even reversed, as competing sectors from other countries are now also taxed. This reduces substitution away from sectors within France. On the other hand, there are also adverse effects, both on the sectoral and aggregate levels. On the sector level, sectors traditionally importing carbon-intensive inputs are now facing higher costs, suppressing output in carbon-intensive sectors whilst triggering substitution towards less carbon-intensive ones. However, the overall increased tax burden for both French industry and consumers raises the price level for all sectors. Thereby, part of the output is suppressed for all sectors. Both mechanisms can be understood analogously to a substitution and an income effect, respectively. Comparing the scenarios of a European and global carbon price shows that there is significant sectoral heterogeneity as to which effects dominate. In Figure 7, we further depict the changes in output across sectors in France for the three taxation scenarios. We see that taxation in Europe produces relatively similar results for a carbon tax only in France, with the contractions in output for carbon-intensive sectors being slightly lower when all of Europe applies a carbon price. Relating to the discussion above, this means the reduced substitution away from French sectors towards other non-taxed EU countries is not yet overcompensated by an overall increased tax burden. This finding is summarised in a reduced welfare cost, of only 0.0017% as compared to 0.0036% when only France was taxed.

Figure 7. Sectoral output growth over varying taxation schemes



Note: The figure shows the impact of various carbon tax scenarios on sectoral output in France. The baseline is the taxation in France (light blue bars), which we can now compare with an EU-wide tax (dark blue bars) and a worldwide tax (orange bars).

When extending the coverage of the carbon price globally, results change significantly. To illustrate the underlying mechanisms, it makes sense to discuss the results for two representative sectors, Electrical Equipment, a sector with low carbon intensity along the value chain, and Refined Petroleum, a sector that displays high carbon intensities.

For Electrical Equipment, we see that whereas the sector had benefitted from carbon pricing in France due to wage decreases and a low tax burden, the benefit decreases for a European carbon tax and is even reversed in the case of global taxation. The reason is that, for global taxation, wages in France increase due to the overall upward pressure on labor demand. Thereby, there is now a negative spill-over through the wage channel for sectors otherwise only marginally affected by carbon pricing. Further, the increase in overall tax burden when extending the coverage suppresses output for all sectors, *ceteris paribus*. Together, this means that global taxation suppresses output in sectors that benefit from an introduction of a carbon price with more limited geographical coverage.

Conversely, many of the carbon-intensive sectors, suffering from carbon taxation in France, benefit from the introduction of a global carbon tax. Looking at "Refined Petroleum", we see that a global carbon tax results in significant increases in output by almost 10%. The reason is here that when the tax coverage is extended globally, what is now a very relevant factor for highly traded sectors is the international comparison in tax burdens. The French Petroleum sector has a carbon intensity that is almost half of the global average, and the international substitutability of products from different origins is estimated to be very high (Caliendo and Parro, 2015). Thereby, the sector now gains a significant competitive advantage in global competition. Given the strong international substitutability, this benefits the sector greatly as consumers shift strongly towards French "Refined Petroleum", away from alternatives from countries where the carbon intensity and thus tax burden is higher.

This channel mostly applies to sectors where there is a high carbon intensity in general, but French sectors have a lower intensity as compared to the global average. Therefore, we do not see such an increase for sectors with a very low carbon intensity, such as Electrical Equipment, where this effect plays a minor role and the above-discussed mechanisms suppressing output dominate. Whilst there is still substitution away from carbon-intensive sectors towards sectors with lower carbon emissions, we observe that a gain in international competitiveness overcompensates this effect, leading to increases in overall output for the emission-intensive sectors in France.

Thereby, the overall welfare change for France is an increase of 0.0031%. This can be largely explained by an increase in domestic real wages by between 0.005 and 0.009%, depending on the skill level. Given the assumptions on the production function in the model, it is likely that incomplete coverage of a carbon tax largely shifts the sourcing of inputs to non-taxed countries, whilst global carbon taxation triggers a substitution towards local value-added, benefitting local workers. Given a relative advantage in terms of carbon intensity, as is the case for France, this effect can dominate the increase in tax burden, especially when the tax revenues are rebated back to local consumers.

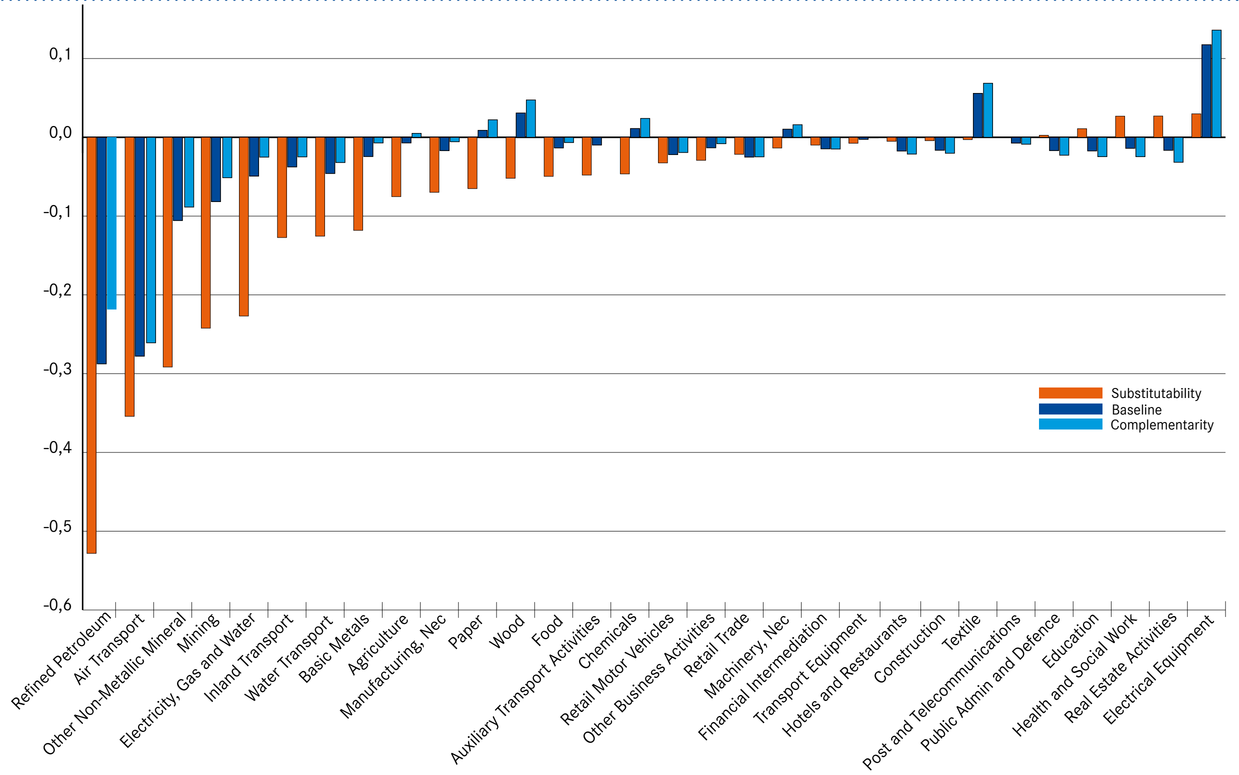
Alternative calibration: Varying the elasticities of substitution

As has become evident, the substitution pattern underlying the model plays a major role in shaping the results. All results presented above utilize the baseline calibration implemented by Baqaee and Farhi (2019) in their original paper. Specifically, the main substitution patterns to specify are the elasticity of substitution across sectors in consumption, the elasticity of substitution across composite value-added and intermediates, and the substitution across intermediate inputs from different sectors. The baseline calibration assumes a modest complementarity for all these substitution patterns. The elasticity of substitution within a sector for sourcing from different countries is taken from the sector-specific estimates of Caliendo and Parro (2015). They are all above one, consistent with the empirical literature.

To determine the sensitivity of our results and the assumption on the substitution patterns, we vary these elasticities and run scenarios with high degrees of substitutability and complementarity. To simplify things, we set the same elasticity of substitution at every point of the production and consumption network, either 0.01 under the scenario with high complementarities, or 5 when we want to give more room for substitution. These extreme scenarios are not meant to be realistic. The baseline calibration already uses the most plausible elasticities given the existing literature trying to pin down the corresponding parameters. The objective is to establish a tentative range of values that this type of model can produce.

We report the results of sectoral output growth in France for domestic carbon taxation for these scenarios in Figure 8. As expected, we can see that the stronger the degree of substitutability, the more negatively affected all sectors in France. Given France is the only country taxed in this scenario, the increases in cost for French products trigger a stronger substitution away from them the easier they are to replace, both in final and intermediate consumption. Especially for the case of very strong substitutability, the negative impacts on the emission-intensive sectors are far more pronounced, with over 50% for "Refined Petroleum", for which the elasticity makes the starkest difference. The reasoning is simply that this scenario sets a very high substitutability in both production and consumption, meaning that both the production and consumption taxes have a very negative effect on the output in this sector. For sectors benefitting from a carbon tax in France, the increase in substitutability suppresses their benefits. Whilst domestically, they now receive more substitution from carbon-intensive sectors, increases in substitutability in other countries mean even their low tax burden induces significant substitution away from them. It seems this effect dominates the increased domestic substitution.

Figure 8. Sectoral output growth over varying elasticities of substitution



Limitations of the Analysis

Offering a comprehensive way to model global interdependencies along the value chain, our analysis comes with some important limitations to consider when interpreting the results. Firstly, energy is treated like any other input in the production function, meaning the substitutability between coal and electricity is like between any two other sectors. There has been more explicit modeling of substitution between different energy inputs, for instance in Devulder and Lisack (2020). Focusing on carbon taxation exclusively in France, they find more pronounced impacts on the petroleum sector.This result is to be expected if it is easier for other sectors to substitute petroleum with other energy sources. Given these assumptions, we might underestimate the impact of the tax on some sectors by under-quantifying how easily they can be replaced in consumption and intermediate input use.

Additionally, technology is kept constant in the model. This means that all results ignore potential adjustments to lower the carbon intensity in heavily taxed sectors. We thereby overstate the triggered substitution patterns yet underestimate the potential of carbon pricing tools to reduce greenhouse gas emissions. The reductions in emissions need to be interpreted as possible reductions achievable solely through a substitution away from heavily emitting sectors. The redistribution amongst sectors might be lower if today's carbon-intensive sectors switch to less emitting technologies. An additional mechanism not modeled is an intra-industry selection due to carbon taxation, where less carbon-intensive firms within a sector gain market share as a response to carbon pricing, thereby lowering the average carbon intensity and the exposure of this sector. Accounting for this can further lower the observed substitution patterns, as argued by Giovanni, Levchenko, and Mejean (forthcoming).

Discussion and Policy Conclusions

In this Focus, we have investigated the impact of feeding a carbon price shock into the state-of-the-art global input-output framework by Baqaee and Farhi (2019), running scenarios with varying coverage of the carbon pricing scheme, applying only to France, the EU, or globally. Computing the resulting direct and indirect tax burdens for a \$100/ton tax, we find the overall tax burden is limited, ranging from a maximum of 8% for Air Transport to a negligible amount in the service sectors. Some sectors, such as Construction, display a large discrepancy showing the importance of considering the tax burden along the entire supply chain. For Refined Petroleum, in addition to a 2% tax burden on production in France, there is an additional 12.6% consumption tax.

Given this tax burden, we find negative, but small impacts on the French economy as a whole. However, the model produces substantial reallocation of activity across sectors. As expected, carbon-intensive sectors are adversely affected, with the highest output reductions for Refined Petroleum and Air Transport at almost 30%, with some sectors increasing their output because of substitution towards less carbon-intensive sectors. Overall, a $100/ton carbon tax on production emissions for all sectors as well as a final consumption tax for Refined Petroleum reduces welfare, as measured in terms of real consumption, by only 0.0036%.

Interestingly, extending the carbon price to all of Europe reduces the substitution away from French emission-intensive sectors by a small margin, reducing the overall welfare loss to 0.0017%. Extending it further to a global agreement, the impact would be positive for France, with a welfare increase of 0.0031%.

In terms of climate policy goals, our results indicate a limited potential of sole substitution away from emitting sectors to reduce greenhouse gas emissions. Whilst this mechanism can play a role in reaching the ambitious climate goals, it seems evident that either technological progress to reduce the emission intensity of production ("green growth") or an overall reduction in output ("degrowth") needs to accompany these substitution patterns to reach substantial emission reductions. One possibility that carbon pricing directly offers is to use the tax revenues in a more targeted way, for example by encouraging technological progress in heavily emitting sectors.

Crucially, the study highlights the importance of considering heterogeneity across sectors along the entire value chain when quantifying the expected impacts of carbon policies. Whilst in the long run, there is no economic reason to protect certain heavily emitting sectors from the impact of carbon pricing, there is a need to moderate the economic consequences of resulting transitions.[10] Our analysis indicates the most affected sectors for France, suggesting where potential social or labor market programs might need to be targeted.

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[10] An exception is the case when carbon pricing is strongly heterogeneous and there is a large risk of carbon leakage.

Appendix: Discussion of the model

Models of global input-output networks have been used previously to quantify the impacts of disturbances in global supply chains (Baqaee and Farhi 2019; Baqaee et al. 2022) or carbon pricing scenarios (Devulder and Lisack 2020). This *Focus* uses the model developed by Baqaee and Farhi (2019), which derives a generalized method for the computation of general equilibrium effects emerging from generic shocks to the equilibrium allocation.

Calibrating the model using data from the WIOD (World input-Output Database) for 41 countries (40 countries and the rest of the world aggregate) and 30 sectors, the model allows for substitution in consumption and production along the entire value chain.[11] This is critical, as carbon pricing policies, in addition to directly affecting the taxed products, also have indirect implications propagating through the supply chain upstream and downstream. On the consumption side, the model assumes a nested CES structure with an elasticity of substitution across industries calibrated to 0.2 and elasticities of substitution across countries calibrated with industry-specific values taken from Caliendo and Parro, 2015).[12] On the production side, the model also assumes CES aggregators. Value-added substitutes with intermediate consumption at a rate of 0.5. Primary factors substitute with each other with an elasticity of 1. Sectoral goods substitute with each other at a rate of 0.2 when varieties of specific goods substitute across countries at a rate also calibrated based on Caliendo and Parro (2015). Finally, the model assumes full pass-through and exogenous markups. In this context, a carbon tax drives a wedge between the producer price and the price the buyer, either a downstream firm or a final consumer, must pay.

We calibrate sectoral carbon prices in proportion to observed emissions, from the environmental accounts of the WIOD database. Output and consumption taxes are set in proportion to the value of the corresponding flow. We ran two versions of the model that differ by the treatment of tax revenues. In the baseline calibration, tax revenues are distributed lump-sum to the domestic household. We also run a version in which taxes are a pure distortion, that does not generate any revenues.

Intuitively, introducing a carbon tax at a given point in the supply chain has the following implications:

- Downstream: Introducing a carbon tax for some production steps causes an increase in prices for all agents downstream. If an upstream supplier emits during production, a carbon tax inflates its price, with consequences on the marginal cost of its downstream partners. The propagation through prices continues until the product reaches the final consumer. The chain of price increases induces quantity adjustments throughout the entire supply chain.
- Upstream: The same carbon tax also has indirect effects on all agents upstream of the taxed production step through quantity adjustments. If a downstream industry emits during production, the carbon tax raises its price. This causes a demand reduction, and thereby a reduction of its demand for intermediate inputs from its entire supply chain.

Thus, introducing a carbon tax is expected to shape the sectoral output and consumption amounts in the following way:

- Substitution of intermediate inputs: Firms adjust their input use away from heavily emitting (thus heavily taxed) inputs.
- Substitution in the final consumption basket: consumers substitute away from products that come from heavily emitting (thus heavily taxed) supply chains.

In both cases, the substitution can take place within the same industry, across more or less-taxed industries, or across countries that display heterogeneous taxes. It is important to note that these mechanisms mean it is not always straightforward which sectors will be affected. Whilst the heavily polluting and energy-intensive sectors will carry much of the burden, sectors that rely on inputs from these sectors at some points upstream in their supply chain will feel the effects as well. The comparison of the direct and overall tax burden in Figure 2 illustrates the difference. Additionally, sectors that are suppliers to the affected industries will also be impacted by a reduction in the output of their buyers. Even if a sector is neither emission intensive in its production, nor uses inputs that are, it might be affected if its buyers are heavily taxed, causing a downstream output contraction and reducing the demand for its good as an intermediate input.

[11] The baseline year is 2008, using the WIOD 2013 Release.
[12] Consistently with a large literature in international trade, these elasticities of substitution all take values above.

This propagation of a carbon pricing shock makes it critical to account for the entirety of input-output linkages when determining who is affected by carbon taxation, as is allowed in the employed model.

These substitutions allow consumers to compensate for parts of the effects: If a good is 8% more expensive, you partly substitute towards other consumption goods or intermediate inputs, thereby not having to reduce your overall consumption by 8% for a given budget constraint. The true consumption and welfare reduction is thus lower than what would be the case when no substitution is possible.