Taxing the carbon content of consumed goods

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Abstract

This note is concerned by the difference between production-based taxation and consumption-based taxation of CO_2 emissions. We focus on the possible discrepancy between a carbon tax paid by the producer and a tax on the carbon content of the consumed good. We want to appraise if and how incentives from consumption-based taxation are pushed down the production chain. Depending on whether the producer takes as fixed the price he receives or the price paid by the consumer (price the producer receives plus the tax on carbon content), we have two different conclusions. This raises a puzzle: which price should be considered as fixed? We show that, if producers are rational, they should take the price paid by the consumer as given, not the price received by the producer. In this case, the tax on carbon content (consumption-based taxation) is equivalent to the standard carbon tax (production-based taxation). Our analysis stresses the importance of the producer's rationality, as well as the importance of differentiating taxation by the actual carbon content, specific to each producer.

JEL codes: Q52, H2, H3.
Key words: Carbon tax; Tax on carbon content; Optimal taxation; Consumption-based policies; Energy transition.

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1 Introduction

This note focuses on the discrepancy between a carbon tax paid by the producer and a tax on the carbon content of the consumed good. The objective is to understand whether and why the latter may not lead to an optimal solution why the former does. We consider both the case of a tax on the carbon content of final consumption goods and intermediate consumption goods to appraise how the incentives are (or not) pushed down the production chain.

In a first setting, we assume that the producer is price taker and that the tax on carbon content of the consumed good is added to the price received by the producer. The consumer price is therefore the producer price plus the tax. We will then show that the producer lacks incentive to change technology (substitute polluting energy for labor) for the tax on the carbon content to decentralize the optimum. In a second setting, we assume that the price paid by the consumer is fixed, and that the producer takes this price. Then, the decentralized equilibrium matches the optimum. In this case, the price the producer receives is the price paid by the consumer minus the tax on carbon content, which in this case amounts to a carbon tax. The tax on carbon content of the consumed good can then restore the optimum.

This raises a puzzle: which price should be considered as fixed? To answer we abandon modeling the competition with a representative producer and explicitly model a continuum of producers. We then show that if producers are rational, they should take price paid by consumer as given, not price received by producer. In this case, the tax on carbon content is equivalent to the standard carbon tax where the carbon is taxed at the point of emission. This analysis stresses the importance of the producer's rationality, as well as the importance of differentiating taxation by the actual carbon content. If the producer receives the price paid by the consumer minus the tax on carbon content conventionally computed, that is, if the tax does not depend on the quantity of energy the producer actually used, we are back to sub-optimality.

We then extend this result when the production occurs in two stages, i.e. when there is intermediate consumption. We explicit how the incentive from the tax raised is transmitted through the production chain. Assuming that producers have the relevant information and are rational, the decentralized equilibrium with a tax on carbon content is optimal. The discussion highlights that what matters is how such taxation works in practice, which determines whether the agents have the relevant information to get the

suitable incentives to drive the equilibrium toward the optimum.

Our work is related to the discussion between production-based and consumption-based policies (Jakob et al., 2014). More specifically Steckel et al. (2010) have shown that "the way of accounting has neither efficiency nor distributive effects in the presence of a global cap-and-trade regime". However, they assume that carbon contents[1] are fixed and thus emissions are proportional to output. (Jakob et al., 2013) use a similar framework, with fixed carbon content. These works therefore cannot study producer's choices. On the contrary, we are interested to the incentives given to the producers to modify the carbon contents of their output. In our setting, producers can substitute between inputs and thus vary the carbon content of their product. In this more complex setting, we show also that consumption-based and production-based carbon taxation are equivalent and can decentralize the optimal solution.

Our work is thus close to Lininger (2015) who study the difference between production-based and consumption-based policies in a model where the carbon content of goods can be varied by producers (chap. 7 and 8). He simply assumes that taxing consumption-based taxation is equivalent to taxing the energy input but does not provide analytical reasons. Compared to these works, we also restrict ourselves to a single country case. Hence we do not discuss the complex question of carbon leakage and trade.

This note is very close to Gerlagh and Lorang (2023) that consider an economy with material balance and a tax on resource use versus waste. They show that, contrary to a tax on resources, a tax on waste is sub-optimal. The optimality of the waste tax can be recovered with a sufficiently fine grid of goods. Their tax on waste is analog to our tax on carbon content and their resource tax to our standard carbon tax. Our framework is a simpler and allows us to pinpoint the conditions under which there is equivalence between the two types of taxation. If we are correct, then their sub-optimality result relies either on some implicit irrationality of producers, or on a taxation that is levied at the sectoral level and not at the firm level. Another difference is that we refrain from interpreting the continuum of producers as an hedonic pricing issue. A key point is that compared to the existing literature on hedonic pricing (Rosen, 1974; Greenstone, 2017), we have a perfectly homogenous good hence there is no characteristics differentiating them and leading to different marginal utilities. Therefore there is no (hedonic) prices revealing the preferences with respect to some characteristics.

2 Decentralizing the optimum with a (standard) carbon tax

We consider an economy where the only factor of production is labour in quantity L. Labour can be allocated to two sectors. The first sector produces from (fossil) energy and labour $F_1(L_1, E)$ and the second sector from labour only $F_2(L_2)$. For simplicity, we assume that the price of energy in terms of good 2 is fixed by international conditions (small open economy): we have $p_E/p_2 = p$. On the other hand, only good 2 can be traded internationally (in exchange for energy). The use of (fossil) energy automatically results in emissions (no CO_2 capture/storage technology). So taxing energy and taxing emissions are one and the same thing (Mansur, 2012). We will therefore used energy and emissions interchangeably in this note.

[1] Carbon contents (or GHG emissions embodied in a good) is also known in the literature as (consumption-based) emissions intensities.

We first discuss the optimal program under an emission constraintand show that a (production-based) carbon tax can decentralize it.

2.1 Optimal program of planner

The planner seeks to maximise consumer utility $U(C_1, C_2)$ under resource constraints:

$$C_1 = F_1(L_1, E) \tag{1}$$
$$C_2 + p.E = F_2(L_2)\,. \tag{2}$$

This gives the program:

$$\max_{L_1,E} U(F_1(L_1, E), F_2(L - L_1) - pE)\,.$$

The FOCS are:

$$\partial_1 U \partial_L F_1 = \partial_2 U \partial_L F_2 \tag{3}$$
$$\partial_1 U \partial_E F_1 = \partial_2 U p \tag{4}$$

The first FOC equalizes of the marginal social productivities of labour across firms and the second one equalizes the marginal social productivities of energy.

Suppose now that due to climate change and its damages, the planner has some objective in terms of emission reduction. This boils down to a constraint in terms of energy consumption. The planner's programme then has a constraint $E \leq \bar{E}$ with a multiplier λ. The second FOC becomes then:

$$\partial_1 U \partial_E F_1 = \partial_2 U p + \lambda \tag{5}$$

2.2 Decentralizing the optimal solution

We seek to decentralise the optimal solution through prices p_1, p_2, p_E, a wage w and a carbon tax t levied on emission. The program for producer 1 is:

$$\max_{L,E} p_1 F_1(L, E) - wL - p_E.E - t.E$$

It leads to the following FOCs:

$$p_1 \partial_L F_1 = w \tag{6}$$
$$p_1 \partial_E F_1 = p_E + t \tag{7}$$

The FOC of Producer 2's program is

$$p_2 \partial_L F_2 = w. \tag{8}$$

.

Finally the consumer's program FOCs give

$$\frac{p_1}{p_2} = \frac{\partial_1 U}{\partial_2 U}. \tag{9}$$

The consumer program sets the price ratio, the producer 2 program gives the wage. The first FOC of the central planner is satisfied thanks to the first FOC of producer 1 (eq. (6)). The second FOC of producer 1 can be rewritten as:

$$p_1 \partial_E F_1 = p_E + t \tag{10}$$

$$p_2 \frac{\partial_1 U}{\partial_2 U} \partial_E F_1 = p_E + t \tag{11}$$

$$\partial_1 U \partial_E F_1 = \partial_2 U p + t \frac{\partial_2 U}{p_2} \tag{12}$$

Hence we can get the second FOC of optimal planning (equation (5)) by setting: $t = \lambda p_2 / \partial_2 U$. The optimal solution can then be decentralized.

3 Equilibrium with a tax on the carbon content of final consumption goods

Here, we want to investigate the effect of a tax levied on carbon content of goods. The carbon content is the emissions embodied in good per unit of good produced. As producer 2 does not use fossil energy, only good 1 has a non-zero carbon content. If C_1 is the amount produced and E the amount of energy/emissions used, the carbon content of good 1 is $E/C_1 = E/F_1(L_1, E)$. The carbon content thus varies depending on how much labour or energy is used by producer 1.

We start with a market situation and add a tax on carbon content. Let us note p_1^c the price paid by the consumer and p_1^p the price received by the producer. When there was no tax on carbon content, we had $p_1^c = p_1^p$. Now because of the tax of carbon content, we have $p_1^c = p_1^p + t.E/C_1$: carbon content is taxed at rate t (with a slight abuse, we use the same letter as the previous standard carbon tax). Because there is no carbon involved in producing good 2, it is not taxed, so we can still use p_2 without ambiguity.

The producer 2's FOC remains eq. (8) The consumer's FOC remains also eq. (9), or actually $\frac{p_1^c}{p_2} = \frac{\partial_1 U}{\partial_2 U}$.

The producer 1 is a price-taker. The solution depends on which price the producer takes: p_1^p or p_1^c. We investigate these two possibilities before discussing which price should be considered as fixed by a rational producer.

3.1 Producer price as given

In this subsection, we consider producer price p_1^p as given. The program for producer 1 is:

$$\max_{L,E} p_1^p F_1(L, E) - wL - p_E.E$$

The FOC conditions then become:

$$p_1^p \partial_L F_1 = w \tag{13}$$

$$p_1^p \partial_E F_1 = p_E \tag{14}$$

This tax causes equilibrium prices to vary but cannot align producers' programmes with the optimal conditions under benevolent planning. To see that consider that the consumer's FOCs give $\frac{\partial_1 U}{\partial_2 U} = \frac{p_1^p + t.E^e/C_1^e}{p_2}$, with E^e and C_1^e the quantity at equilibrium.

Because of the FOC of producers, we have

$$\frac{\partial_1 U}{\partial_2 U}\frac{\partial_L F_1}{\partial_L F_2} = \frac{p_1^p + t.E^e/C_1^e}{p_2}\frac{w/p_1^p}{w/p_2} = 1 + \frac{t.E^e}{p_1^p.C_1^e} \tag{15}$$

It is not possible to find $t \neq 0$ such that (15) is equivalent to (3).

Therefore, in this setting, taxing carbon content cannot decentralize the optimal solution. The reason is that the producer of carbon-containing good 1 has not sufficiently altered his production methods and does not use enough labour (relative to energy) compared with the social optimum. This is shown in appendix A. By taxing carbon content, consumers are encouraged to alter their consumption pattern, but producers are not encouraged to change their production techniques. We have a sub-optimal situation that is avoided with standard carbon taxation.

Of course, in the special case of a Leontieff technology, substituting energy with labor no longer makes any sense and the optimality of the decentralized equilibrium can be restored with a tax on the carbon content of good 1 (see appendix B and Gerlach et al., 2023).

3.2 Consumer price as given

Here, we consider an alternative assumption: consumer price p_1^c is now taken by producer 1. The program for producer 1 is still:

$$\max_{L,E} p_1^p F_1(L,E) - wL - p_E.E$$

However $p_1^c = p_1^p + tE/C_1$ is now fixed, with $C_1 = F_1(L,E)$. The FOC conditions then become:

$$p_1^c \partial_L F_1 = w \tag{16}$$

$$p_1^c \partial_E F_1 = p_E + t \tag{17}$$

From here, it is clear that the tax on carbon content act as a standard carbon tax. The second FOC of optimal planning (equation (5)) can be simply decentralized by setting: $t = \lambda p_2/\partial_2 U$.

So, when producer 1 takes consumer price, taxing the carbon content can decentralized the optimum.

3.3 Solving the puzzle with a continuum of goods

The two different assumptions then give two different, contradictory results. This raises a puzzle: which assumptions is correct? Should producer 1 take the consumer price p_1^c or the producer price p_1^p as given? Because of perfect competition, producer 1 is a price-taker, but which price does it take?

To answer the puzzle, we have to remember that assuming a unique representative producer 1 as a price-taker is actually a short-hand for a continuum of identical producers in competition. Using such a short-hand introduces some ambiguity, because for example prices or quantities at the market or at the producer level are not distinguished. To solve

the puzzle and find which of the two assumptions is correct, we have to model explicitly a continuum of producers of good 1.

We have a continuum of producers of good 1 (actually only two producers in perfect competition are necessary) indexed by i. Each producer i of good 1 has the following optimization program

$$\max_{L_i,E_i} p_{1i}^p F_1(L_i, E_i) - wL_i - p_E.E_i$$

. The price received by producer i is p_{1i}^p.

The consumer is indifferent between different producers of good 1. Goods 1 have the same characteristics from the point of view of the consumer, although they may be produced differently. Therefore, the consumer only cares about the aggregate amount of good 1 consumed. The consumer thus maximises $U(C_1, C_2)$ with $C_1 = \int C_{1i} di$, subject to the budget constraint $R \geq \int p_{1i}^c C_{1i} di + p_2 C_2$. The price paid by the consumer is producer-specific: p_{1i}^c is the price paid by the consumer for good 1 produced by i. The FOCs of the consumer lead to two different conditions. The first one is the traditional equality of marginal utility between good 1 and good 2: $\partial_1 U / p_{1i}^c = \partial_2 U / p_2$. The second one reads $\partial_1 U / p_{1i}^c = \partial_1 U / p_{1j}^c$. It actually says that prices paid by consumer to different producers should be equal for the goods to be consumed. So consumer's choice actually equalizes the prices p_{1i}^c for different i.

We have only made the specific assumption that consumer is indifferent between different varieties of product 1, but we have not made specific assumption regarding producers: they can be similar or different. In term of market design, we have simply assumed that producers can be differentiated so that each producer can propose its own product with its own price to the market. Consumer's choices will then equalize after-tax prices. However, if the producers are fully rational, they will take as given the price paid by consumer, not the price they received, so that they will maximize their profits with p_1^c given. Therefore the first assumption is not correct. When we explicitly model producers in perfect competition, only the second assumption is rational. We are therefore in the second setting where the consumer price is given (see section 3.2), and in this setting, a tax on carbon content will retrieve the optimal solution.

We can be convinced that rational producers will follow the second assumption from a different perspective. Suppose we are in the equilibrium of the first setting, where all producers have taken producer price p_1^p as given. A (fully) rational producer will have an incentive to deviate from the equilibrium because he would make an extra-profit.

To show that, let us start from the situation where the producer i has (wrongly) taken producer-price as given. Quantities are then L_i, E_i and C_{1i}, and they verify in particular FOCs (13) and (14). Then the producer realizes that he can move along the production frontier to E_i', C_{1i}', L_i' and raise his production price $p_{1i}^{'p} > p_{1i}^p$, such that the price charged to the consumer $p_1^c = p_{1i}^{'p} + t.E_i'/C_{1i}'$ is unchanged. Can he increase his profits? Suppose he reduces energy by a small amount $-dE$ ($E_i' = E_i - dE$) and increases labor by a small ammount dL ($L_i' = L_i + dL$) and keeps total production constant $C_{1i}' = C_{1i}$. His profits were initially

$$\Pi = p_{1i}^p C_{1i} - wL_i - p_E.E_i = p_1^c C_{1i} - wL_i - (p_E + t).E_i \tag{18}$$

They become:

$$\Pi' = p_1^c C_{1i} - w(L_i + dL) - (p_E + t).(E_i - dE) \tag{19}$$
$$= p_1^c C_{1i} - wL_i - (p_E + t).E_i - w.dL + p_E.dE + t.dE \tag{20}$$

In addition, $-wdL + p_E.dE = 0$ for production to be constant and FOCs (13) and (14) to be satisfied, such that $\Pi' = \Pi + t.dE$ and producer i makes an extra profit $t.dE > 0$. By using less energy, the tax on carbon content is reduced so that the producers can increase the price he received while keeping the price for consumer constant.

To conclude, if producers are fully rational, they take consumer price as given and internalize the tax on carbon content. The latter thus acts as a standard carbon tax. The result does not assume that the consumer cares about the carbon content. Goods are differentiated by their carbon content and price, but not in terms of consumer preferences (hence, no hedonic pricing story here). The important assumptions are put on the producer's side and consist of competitive (price-taker) behavior and full rationality.

For the tax on carbon content to restore the optimal solution, it is decisive that the tax on good 1 depends on the actual carbon content of the goods produced. This ensures that producer i receives $p_1^c - t.E_{1i}/C_{1i}$ for each unit of good 1 he sells, thus leading to the internalisation of carbon taxation. If goods 1 are taxed according to the mean carbon content at the sector level (or a convention), then we are back to the setting with the producer price given since in this case producer i will receive $p_1^c - c.E_1/C_1$ per unit of good and thus not internalize the tax on carbon content. Put it differently, for the taxation on the carbon content to transmit the right incentive to producers, it is essential that the carbon content considered in the taxation is the carbon content computed at the firm level, i.e. that it is specific to the production methods of the firm. Using a carbon content at a sectoral level will change prices and consumer decisions but will not give the correct incentives to producers.

4 Taxing the carbon content of intermediate consumption

So far, we have consider only producer that sell their products directly to consumer. We have seen then, that if producers are fully rational, the tax on carbon content will be the same as a standard carbon tax. The question now is whether this equivalence result still holds in a more complex environment where we have intermediate consumption.

We consider a chain of producers such that company 1 produces good 1, not from labour and energy, but from labour and good 3: $Y_1 = F_1(L_1, Y_3)$. Good 3 is produced by a sector 3 from labour and energy $Y_3 = F_3(L_3, E_3)$. By introducing in a new stage in production, we want to understand whether and how the taxation of carbon content is transmitted along the production chain and what are the consequences for producers. In particular, we want to know whether consumption-based taxation can still decentralize the planner's optimum.

4.1 Optimum

Vertical integration of firms through the production function $Y_1 = F_1(L_1, F_3(L_3, E_3))$ provides the optimal solution. With a carbon tax t, the integrated producer's programme is

$$\max_{L_1, L_3, E_3} p_1.F_1(L_1, F_3(L_3, E_3)) - w(L_1 + L_3) - (p_E + t)E_3$$

and the corresponding FOCs are:

$$w = p_1 \partial_L F_1 \tag{21}$$
$$w = p_1 \partial_3 F_1 . \partial_L F_3 \tag{22}$$
$$p_E + t = p_1 \partial_3 F_1 . \partial_E F_3 \tag{23}$$

4.2 Taxing carbon at the point of emission

Taxing carbon at the point of emission corresponds to the "traditional" (production-based) carbon tax. Assuming non-integrated producers and a carbon tax, the programme for producer 1 is

$$\max_{L_1, Y_3} p_1 . F_1(L_1, Y_3) - wL_1 - p_3 . Y_3$$

that leads to the following FOCs:

$$w = p_1 \partial_L F_1 \tag{24}$$
$$p_3 = p_1 \partial_3 F_1 \tag{25}$$

Regarding producer 3

$$\max_{L_3, E_3} p_3 . F_3(L_3, E_3) - wL_3 - (p_E + t) . E_3$$

with the corresponding FOCs:

$$w = p_3 \partial_L F_3 \tag{26}$$
$$p_E + t = p_3 \partial_E F_3 \tag{27}$$

One can observe that the FOCs with non-integrated producers are equivalent to the FOCs at the optimum with $p_3 = p_1 \partial_3 F_1$. Thus, the standard carbon tax can decentralize the optimum.

Equation (27) can be rewritten as $p_3 = (p_E + t)/\partial_E F_3$, i.e. the price of good 3 is equal to the marginal cost (since the production of one additional unit of good 3 requires $1/\partial_E F_3$ emissions which costs $p + t$ per unit). Optimal use in sector 1 leads to

$$p_1 \partial_3 F_1 = p_3 = \frac{p_E + t}{\partial_E F_3} \tag{28}$$

i.e. the marginal productivity of good 3 for producer 1 is equal to its equal and to its marginal cost in terms of emissions.

4.3 Taxing carbon content at the end of the production chain

To introduce a tax on carbon content, we consider that only representative producer 1 sells directly to the consumer while a continuum of producers 3, indexed by i, sells to producer 1.

As we have seen previously, producer 1 will take the price paid by the consumer as given. Because producer 1 does not add any emissions, the carbon content of good 1 is simply the emissions inherited from producers of goods 3, divided by production of good 1, i.e. $\int c_i Y_{3i} di / Y_1$. Producer 1 programme now becomes:

$$\max_{L_1, Y_{3i}} p_1^c . F_1 \left(L_1, \int Y_{3i} di \right) - wL_1 - \int (p_{3i} + tc_i) . Y_{3i} di$$

with $c_i = E_{3i}/Y_{3i}$ the carbon content of good 3 produced by i. This leads to the following FOCs:

$$w = p_1 \partial_L F_1 \tag{29}$$
$$p_{3i} + tc_i = p_1 \partial_3 F_1 \tag{30}$$

This has important implications. Because goods 3 from different producers equally enter the production function 1, producer 1 will use goods 3 with equal after tax price $(p_{3i} + tc_i)$, even if the tax is paid by the consumer. Competition between producers i for selling goods 3 to producer 1 does not lead to equalizing the prices at which goods are traded but equalizing the price completed with the tax on carbon content. We note $p_3^e = p_{3i} + tc_i$ this completed price.

Producer i of good 3 maximises its profits:

$$\max_{L_{3i}, E_{3i}} \Pi_i$$

The profits are given by:

$$\Pi_i = p_{3i}.F_3(L_{3i}, E_{3i}) - wL_{3i} - p_E.E_{3i} \tag{31}$$
$$= (p_3^e - tc_i).F_3(L_{3i}, E_{3i}) - wL_{3i} - p_E.E_{3i} \tag{32}$$
$$= p_3^e F_3(L_{3i}, E_{3i}) - wL_{3i} - (p_E + t).E_{3i} \tag{33}$$

Since, because of competition, producer i takes p_3^e as fixed (and not p_{3i}), the FOCs of producer i are:

$$w = p_3^e \partial_L F_3 \tag{34}$$
$$p_E + t = p_3^e \partial_E F_3 \tag{35}$$

These FOCs are equivalent to FOCs (26) and (27) from a standard carbon tax, with the correspondance $p_3 \leftrightarrow p_3^e$. From there, it is clear that the tax will be passed on to the production chain through the rationality of producers.

We highlight here the importance of not using a representative producer for goods 3. For a representative producer, we could quickly (and wrongly) assume that he takes the price p_{3i} as given (which is not the case). We would then deduce that the optimum could not be recovered with a tax on carbon content (see Appendix C).

On the contrary, with competing producers 3, we have two equivalent ways of taxing goods, that both lead to optimum: a (production-based) carbon tax and a tax on the carbon content (consumption-based carbon tax). Indeed, in the case of competing producers 3 with a tax on carbon content, who then take as given the price of good 3 plus the tax on the carbon content (p_3^e), the FOCs become similar to the optimality conditions, when considering the price ensuring the equilibrium p_3^e.

It is however very important to observe that the prices of goods 3 do not have the same value in both cases. With competing producers 3 and a tax on carbon content, the prices of goods 3 are equal to the marginal costs minus the tax on carbon content, i.e.$p_{3i} = \frac{p_E + t}{\partial_E F_3} - t\frac{E_{3i}}{Y_{3i}}$, while the price is equal to the marginal costs only (see (28)) in the case of a standard carbon tax. The prices at which goods are traded also have a different purpose. With a standard carbon tax, the prices alone serve as the coordinating mechanism between producers with competition leading to their equalization. They transmit information about

marginal costs. With a tax on carbon content, it is the prices plus the tax on carbon content that play this role. Prices p_{3i} alone convey a wrong information, they have to be completed with information about the carbon content of the good and the amount of the tax to transmit the right information at the margin ($p_3^e = p_{3i} + tc_i$). The situation is thus more demanding in terme of information, as the information has to be transmitted through several channels.

4.4 Discussion

Assuming competitive and rational behavior of producers is enough to have the suitable incentive so that the decentralized equilibrium with taxation on carbon content leads to the optimal solution. This is the case when goods are taxed according to their actual, firm-specific, carbon content and not according to a generic, sectoral carbon content.

This analysis raises several questions on the realism of the setting we introduce. First, we have seen that prices alone cannot transmit the information but have to be completed with the tax on carbon content. How can this coordination work if only market prices and not "completed" prices are observed? The information delivered by prices is not sufficient but has to be supplemented with another information system that will publicly deliver data on carbon content of traded goods Thus there is a need to set up another information system. This raises the question of the (transaction) costs of building this information system so that the actual carbon content of goods can be tracked and made as available as information on prices. It also raises the question of how would producers process these new pieces of information, and of whether they would draw the same conclusions as a perfectly rational producer.

Finally, our analysis has used tools from static equilibrium analysis. There is also an implementation issue during the transition when the tax starts to be imposed, before the new equilibrium price p_1 (or p_3) is reached. In particular, producers of good 1 (good 3) are not immediately or directly affected by the tax on the carbon content which strikingly differs from a traditional carbon tax that is paid by the producer to the government. Therefore the dynamic of adjusting to a new tax will likely differ when the tax is levied on emissions or when it is levied on carbon content.

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APPENDIX

A On the sub-optimality of a tax on the carbon content

Let us start from a situation of market equilibrium with taxation on the carbon content. Let us then increase the amount of labour in sector 1 by h (and therefore decrease it by h in sector 2). Consumer utility changes from

$$\begin{aligned}\partial_1 U \partial_L F_1.h - \partial_2 U \partial_L F_2.h &= \left(\frac{\partial_1 U}{p_1^p} - \frac{\partial_2 U}{p_2}\right) wh \\ &= \frac{\partial_2 U}{p_2} \frac{c.E^e}{p_1^p.C_1^e} wh\end{aligned}$$

For any $c > 0$, it is socially beneficial to increase the production of good 1 by using more labour (and therefore reducing the carbon content of 1). Given the relative price system, the producer of good 1 has no incentive to do so.

B Case of a Leontieff technology

Let us consider that $E = k.L_1$. Hence the programme of the planner becomes:

$$\max_{L_1} U(F_1(L_1), F_2(L - L_2) - pkL_1)$$

with a constraint $k.L_1 \leq \bar{E}$ associated with a multiplier λ. and the optimality condition is:

$$\partial_1 U \partial_L F_1 = \partial_2 U(\partial_L F_2 + p.k) + k\lambda \Leftrightarrow \frac{\partial_1 U \partial_L F_1}{\partial_2 U \partial_L F_2} = 1 + k\frac{p + \lambda/\partial_2 U}{\partial_L F_2} \tag{36}$$

With a tax on the producer, the programme of producer 1 becomes:

$$\max_{L_1} p_1 F_1(L_1) - wL_1 - p_E kL_1 - tkL_1$$

and the FOC is:

$$p_1 \partial_L F_1 = w + k(p_E + t)$$

The programme of producer 2 leads to:

$$p_2 \partial_L F_2 = w$$

On the side of the consumer, we still have:

$$\frac{\partial_1 U}{\partial_2 U} = \frac{p_1}{p_2}$$

Hence at the decentralized equilibrium:

$$\frac{\partial_1 U}{\partial_2 U} \frac{\partial_L F_1}{\partial_L F_2} = 1 + k\frac{p_E + t}{w}$$

which is equivalent to equation (36) if $t = \lambda p_2/\partial_2 U$. This is similar to the result when substitution between labor and energy is possible.

If the carbon content of good 1 is taxed, we have obtained equation (15) that is equivalent to (36) iff

$$k\frac{p + \lambda/\partial_2 U}{\partial_L F_2} = \frac{c.E^e}{p_1.C_1^e} \Leftrightarrow c = p_1 \frac{C_1^e}{E^e} k\frac{p + \lambda/\partial_2 U}{\partial_L F_2} = p_1 \frac{C_1^e}{E^e} \frac{k}{w}(p_E + p_2 \lambda/\partial_2 U)$$

C On the sub-optimality in case of a representative producer for good 3

Then the corresponding FOCs would be:

$$w = p_{3i}\partial_L F_3 \tag{37}$$

$$p_E = p_{3i}\partial_E F_3 \tag{38}$$

and equations (30) and (38) lead to

$$p_1\partial_3 F_1 = \frac{p_E}{\partial_E F_3} + \frac{t}{Y_{3i}/E_{3i}}$$

that differs from equation (28) that prevails at the optimum.