Do Renewable Energy Policies Reduce Carbon Emissions? On Caps and Inter-Industry Leakage*

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Abstract

In a parsimonious two-sector general equilibrium model we challenge the widely held tenet that within a cap-and-trade system renewable energy policies have no effect on carbon emissions. If the cap does not capture all sectors, we demonstrate that variations of a renewable energy subsidy change aggregate carbon emissions through an inter-industry leakage effect. We decompose this effect into intuitively intelligible components that depend in natural ways on measurable elasticity parameters. Raising the subsidy always reduces emissions if funded by a lump-sum tax, reinforcing recent findings that tightening evironmental regulation can cause negative leakage. However, if the subsidy is funded by a levy on electricity it can increase emissions. These results provide a valuable basis for an informed design of renewable energy policies and an accurate assessment of their effectiveness. We highlight how a state-of-the-art statistic used by governments to gauge such effectiveness—"virtual emission reductions"—is biased, because inter-industrial leakage effects are not captured.

1 Introduction

Electricity generation currently goes through a massive transformation away from fossil fuel combustion towards renewable sources of energy. This process is spurred by a set of public policies involving both quotas (or "portfolio standards") and subsidies—the latter typically in the form of feed-in tariffs (FIT), which come in the guise of minimum prices or piece rate subsidies for electricity produced from renewables. At the end of 2015 renewable energy policies could be found in 146 countries, FITs in 75 countries at the

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national level and in 35 states or provinces (see REN21, 2016, p. 107 and following).[1] A prominent example is the German Renewable Energy Act (*Erneuerbare-Energien-Gesetz, EEG*). The EEG-tariff averaged across technologies reached 18 cents per kWh in 2013 while the average spot price of electricity was about 4 cents per kWh, resulting in net subsidy payments of €20.36 billion (BMWE, 2014).

The dominant objective behind renewable energy policies is carbon emissions abatement. Indeed, the electricity industry is the by far largest carbon emitter and therefore a natural first-order target for climate policy.[2] However, the effectiveness of renewable energy promotion as a climate policy tool is debated: a widely held tenet among researchers is that it has no effect on total carbon emissions at all if the electricity industry is also subject to a cap-and-trade system (CAT), as in the EU, parts of the US, China (starting from 2016), and other regions (Fischer & Preonas, 2010; Fowlie, 2010; Goulder, 2013; Böhringer, 2014).[3] The argument is simple and convincing: as long as the cap is binding, emissions are fixed by the volume of permits. Additional instruments applied to the same industry merely reallocate emissions between sources and—by moving them away from where abatement is cheapest—raise total abatement costs. This has been used to argue against FIT policies or the explicit targets for renewables in the EU complementing carbon abatement targets (Böhringer et al., 2009).

There is nothing wrong with this argument if the electricity industry is considered in isolation from the rest of the economy.[4] However, in the present paper we demonstrate that if economy-wide adjustments are taken into account, then the argument is incomplete because it ignores *inter-industry leakage effects*. Within a parsimonious two-sectors/goods, two-inputs general equilibrium model that explicitly considers the industries outside the CAT and their linkages to the electricity industry, we show that renewable energy policies indeed alter economy-wide carbon emissions even if the electricity industry is under a CAT. The basic intuition is simple: All existing CATs cover only a fraction of the carbon emitting industries. For example, the EU ETS applies to electricity and some other major industries, and covers only about 45% of total greenhouse gas emissions produced within the EU (European Commission, 2013).[5] Significant greenhouse gas emitting sectors such as transportation and agriculture remain outside. In such settings renewable energy policies generally induce changes in emissions produced by industries outside the CAT.

[1] The first FIT scheme was introduced in the US by the Public Utility Regulatory Policies Act (PURPA), a part of the 1978 National Energy Act (NEA). Germany (1990), Switzerland (1991), Italy (1992), Denmark (1993), India (1993), Luxembourg (1994), Spain (1994) and Greece (1994) followed in the first half of the 1990s. The trend culminated between 2001 and 2011 with more than 100 countries enacting a FIT scheme, including France (2001), Brazil (2003), China (2005), California (2008), Japan (2009) and the United Kingdom (2010). See REN21 (2016, p. 107 and following) for an overview.

[2] It accounts for about two fifth of total carbon emissions in the EU and the US (USEIA, 2013; IEA, 2014).

[3] CATs are one of the most common instruments to regulate carbon emissions. For example, within the EU the electricity industry is also subject to the EU Emissions Trading System (EU ETS), and in parts of the US to similar CATs such as the California-Québec Agreement (the remainder of the Western Climate Initiative) and the Regional Greenhouse Gas Initiative (RGGI). Until recently, Australia had plans to convert what currently is effectively a carbon tax into a CAT in 2015 and China has started a number of city-level CATs for carbon emissions in 2013 to gain experience for a national program scheduled to be introduced in 2016 (Qui, 2013; New York Times, 2014).

[4] Several authors have argued that despite the zero impact on GHG emissions, feed-in tariffs might still be desirable if they help to achieve other objectives or fix additional market failures (Sijm, 2005; Böhringer et al., 2009; Lehmann & Gawel, 2013). However, none of them has argued against the zero impact hypothesis itself.

[5] Similarly, the RGGI covers only the electricity industry of several states in the eastern part of the US.

These so called (inter-industry) leakage effects are mediated by demand shifts on the factor markets (capital and labor) and the associated price adjustments.[6]

Baylis et al. (2013, 2014) analyze such leakage effects in a setting where both sectors are regulated by a carbon tax and one tax is varied. In a similar model, Perino (2015) considers a setting in which one of the sectors is regulated by a CAT instead of a tax and analyzes the effects of an information campaign that increases consumer's "green awareness". The model developed here shares the feature of possible inter-industry leakage effects, and that there is one sector regulated by a CAT, but it differs from the previous papers structurally and with respect to the policy instruments analyzed: we consider two instead of one technology in the capped sector and analyze the effects of policies that drive substitution between them. The direction and magnitude of the associated leakage effects are non-obvious and cannot be analyzed in the simpler models of Baylis et al. (2013, 2014) and Perino (2015).

We develop the basic model in section 2. In section 3 we identify the inter-industry leakage effect induced by a variation of a FIT, and decompose it into intuitively intelligible components that depend in natural ways on measurable elasticity parameters. In contrast to the arguments in the existing literature on overlapping instruments, such variation generally has a net impact on carbon emissions. Specifically, we show that raising the FIT unambiguously reduces emissions if the abatement subsidy is tax-funded. On the one hand, this reinforces the finding of Baylis et al. (2013, 2014) that tightening evironmental regulation can cause negative leakage. On the other hand, it contrasts to their result that an increase of a carbon tax can increase aggregate emissions (we explain why in section 3). However, as we show in section 4, raising the FIT can increase emissions in our model if it is funded by a levy on electricity consumption. Even if emissions decrease, for a given raise of the FIT level levy-funding always performs worse in terms of emissions than tax-funding, and the disadvantage is increasing in the relative size of the renewable electricity industry.

We believe that those results have important ramifications for the design of renewable energy policies overlapping a CAT, and are a valuable basis for an informed and accurate assessment of their effectiveness. To substantiate this point, we highlight in section 5 that (and how) a current state-of-the-art statistic that many governments use to gauge the impact of their renewable energy policies, so-called "virtual emission reductions" (VER), is biased, inter alia because inter-industrial leakage effects are not captured by it. This can provide guidance for analysts in estimating the effects of renewable energy policies on carbon emissions more accurately. We conclude in section 6.

[6]In the context of unilateral climate policy, international leakage effects are well established (see for example Babiker, 2005, Eichner & Pethig, 2011, Burniaux & Martins, 2012, or Martin et al., 2014): a major concern is that tightening of carbon regulation in one part of the world *increases* aggregate carbon emissions (see van der Werf & Di Maria, 2012, for an overview). In this stream of literature, however, the focus is on changes in the cap itself rather than on the effect of overlapping instruments.

2 The basic model

In this section we develop a general equilibrium model in the style of the tax incidence literature (Harberger, 1962; Fullerton & Metcalf, 2002) that captures the essential features described in the introduction.

There is a representative household endowed with one unit of a perfectly mobile factor L (termed "labor-capital" in the following), which is numeraire. There are two consumption goods, X and Y, which we call "electricity" (Y) and "anything else" (X).

Households maximize a homothetic utility function $u(x,y)$, with x and y representing the quantities of X and Y consumed, respectively. It is twice continuously differentiable and exhibits strictly positive marginal utilities, which are strictly decreasing in a good's own quantity and strictly increasing in the other good's quantity, respectively.

The goods are produced in competitive industries. All firms are owned by the representative household. Each industry $i = X,Y$ uses labor-capital and carbon as factors of production in quantities L_i and E_i, respectively.

In industry X there is a single constant returns technology $X = X(L_X, E_X)$ that uses quantity L_X of labor-capital and quantity E_X of carbon emissions.[7] In the electricity industry there is a constant returns "conventional" technology $Y_D(L_{YD}, E_Y)$, and a "clean" or "green" technology $Y_C(L_{YC})$ that uses only labor-capital, i.e. is perfectly clean. All production functions are twice continuously differentiable and exhibit strictly positive marginal products, which are strictly decreasing in a factor's own quantity and strictly increasing in the other factor's quantity (if applicable), respectively.[8]

Market prices of X and Y are denoted p_X and p_Y, respectively. A FIT t is a minimum price received by the green producers that is above the the market price p_Y faced by consumers and conventional producers, $t > p_Y$.[9]

Since labor-capital is perfectly mobile across industries it earns the same return, denoted w (which is equal to unity because labor-capital is numeraire), in either industry.

The supply of carbon emissions is regulated by a CAT with fixed and binding cap C in industry Y, and by a carbon tax $\tau \geq 0$ in industry X. Permits are auctioned off at price r.

In section 3 we assume that the government's budget, which is the sum of the carbon pricing revenues, $\tau E_X + rE_Y$, less the subsidy payments, $(t - p_Y)Y_C$, is returned to the households via lump-sum rebate (in case it is negative it amounts to a lump-sum tax).[10] In section 4 the subsidy is funded by a levy on the price

[7]For sake of parsimony we abuse notation in denoting by X the label of the good (and industry), the quantity of that good supplied, and the production function. We do likewise in industry Y.

[8]We also assume that in industry X the marginal product of emissions drops to zero for a finite input quantity. This assures that factor demand is not infinite for a price of zero, which is relevant because we allow for a zero carbon price below.

[9]The case where $t \leq p_Y$ is of no theoretical and empirical relevance because the FIT would not be binding.

[10]Clearly, a lump-sum tax is unrealistic. However, (i) it can be viewed as an approximation of an income tax, especially in a model where labor supply is fixed, and (ii) it is a useful (because simple) benchmark case to which more complex settings can be insightfully compared (as we do in section 4). Furthermore, we essentially consider a case in which the FIT is refunded by a "tax" on outputs

of electricity instead of a lump-sum tax, a case that is common in practice.

3 Inter-industry leakage

In this section we present our key results. Assuming that our previously described economy is in (interior) equilibrium, we analyze the comparative static effect on aggregate carbon emissions of a small exogenous change of the FIT level. To this end we derive a log-linearized system of differential equations from the basic model in appendix A, which can be solved for the change of aggregate emissions induced by an adjustment of the FIT. We use the standard "hat notation" to refer to a fractional (or percentage) change in a given variable.

We present the results, their intuition and numerical illustrations with parameter values derived from empirical data here, formal proofs are relegated to appendix B.

Lemma 1. *If the FIT level is changed by $\hat{t}$ percent, then total emissions change by $\hat{E} = \phi \hat{E}_X$ percent, where $\phi \equiv E_X/E$ is industry X's emissions as a fraction of total emissions.*

Since emissions in the electricity industry are fixed through the CAT, any change in total emissions must come from industry X. Thus, to identify $\hat{E}$ we need to identify $\hat{E}_X$. If a policy intervention is targeted at industry Y, which is the case here, $\hat{E}_X$ is commonly called *leakage effect*, since it is an effect on emissions outside the targeted industry.

Lemma 2. *If the FIT level is changed by $\hat{t}$ percent, then emissions is industry X change by $\hat{E}_X = \hat{X}$ percent.*

Since factor prices in industry X do not change (recall that labor-capital is numeraire and the carbon price is fixed by assumption) the input ratio is constant. Thus, since there is no factor substitution, an ε percent change of output requires a change of emissions by ε percent as well.

Lemmas 1 and 2 immediately yield:

Corollary 1. *If the FIT level is changed by $\hat{t}$ percent, then total emissions change by $\hat{E} = \phi \hat{X}$ percent.*

That is, the change of total emissions is proportional to the change of output in industry X. The key question, therefore, is how a given change of the FIT level affects output in industry X.[11] Before going into the formal derivation of this effect in subsection 3.3, we first characterize three channels through which it materializes: drawing on a terminology proposed by Baylis et al. (2013, 2014),[12] the effect can be

in section 4: there the FIT is refunded by "taxing" electricity (good Y). The case in which the FIT is refunded by a tax on good X is rather straightforward: the decrease of emissions in response to an increase of the FIT level would be even stronger compared to the benchmark case, because the increasing tax burden directly induces firms in sector X to reduce output. We thank an anonymous referee for raising that point.

[11] We note that lemmas 1 and 2 (and therefore corollary 1) hold for any exogenous shock to the economy, specifically any type of policy intervention in industry Y. The same is true for lemmas 3, 4, 5, 6 and 7 in the following subsections.

[12] In a similar model but without a green energy sector and without a CAT, Baylis et al. (2013, 2014) identify two channels through which an exogenous carbon emission tax adjustment in industry Y can leak over to industry X: the *terms-of-trade effect* (TTE) and the

decomposed into (i) a *direct abatement resource effect* (DARE), (ii) an *indirect abatement resource effect* (IARE), and an *indirect terms-of-trade effect* (ITTE).

3.1 The direct abatement resource effect (DARE)

The following result is critical for both abatement resource effects, because it relates the change in each electricity sub-sector's absorption of labor-capital to the net effect in sector X:

Lemma 3. *If the FIT level is changed by $\hat{t}$ percent, then output in industry X changes by*

$$\hat{X} = -\frac{L_{YD}\hat{L}_{YD} + L_{YC}\hat{L}_{YC}}{L_X}$$

percent.[13]

Since labor-capital supply is fixed in our economy, any change of its use in industry Y is necessarily accompanied by an inverse change in industry X. If a policy intervention in industry Y induces a decrease of labor-capital demand in that industry, there will be (off-equilibrium) downward pressure on the wage rate which will be exploited by industry X; in the opposite case, industry Y firms bid the wage rate up (off-equilibrium) such that labor-capital travels from X to Y.

Together with lemma 3 the following result is the key step in establishing the DARE:

Lemma 4. *If the FIT level is changed by $\hat{t}$ percent, then labor-capital input in the green electricity industry changes by $\hat{L}_{YC} = \rho\hat{t}$ percent, where $\rho > 0$ denotes the elasticity of green electricity producer's demand for labor-capital with respect to its real price,*[14] *and output by $\hat{Y}_C = \vartheta\rho\hat{t}$ percent, where $\vartheta \in]0,1[$ denotes factor costs as a fraction of revenues in the green electricity industry.*

Hence, if the FIT level is increased ($\hat{t} > 0$), investment in green electricity ($\hat{L}_{YC} > 0$) and hence green power output increases as well ($\hat{Y}_C > 0$). However, since labor-capital supply is fixed, this implies that labor-capital must move out of the conventional electricity industry and sector X. Corollary 1, lemma 1 and lemma 2 immediately yield:

Corollary 2. *If the FIT level is changed by $\hat{t}$ percent, then total carbon emissions change by*

$$\hat{E} = -\frac{\phi}{L_X}\left(\hat{L}_{YD}L_{YD} + L_{YC}\rho\hat{t}\right)$$

abatement resource effect (ARE). We need to adapt this terminology because we explicitly model a CAT, such that the carbon price in sector Y is endogenous, have two technologies in sector Y, and focus on instruments that are overlapping with the CAT. The TTE and the ARE also appear in our model, but in a slightly different and more complex form. This is due to the facts (i) that a variation of the FIT has an additional ARE (which we term *direct* ARE below), independently from the carbon price r, and (ii) that r is *endogenous* in our model.

[13] Note that since aggregate supply is normalized to unity, L_X, L_{YD}, and L_{YC} are absolute quantities and shares of total supply employed in the production of X, Y_D, and Y_C, respectively, at the same time.

[14] The elasticity is defined formally by expression 27 in appendix A.

percent.

To the extent the green electricity industry bids away labor-capital from sector X, total emissions decline. This is the basic idea behind the DARE. The size of the DARE depends on ρ: the more elastic green electricity producer's demand for labor-capital is with respect to its real price, the larger the effect. Furthermore, for a given elasticity the effect size is increasing in the relative (*ex ante*) size of the green electricity industry within the labor-capital market.

3.2 The indirect effects

The indirect effects (IARE and ITTE) stem from adjustments in the conventional electricity industry. Analogous to lemma 4 the following holds:

Lemma 5. *If the FIT level is changed by $\hat{t}$ percent, then labor-capital input in the conventional electricity industry changes by $\hat{L}_{YD} = \sigma_Y \hat{r}$ percent, where $\sigma_Y > 0$ denotes the elasticity of technical substitution, and output by $\hat{Y}_D = \theta_{YL}\sigma_Y \hat{r}$ percent, where $\theta_{YL} \in]0,1[$ is equal to the labor-capital payroll share of total costs.*

Hence, the size of the conventional electricity industry and the permit price move in the same direction. The industry demands additional labor-capital if r increases (because firms substitute away from carbon), and vice versa. For a given price change, the size of this effect depends on the ease of substitution between labor-capital and carbon: if substitution is technically difficult (σ_Y close to zero) the effect is small; if it is easy (σ_Y distant from zero), then the effect is large. This substitution is the source of the "abatement resource effect" (ARE) in Baylis et al. (2013, 2014): since they consider an exogenous increase of r, their ARE is direct and unambiguously negative (see appendix C). In our model the effect is indirect, because r is only a mediating variable. For this reason we term it *indirect* abatement resource effect (IARE).

Moreover, r is also the source of adjustments in consumer behavior.

Lemma 6. *If the FIT level is changed by $\hat{t}$ percent, then output in industry X changes by $\hat{X} = \hat{Y} + \varsigma \hat{p}_Y$ percent, where $\varsigma > 0$ is the household's elasticity of substitution between consumption goods X and Y.*

Households shift demand away from good Y into good X if the retail price p_Y increases, and vice versa. The size of this response depends on the degree of substitutability in consumption, as reflected in the elasticity parameter ς: if ς is close to zero, then the goods do not substitute for one another well in consumption, and the response to price changes is small. If ς is distant from zero (in particular greater than one), then the two goods are similar in terms of consumption experience, such that the response to price changes is large.

Lemma 7. *If the FIT level is changed by $\hat{t}$ percent, then the electricity price changes by $\hat{p}_Y = \theta_{YE}\hat{r}$ percent, where $\theta_{YE} \in]0,1[$ is equal to the permit toll share of total costs in the conventional electricity industry.*

Hence, the electricity retail price and the permit price move in the same direction. Combining lemmas 6 and 7 we can conclude that changes in the permit price r lead to changes in the retail price p_Y, which in turn induce consumers to substitute one good for the other. This is the source of the "terms-of-trade effect" (TTE) in Baylis et al. (2013, 2014): if r would be exogenously increased, the price p_Y would increase as well and consumers would substitute away from Y into X. All else equal, this would increase emissions, i.e. the TTE would be unambiguously positive (see appendix C). Again, in our model the effect is indirect, because r is endogenous, such that we call it *indirect* terms-of-trade effect (ITTE). Identifying both the IARE and the ITTE requires solving for the comparative static change of r in response to the FIT variation.

Lemma 8. *If the FIT level is changed by $\hat{t}$ percent, then the permit price changes by $\hat{r} = -\gamma\hat{t}$ percent, where*

$$\gamma = \frac{(L_X \alpha_C \vartheta + L_{YC})\,\rho}{(L_X \alpha_D \theta_{YL} + L_{YD})\,\sigma_Y + L_X \theta_{YE} \varsigma} > 0$$

and $\alpha_C = Y_C/Y$ and $\alpha_D = Y_D/Y$ are the shares of green and conventional electricity as fractions of total electricity output, respectively.

Thus, the FIT level and the permit price move in opposite directions. The following result is a direct consequence of lemmas 5 and 8:

Corollary 3. *If the FIT level is changed by $\hat{t}$ percent, then labor-capital input in the conventional electricity industry changes by $\hat{L}_{YD} = -\sigma_Y \gamma \hat{t}$ percent and output by $\hat{Y}_D = -\theta_{YL}\sigma_Y \gamma \hat{t}$ percent.*

The intuition behind lemma 8 and corollary 3 is the following: In response to an increase of the FIT level, the green electricity industry grows and bids away labor-capital from the other industries. All else equal, the conventional electricity industry contracts and hence the demand for permits declines. As a result, the permit price drops. Conventional electricity firms substitute from labor-capital into carbon (i.e. increase their carbon intensity) which became cheaper. Overall, there is no reduction of emissions in industry Y, but a reduction of labor-capital input and output in industry Y_D. The size of those adjustments depends on the key elasticity parameters ρ, σ_Y and ς. Ceteris paribus, the more the green electricity industry grows in response to a given raise of the FIT level (i.e. the greater the value of ρ), the more labor-capital it bids away from the conventional electricity industry, the more the latter contracts at given prices, and the more the permit price must decrease in order to keep the permit market cleared. The other two elasticities dampen the effect: the easier conventional electricity firms can substitute between labor-capital and carbon (i.e. the greater the value of σ_Y), the less the permit price must decline in order to keep the permit market cleared; the more substitutable the two final goods are for the consumers (i.e. the greater the value of ς), the more they raise their demand for electricity as r and in turn p_Y falls.

In sum, a raise of the FIT level decreases the permit price, from which in turn two adjustments follow:

First, the electricity price p_Y falls (see lemmas 7 and 8) which induces consumers to substitute away from X into Y. Thus, this adjustment tends to decrease output and emissions in industry X. This is the ITTE.

Second, labor-capital laid-off in the conventional electricity industry (corollary 3) moves to industry X, tending to increase output and emissions there. This is the IARE. Thus, if a raise of the FIT level is defined as a "tightening" of regulation in industry Y, then the two leakage effects (IARE and ITTE) have exactly the opposite sign as in Baylis et al. (2013, 2014, BFK hereafter): a tightening induces a negative ITTE and a positive IARE. This is because in BFK a "tightening" of regulation is an exogenous increase of the carbon price (with all other parameters constant), which results in $\hat{E}_Y < 0$ because in their model emissions are not fixed in sector Y. However, this can be interpreted in two ways: (i) an exogenous raise of a carbon tax ($\hat{r} > 0$) such that firms adjust their emissions downwards ($\hat{E}_Y < 0$), or (ii) an exogenous reduction of the cap by the same amount $\hat{E}_Y < 0$, resulting in an increase of the permit price ($\hat{r} > 0$). If they would assume the cap to be fixed, there would apparently be no intervention to be analyzed, because then $\hat{r} = 0$. In our setting the cap *is* assumed to be fixed, but the permit price can change because there is a second instrument: the FIT. Because an increase of the FIT level reduces the permit price, our IARE and ITTE have the opposite sign as the ARE and TTE, respectively, in BFK.

3.3 The total effect

The following theorem is the formal expression of the above intuition:

Theorem 1. *If the FIT level is changed by $\hat{t}$ percent, total emissions change by $\hat{E} = \phi\Lambda\hat{t}$ percent, with $\Lambda < 0$. Furthermore, $\Lambda = \Lambda_{\text{DARE}} + \Lambda_{\text{IARE}} + \Lambda_{\text{ITTE}}$ with $\Lambda_{\text{DARE}} < 0$ being the direct abatement resource effect, $\Lambda_{\text{IARE}} > 0$ being the indirect abatement resource effect, and $\Lambda_{\text{ITTE}} < 0$ being the indirect terms-of-trade effect.*

Thus, if the FIT level is raised, aggregate carbon emissions decrease. Λ represents the "leakage effect", i.e. the elasticity of industry X's emissions with respect to the FIT level in the other industry. If the FIT level is increased by some small amount, carbon emissions tend to increase through the IARE and to decrease through the DARE and the ITTE.

We can also say something about the magnitude of the effect as a function of the key elasticity parameters:

Corollary 4. *The magnitude $|\Lambda|$ is increasing in ρ and ς (Λ is decreasing and linear in ρ, and decreasing, convex and finitely convergent in ς), and decreasing in σ_Y (Λ is increasing, concave and finitely convergent in σ_Y). Specifically,*

- Λ_{DARE} *is strictly decreasing and linear in ρ, and independent from σ_Y and ς,*

- Λ_{IARE} *is increasing and linear in* ρ, *increasing, concave and finitely convergent in* σ_Y, *and decreasing, convex and convergent to zero in* ς, *and*

- Λ_{ITTE} *is decreasing and linear in* ρ, *increasing, concave and convergent to zero in* σ_Y, *and decreasing, convex and finitely convergent in* ς.

Those dependencies are intuitive. First, the DARE does only depend on the elasticity of investment in green power with respect to the FIT level (as captured by ρ) since it is a direct effect that is not mediated by the permit or electricity prices.

Second, the easier conventional electricity producers can substitute between labor-capital and carbon (as captured by σ_Y), the less labor-capital they release in response to a falling permit price, and hence the smaller the IARE. However, the effect also depends indirectly on the household's preferences (as captured by ς) and the elasticity of investment in green power with respect to the FIT (as captured by ρ), because they moderate the magnitude of the permit price adjustment (see lemma 8).

Finally, the more substitutable the two final goods are (as captured by ς), the more sensitive households respond to electricity price changes, and the larger the ITTE is in absolute value. More specifically, it holds that

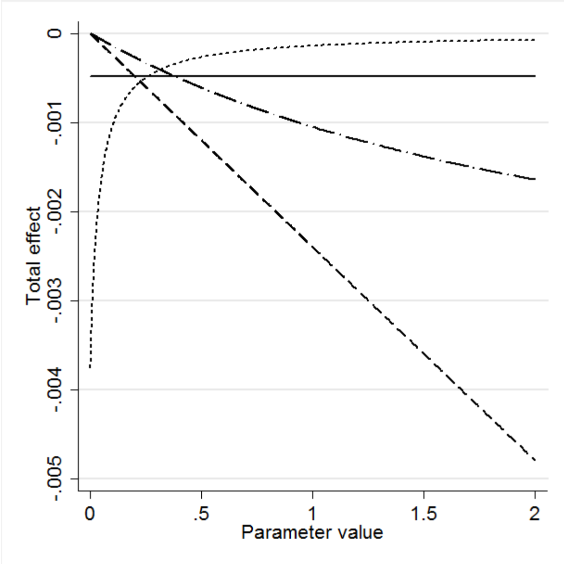
$$\eta = -\upsilon + (1-\upsilon)\varsigma \Leftrightarrow \varsigma = \frac{\eta + \upsilon}{1-\upsilon} \tag{1}$$

where υ is the share of income spent on electricity and η is the price elasticity of electricity demand. Hence, the absolute magnitude of the ITTE is increasing in both the former and the latter. Like the IARE, however, the ITTE also depends indirectly on the technologies in conventional electricity production (as captured by σ_Y) and the elasticity of investment in green power with respect to the FIT (as captured by ρ), because they moderate the magnitude of the electricity price adjustment (see lemmas 7 and 8).

The IARE works against the DARE and the ITTE, but the indirect effects are always of second order compared to the DARE, such that emissions will always decline in response to an increase of the FIT level. The order of magnitude of this decline depends on the parameters. Figure 1 illustrates this by means of a numerical simulation of the model with parameter values derived from 2011 European Union (EU) data.[15]

[15] We emphasize that this exercise is just an illustration of the above theoretical results, it is *not* an empirical estimation of actual leakage effects, or a calibrated model of any actual FIT-scheme. We consider the case where industry Y is electricity generation and X is the rest of the economy. We use EU data, because in the EU electricity generation is under a union-wide CAT (the EU ETS). Emissions data comes from the EUROSTAT air emission accounts. Total greenhouse gas emissions measured in CO_2 equivalents amount to 4,607.785 million tonnes. NACE industry D "electricity, gas, steam, and air-conditioning supply" contributed 27%. We calculate a 2011 average European Emission Allowance (EUA) Future price (daily over-the-counter closing price for EUAs to be delivered at the end of 2012) of €13.83 per ton, using data from the European Energy Exchange (EEX). Based on estimates of marginal abatement costs in non-ETS sectors we set the carbon price in sector X to €25 per ton. From the EUROSTAT national accounts we get a GDP of €12,711,206.8 million to which NACE industry D contributed €219,913 million. The US Energy Information Administration (EIA) reports a total electricity production of 3,089.735 billion kWh, of which 684.826 billion kWh come from renewables. From those data we obtain $\theta_{YE} = 0.078$, $L_X = 0.922$, $\alpha_C = 0.222$, and $\phi = 0.730$. We assume that the elasticities of output with respect to labor-capital are identical in the two electricity sub-industries, such that $\vartheta = 0.922$. We also use α_C as a weight to allocate labor-capital to the electricity sub-industries, yielding $L_{YC} = 0.0173$ and $L_{YD} = 0.0607$. With respect to the key elasticity parameters, we have a direct estimate from Okagawa & Ban (2008) to set $\sigma_Y = 0.256$. Relevant estimates for ρ vary substantially: Johnson (2011) reports a price elasticity of renewable electricity generation of more than two, Smith & Urpelainen (2014) estimate the elasticity with respect to FITs

Figure 1: Numerical illustrations of the leakage effect.



Shown is the calibrated total leakage effect Λ (solid), and its dependence on ρ (dashed), σ_Y (dotted), and ς (dash-dotted), with the other two elasticity parameters set to their calibration values, respectively.

Shown is the total leakage effect Λ, both fully calibrated (the horizontal, solid line) and as a function of the three elasticity parameters, respectively (holding the other two at the above values), on a domain of sensible values from zero to two.

4 Levy-funding

Among countries that maintain a FIT, it is common to fund the subsidy $(t - p_Y)Y_C$ not by a lump sum (or other) tax but by a levy on electricity. This is the case for the FIT schemes e.g. in the UK, Germany, Ireland, or Australia. Under this funding mode electricity users have to pay a surcharge

$$s = \frac{(t - p_Y)Y_C}{Y} = \alpha_C(t - p_Y)$$

on every unit of electricity consumed, that is, the effective end user price is

$$p_Y + s = \alpha_D p_Y + \alpha_C t$$

In this setting the FIT directly affects the end user price and hence the household's substitution condition. The following result replaces lemma 6.

Lemma 9. *If the FIT level is changed by $\hat{t}$ percent, then output in industry X changes by* $\hat{X} = \varsigma(\psi_D \hat{p}_Y + \psi_C \hat{t}) +$

much lower (below 0.02). We take a mid-way here by setting $\rho = 0.2$. Finally, the empirical literature estimates the price elasticity of demand for electricity to be around -0.4., and households spend approximately three percent of their income on electricity (Baylis et al., 2014), such that $\varsigma = 0.38$ follows from equation 1.

$\hat{Y}$ percent, where $\varsigma > 0$ is the household's elasticity of substitution between consumption goods X and Y, and ψ_D and ψ_C are the incomes earned in sub-industries Y_D and Y_C, respectively, as fractions of total incomes earned in industry Y (such that $\psi_D + \psi_C = 1$).

The primary difference to the benchmark setting with a lump-sum tax follows from what we know about the structure of the leakage effect. An increase of the FIT level will increase the surcharge s, since t increases and p_Y decreases. Everything else equal this creates a direct incentive for consumers to substitute away from electricity into X: we call this *direct terms-of-trade effect* (DTTE). The DTTE causes an increase in emissions because it raises production in industry X. It therefore has the opposite sign as the ITTE. The sum of the DTTE and the ITTE, the total terms-of-trade effect, depends on whether the gross end user price increases or decreases: if s grows more than p_Y declines then the gross price increases in response to the intervention, such that consumers substitute into X—in this case the DTTE dominates the ITTE. If the net price p_Y declines more than s grows, the opposite happens.

Lemma 8 still holds in essence, but needs a slight adjustment because the financing mode also affects the magnitude of the permit price change in response to a variation of the FIT level, such that the indirect effects (ITTE and IARE) are not identical in the two settings. We denote the permit price adjustment parameter $\tilde{\gamma}$ to indicate that it is different from γ, but note that they have similar properties. Important for the present purposes is the following:

Lemma 10. *If the FIT level is changed by $\hat{t}$ percent, then $\tilde{\gamma} > \gamma$, and the difference $\tilde{\gamma} - \gamma$ is increasing in ψ_C.*

Hence, the permit price adjustment to a given change of the FIT level is unambiguously larger if the FIT is financed by a levy compared to the benchmark case in which it is financed by a lump-sum tax. This holds because raising the FIT level directly increases the electricity price through the levy and induces consumers to substitute away from Y, such that the electricity industry contracts and the permit price decreases. Note that this happens even if the green electricity industry does not expand at all (i.e. $\rho = 0$)—in this case the FIT is just a transfer of income from electricity consumers to producers of renewable energy.

The following result is the analogue to theorem 1 with tax-funding replaced by levy-funding, where a tilde above a variable indicates that its value differs from the baseline setting with a lump-sum tax.

Theorem 2. *If the FIT level is changed by $\hat{t}$ percent, total emissions change by $\hat{E} = \phi\tilde{\Lambda}\hat{t}$ percent, with $\tilde{\Lambda} \geq 0$ if and only if $\psi_C \geq \bar{\psi}_C$. Furthermore, $\tilde{\Lambda} = \tilde{\Lambda}_{\text{DARE}} + \tilde{\Lambda}_{\text{IARE}} + \tilde{\Lambda}_{\text{ITTE}} + \tilde{\Lambda}_{\text{DTTE}}$ with $\tilde{\Lambda}_{\text{DARE}} < 0$ being the direct abatement resource effect, $\tilde{\Lambda}_{\text{IARE}} > 0$ being the indirect abatement resource effect, and $\tilde{\Lambda}_{\text{ITTE}} < 0$ being the indirect terms-of-trade effect, and $\tilde{\Lambda}_{\text{DTTE}}$ being the direct terms-of-trade effect.*

Thus, if the FIT level is raised, aggregate carbon emissions can either increase or decrease, depending on the initial size of the green electricity industry. There are similarities and differences between Λ and

Table 1: Summary of the settings with tax funding and levy funding.

	FIT is	
	Tax funded	Levy funded
DARE	−	−
IARE	+	+
ITTE	−	−
DTTE	0	−
Total	−	ambiguous

$\tilde{\Lambda}$. First, the DARE is entirely unaffected by the funding-mode: for green electricity producers, it does not matter where the FIT comes from.

Second, the IARE and the ITTE have essentially the same properties under the two funding modes, but differ in size because the permit price adjustment differs: a given raise of the FIT reduces the permit price more under levy funding than under tax funding (see lemma 10).

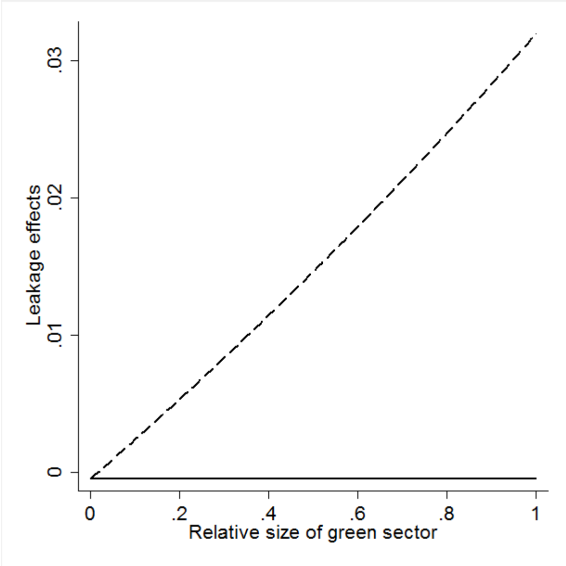
Finally, there is a new leakage term, the DTTE, arising from the change of the levy as explained above. The size of this effect depends on the household's preferences as captured by the elasticity of substitution ς: If the two final goods are not substitutable at all ($\varsigma = 0$), the effect vanishes, and it increases in the degree of substitutability. Recalling identity 1, this is equivalent to the size of the DTTE being increasing in both the share of income spent on electricity and the price elasticity of electricity demand. Table 1 summarizes the direction of the leakage effects if the FIT level is increased.

Corollary 5. *For a given change $\hat{t}$ of the FIT level it holds that $\tilde{\Lambda} > \Lambda$. The difference $\tilde{\Lambda} - \Lambda$ is increasing in ψ_C.*

Thus, a levy-funded FIT is unambiguously less effective in curbing emissions than the tax-funded FIT. The DTTE is critical in understanding this difference: under levy-funding a raise of the FIT level directly increases the electricity price through the surcharge and induces consumers to substitute away from Y into X, raising output and emissions there. Furthermore, this shortfall is increasing with the share of income earned in the green electricity industry, because a high income earned in the green electricity industry, either because the industry is large in terms of output or the FIT is high in absolute value, requires a large subsidy budget, and raising the budget distorts prices under levy-funding but not under tax-funding.

Even more importantly, while a raise of the FIT always reduces emissions under tax-funding, it can *increase* emissions under levy funding. To illustrate, consider the extreme case in which the FIT fails to expand the green electricity industry at all (i.e. $\rho = 0$). In this case, the FIT is just a transfer of income and the DARE will be zero. However, since the electricity price increases through the levy, consumers substitute away from Y into X, raising emissions. If the consumer's elasticity of substitution is high or incomes earned in the green electricity industry are sizable (or both), then this effect can be sufficiently

Figure 2: Numerical illustrations of the differences between levy- and tax-funding.



The figure shows Λ (solid) and $\tilde{\Lambda}$ (dashed) as a functions of ψ_C.

large to raise emissions beyond the *ex ante* level. Numerical simulations of the model with 2011 EU data (see note 15) suggest that this case is empirically relevant. Figure 2 shows that emissions increase already at very small values of ψ_C, that is, when incomes earned in the green electricity industry are between one and two percent as a fraction of total incomes earned in electricity production. However, the share of electricity produced from renewable sources within the EU was already at 22% in 2011. Since ψ_C is just α_C but weighted by retail prices, and $t > p_Y$, the fraction of incomes earned in green electricity production is likely already beyond the threshold in most member states. Returning to the German example mentioned in the introduction, we have $\psi_C = 0.549$.[16]

Wrapping up, tax-funding always performs better in terms of emissions than levy-funding. Moreover, this advantage is increasing in the relative size (as defined in terms of income earned) of the green electricity industry. Importantly, raising the FIT under levy-funding can actually *increase* emissions.

5 On the bias of virtual emission reduction estimates

We believe that the results in the previous sections are a valuable basis for an informed and accurate assessment of renewable energy policies overlapping a CAT. To substantiate this point, we highlight in this section that (and how) a current state-of-the-art statistic that many governments use to gauge the impact of their renewable energy policies, so-called "virtual emission reductions" (VER), is biased, inter alia because inter-industrial leakage effects are not captured by it. The virtual emission reduction approach essentially assumes that each kWh of green electricity replaces one kWh of conventional electricity, and the VER is

[16]The average feed-in tariff across technologies is about the fourfold, 17 cents per kWh, of the average spot price of 4 cents per kWh (BMWE, 2014). The share of electricity production from renewables sources was 22.2% in 2011, yielding $\psi_C = 0.549$.

the counter-factual quantity of emissions that would have been generated if the additional amount of green electricity were supplied by conventional means (Marcantonini & Ellerman, 2013; UBA, 2013). Indeed, in an ambitious climate policy impact analysis, The Economist (2014) recently appealed to the concept by claiming that

> "it is fairly easy to estimate how much carbon a new field full of solar cells or a nuclear-power plant saves by looking at the amount of electricity it produces in a year and how much carbon would have been emitted if fossil fuels had been used instead, based on the local mix of coal, gas and oil."

In fact, it is not that easy.[17] To see why, we develop an exact definition of VER in terms of our model. Suppose green electricity output increases (exogenously) by dY_C, or equivalently in relative terms by $\hat{Y}_C$. Emissions per unit of output in conventional electricity production are E_Y/Y_D, such that the VER associated with the increase is

$$\text{VER}\left(\hat{Y}_C\right) = \frac{dY_C E_Y}{Y_D} = \frac{Y_C E_Y}{Y_D}\hat{Y}_C$$

For a raise $\hat{t}$ of the FIT level, we have $\hat{Y}_C = \vartheta\rho\hat{t}$, and hence

$$\text{VER}\left(\hat{t}\right) = \frac{Y_C E_Y \vartheta\rho}{Y_D}\hat{t}$$

By dividing both sides by the ex ante level of emissions, we can make the statistic comparable to the proportional change notation of our analysis above

$$\widehat{\text{VER}}\left(\hat{t}\right) = \frac{Y_C E_Y \vartheta\rho}{Y_D E}\hat{t} = (1-\phi)\frac{\alpha_C}{\alpha_D}\vartheta\rho\hat{t}$$

As an estimate of the actual impact of the FIT on emissions in the setting we study above the VER statistic has a number of issues. First, the one-to-one displacement of conventional by green electricity effectively amounts to the assumption that aggregate electricity output is constant. This is generally not the case. Indeed, in the context of our model we demonstrated above that industry Y's output may either increase or decrease in response to a variation of the FIT.

Second, the VER statistic ignores overlapping regulatory instruments applied to the same industry. Specifically, if the electricity industry is subject to a CAT, then emissions produced under the system are not reduced at all, but the VER statistic indicates a reduction.[18]

Third, the VER statistic ignores inter-industrial leakage effects. Indeed, we showed above that such effects exist. A natural question is how the VER statistic performs relative to the true effect identified

[17] On a related complication—identifying the marginal plant that corresponds to a change in electricity demand—see Zivin et al. (2014).

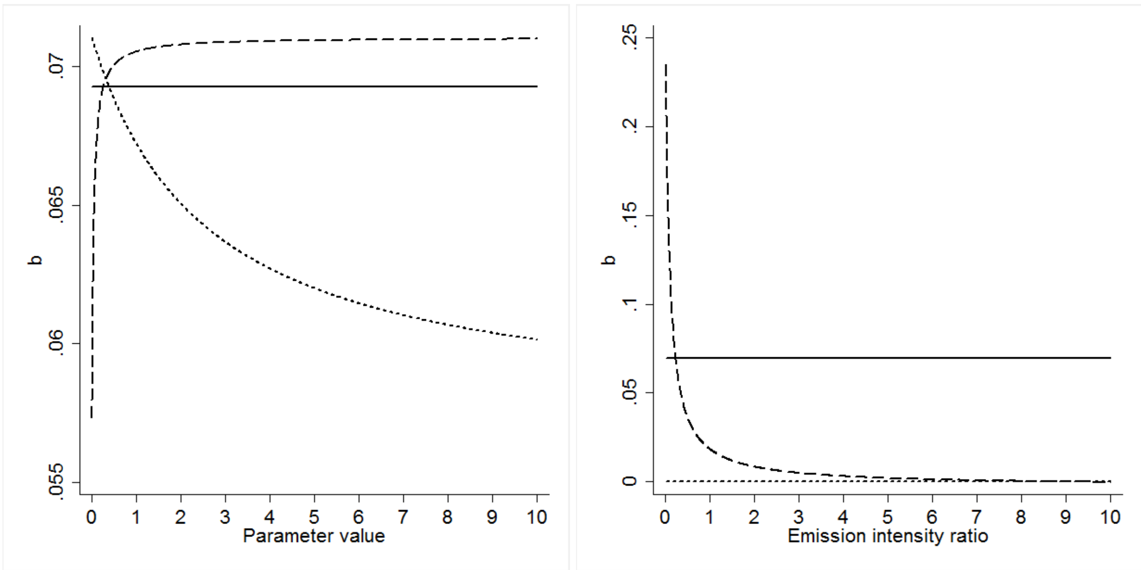
[18] This amounts to the assumption that the cap will be no longer binding.

above, that accounts for those issues. We find the following:

Theorem 3. *The difference between the VER and the actual emission reduction is generally different from zero. For* $\hat{t} > 0$ *it is increasing in* ρ, σ_Y *and the emission intensity of industry* Y, *and decreasing in* ς *and the emission intensity of industry* X.

Figure 3: Numerical illustrations of the "bias elasticity" b.

(a) **(b)**



Panel (a) shows the value of b with all parameters set to the reference case (solid) and as functions of the elasticity parameters σ_Y (dashed) and ς (dotted). Panel (b) shows the value of b with all parameters set to the reference case (solid) and as a function of the emission intensity ratio (dashed), the dotted line is the zero-axis.

Numerical simulations of the model with a tax-funded subsidy, using 2011 EU data (see note 15), illustrated in figure 3, suggest that under empirically plausible parameter values the VER statistic tends to over-estimate the size of emission reductions in response to increases of a FIT. Furthermore, it is unable to capture the possibility of emission increases. In the simulation, a ten percent raise of the FIT level yields a virtual emissions reduction of 0.14%. In appendix B.15 we show that the difference between the VER and the actual emissions change has the form $B = b\rho\hat{t}$, where the value of the "bias elasticity" b is a function of the other parameters in the model, and figure 3a shows that $b < 0$ (i.e. underestimation) is a theoretical possibility with limited practical relevance. With all parameters set to the reference case we have $b = .0693$ (depicted by the solid lines in the figure) and $B = .0139\hat{t}$. Hence, if a government agency reports a VER of, say, 0.14% in response to a 10% increase of the FIT level, the true theoretical emissions reduction is only 0.001%. The dashed and dotted curves in figure 3a show how b depends on the two elasticity parameters σ_Y and ς on a large domain from zero to ten. Note that their effects on b are very small. The dashed curve in figure 3b shows how b depends on the ratio of the emission intensities in industries X and Y, respectively. b gets negative at a ratio of about 9.28, which means that the emission intensity in the non-capped industry

X is more than nine times higher as in the capped (electricity) industry Y. Since any real-world CAT is focused on the most "dirty" industries in the economy, this is hardly a case of practical relevance (in our reference scenario the ratio is about 0.22).

6 Conclusion

By means of a parsimonious general equilibrium model we inspected the widely held tenet that renewable energy policies have no effect on carbon emissions if the electricity industry is subject to a CAT. Our contribution is threefold:

First, contrary to the hypothesis, we find that variations of a FIT generally have a net impact on carbon emissions through an inter-industrial leakage effect. We decompose this effect into intuitively intelligible components, and show that they depend in natural ways on measurable elasticity parameters. We believe that this constitutes a valuable basis for an informed assessment of the effectiveness of renewable energy policies overlapping a CAT.

Second, we demonstrate that the subsidization of renewable energy reduces emissions if funded by a lump-sum tax, but can increase emissions if funded by a levy on electricity. But even if emissions decrease in the latter case, for a given raise of the FIT level levy-funding always performs worse in terms of emissions than tax-funding, and the disadvantage is increasing in the relative size of the renewable electricity industry. If environmental performance of the FIT scheme is the main policy objective, this result has important practical implications.[19] First, governments planning the introduction of a FIT scheme can improve environmental performance if it is funded from general tax revenues instead of a levy on electricity consumption, because it avoids the levy-induced incentive to substitute into goods that are produced outside the CAT.[20] Second, governments already having a levy-financed FIT scheme in place, such as the UK or Germany, can avoid causing an increase in emissions by switching to tax funding: the larger the green electricity industry already has grown, the more a switch improves the environmental performance of the scheme.

Third, we show that the commonly used indicator of "virtual emissions reductions" (VER), which is defined as the (counter-factual) quantity of emissions that would have been generated if the additional amount of green electricity were supplied by conventional means, is a biased measure of the effect of renewable energy policies on carbon emissions, most importantly because it ignores the CAT and the leakage effects

[19]The condition is important, such that the following suggestions are not to be read unconditionally prescriptive. We do *not* claim that tax-funded FITs are generally preferable over levy-funded ones, (i) because this claim would not be backed by our positive results, and (ii) because there may be practical constraints. For example, levy-funded FITs may be ruled out in the EU as they would meet the criteria for state aid, in contrast to levy-funded schemes, or tax-funded schemes could make FITs subject to constant political re-negotiations of budget allocation, which would in turn increase political uncertainty. We thank an anonymous referee for raising that point and the examples.

[20]Of course, there are no lump-sum taxation systems. However, the broader the tax base, the closer the system comes to this benchmark.

identified in this paper. Simulations with empirically plausible parameter values suggests that the VER statistic tends to over-estimate the size of emission reductions in response to increases of a FIT by more than an order of magnitude. This provides guidance to analysts in estimating the effects of renewable energy policies on carbon emissons more accurately.

We conclude with a few comments on three of our assumptions and their implications for the results' policy relevance.[21] First, we assume that only one of the two sectors is covered by a CAT. With respect to the current state of affairs, this is a realistic assumption. Recall for instance, that the EU ETS covers less than half of carbon emissions produced within the EU. However, since the magnitude of the leakage effects identified in this paper tends to increase with the share of emissions that are generated outside of the CAT, they can be muted by expanding the CAT to include more (or all) emissions.

Second, the assumption of labor-capital being mobile between conventional and green electricity production is plausible only in mid- to long-term time frames, in the short term there might be frictions that mitigate the effects identified in this paper.

Third, the assumption of a fixed cap is plausible only within a given planning period of the CAT. For example, a phase of the EU ETS runs for seven to ten years. After that, the cap is re-negotiated and it is likely that negotiators take into account the outcomes of the previous phase. Thus, in a long-term perspective the cap is endogenous.

The last two points imply that our results are practically most relevant in a "mid-term" perspective. However, the decomposition of the leakage effect suggests some principles of a long-term analysis. In fact, adjusting the cap is equivalent to the type of intervention that Baylis et al. (2013, 2014) consider: relaxing the cap directly decreases the permit price, and vice versa. Thus, a cap adjustment just overlays the FIT-induced leakage effects with the cap-induced leakage effects ARE and TTE. Tightening the cap induces a negative ARE and a positive TTE. Based on this observation, it is readily apparent that the indirect FIT-induced effects (IARE and ITTE) can be completely neutralized by a cap adjustment that puts the carbon price back to its ex ante level. Thus, if the policy-objective is to decrease emissions, a downwards adjustment of the cap is reasonable if the IARE is greater than the ITTE (i.e. the net indirect leakage effect is positive), and vice versa. We leave the rigorous investigation of such long-term feedback dynamics between FIT variations and cap adjustments, driven e.g. by reductions in marginal abatement costs or shifts in lobbying activities, for future research.

[21] We thank an anonymous referee for raising the first two points.

A The log-linearized basic model

Carbon emissions

By construction aggregate emissions are $E = E_X + E_Y$. Take the natural logarithm of both sides, totally differentiate, and multiply both sides by $E_X E_Y / E_X E_Y$ to get

$$\frac{dE}{E} = \frac{E_X}{E}\frac{dE_X}{E_X} + \frac{E_Y}{E}\frac{dE_Y}{E_Y}$$

Defining $\phi_X \equiv E_X/E$ and $\phi_Y \equiv E_Y/E$ yields

$$\hat{E} = \phi_X \hat{E}_X + \phi_Y \hat{E}_Y \tag{2}$$

Market clearance conditions

In equilibrium all markets must clear, that is, $X = x$,. $Y = y$, $E_Y = C$, and $L_X + L_{YD} + L_{YC} = 1$. Take the natural logarithm of the final product market clearance conditions and totally differentiate to get

$$\frac{dX}{X} = \frac{dx}{x} \equiv \hat{X} = \hat{x} \tag{3}$$

$$\frac{dY}{Y} = \frac{dy}{y} \equiv \hat{Y} = \hat{y} \tag{4}$$

Do the same with the permit market clearance condition,

$$\frac{dE_Y}{E_Y} = \frac{dC}{C} \equiv \hat{E}_Y = \hat{C} \tag{5}$$

Finally, take the natural logarithm of the labor-capital market clearance condition, totally differentiate, and multiply both sides by $L_X L_{YD} L_{YC} / L_X L_{YD} L_{YC}$ to get

$$\frac{dL_X}{L_X}L_X + \frac{dL_{YD}}{L_{YD}}L_{YD} + \frac{dL_{YC}}{L_{YC}}L_{YC} = 0 \equiv \hat{L}_X L_X + \hat{L}_{YD} L_{YD} + \hat{L}_{YC} L_{YC} = 0 \tag{6}$$

Households

Households spend their incomes M by demanding quantity x of good X and quantity y of good Y. Formally, (x, y) maximizes u subject to the budget constraint $p_X x + p_Y y \leq M$, whereas income is the sum of labor-capital income, w, profits earned in industry X, $p_X X - wL_X - \tau E_X$, industry Y_D, $p_Y Y_D - wL_{YD} - rE_Y$, and industry Y_C, $p_Y Y_C - wL_{YC}$, and the government rebate $\tau E_X + rE_Y$, i.e.

$$M = p_X X + p_Y (Y_D + Y_C) + w(1 - L_X - L_{YD} - L_{YC})$$

If (x, y) is a solution to the optimization program, then it is a Karush-Kuhn-Tucker point satisfying the the stationarity conditions

$$\frac{\partial u(\cdot)}{\partial x} - \lambda_H p_X = 0$$

$$\frac{\partial u(\cdot)}{\partial y} - \lambda_H p_Y = 0$$

the primal feasibility condition $p_X x + p_Y y - M \leq 0$, the dual feasibility condition $\lambda_H \geq 0$, and the complementary slackness condition $\lambda_H (p_X x + p_Y y - M) = 0$. Since u is concave and the constraint continuously differentiable and convex, they are also sufficient. By strict monotonicity of u, the constraint will be binding,

$$p_X x + p_Y y = p_X X + p_Y (Y_D + Y_C) + w(1 - L_X - L_{YD} - L_{YC})$$

Rearranging yields

$$p_X (x - X) + p_Y (y - Y_D + Y_C) = w(1 - L_X - L_{YD} - L_{YC})$$

and considering the market clearance conditions shows that the equation is true in any equilibrium.

Rearrange the stationarity conditions to get

$$\frac{\partial u(\cdot)/\partial x}{\partial u(\cdot)/\partial y} = \frac{p_X}{p_Y} \tag{7}$$

Taking the natural logarithm and totally differentiating yields

$$d\ln\left(\frac{\partial u(\cdot)/\partial x}{\partial u(\cdot)/\partial y}\right) = \frac{dp_X}{p_X} - \frac{dp_Y}{p_Y} \tag{8}$$

Define the elasticity of substitution

$$\varsigma \equiv \frac{\frac{d(y/x)}{y/x}}{\frac{d(p_X/p_Y)}{p_X/p_Y}}$$

and use equation 7 to get

$$\varsigma = \frac{\frac{d(y/x)}{y/x}}{\frac{d\left(\frac{\partial u(\cdot)/\partial x}{\partial u(\cdot)/\partial y}\right)}{\frac{\partial u(\cdot)/\partial x}{\partial u(\cdot)/\partial y}}} = \frac{d\ln(y/x)}{d\ln\left(\frac{\partial u(\cdot)/\partial x}{\partial u(\cdot)/\partial y}\right)} = \frac{\frac{dy}{y} - \frac{dx}{x}}{d\ln\left(\frac{\partial u(\cdot)/\partial x}{\partial u(\cdot)/\partial y}\right)}$$

Use this equation to substitute the left-hand side of equation 8 to get

$$\frac{dy}{y} - \frac{dx}{x} = \varsigma \left(\frac{dp_X}{p_X} - \frac{dp_Y}{p_Y} \right) \equiv \hat{y} - \hat{x} = \varsigma \left(\hat{p}_X - \hat{p}_Y \right) \tag{9}$$

Firms

In industry X, each firm demands an input bundle (L_X, E_X) and supplies output quantity X to maximize profit $p_X X - wL_X - \tau E_X$ subject to the technology constraint $X \leq X(L_X, E_X)$ and taking the prices as given. If (L_X, E_X, X) is a solution to the optimization program, then it is a Karush-Kuhn-Tucker point satisfying the the stationarity conditions

$$-w - \lambda_X \frac{\partial X(\cdot)}{\partial L_X} = 0 \tag{10}$$

$$-\tau - \lambda_X \frac{\partial X(\cdot)}{\partial L_X} = 0 \tag{11}$$

$$p_X - \lambda_X = 0 \tag{12}$$

the primal feasibility condition $X - X(L_X, E_X) \leq 0$, the dual feasibility condition $\lambda_X \geq 0$, and the complementary slackness condition $\lambda_X (X - X(L_X, E_X)) = 0$. Since the profit function is concave and the constraint continuously differentiable and convex, they are also sufficient.

By stationarity condition 12 and the complementary slackness condition we have

$$p_X (X - X(L_X, E_X)) = 0$$

By the restriction to strictly interior equilibria ($p_X > 0$) this equation is true if and only if

$$X = X(L_X, E_X)$$

Take the natural logarithm of both sides, totally differentiate, and multiply both sides by $L_X E_X / L_X E_X$, to get

$$\frac{dX}{X} = \frac{L_X}{X} \frac{\partial X(\cdot)}{\partial L_X} \frac{dL_X}{L_X} + \frac{E_X}{X} \frac{\partial X(\cdot)}{\partial E_X} \frac{dE_X}{E_X}$$

Take the stationarity conditions to substitute the marginal products $\partial X(\cdot) / \partial L_X$ and $\partial X(\cdot) / \partial L_X$,

$$\frac{dX}{X} = \frac{wL_X}{p_X X} \frac{dL_X}{L_X} + \frac{\tau E_X}{p_X X} \frac{dE_X}{E_X}$$

Denoting the the factor claims as shares of total revenues by $\theta_{XL} \equiv wL_X / p_X X$ and $\theta_{XE} \equiv \tau E_X / p_X X$, respectively, yields

$$\hat{X} = \theta_{XL} \hat{L}_X + \theta_{XE} \hat{E}_X \tag{13}$$

Now, by constant returns to scale the function $X(L_X, E_X)$ is linearly homogeneous, such that it follows from Euler's homogeneous function theorem that

$$X(\cdot) = \frac{\partial X(\cdot)}{\partial L_X} L_X + \frac{\partial X(\cdot)}{\partial E_X} E_X$$

Taking again the stationarity conditions to substitute the marginal products $\partial X(\cdot)/\partial L_X$ and $\partial X(\cdot)/\partial L_X$ yields after rearrangement

$$p_X X = wL_X + \tau E_X \tag{14}$$

Note that by this zero-profit condition we have $\theta_{XL} + \theta_{XE} = 1$. Take the natural logarithm of 14, totally differentiate, and multiply both sides by $wL_X \tau E_X / wL_X \tau E_X$ to get

$$\frac{dp_X}{p_X} + \frac{dX}{X} = \frac{wL_X}{p_X X}\left(\frac{dw}{w} + \frac{dL_X}{L_X}\right) + \frac{\tau E_X}{p_X X}\left(\frac{d\tau}{\tau} + \frac{dE_X}{E_X}\right)$$

or equivalently

$$\hat{p}_X + \hat{X} = \theta_{XL}\left(\hat{w} + \hat{L}_X\right) + \theta_{XE}\left(\hat{\tau} + \hat{E}_X\right) \tag{15}$$

Now rearrange the stationarity conditions 10, 11 and 12 to get

$$\frac{\partial X(\cdot)/\partial L_X}{\partial X(\cdot)/\partial E_X} = \frac{w}{\tau} \tag{16}$$

Taking the natural logarithm and totally differentiating yields

$$d\ln\left(\frac{\partial X(\cdot)/\partial L_X}{\partial X(\cdot)/\partial E_X}\right) = \frac{dw}{w} - \frac{d\tau}{\tau} \tag{17}$$

Define the elasticity of technical substitution

$$\sigma_X \equiv \frac{\frac{d(E_X/L_X)}{E_X/L_X}}{\frac{d(w/\tau)}{w/\tau}}$$

and use equation 16 to substitute w/τ to get

$$\sigma_X = \frac{\frac{d(E_X/L_X)}{E_X/L_X}}{\frac{d\left(\frac{\partial X(\cdot)/\partial L_X}{\partial X(\cdot)/\partial E_X}\right)}{\frac{\partial X(\cdot)/\partial L_X}{\partial X(\cdot)/\partial E_X}}} = \frac{d\ln(E_X/L_X)}{d\ln\left(\frac{\partial X(\cdot)/\partial L_X}{\partial X(\cdot)/\partial E_X}\right)} = \frac{\frac{dE_X}{E_X} - \frac{dL_X}{L_X}}{d\ln\left(\frac{\partial X(\cdot)/\partial L_X}{\partial X(\cdot)/\partial E_X}\right)}$$

Use this equation to substitute the left-hand side of equation 17 to get

$$\frac{dE_X}{E_X} - \frac{dL_X}{L_X} = \sigma_X \left(\frac{dw}{w} - \frac{d\tau}{\tau} \right) \equiv \hat{E}_X - \hat{L}_X = \sigma_X (\hat{w} - \hat{\tau}) \tag{18}$$

Repeat the same steps for industry Y_D to get the equations

$$\hat{Y}_D = \theta_{YL} \hat{L}_{YD} + \theta_{YE} \hat{E}_Y \tag{19}$$

$$\hat{p}_Y + \hat{Y}_D = \theta_{YL} \left(\hat{w} + \hat{L}_{YD} \right) + \theta_{YE} \left(\hat{r} + \hat{E}_Y \right) \tag{20}$$

$$\hat{E}_Y - \hat{L}_{YD} = \sigma_Y (\hat{w} - \hat{r}) \tag{21}$$

In industry Y_C, each firm demands an input quantity L_{YC} and supplies output quantity Y_C to maximize profit $tY_C - wL_X$ subject to the technology constraint $Y_C \leq Y_C(L_{YC})$ and taking the prices as given. If (L_{YC}, Y_C) is a solution to the optimization program, then it is a Karush-Kuhn-Tucker point satisfying the the stationarity conditions

$$-w - \lambda_{YC} \frac{dY_C(\cdot)}{dL_{YC}} = 0 \tag{22}$$

$$t - \lambda_{YC} = 0 \tag{23}$$

the primal feasibility condition $Y_C - Y_C(L_{YC}) \leq 0$, the dual feasibility condition $\lambda_{YC} \geq 0$, and the complementary slackness condition $\lambda_{YC}(Y_C - Y_C(L_{YC})) = 0$. Since the profit function is concave and the constraint continuously differentiable and convex, they are also sufficient.

By stationarity condition 23 and the complementary slackness condition we have

$$t(Y_C - Y_C(L_{YC})) = 0$$

By $t > p_Y > 0$ this equation is true if and only if

$$Y_C = Y_C(L_{YC})$$

Take the natural logarithm of both sides, totally differentiate, multiply both sides by L_{YC}/L_{YC}, and take the stationarity conditions to substitute the marginal product $dY_D(\cdot)/\partial L_{YC}$ to get

$$\frac{dY_C}{Y_C} = \frac{wL_{YC}}{tY_C} \frac{dL_{YC}}{L_{YC}}$$

Defining the the labor-capital claim as a share of total revenues by $\vartheta \equiv wL_{YC}/tY_C$ yields

$$\hat{Y}_C = \vartheta \hat{L}_{YC} \tag{24}$$

Now rearrange the stationarity conditions 22 and 23 to get

$$\frac{dY_C(\cdot)}{dL_{YC}} = \frac{w}{t} \tag{25}$$

Taking the natural logarithm and totally differentiating yields

$$d\ln\left(\frac{dY_C(\cdot)}{dL_{YC}}\right) = \frac{dw}{w} - \frac{dt}{t} \tag{26}$$

Define the elasticity of green electricity producer's demand for labor-capital with respect to its real price

$$\rho \equiv \frac{\frac{dL_{YC}}{L_{YC}}}{\frac{d(w/t)}{w/t}} \tag{27}$$

and use equation 25 to substitute w/t to get

$$\rho = \frac{\frac{dL_{YC}}{L_{YC}}}{\frac{d(dY_C(\cdot)/dL_{YC})}{dY_C(\cdot)/dL_{YC}}} = \frac{\frac{dL_{YC}}{L_{YC}}}{d\ln\left(\frac{dY_C(\cdot)}{dL_{YC}}\right)}$$

Use this equation to substitute the left-hand side of equation 26 to get

$$\frac{dL_{YC}}{L_{YC}} = \rho\left(\frac{dt}{t} - \frac{dw}{w}\right) \equiv \hat{L}_{YC} = \rho\left(\hat{t} - \hat{w}\right) \tag{28}$$

Finally, take the natural logarithm of $Y = Y_D + Y_C$, totally differentiate and multiply both sides by $Y_D Y_C / Y_D Y_C$, respectively, to get

$$\frac{dY}{Y} = \frac{Y_D}{Y}\frac{dY_D}{Y_D} + \frac{Y_C}{Y}\frac{dY_C}{Y_C}$$

Defining the shares of conventional and green electricity, respectively, as a fraction of total electricity output, $\alpha_D = Y_D/Y$ and $\alpha_C = Y_C/Y$, yields

$$\hat{Y} = \alpha_D \hat{Y}_D + \alpha_C \hat{Y}_C \tag{29}$$

For later reference, note that $w = 1$ (labor-capital is numeraire), τ and C are constants, such that

$$\frac{dw}{w} = 0 \equiv \hat{w} = 0 \tag{30}$$

$$\frac{d\tau}{\tau} = 0 \equiv \hat{\tau} = 0 \tag{31}$$

$$\frac{dC}{C} = 0 \equiv \hat{C} = 0 \tag{32}$$

Finally, note that $\sigma_X > 0$, $\sigma_Y > 0$, and $\varsigma > 0$ by the (strict) substitutability assumptions, and that $\rho > 0$ by the (strict) monotonicity assumption.

B Proofs

B.1 Proof of lemma 1

Use equation 5 to substitute $\hat{E}_Y$ in equation 2, and in turn equation 32 to substitute $\hat{C}$.

B.2 Proof of lemma 2

Use equation 18 to substitute $\hat{L}_X$ in equation 13, and in turn equations 30 and 31 to substitute $\hat{w}$ and $\hat{\tau}$, respectively.

B.3 Proof of lemma 3

Use equation 18 to substitute $\hat{L}_X$ in equation 6, and in turn equations 30 and 31 to substitute $\hat{w}$ and $\hat{\tau}$, respectively, to get

$$\hat{L}_X \hat{E}_X + \hat{L}_{YD} L_{YD} + \hat{L}_{YC} L_{YC} = 0$$

Now use lemma 2 to substitute $\hat{E}_X$.

B.4 Proof of lemma 4

Use equation 30 to substitute $\hat{w}$ in equation 28 to get $\hat{L}_{YC} = \rho \hat{t}$. Use this equation to substitute $\hat{L}_{YC}$ in equation 24 to get $\hat{Y}_C = \vartheta \rho \hat{t}$. By the assumption of decreasing marginal products (which also implies decreasing returns to scale here) $Y_C(L_{YC})$ is strictly concave such that $Y_C(nL_{YC}) = n^k Y_C(L_{YC})$ with $k < 1$ holds for any $n > 0$, and therefore by Euler's homogeneous function theorem and the stationarity conditions 22 and 23 we have

$$kY_C(L_{YC}) = \frac{w}{t} L_{YC} \Leftrightarrow tkY_C(L_{YC}) = wL_{YC}$$

Since $k < 1$, this equation can only be true if $tY_C > wL_{YC}$. By the definition of ϑ this implies $\vartheta < 1$.

B.5 Proof of lemma 5

Use equation 5 to substitute $\hat{E}_Y$ in equation 21, and in turn equation 32 to substitute $\hat{C}$ to get $\hat{L}_{YD} = \sigma_Y \hat{r}$. Now use this equation to substitute $\hat{L}_{YD}$ and again equations 5 and 21 to substitute $\hat{E}_Y$ in equation 19.

B.6 Proof of lemma 6

Use conditions 3 and 4, respectively, to substitute $\hat{y}$ and $\hat{x}$ in equation 9. Now use equation 14 to substitute $\hat{p}_X$ and equation 13 to substitute $\hat{X}$. Finally, use equations 30 and 31 to substitute $\hat{w}$ and $\hat{\tau}$, respectively.

B.7 Proof of lemma 7

Use equation 19 to substitute $\hat{Y}_D$ and equation 20. Now use equations 5 and 32 to substitute $\hat{E}_Y$ and equation 30 to substitute $\hat{w}$.

B.8 Proof of lemma 8

By lemma 6 it holds that $\hat{X} = \varsigma \hat{p}_Y + \hat{Y}$. Use condition 29 to substitute $\hat{Y}$ and lemma 7 to substitute $\hat{p}_Y$ to get

$$\hat{X} = \varsigma \theta_{YE} \hat{r} + \alpha_D \hat{Y}_D + \alpha_C \hat{Y}_C \tag{33}$$

Now use lemma 4 to substitute $\hat{Y}_C$ and lemma 5 to substitute $\hat{Y}_D$:

$$\hat{X} = (\varsigma \theta_{YE} + \alpha_D \theta_{YL} \sigma_Y) \hat{r} + \alpha_C \vartheta \rho \hat{t} \tag{34}$$

Finally, using lemma 3 to substitute $\hat{X}$, and in turn lemmas 4 and 5 to substitute $\hat{L}_{YC}$ and $\hat{L}_{YD}$, respectively, yields after rearrangement

$$\hat{r} = -\underbrace{\left[\frac{(L_X \alpha_C \vartheta + L_{YC})\,\rho}{(L_X \alpha_D \theta_{YL} + L_{YD})\,\sigma_Y + L_X \theta_{YE} \varsigma}\right]}_{:=\gamma} \hat{t} \tag{35}$$

Since all parameters within the brackets are strictly positive, it holds that $\gamma > 0$. Furthermore, it is easy to see that the term in brackets is linearly increasing in ρ, and decreasing and concave in σ_Y and ς, with $\gamma \to 0$ for $\sigma_Y \to \infty$ or $\varsigma \to \infty$ or both.

B.9 Proof of theorem 1

Consider equation 33. Use equation 13 to substitute $\hat{X}$, equation 24 to substitute $\hat{Y}_C$, and equation 19 to substitute $\hat{Y}_D$ to get

$$\theta_{XL} \hat{L}_X + \theta_{XE} \hat{E}_X = \varsigma \theta_{YE} \hat{r} + \alpha_D \left(\theta_{YL} \hat{L}_{YD} + \theta_{YE} \hat{E}_Y\right) + \alpha_C \vartheta \hat{L}_{YC}$$

Now use use equations 18, 30 and 31 to substitute $\hat{E}_X$, and equations 5 and 32 to substitute $\hat{E}_Y$ to get

$$\hat{L}_X = \varsigma\theta_{YE}\hat{r} + \alpha_D\theta_{YL}\hat{L}_{YD} + \alpha_C\vartheta\hat{L}_{YC}$$

Using equation 6 to substitute $\hat{L}_{YD}$ and $\hat{L}_{YC}$ yields after some rearrangement

$$\hat{L}_X\left(1 + \underbrace{\alpha_D\theta_{YL}\frac{L_X}{L_{YD}} + \alpha_C\vartheta\frac{L_X}{L_{YC}}}_{:=\delta}\right) = \varsigma\theta_{YE}\hat{r} - \alpha_D\theta_{YL}\frac{L_{YC}}{L_{YD}}\hat{L}_{YC} - \alpha_C\vartheta\frac{L_{YD}}{L_{YC}}\hat{L}_{YD}$$

Note that $\delta > 0$ since all parameters in the expression are strictly positive. Finally, using lemma 2 to substitute $\hat{L}_X$, lemma 4 to substitute $\hat{L}_{YC}$, lemma 5 to substitute $\hat{L}_{YD}$, lemma 8 to substitute $\hat{r}$, and rearranging yields

$$\hat{E}_X = \left[\underbrace{\gamma\frac{\alpha_C\vartheta L_{YD}}{(1+\delta)L_{YC}}\sigma_Y}_{\Lambda_{\text{IARE}}}\underbrace{-\gamma\frac{\theta_{YE}}{(1+\delta)}\varsigma}_{\Lambda_{\text{ITTE}}}\underbrace{-\frac{\alpha_D\theta_{YL}L_{YC}}{(1+\delta)L_{YD}}\rho}_{\Lambda_{\text{DARE}}}\right]\hat{t}$$

The term in brackets is the total leakage effect. Completely resolved, it has the form

$$\Lambda = \frac{[(L_{YD}\alpha_C\vartheta - L_{YC}\alpha_D\theta_{YL})\,\sigma_Y - L_{YC}\theta_{YE}\varsigma]\,\rho}{(L_X\alpha_D\theta_{YL} + L_{YD})\,\sigma_Y + L_X\theta_{YE}\varsigma} \tag{36}$$

Since the denominator is strictly positive, $\Lambda \geq 0$ if and only if the expression in square brackets in the numerator is greater or equal to zero. Rearranging this condition yields

$$\frac{\varsigma}{\sigma_Y} \leq \frac{L_{YD}\alpha_C\vartheta - L_{YC}\alpha_D\theta_{YL}}{L_{YC}\theta_{YE}} \tag{37}$$

Using the definitions of the parameters α_C, α_D, θ_{YL}, θ_{YE} and ϑ we have equivalently

$$\frac{\varsigma}{\sigma_{YD}} \leq \frac{wL_{YD}Y_D}{rE_YY}\left(\frac{p_Y}{t} - 1\right) \tag{38}$$

By assumption $t > p_Y$ the right-hand side is strictly negative. Since by $\varsigma > 0$ and $\sigma_Y > 0$ the left-hand side is strictly positive, the condition is false, such that $\Lambda \geq 0$ is impossible. Conversely,

$$\frac{\varsigma}{\sigma_{YD}} > \frac{wL_{YD}Y_D}{rE_YY}\left(\frac{p_Y}{t} - 1\right)$$

is true such that $\Lambda < 0$ is true.

B.10 Proof of corollary 4

The DARE is given by

$$\Lambda_{\text{DARE}} = -\left[\frac{\alpha_D \theta_{YL} L_{YC}}{(1+\delta) L_{YD}}\right] \sigma_{YC}$$

Since all parameters in brackets are strictly positive, the negative sign out front implies that Λ_{DARE} is strictly negative (given $\rho > 0$). Differentiating Λ_{DARE} with respect to the elasticity parameters yields

$$\frac{\partial \Lambda_{\text{DARE}}}{\partial \rho} = -\frac{\alpha_D \theta_{YL} L_{YC}}{(1+\delta) L_{YD}} < 0, \qquad \frac{\partial^2 \Lambda_{\text{DARE}}}{\partial \rho^2} = 0$$

$$\frac{\partial \Lambda_{\text{DARE}}}{\partial \sigma_Y} = \frac{\partial \Lambda_{\text{DARE}}}{\partial \varsigma} = 0$$

proving the remaining claims about the DARE.

Substituting γ using equation 35, the ITTE is given by

$$\Lambda_{\text{ITTE}} = -\frac{\theta_{YE}(L_X \alpha_C \vartheta + L_{YC}) \rho \varsigma}{(1+\delta)\left[(L_X \alpha_D \theta_{YL} + L_{YD}) \sigma_Y + L_X \theta_{YE} \varsigma\right]}$$

Since all parameters are strictly positive, the negative sign out front implies that $\Lambda_{\text{ITTE}} < 0$. For clarity, substitute

$$\theta_{YE}(L_X \alpha_C \vartheta + L_{YC}) \equiv A$$

$$(1+\delta)(L_X \alpha_D \theta_{YL} + L_{YD}) \equiv B$$

$$(1+\delta) L_X \theta_{YE} \equiv C$$

for the moment, and note that all three elements are strictly positive. Differentiating Λ_{ITTE} with respect to the elasticity parameters

$$\frac{\partial \Lambda_{\text{ITTE}}}{\partial \rho} = -\frac{A\varsigma}{B\sigma_Y + C\varsigma} < 0, \qquad \frac{\partial^2 \Lambda_{\text{ITTE}}}{\partial \rho^2} = 0$$

$$\frac{\partial \Lambda_{\text{ITTE}}}{\partial \sigma_Y} = \frac{AB\rho\varsigma}{(B\sigma_Y + C\varsigma)^2} > 0, \qquad \frac{\partial^2 \Lambda_{\text{ITTE}}}{\partial \sigma_Y^2} = -\frac{2AB^2\rho\varsigma}{(B\sigma_Y + C\varsigma)^3} < 0$$

$$\frac{\partial \Lambda_{\text{ITTE}}}{\partial \varsigma} = -\frac{AB\rho\sigma_Y}{(B\sigma_Y + C\varsigma)^2} < 0, \qquad \frac{\partial^2 \Lambda_{\text{ITTE}}}{\partial \varsigma^2} = \frac{2ABC\rho\sigma_Y}{(B\sigma_Y + C\varsigma)^3} > 0$$

and taking limits

$$\lim_{\sigma_Y\to\infty}\Lambda_{\text{ITTE}}=0,\quad \lim_{\varsigma\to\infty}\Lambda_{\text{ITTE}}=\frac{A}{C}\rho>0$$

proves the remaining claims about the ITTE.

Substituting γ using equation 35, the IARE is given by

$$\Lambda_{\text{IARE}}=\frac{\alpha_C\vartheta L_{YD}\left(L_X\alpha_C\vartheta+L_{YC}\right)\rho\sigma_Y}{(1+\delta)\left[L_{YC}\left(L_X\alpha_D\theta_{YL}+L_{YD}\right)\sigma_Y+L_{YC}L_X\theta_{YE}\varsigma\right]}$$

Since all parameters are strictly positive we have that$\Lambda_{\text{IARE}}>0$. For clarity, substitute

$$\alpha_C\vartheta L_{YD}\left(L_X\alpha_C\vartheta+L_{YC}\right)\equiv A$$

$$(1+\delta)L_{YC}\left(L_X\alpha_D\theta_{YL}+L_{YD}\right)\equiv B$$

$$(1+\delta)L_{YC}L_X\theta_{YE}\equiv C$$

for the moment, and note that all three elements are strictly positive. Differentiating Λ_{IARE} with respect to the elasticity parameters

$$\frac{\partial\Lambda_{\text{IARE}}}{\partial\rho}=\frac{A\varsigma}{B\sigma_Y+C\varsigma}>0,\qquad \frac{\partial^2\Lambda_{\text{IARE}}}{\partial\rho^2}=0$$

$$\frac{\partial\Lambda_{\text{IARE}}}{\partial\sigma_Y}=\frac{AC\rho\varsigma}{\left(B\sigma_Y+C\varsigma\right)^2}>0,\quad \frac{\partial^2\Lambda_{\text{IARE}}}{\partial\sigma_Y^2}=-\frac{2ABC\rho\varsigma}{\left(B\sigma_Y+C\varsigma\right)^3}<0$$

$$\frac{\partial\Lambda_{\text{IARE}}}{\partial\varsigma}=-\frac{AC\rho\sigma_Y}{\left(B\sigma_Y+C\varsigma\right)^2}<0,\quad \frac{\partial^2\Lambda_{\text{IARE}}}{\partial\varsigma^2}=\frac{2AC^2\rho\sigma_Y}{\left(B\sigma_Y+C\varsigma\right)^3}>0$$

and taking limits

$$\lim_{\sigma_Y\to\infty}\Lambda_{\text{IARE}}=\frac{A}{C}\rho>0,\quad \lim_{\varsigma\to\infty}\Lambda_{\text{IARE}}=0$$

proves the remaining claims about the IARE.

Differentiating Λ with respect to σ_Y yields

$$\frac{\partial\Lambda}{\partial\sigma_Y}=\underbrace{\frac{\partial\Lambda_{\text{DARE}}}{\partial\sigma_Y}}_{=0}+\underbrace{\frac{\partial\Lambda_{\text{IARE}}}{\partial\sigma_Y}}_{>0}+\underbrace{\frac{\partial\Lambda_{\text{ITTE}}}{\partial\sigma_Y}}_{>0}>0$$

$$\frac{\partial^2 \Lambda}{\partial \sigma_Y^2} = \underbrace{\frac{\partial^2 \Lambda_{\text{DARE}}}{\partial \sigma_Y^2}}_{=0} + \underbrace{\frac{\partial^2 \Lambda_{\text{IARE}}}{\partial \sigma_Y^2}}_{<0} + \underbrace{\frac{\partial^2 \Lambda_{\text{ITTE}}}{\partial \sigma_Y^2}}_{<0} < 0$$

i.e. Λ is increasing and concave in parameter σ_Y. Furthermore,

$$\lim_{\sigma_Y \to \infty} \Lambda = \frac{L_{YD}\alpha_C \vartheta - L_{YC}\alpha_D \theta_{YL}}{L_X \alpha_D \theta_{YL} + L_{YD}} \rho$$

Differentiating Λ with respect to ς yields

$$\frac{\partial \Lambda}{\partial \varsigma} = \underbrace{\frac{\partial \Lambda_{\text{DARE}}}{\partial \varsigma}}_{=0} + \underbrace{\frac{\partial \Lambda_{\text{IARE}}}{\partial \varsigma}}_{<0} + \underbrace{\frac{\partial \Lambda_{\text{ITTE}}}{\partial \varsigma}}_{<0} < 0$$

$$\frac{\partial^2 \Lambda}{\partial \varsigma^2} = \underbrace{\frac{\partial^2 \Lambda_{\text{DARE}}}{\partial \varsigma^2}}_{=0} + \underbrace{\frac{\partial^2 \Lambda_{\text{IARE}}}{\partial \varsigma^2}}_{>0} + \underbrace{\frac{\partial^2 \Lambda_{\text{ITTE}}}{\partial \varsigma^2}}_{>0} > 0$$

i.e. Λ is decreasing and convex in parameter ς. Furthermore,

$$\lim_{\varsigma \to \infty} \Lambda = -\frac{L_{YC}}{L_X} \rho$$

Finally, consider the properties of Λ with respect to ρ. First, we have

$$\frac{\partial^2 \Lambda}{\partial \rho^2} = \underbrace{\frac{\partial^2 \Lambda_{\text{DARE}}}{\partial \rho^2}}_{=0} + \underbrace{\frac{\partial^2 \Lambda_{\text{IARE}}}{\partial \rho^2}}_{=0} + \underbrace{\frac{\partial^2 \Lambda_{\text{ITTE}}}{\partial \rho^2}}_{=0} = 0$$

such that Λ is definitely linear in ρ. To identify the slope, differentiate expression 36

$$\frac{\partial \Lambda}{\partial \rho} = \frac{(L_{YD}\alpha_C \vartheta - L_{YC}\alpha_D \theta_{YL})\, \sigma_Y - L_{YC}\theta_{YE}\varsigma}{(L_X \alpha_D \theta_{YL} + L_{YD})\, \sigma_Y + L_X \theta_{YE}\varsigma} \tag{39}$$

Since the denominator is strictly positive the expression is greater or equal to zero if and only if the numerator is greater or equal to zero. Rearranging this condition yields condition 37 (or equivalently condition 38), which is false, as shown above, such that Λ must be strictly decreasing in ρ.

B.11 Proof of lemma 9

Let $P_Y \equiv p_Y + s$ denote the gross price of Y. Then equation 9 changes to

$$\frac{dy}{y} - \frac{dx}{x} = \varsigma \left(\frac{dp_X}{p_X} - \frac{dP_Y}{P_Y} \right) \equiv \hat{y} - \hat{x} = \varsigma \left(\hat{p}_X - \hat{P}_Y \right) \tag{40}$$

Use the definition of s to substitute s in the definition of P_Y, and consider the definitions α_C and α_D to get

$$P_Y = \alpha_D p_Y + \alpha_C t$$

Take the natural logarithm and totally differentiate to obtain

$$\frac{dP_Y}{P_Y} = \frac{p_Y Y_D}{p_Y Y_D + tY_C}\frac{dp_Y}{p_Y} + \frac{tY_C}{p_Y Y_D + tY_C}\frac{dt}{t}$$

Defining $\psi_D \equiv p_Y Y_D / (p_Y Y_D + tY_C)$ and $\psi_C \equiv tY_C / (p_Y Y_D + tY_C)$ yields

$$\hat{P}_Y = \psi_D \hat{p}_Y + \psi_C \hat{t}$$

Use this to substitute $\hat{P}_Y$ in equation 40.

B.12 Proof of lemma 10

By lemma 9 it holds that $\hat{X} = \varsigma\,(\psi_D \hat{p}_Y + \psi_C \hat{t}) + \hat{Y}$. Use equation 29 to substitute $\hat{Y}$ and lemma 7 to substitute $\hat{p}_Y$ to get

$$\hat{X} = \varsigma\,(\psi_D \theta_{YE} \hat{r} + \psi_C \hat{t}) + \alpha_D \hat{Y}_D + \alpha_C \hat{Y}_C \tag{41}$$

Now use lemma 4 to substitute $\hat{Y}_C$ and lemma 5 to substitute $\hat{Y}_D$:

$$\hat{X} = (\varsigma \psi_D \theta_{YE} + \alpha_D \theta_{YL} \sigma_Y)\,\hat{r} + (\varsigma \psi_C + \alpha_C \vartheta \rho)\,\hat{t}$$

Finally, using lemma 3 to substitute $\hat{X}$, and in turn lemmas 4 and 5 to substitute $\hat{L}_{YC}$ and $\hat{L}_{YD}$ yields after rearrangement

$$\hat{r} = -\underbrace{\left[\frac{(L_X \alpha_C \vartheta + L_{YC})\,\rho + L_X \psi_C \varsigma}{(L_X \alpha_D \theta_{YL} + L_{YD})\,\sigma_Y + L_X \theta_{YE} \psi_D \varsigma}\right]}_{\equiv \tilde{\gamma}} \hat{t} \tag{42}$$

Since all parameters in the expression in brackets are strictly positive, it holds that $\tilde{\gamma} > 0$. Furthermore, $\tilde{\gamma}$ is apparently linearly increasing in ρ, and decreasing and concave in σ_Y, with $\tilde{\gamma} \to 0$ for $\sigma_Y \to \infty$. We also have $\partial\tilde{\gamma}/\partial\varsigma > 0$, $\partial^2\tilde{\gamma}/\partial\varsigma^2 < 0$, and

$$\lim_{\varsigma\to\infty} \tilde{\gamma} = \frac{\psi_C}{\theta_{YE}\psi_D}$$

i.e. $\tilde{\gamma}$ is increasing, concave and finitely convergent in ς.

Finally, $\tilde{\gamma}$ is increasing in ψ_C, as ψ_C is in the numerator and $\psi_D = 1 - \psi_C$ is in the denominator. For $\psi_C = 0$ equation 42 becomes identical to equation 35, that is, $\tilde{\gamma} = \gamma$. However, from the assumption $\psi_C > 0$ it follows that (because $\tilde{\gamma}$ is increasing in ψ_C) $\tilde{\gamma} > \gamma$.

B.13 Proof of theorem 2

Consider equation 41. Use equation 13 to substitute $\hat{X}$, equation 24 to substitute $\hat{Y}_C$, and equation 19 to substitute $\hat{Y}_D$ to get

$$\hat{X} = \varsigma\left(\psi_D \theta_{YE} \hat{r} + \psi_C \hat{t}\right) + \alpha_D \theta_{YL} \hat{L}_{YD} + \alpha_C \vartheta \hat{L}_{YC}$$

Now use use equations 18, 30 and 31 to substitute $\hat{E}_X$, and equations 5 and 32 to substitute $\hat{E}_Y$ to get

$$\hat{L}_X = \varsigma\left(\psi_D \theta_{YE} \hat{r} + \psi_C \hat{t}\right) + \alpha_D \theta_{YL} \hat{L}_{YD} + \alpha_C \vartheta \hat{L}_{YC}$$

Using equation 6 to substitute $\hat{L}_{YD}$ and $\hat{L}_{YC}$, and in turn lemma 2 to substitute $\hat{L}_X$, lemma 4 to substitute $\hat{L}_{YC}$, lemma 5 to substitute $\hat{L}_{YD}$, lemma 8 to substitute $\hat{r}$, and rearranging yields

$$\hat{E}_X = \left[\underbrace{\tilde{\gamma} \frac{\alpha_C \vartheta L_{YD}}{(1+\delta) L_{YC}} \sigma_Y}_{\tilde{\Lambda}_{\text{IARE}}} \underbrace{- \tilde{\gamma} \frac{\psi_D \theta_{YE}}{(1+\delta)} \varsigma}_{\tilde{\Lambda}_{\text{ITTE}}} \underbrace{- \frac{\alpha_D \theta_{YL} L_{YC}}{(1+\delta) L_{YD}} \rho}_{\Lambda_{\text{DARE}}} \underbrace{+ \frac{\psi_C}{(1+\delta)} \varsigma}_{\Lambda_{\text{DTTE}}} \right] \hat{t}$$

The term in brackets is the total leakage effect. Completely resolved, it has the form

$$\tilde{\Lambda} = \frac{\left[\left(L_{YD} \alpha_C \vartheta - L_{YC} \alpha_D \theta_{YL}\right) \sigma_Y - \psi_D L_{YC} \theta_{YE} \varsigma\right] \rho + \psi_C L_{YD} \sigma_Y \varsigma}{\left(L_X \alpha_D \theta_{YL} + L_{YD}\right) \sigma_Y + \psi_D L_X \theta_{YE} \varsigma} \tag{43}$$

The leakage effect can now be positive. To see this, consider the case $\sigma_{YC} = 0$, such that industry Y_C does not expand at all. In this case, we have

$$\tilde{\Lambda} = \frac{\psi_C L_{YD} \sigma_Y \varsigma}{\left(L_X \alpha_D \theta_{YL} + L_{YD}\right) \sigma_Y + \psi_D L_X \theta_{YE} \varsigma}$$

which is strictly positive. Generally, $\tilde{\Lambda} \geq 0$ if and only if the the numerator of 43 is greater or equal to zero. Rearranging this condition yields

$$\psi_C \geq \underbrace{\frac{\left(L_{YC} \theta_{YE} \varsigma + \left(L_{YC} \alpha_D \theta_{YL} - L_{YD} \alpha_C \vartheta\right) \sigma_Y\right) \rho}{\left(L_{YC} \theta_{YE} \rho + L_{YD} \sigma_Y\right) \varsigma}}_{\equiv \bar{\psi}_C} \tag{44}$$

i.e. if the share of income earned in industry Y_C is sufficiently large.

B.14 Proof of corollary 5

The difference between the leakage effects in the levy case and the lump-sum case is

$$\begin{aligned}
\tilde{\Lambda} - \Lambda &= \left(\tilde{\Lambda}_{\text{IARE}} + \tilde{\Lambda}_{\text{ITTE}} + \Lambda_{\text{DARE}} + \Lambda_{\text{DITTE}}\right) - \left(\Lambda_{\text{IARE}} + \Lambda_{\text{ITTE}} + \Lambda_{\text{DARE}}\right) \\
&= \left(\tilde{\Lambda}_{\text{IARE}} - \Lambda_{\text{IARE}}\right) + \left(\tilde{\Lambda}_{\text{ITTE}} - \Lambda_{\text{ITTE}}\right) + \Lambda_{\text{DITTE}} \\
&= (\tilde{\gamma} - \gamma) \frac{\alpha_C \vartheta L_{YD}}{(1+\delta) L_{YC}} \sigma_Y + (\gamma - \tilde{\gamma}\psi_D) \frac{\theta_{YE}}{(1+\delta)} \varsigma + \frac{\psi_C}{(1+\delta)} \varsigma \\
&= \frac{\tilde{\gamma} - \gamma}{\gamma} \Lambda_{\text{IARE}} - \frac{\gamma - \tilde{\gamma}\psi_D}{\gamma} \Lambda_{\text{ITTE}} + \Lambda_{\text{DTTE}} \\
&= \frac{\tilde{\gamma} - \gamma}{\gamma} \Lambda_{\text{IARE}} + \left(\frac{\tilde{\gamma}\psi_D}{\gamma} - 1\right) \Lambda_{\text{ITTE}} + \Lambda_{\text{DTTE}}
\end{aligned} \tag{45}$$

Now, first observe that if $\psi_C = 0$ we have $\tilde{\gamma} = \gamma$ by lemma 10 and hence $\tilde{\Lambda} - \Lambda = 0$. For any $\psi_C > 0$, we have $\tilde{\gamma} > \gamma$ by lemma 10. Since $\frac{\tilde{\gamma}}{\gamma} > 0$, all terms in equation 45 are positive for $\psi_C > 1$, and $\tilde{\Lambda} - \Lambda$ is strictly increasing in ψ_C.

B.15 Proof of theorem 3

Define the concept of *actual emission reduction* (in relative terms) as

$$\widehat{\text{AER}} \equiv -\hat{E}$$

which is by lemma 1 and theorem 1 equal to $-\phi\Lambda\hat{t}$.

Define the bias of the VER statistic as

$$B \equiv \widehat{\text{VER}} - \widehat{\text{AER}}$$

such that $B > 0$ indicates that the VER overestimates the actual emission reduction, and $B < 0$ indicates an underestimation. Using the definitions of the two right-hand side quantities yields

$$B = \left[(1-\phi) \frac{\alpha_C}{\alpha_D} \vartheta \rho + \phi \Lambda\right] \hat{t}$$

Substituting Λ using equation 36, we get

$$B = \underbrace{\left[(1-\phi) \frac{\alpha_C}{\alpha_D} \vartheta + \phi \frac{\left[(L_{YD}\alpha_C\vartheta - L_{YC}\alpha_D\theta_{YL})\,\sigma_Y - L_{YC}\theta_{YE}\varsigma\right]}{(L_X\alpha_D\theta_{YL} + L_{YD})\,\sigma_Y + L_X\theta_{YE}\varsigma}\right]}_{b} \rho\hat{t} \tag{46}$$

Thus, the bias is a linear function of $\hat{t}$ and ρ.

By direct application of theorem 1, b is strictly increasing and concave in σ_Y, and strictly decreasing and convex in ς. Furthermore, substituting the parameters ϕ, α_C, α_D, ϑ, θ_{YL}, and θ_{YE} using their definitions, it holds that $b \leq 0$ (i.e. consistent underestimation) if

$$QwL_{YD}p_Y\rho + RYY_D\varsigma \leq 0$$

with

$$Q = tY_DY_C^2(E-E_X)\left(p_YwY_D^2L_X+Y\right)+E_X\left(tY_C^2-p_YY_D^2\right)$$

$$R = tw^2Y_DY_C^2L_XL_{YD}(E-E_X)-rE_XE_Y$$

otherwise $b > 0$ (i.e. consistent overestimation).

The bias B is zero only if b is zero (assuming $\hat{t} > 0$, otherwise the analysis is meaningless), otherwise $B \neq 0$.

Rearranging the term Q yields

$$Q = \left(tY_C^2Y_DE_Y - \frac{E_X}{wL_X}\right)Q_1 + Q_2$$

with

$$Q_1 = \frac{p_YY_DwL_X}{tY_C} > 0$$

and

$$Q_2 = Y_DY_CE_Y\frac{Y_C+Y_D}{Y_D} + E_X\frac{Y_C}{Y_D} > 0$$

i.e. the lower the emission intensity in industry X the more likely Q is positive.

Rearranging the term R yields

$$R = \left(tY_CwL_Y\frac{Y_C}{r} - \frac{E_X}{wL_X}\right)R_1$$

with

$$R_1 = rE_YwL_X > 0$$

Again, the lower the emission intensity in industry X the more likely R is positive. In sum, the lower the emission intensity in industry X, the more likely $b > 0$ and hence $B > 0$ (i.e. consistent overestimation).

C Replication of Baylis et al. (2013, 2014)

Baylis et al. (2013, 2014, , BFK hereafter) analyze the setting $\hat{r} > 0$ with $\hat{t} = \hat{\tau} = 0$, that is, the effects of an exogenous increase of the carbon price (in a setting with permit scheme this amounts to reducing the cap $\bar{E}$ such that the respective price change results) with all other parameters constant.

By lemma 6 it holds that $\hat{X} = \varsigma \hat{p}_Y + \hat{Y}$. Using lemma 2 to substitute $\hat{X}$, lemma 7 to substitute $\hat{p}_Y$, equation 29 to substitute $\hat{Y}$, and assumption $\hat{t} = 0$ we get

$$\hat{E}_X = \varsigma \theta_{YE} \hat{r} + \alpha_D \hat{Y}_D \tag{47}$$

Now, by equations 19 and 21 it holds that

$$\hat{Y}_D = \hat{L}_{YD} - \theta_{YE} \sigma_Y \hat{r}$$

Using lemmas 2 and 3 to substitute $\hat{L}_{YD}$, and assumption $\hat{t} = 0$ we get

$$\hat{Y}_D = -\frac{L_X}{L_{YD}} \hat{E}_X - \theta_{YE} \sigma_Y \hat{r} \tag{48}$$

Using equation 48 to substitute $\hat{Y}_D$ in equation 47 yields

$$\hat{E}_X = \beta \left[\varsigma - \alpha_D \sigma_{YD} \right] \theta_{YE} \hat{r} = \left[\underbrace{\beta \varsigma \theta_{YE}}_{\text{TTE}} - \underbrace{\beta \alpha_D \sigma_Y \theta_{YE}}_{\text{ARE}} \right] \hat{r} \tag{49}$$

with

$$\beta \equiv \left(1 + \alpha_D \frac{L_X}{L_{YD}} \right)^{-1}$$

Expression 49 is the analogue to expression 11 in BFK. An exogenous increase of the carbon price ($\hat{r} > 0$) induce two leakage effects that operate in different directions: the first effect is the TTE that happens because the higher price of Y induces consumer substitution into X (to an extent that depends on the elasticity of substitution ς). Alone, it would raise output of X and therefore raise E_X (positive leakage). The second effect is the ARE that happens because the firms in industry Y_D substitute from carbon into labor-capital for abatement (to an extent that depends on the elasticity of technical substitution σ_Y) and thus bid labor-capital away from industry X. Alone, it would decrease the output of X and emissions E_X (because of constant factor prices firms in that industry choose not to substitute but reduce the input of both factors), and is therefore a negative leakage term.

But note that in BFK setting we have at the same time $\hat{E}_Y < 0$, that is, emissions in industry Y are not constant. They allow for both a carbon tax or a cap-and-trade scheme, such that the following two interventions are equivalent in their setting: (i) an exogenous raise of a carbon tax ($\hat{r} > 0$) such that firms adjust their emissions downwards ($\hat{E}_Y < 0$), or (ii) an exogenous reduction of the cap by the same amount

$\hat{E}_Y < 0$, resulting in an increase of the permit price ($\hat{r} > 0$). If they would assume the cap to be fixed, there would apparently be no intervention to be analyzed, because then $\hat{r} = 0$. In our setting the cap *is* assumed to be fixed, but the permit price can change because there is a second instrument: the FIT.

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