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

Johannes Jarke* Grischa Perino†

Abstract

Climate policies overlapping a cap-and-trade scheme are generally considered not to change domestic emissions. In a two-sector general equilibrium model where only one sector is covered by a cap, we find that such policies do have a net impact on carbon emissions through inter-industry leakage. Promotion of renewable energy reduces emissions if tax-funded, but can increase emissions if funded by a levy on electricity. Replacing fossil fuels by electricity in uncapped sectors (e.g. power-to-heat or electric cars) and increases in the efficiency of electricity use reduce domestic emissions. Moreover, the commonly used measure to assess renewable energy policies is biased.

1 Introduction

The promotion of renewable sources of energy is among the most common instruments in the climate policy toolbox.[1] Yet, The Economist (2014) recently stressed that it is also among the most expensive ones.[2] At the same time, even the effectiveness (let alone efficiency) of renewable energy subsidy schemes is debated.

In fact, a widely held tenet among environmental economists is that policies promoting renewable energy have no effect on total greenhouse gas (GHG) emissions at all if the power sector is subject to a cap-and-trade scheme, as in the EU, parts of the US, China (starting from 2016), and other regions (Fischer & Preonas, 2010; Fowlie, 2010; Goulder, 2013; Böhringer, 2014). The argument is simple and convincing: as long as the cap is binding, total emissions do not change. Additional instruments applied to the same sector merely reallocate emissions between sources and hence raise total abatement costs. This has been used to argue against such policies, such as the feed-in tariff scheme in Germany (BMWA, 2004), or the explicit targets for renewables in the European Union complementing GHG reduction targets (Böhringer et al., 2009).

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There is nothing wrong with this point, other than that it ignores intra- and inter-temporal leakage effects.[3] No existing cap-and-trade scheme covers all GHG emissions in a country or region let alone the entire world. Hence, if one takes a general equilibrium perspective where only some of the sectors face an aggregate upper bound on emissions, then changes in factor uses in those sectors can have knock-on effects causing emissions to leak in or out. In the context of unilateral climate policy these leakage effects are well established:[4] a major concern is that tightening of carbon regulation in one part of the world *increases* aggregate carbon emissions, an effect termed «green paradox» (see van der Werf & Di Maria, 2012, for an overview).[5]

In this paper we analyze a parsimonious two-sector, two-goods, two-inputs general equilibrium model designed to understand the impact on total emissions of renewable energy policies overlapping a cap-and-trade scheme that covers only one of the two sectors. As a core exercise we solve for the comparative static effects induced by a variation of a feed-in tariff, which can also be interpreted as variation of a quota or portfolio standard, and identify the inter-sectoral leakage effect conditional on key elasticity parameters. We find that, contrary to the arguments in the existing literature on overlapping instruments, that such variations *do* have a net impact on GHG emissions. Specifically, we show that raising the FIT unambiguously reduces emissions if the subsidy scheme is tax-funded, but can increase emissions if it is funded by a levy on electricity consumption. Furthermore, the latter funding mode always performs worse in terms of emissions than the former, and the disadvantage is increasing in the relative size of the renewable electricity sector. This result has important implications for existing FIT schemes.

Further extensions yield the following results. First, policies supporting technologies that use electricity instead of fossil fuels outside the cap-and-trade system, such as electric cars or power-to-heat, not only reduce GHG emissions directly, but they reinforce the emission reducing effect of a FIT. Furthermore, as a secondary effect the FIT also renders the adoption of such technologies more attractive. Thus, there is an pronounced complementarity between the two policies.

Second, policies supporting the technical efficiency of electricity consumption supplement the FIT scheme in reducing emissions as well, because they induce a direct incentive for consumers to substitute into electricity, and hence away from goods produced outside the cap-and-trade system.

Third, we make explicit a set of assumptions underlying the virtual emission reductions (VER) statistic, a commonly used measure to gauge the impact of renewable energy policies, and show that it is a biased estimate of actual emission reductions in response to a FIT raise, because it ignores most of the effects identified in this paper.

The remainder of the paper is structured as follows. We provide a brief institutional background and empirical examples in section 2. Based on the stylized facts, we develop the basic model in section 3. In section 4 we derive the main results, section 5 is devoted to extensions and further results. We conclude in section 6.

2 Institutional background

Cap-and-trade schemes are one of the most common instruments to regulate GHG emissions. They are operating in the European Union (EU) in the form of the EU Emission Trading Scheme (EU ETS) and in North America under 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 in effect is a carbon tax into a cap-and-trade scheme in 2015 and China has started a number of city-level cap-and-trade programs for carbon emissions in 2013 to gain experience for a national program scheduled to be interoduced in 2016 (Qui, 2013; New York Times, 2014). These schemes generally cover only a fraction of emissions even within their own jurisdiction because they cover only a subset of industries. For example, the EU-ETS applies to electricity and some other major industries (e.g. ion and steel, refinery and coking, cement and lime, glass and ceramics, pulp and paper), but covers only about 45 percent of total GHG emissions produced in the EU's economy (European Commission, 2013). Similarly, the RGGI covers only the power sector of several states in the eastern part of the US.[6] Hence, on top of the often discussed leakage effects across jurisdictions there is scope for emission leakage within jurisdictions.

A common instrument to support the diffusion of renewable energies are feed-in tariffs (FITs). A FIT is in effect a long-term contract that guarantees a particular minimum price or piece rate subsidy for output produced with a particular renewable energy technology (e.g. solar, water, wind, and biomass). In early 2013, 71 countries had some form of FIT policy in place (REN21, 2013, p. 68).

A prominent example of such a FIT policy is the German Renewable Energy Act (*Erneuerbare-Energien-Gesetz*, *EEG*). It is the successor of the first FIT in Europe, the 1991 Electricity Feed-In Act (*Stromeinspeisungsgesetz*).[7] The Act (i) compelled the then monopolistic grid-running companies that also owned most of the generating capacity to grant any green electricity producer access to the network and (ii) guaranteed minimum compensations for any kWh of green electricity fed in. In 2000 the Act was replaced by the Renewable Energy Act that included additional renewable energy technologies (e.g. geo-thermal energy plants) and raised the FITs significantly. The tariffs were between 6.19 and 9.10 cents per kWh for wind power and at least 50.6 cents for solar power. Purchase guarantees were extended to 20 years. The Act commands grid-running companies to feed-in any amount of green electricity and compensate the producers with the applicable tariff. The difference between the tariff payments and the proceeds from selling the electricity at the electricity exchange EPEX spot market is financed through a levy on electricity (*EEG-Umlage*). The Act has been amended several times since its inception with average feed-in tariffs across technologies reaching 18 cents per kWh in 2013 while the average spot price of electricity was about 4 cents per kWh, resulting in a net subsidy of €23.6 billion and a levy of 6.24 cents per kWh to be paid by electricity users in 2014 (BMWE, 2014).[8] The Renewable Energy Act has been rated as the world's most effective policy in accelerating the renewable deployment (Jacobsson & Lauber, 2006; Lipp, 2007), and many countries within and outside the EU enacted similar policies.

However, since the European electricity sector is subjected to the EU ETS, none of these policies have a direct impact on GHG emissions despite their sometimes remarkable success in stimulating the diffusion of renewable energies. As long as the overall cap is binding in the long run, the emissions saved in the power sector are merely reallocated within the cap-and-trade scheme and increase emissions in other sectors (and perhaps in other countries) by the same amount. However, the contribution of this paper is to show that FITs generally have *indirect* («domestic leakage») effects on GHG emissions by inducing changes of output in the sectors *not* covered by the regulatory instruments.

3 The model

In this section we develop a stylized general equilibrium model in the style of the tax incidence literature (Harberger, 1962), and similar to the carbon leakage models of Baylis et al. (2013, 2014), that captures the essential features described in the previous section.

3.1 Households

We consider an economy with a large collection of identical households with mass normalized to unity. Each household is endowed with one unit of factor L and consumes two goods, X and Y. The factor L can be considered as labor, capital, or a composite of the two, and is assumed to be perfectly mobile within the economy. We call L «labor-capital» in what follows and choose it as numeraire. We intend that Y represents goods that are produced under the cap-and-trade scheme, and X goods that are produced outside the scheme. For concreteness, we call Y «electricity» and X «rest of the economy».[9]

Households are assumed to have consistent preferences over the entire consumption set, described by the homothetic utility function $u(x,y)$, where x and y represent the quantities of goods X and Y consumed, respectively, and always demand the most preferred among the affordable bundles. We assume that u is strictly monotonic and concave in each quantity (representing non-satiation and a preference for mixtures). For convenience we assume that $u(\cdot)$ is twice continuously differentiable.

3.2 Production

The two consumption goods are produced in competitive sectors X and Y, respectively.[10] All firms are owned by the domestic households. Each sector $i = X,Y$ uses labor-capital and carbon as factors of production in quantities L_i and E_i, respectively.

There is a single production technology in sector X described by the constant returns production function $X = X(L_X, E_X)$.[11] Marginal products are strictly decreasing and drop to zero for a finite input quantity.[12] In the electricity sector each supplier may employ a «conventional» technology $Y_D(L_{YD}, E_Y)$ with decreasing marginal products and constant returns, and a decreasing returns «green» technology $Y_C(L_{YC})$ that uses only labor-capital, i.e. is perfectly clean. We have $Y = Y_D + Y_C$ and $L_Y = L_{YD} + L_{YC}$. For convenience, we assume that all production functions are twice continuously differentiable.

3.3 Markets and regulation

There are four markets in the economy, two final good markets and two factor markets. On the former, households' demand and firms' supply of the consumption goods X and Y meet. Market prices are denoted p_X and p_Y, respectively. There is a FIT that regulates the Y-market: consumers purchase at price p_Y, conventional producers sell at price p_Y, and green producers sell at the tariff $t \geq p_Y$.[13]

On the labor-capital market households supply their factor endowment to firms. By assumption labor-capital is in fixed supply at quantity 1. Since it is perfectly mobile across sectors it earns the same return, denoted w, in either sector.[14]

Emission supply is regulated by a tradable-permit scheme in sector Y, and by another emission pricing instrument in sector X. Thus, strictly speaking, there are two GHG emission markets. Firms in sector Y operate at a market with supply fixed at an exogenous and binding cap $\bar{E}$. Permits are auctioned off at price r. Firms in sector X operate in a market with perfectly elastic supply at a price $\tau \geq 0$, that may be zero (such that the sector is not regulated in any way).

The government's budget, which is the sum of the carbon pricing revenues, $\tau E_X + rE_Y$, less the subsidy payments, $Y_C(t - p_Y)$, is returned to the households via lump-sum rebate.

4 Main results

In this section we present our key results. Assuming that our previously described economy is in equilibrium, we consider a small exogenous variation of the FIT and solve for the associated comparative static adjustments, focusing on the change of aggregate carbon emissions.[15] For expositional convenience, we will report those adjustments in terms of growth rates: for any variable V, the associated proportional change is denoted $\hat{V}$ (where positive values represent comparative static growth, and negative values depreciation).

To maximize clarity, we will just state the results (in a step-wise fashion) and explain the intuition behind them in the main text, formal proofs are relegated to appendix A.

Lemma 4.1. *Let $\hat{E}$ be the proportional change of aggregate emissions. Then $\hat{E} = \phi \hat{E}_X$, where $\phi = {}^{E_X}/_{E}$ is the ex-ante share of sector X's emissions of total emissions and $\hat{E}_X$ is the proportional change of that sector's emissions.*

Proof. Appendix A.1. □

This result is a fairly simple starting point: Since emissions in the electricity sector are fixed through the permit scheme, any change in total emissions must come from sector X.[16] Thus, to identify $\hat{E}$ we need to identify $\hat{E}_X$. In case a policy intervention is targeted at sector Y, which is the case in the present paper, $\hat{E}_X$ is commonly called *leakage effect*, since it is an effect on emissions outside the targeted sector.[17] A tightening of regulation is said to result in a (weak) *green paradox* if $\hat{E} > 0$ (Sinn, 2008; van der Werf & Di Maria, 2012), which in our context is equivalent to the domestic leakage effect being positive.

The next result establishes that the change of emissions in sector X is proportional to the change of output in that sector:

Lemma 4.2. *Let $\hat{X}$ be the growth of output in sector X. Then $\hat{E}_X = \hat{X}$.*

Proof. Appendix A.2. □

The intuition behind this result is the following: Since factor prices in sector 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, a ε percent change of output requires a change of emissions by ε percent as well.

Lemmas 4.1 and 4.2 immediately yield

Corollary 4.1. $\hat{E} = \phi\hat{X}$.

That is, the change of aggregate emissions is proportional to the change of output in sector X. The key question, therefore, is how a given policy intervention in sector Y affects output in sector X. Baylis et al. (2013, 2014) identify two channels: the *terms-of-trade effect* (TTE) and the *abatement resource effect* (ARE). The TTE occurs if the policy intervention changes the final goods price ratio and induces consumers to substitute one final good for the other. The ARE occurs if the policy intervention induces firms in sector Y_D to substitute between carbon and labor-capital, such that the latter is either bidden away from or made available to sector X.

In the remainder of the present paper we adapt the above terminology to our purposes. As a first step, it is useful to be explicit about the similarities and differences between the analysis of Baylis et al. (2013, 2014) and ours. Baylis et al. (2013, 2014) consider an exogenous variation of the carbon price r, with τ fixed and without an alternative technology or additional regulatory instrument in sector Y. For convenient reference, we replicate their key results in the context of our model formally in appendix B. The essence is simple: First, an exogenous increase of r raises the final good price p_Y, such that households substitute away from Y into X. *Ceteris paribus*, this adjustment would raise production of good X and hence (see corollary 4.1) carbon emissions. This is the TTE.

Second, an exogenous increase of r induces firms in sector Y to substitute from carbon into labor-capital for abatement and thus bid away labor-capital from sector

X. Alone, this adjustment would curtail production of good X and hence (see again corollary 4.1) carbon emissions. This is the ARE. Since the TTE is unambiguously positive and the ARE is unambiguously negative, the overall effect on sector X's emissions is ambiguous and depends on which of the two effects is larger.

As described in the previous section, we consider a different policy intervention in a somewhat richer setting. The TTE and the ARE also appear in our model, but in a slightly different and more complicated 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. Along these lines, we are going to decompose the overall effect of a FIT variation on carbon emissions into three effects: (i) the *direct abatement resource effect* (DARE), (ii) the *indirect abatement resource effect* (IARE), and the *indirect terms-of-trade effect* (ITTE). Before deriving the decomposition and the properties of the individual effects formally in subsection 4.3, we briefly characterize the mechanics behind the DARE (subsection 4.1) and the indirect effects (subsection 4.2).

4.1 The direct abatement resource effect (DARE)

The following result is critical for both AREs:

Lemma 4.3. *Let $\hat{L}_i$ be the proportional change of labor-capital input in sector i. Then $\hat{X} = \hat{L}_X$ and*[18]

$$\hat{L}_X = -\frac{1}{L_X}\left(L_{YD}\hat{L}_{YD} + L_{YC}\hat{L}_{YC}\right)$$

Proof. Appendix A.3. □

Since labor-capital supply is fixed in our economy, any change of its use in sector Y is necessarily accompanied by an inverse change in sector X.[19] If a policy intervention in sector Y induces a decrease of labor-capital demand in that sector, there will be (off-equilibrium) downward pressure on the wage rate which will be exploited by sector X; in the opposite case, sector Y firms bid the wage rate up (off-equilibrium) such that labor-capital travels from X to Y.

Together with lemma 4.3 the following result is the key step in establishing the DARE:

Lemma 4.4. *Let σ_{YC} denote the elasticity of labor-capital demand with respect to real factor cost, and θ_{YC} the elasticity of output with respect to labor-capital input in the green electricity sub-sector. Then $\hat{L}_{YC} = \sigma_{YC}\hat{t}$, and $\hat{Y}_C = \theta_{YC}\sigma_{YC}\hat{t}$ with $\theta_{YC} < 1$.*

Proof. Appendix A.4. □

Thus, the green electricity sector expands (or contracts) proportionally to the FIT variation: If the FIT 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, the increased labor-capital demand must come from somewhere else, either the conventional electricity sector or sector X. Corollary 4.1, lemma 4.1 and lemma 4.2 immediately yield

Corollary 4.2. $\hat{E} = -\frac{\phi}{L_X}\left(\hat{L}_{YD}L_{YD} + L_{YC}\sigma_{YC}\hat{t}\right)$.

To the extent the green electricity sector bids away labor-capital from sector X, output and emissions decline. This is the DARE. The size of the DARE depends on σ_{YC}, the elasticity of labor-capital demand with respect to real factor cost in the green electricity sector: the more elastic, the larger the effect. Furthermore, for a given elasticity the effect size is increasing in the relative (*ex ante*) size of the green electricity sector within the labor-capital market.

4.2 The indirect effects

The indirect effects (IARE and ITTE) stem from adjustments in the conventional electricity sector. As a first step, we can prove a result analogous to lemma 4.4:

Lemma 4.5. *Let σ_{YD} denote the elasticity of technical substitution, and θ_{YDL} the elasticity of output with respect to labor-capital input in the conventional electricity sub-sector. Then $\hat{L}_{YD} = \sigma_{YD}\hat{r}$, and $\hat{Y}_D = \theta_{YDL}\sigma_{YD}\hat{r}$, where θ_{YDL} is equal to the labor-capital payroll share of total costs and thus* $0 < \theta_{YDL} < 1$.

Proof. Appendix A.5. □

Hence, the expansion (or contraction) of the conventional electricity sector is proportional to the adjustment of the permit price. The sector demands additional labor-capital if r increases (because firms substitute away from carbon), and lays off labor-capital if r decreases (because firms substitute into carbon). 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_{YD} close to zero) the effect is small; if it is easy (σ_{YD} distant from zero), then the effect is large. This substitution is the source of the ARE in Baylis et al. (2013, 2014): since they consider an exogenous increase of r, their ARE is direct and unambiguously negative (electricity producers substitute into labor-capital, which is bidden away from sector X; see appendix B). In our model the effect is more indirect, because r is only a mediating variable. For this reason we term it *indirect* abatement resource effect (IARE). Identifying the IARE requires to solve for the actual comparative static change of r in response to the FIT variation, which we do below. Before that, we show that a change of r is also the source of adjustments in consumer behavior.

Lemma 4.6. *Let ς be the households' elasticity of substitution between consumption goods X and Y. Then $\hat{X} - \hat{Y} = \varsigma\hat{p}_Y$.*

Proof. Appendix A.6. □

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, 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 4.7. *Let θ_{YDE} denote the elasticity of output with respect to carbon input in the conventional electricity sub-sector. Then $\hat{p}_Y = \theta_{YDE}\hat{r}$, where θ_{YDE} is equal to the permit toll share of total costs, and $\theta_{YDE} = 1 - \theta_{YDL}$ such that $0 < \theta_{YDE} < 1$.*

Proof. Appendix A.7. □

Hence, the adjustment of final good Y's retail price is proportional to the adjustment of the permit price. Combining lemmas 4.6 and 4.7 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 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. Alone, this would increase emissions, i.e. the TTE would be unambiguously positive. This is exactly what Baylis et al. (2013, 2014) demonstrate (see appendix B for a replication). Again, in our model the effect is more indirect, because r is endogenous, such that we call it *indirect* terms-of-trade effect (ITTE). Identifying the ITTE again requires to solve for the actual comparative static change of r in response to the FIT variation, which we do now.

Lemma 4.8. *$\hat{r} = -\gamma\hat{t}$, where $\gamma = 0$ if and only if $\sigma_{YC} = 0$, and for $\sigma_{YC} > 0$*

- *$\gamma > 0$*
- *γ is strictly increasing and linear in σ_{YC}*
- *γ is strictly decreasing and concave in σ_{YD} and ς, with $\gamma \to 0$ for $\sigma_{YC} \to \infty$ or $\varsigma \to \infty$ or both.*

Proof. Appendix A.8. □

Thus, the adjustment of the equilibrium permit price is negatively proportional to the change of the FIT: a raise of the FIT leads to a decrease of the carbon price in sector Y. The following result is a direct consequence of lemmas 4.5 and 4.8:

Corollary 4.3. *The expansion of the conventional electricity sector is negatively proportional to the FIT change: $\hat{L}_{YD} = -\sigma_{YD}\gamma\hat{t}$, and $\hat{Y}_D = -\theta_{YDL}\sigma_{YD}\gamma\hat{t}$.*

The intuition behind lemma 4.8 and corollary 4.3 is the following: In response to an increase of the FIT, the green electricity sector grows and bids away labor-capital from the other sectors. Off equilibrium, that is, at the initial equilibrium prices this gives firms in those sectors an incentive to reduce output and therewith to reduce carbon emissions. But then the demand for permits declines below the cap, i.e. there will be excess supply of permits. As a result, the permit price will fall and conventional electricity firms respond by substituting from labor-capital into carbon (i.e. increasing their carbon intensity) until the permit market is cleared again. In the new equilibrium there will be no reduction of emissions in sector Y, but a reduction of labor-capital input and output in sector Y_D. The size of those adjustments depends on the key elasticity parameters σ_{YC}, σ_{YD} and ς. *Ceteris paribus*, the more elastic the green electricity sector grows in response to a given FIT-raise, the more labor-capital it bids away from the conventional electricity sector, the more that sector will contract at given prices, and the more the permit price must decrease in order to keep the permit market cleared. The other two elasticities work against this mechanism: the easier conventional electricity firms can substitute between labor-capital and carbon, 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, the more they raise their demand for electricity as r and in turn p_Y falls, which is met by conventional producers.

In sum, a raise of the FIT decreases the permit price, from which in turn two adjustments follow: First, the electricity price p_Y falls (see lemmas 4.7 and 4.8) which incentivizes consumers to substitute away from X into Y. Alone, this adjustment tends to decrease output and emissions in sector X. This is the ITTE.

Second, labor-capital laid-off in the conventional electricity sector (corollary 4.3) moves to sector X, tending to increase output and emissions there. This is the IARE. Thus, if a raise of the FIT is defined as a «tightening» of regulation in sector Y, then the two leakage effects (IARE and ITTE) have exactly the opposite sign as in Baylis et al. (2013, 2014): a tightening induces a negative ITTE and a positive IARE. We now show this formally.

4.3 The total effect

Let Λ denote the elasticity of sector X's emissions with respect to the FIT (the «leakage effect»), that is, $\hat{E}_X = \Lambda\hat{t}$ and (by lemma 4.1) $\hat{E} = \phi\Lambda\hat{t}$.

Theorem 4.1. *If the FIT is raised by $\hat{t}$, emissions will decrease ($\Lambda \leq 0$, with equality if and only if $\sigma_{YC} = 0$), and the size of this decrease is increasing in σ_{YC} and ς (Λ is decreasing and linear in σ_{YC}, and decreasing and convex in ς), and decreasing in σ_{YD}.*[20] *The effect Λ is a cumulative compound of*

- *a direct abatement resource effect Λ_{DARE} that decreases emissions ($\Lambda_{\text{DARE}} \leq 0$ with equality if and only if $\sigma_{YC} = 0$), and is strictly decreasing and linear in σ_{YC}, and independent from σ_{YD} and ς,*

- *an indirect abatement resource effect Λ_{IARE} that increases emissions ($\Lambda_{\text{IARE}} \geq 0$ with equality if and only if $\sigma_{YC} = 0$ or $\sigma_{YD} = 0$ or both), and is increasing and linear in σ_{YC}, increasing and concave in σ_{YD}, and decreasing, convex, and convergent to zero in ς,*

- *an indirect terms-of-trade effect* Λ_{ITTE} *that decreases emissions* ($\Lambda_{\text{ITTE}} \leq 0$ *with equality if and only if* $\sigma_{YC} = 0$ *or* $\varsigma = 0$ *or both), and is decreasing and linear in* σ_{YC}*, increasing, concave, and convergent to zero in* σ_{YD}*, and decreasing and convex in* ς.

Proof. Appendix A.9. □

Thus, if the FIT is increased by some small amount, carbon emissions tend to increase through the IARE and to decrease through the DARE and the ITTE. The DARE captures emissions reduced through the reduction of output in sector X due to the loss of labor-capital to the green electricity sector. It is intuitive that this effect does not depend on the technologies in conventional electricity production (as captured by σ_{YD}) or households' preferences (as captured by ς), but only on the elasticity of investment in green power with respect to the FIT (as captured by σ_{YC}).

The IARE catches the emissions increased through the expansion of sector X due to the absorption of labor-capital released by conventional electricity producers in the course of increasing their carbon intensity. The first-order moderating parameter is correspondingly the conventional electricity producers' elasticity of technical substitution (σ_{YD}) : the easier they can substitute between labor-capital and carbon, the less labor-capital they release in response to a falling permit price, and hence the smaller the ITTE in absolute value. However, the effect also depends indirectly on the households' preferences (as captured by ς) and the elasticity of investment in green power with respect to the FIT (as captured by σ_{YC}), because they moderate the magnitude of the permit price adjustment (see lemma 4.8).

Finally, the ITTE captures emissions reduced through the reduction of output in sector X due to consumers' substitution into electricity. Clearly, the principal parameter moderating the size of this effect is the consumers' elasticity of substitution (ς): the more substitutable the two final goods are, the more sensitive households respond to electricity price changes, and the larger the ITTE is in absolute value. More specifically,

$$\eta = -\upsilon + (1-\upsilon)\varsigma \Leftrightarrow \varsigma = \frac{\eta + \upsilon}{1-\upsilon} \tag{4.3.1}$$

where υ is the share of income spent on electricity and η is the price elasticity of electricity demand, 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_{YD}) and the elasticity of investment in green power with respect to the FIT (as captured by σ_{YC}), because they moderate the magnitude of the electricity price adjustment (see lemmas 4.7 and 4.8).

The IARE works against the DARE and the ITTE, but a «green paradox» in response to a raise of the FIT can be ruled out, because the indirect effects are always of second order compared to the DARE, such that emissions will always decline. The order of magnitude of this decline depends on the parameters. We illustrate this numerically below.

4.4 Numerical illustration

To get a «feel» for the result we calibrate the model numerically and illustrate the leakage effects, and their dependence on the elasticity parameters, graphically. Furthermore, we use data and estimates from the literature to set the parameters to empirically plausible values, such that we can roughly gauge the orders of magnitude. We emphasize that this exercise is just an illustration of the above theoretical result, it is *not* an empirical estimation of actual leakage effects, or a calibrated model of any actual FIT-scheme.

We consider the case where sector Y is electricity generation and X is the rest of production in the economy. First, we adopt the values $\theta_{YDE} = 0.147$, $\theta_{XE} = 0.01$, and $L_X = 0.982$ from Baylis et al. (2014), that are based on world aggregate data from the Global Trade Analysis Project (GTAP) for the year 2004.[21] We assume that the elasticities of output with respect to labor-capital are identical in the two electricity sub-sectors, such that $\theta_{YC} = 0.853$.

We use 2004 world aggregate data on electricity production from the US Energy Information Administration (EIA) to get $\alpha_C = 0.188$.[22] We also use this value as a weight to allocate labor-capital to the electricity sub-sectors, yielding $L_{YD} = 0.0118$ and $L_{YC} = 0.0062$. We set $\phi = 0.405$ based on 2005 data from the USEPA (2014).

With respect to the key elasticity parameters, we have a direct estimate from Okagawa & Ban (2008) to set $\sigma_{YD} = 0.256$. Relevant estimates for σ_{YC} vary somewhat: Johnson (2011) finds the price elasticity of renewable electricity generation to be larger than two, Smith & Urpelainen (2014) finds its elasticity with respect to FITs much lower (below 0.02).[23] We take a mid-way here by setting $\sigma_{YD} = 0.2$, and report scenarios with alternative values in the appendix.

Finally, the empirical literature estimates the price elasticity of demand for electricity, denoted η, to be around -0.4.[24], and households spend approximately three percent of their income on electricity (Baylis et al., 2014), such that $\varsigma = 0.38$ follows from equation 4.3.1.

The full calibration returns $\Lambda_{\text{DARE}} = -8.66 \cdot 10^{-4}$, $\Lambda_{\text{ITTE}} = -9.38 \cdot 10^{-5}$, and $\Lambda_{\text{IARE}} = 1.31 \cdot 10^{-4}$, such that the total leakage effect is $\Lambda = -8.29 \cdot 10^{-4}$. Thus, given the parameter values, the DARE is clearly the dominant effect such that emissions decrease by a small amount in response to a FIT increase.

More interesting is how the leakage effects depend on the principal elasticity parameters σ_{YC}, σ_{YC}, and ς. Figure 1 illustrates each individual and the total leakage effects both fully calibrated (the horizontal, solid lines) and as functions of the three elasticity parameters, respectively (holding the other two at the above values), on a domain of sensible values from zero to two. Figure 2 illustrates the role of the three elasticity parameters σ_{YC}, σ_{YD}, and ς in more detail. The illustrations highlight two related facts: First, σ_{YC} is clearly the first-order actuating factor of the leakage effect. The influence of the other to elasticity parameters is very small. Second, the DARE is the dominant leakage effect, the indirect effects are comparatively small.[25]

Figure 1: The calibrated leakage effects (solid), and their dependence on σ_{YC} (dashed), σ_{YD} (dotted), and ς (dash-dotted), with the other two elasticity parameters set to their calibration values, respectively. Panel (a) shows the DARE, panel (b) the ITTE, panel (c) the IARE, and panel (d) the total effect.

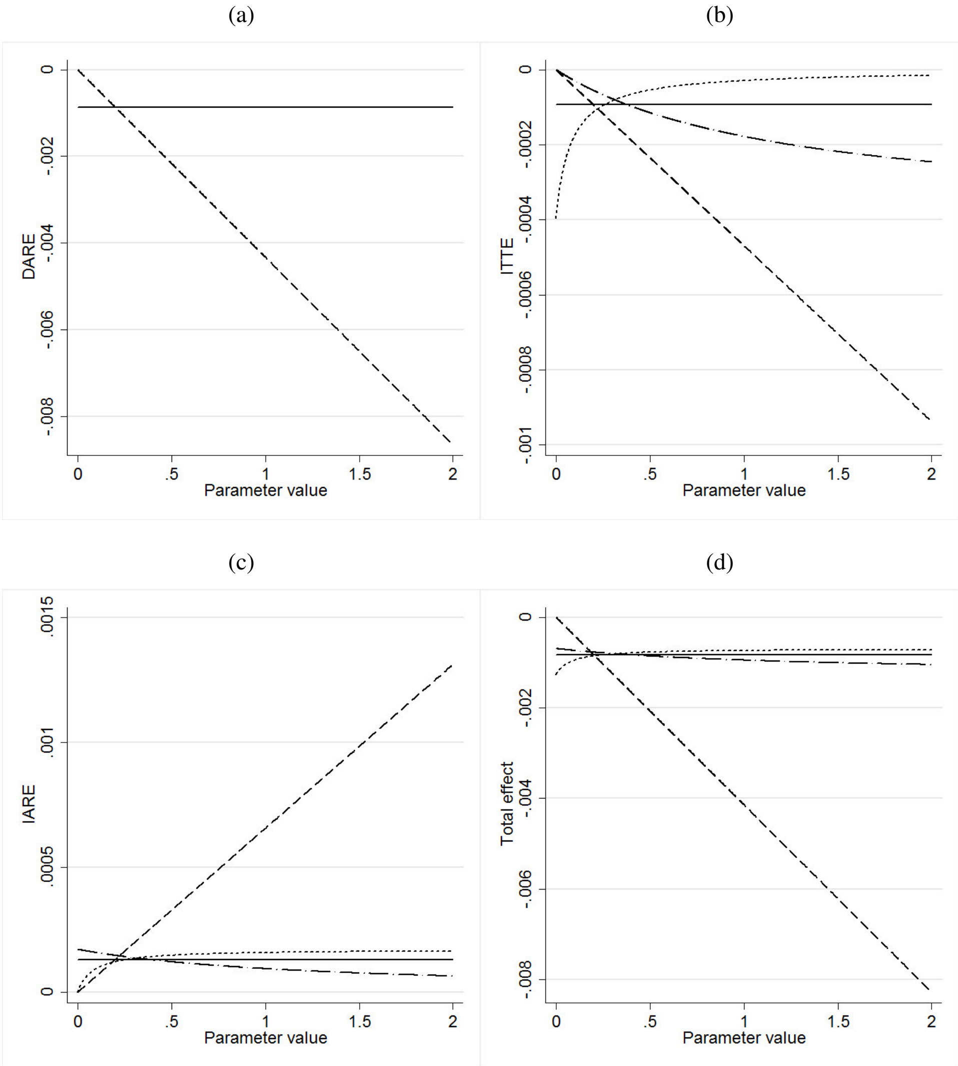
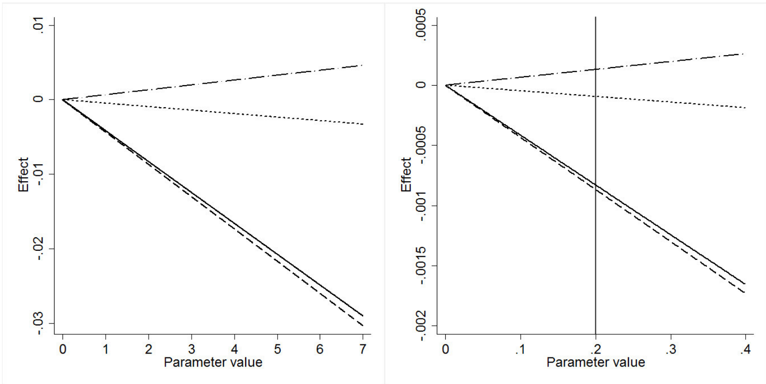
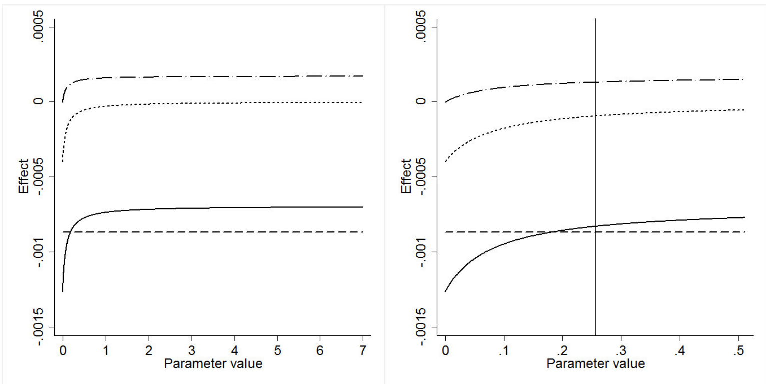


Figure 2: The roles of the elasticity parameters σ_{YC}, σ_{YD}, and ς in accentuating the DARE (dashed), the ITTE (dotted), the IARE (dash-dotted), and the total leakage effect (solid). Panel (a) shows that leakage effects as functions of σ_{YC}, panel (b) as functions of σ_{YD}, and panel (c) as functions of ς. The left-hand figures, respectively, show the graphs on a common domain from zero to seven, the right-hand figures on a restricted domain centered around the actual parameter value (indicated by a vertical line).

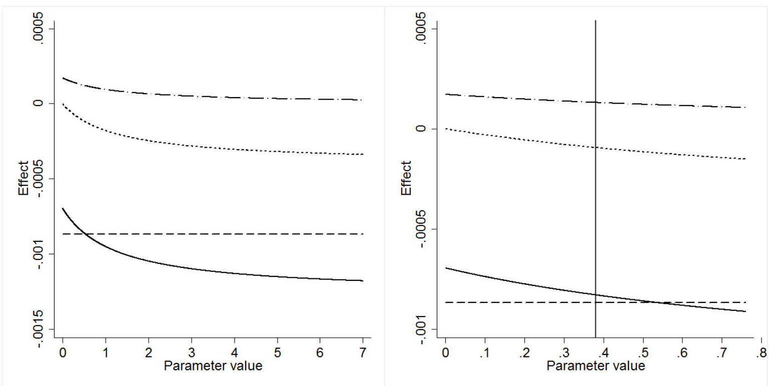
(a)



(b)



(c)



5 Further results and extensions

Based on theorem 4.1 as a benchmark, we now consider five interesting extensions. In section 5.1 we adjust the result to a setting in which the subsidy is funded by a levy on electricity consumption. In section 5.2 we consider the case in which electricity is also a factor of production in sector X. In section 5.3 we analyze the effects of increases in the technical efficiency of electricity usage. In section 5.4 we make explicit a set of assumptions underlying the virtual emission reductions (VER) statistic and show that it is a biased estimate of actual emission reductions in response to a FIT raise. Finally, we comment on the possibility of cap adjustments in section 5.5.

5.1 What if the FIT is funded by a levy on electricity?

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. As outlined in section 2, this is the case for the German *EEG-Umlage*, but also for the FIT schemes in the UK, Ireland, or Australia, for instance. 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 households' substitution condition. The following result replaces lemma 4.6.

Lemma 5.1. *Let ς be the households' elasticity of substitution between consumption goods X and Y, and ψ_D and ψ_C the incomes earned in sub-sectors Y_D and Y_C, respectively, as fractions of total incomes earned in the sector Y (such that $\psi_D + \psi_C = 1$). Then $\hat{X} - \hat{Y} = \varsigma(\psi_D \hat{p}_Y + \psi_C \hat{t})$.*

Proof. Appendix A.10. □

The first-order difference to a setting with lump-sum tax is intuitive from what we know about the structure of the leakage effect. An increase of the FIT will increase the surcharge s, since t increases and p_Y decreases. This alone causes a direct incentive for consumers to substitute away from electricity into X: we call this *direct terms-of-trade effect* (DTTE). Alone, the DTTE causes a growth in emissions because it raises production and hence emissions in sector 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 4.8 (the permit price adjustment is negatively proportional to the FIT variation) still holds in essence, but we need to recognize that the financing mode does also affect the size of the permit price adjustment to a variation of the FIT, such that the indirect effects (ITTE and IARE) are not identical in the two settings. We denote the adjustment parameter $\tilde{\gamma}$ to indicate that it is different from γ, but note that $\tilde{\gamma}$ has similar properties to the ones stated in lemma 4.8. Important for the present purposes is the following

Lemma 5.2. *$\tilde{\gamma} > \gamma$, and the difference $\tilde{\gamma} - \gamma$ is increasing in ψ_C.*

Proof. Appendix A.11. □

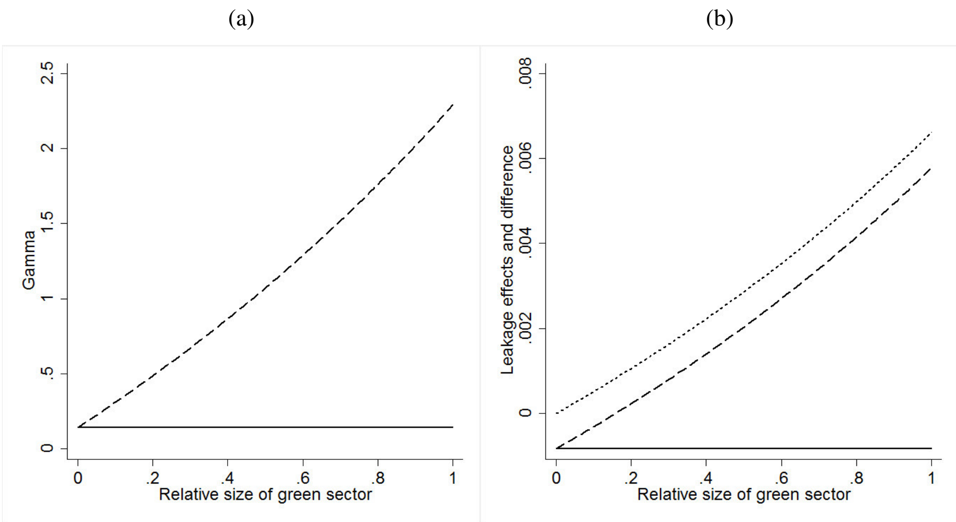
This means that the permit price adjustment to a given change of the FIT is unambiguously larger if the FIT is financed by a levy compared to the baseline case in which it is financed by a lump-sum tax. This is the case because raising the FIT directly increases the electricity price through the levy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

Analogous to the previous section we denote the elasticity of sector X's emissions with respect to the FIT that is funded by a levy on consumption of good Y by $\tilde{\Lambda}$ (i.e. $\hat{E}_X = \tilde{\Lambda}\hat{t}$) such that by lemma 4.1 $\hat{E} = \phi\tilde{\Lambda}\hat{t}$. The following result is the analogue to theorem 4.1 with tax-funding replaced by levy-funding, where a tilde above a variable indicates that it generally differs from the baseline setting with a lump-sum tax.

Theorem 5.1. *If a FIT funded by a levy on electricity is raised by $\hat{t}$, emissions will increase only if incomes earned in sector Y_C exceed a certain threshold, otherwise emissions will decrease ($\tilde{\Lambda} \gtreqless 0$, with $\Lambda \geq 0$ if and only if $\psi_C \geq \bar{\psi}_C$). The effect $\tilde{\Lambda}$ is a cumulative compound of*

- *a direct abatement resource effect Λ_{DARE} that decreases emissions ($\Lambda_{\text{DARE}} \leq 0$) and is identical under tax and levy funding,*
- *an indirect abatement resource effect $\tilde{\Lambda}_{\text{IARE}}$ that increases emissions ($\tilde{\Lambda}_{\text{IARE}} \geq 0$) , and is larger in absolute size under levy funding than under tax funding ($\tilde{\Lambda}_{\text{IARE}} > \Lambda_{\text{IARE}}$),*
- *an indirect terms-of-trade effect $\tilde{\Lambda}_{\text{ITTE}}$ that decreases emissions ($\tilde{\Lambda}_{\text{ITTE}} \leq 0$), and is larger in absolute size under levy funding than under tax funding ($\tilde{\Lambda}_{\text{ITTE}} < \Lambda_{\text{ITTE}}$),*
- *a direct terms-of-trade effect Λ_{DTTE} that increases emissions ($\Lambda_{\text{DTTE}} \geq 0$ with equality if and only if $\varsigma = 0$), and is present only under levy funding.*

Figure 3: Differences between levy- and tax-funding. Panel (a) shows γ (solid) and $\tilde{\gamma}$ (dashed) as functions of ψ_C, panel (b) Λ (solid), $\tilde{\Lambda}$ (dashed), and the difference $\tilde{\Lambda} - \Lambda$ (dotted) as a functions of ψ_C.



Furthermore, a change of the FIT always produces more emissions under levy funding than under tax funding ($\tilde{\Lambda} > \Lambda$), and the difference $\tilde{\Lambda} - \Lambda$ is increasing in ψ_C, the share of incomes earned in sector Y_C.

Proof. Appendix A.12. □

There are similarities and differences between Λ and $\tilde{\Lambda}$. First, the DARE is entirely unaffected by the funding-mode, which is rather intuitive: for green electricity producers, it does not matter where a given 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 5.2).

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 households' preferences as captured by the elasticity of substitution ς: If the two final goods are not substitutable at all ($\varsigma = 0$), the effect vanishes; conversely, the DTTE increases in the degree of substitutability. Recalling identity 4.3.1, we can say equivalently that the size of the DTTE is increasing in both the share of income spent on electricity and the price elasticity of electricity demand.

The DTTE is critical in understanding the differential effects of a FIT variation under the two funding modes. Because under levy-funding a raise of the FIT directly increases the electricity price through the surcharge and induces consumers to substitute away from Y into X, the levy-funded FIT is unambiguously less effective in curbing emissions than the tax-funded FIT. Furthermore, this shortfall is increasing with the share of income earned in the green electricity sector, as illustrated in figure 3, using the parameter values from the previous section. This is because a high income earned in the green electricity sector, either because the sector 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 sector at all (i.e. $\sigma_{YC} = 0$). In this case, the FIT is just a transfer of income and the DARE will be zero. However, since the electricity price is raised through the levy, consumers substitute away from Y into X, raising emissions. If the consumers' elasticity of substitution is high or incomes earned in the green electricity sector are sizable (or both), then this effect can be sufficiently large to raise emissions beyond the *ex ante* level. Using the parameter values from above, figure 3b shows that this happens already at around $\bar{\psi}_C = 0.2$, that is, when incomes earned in the green electricity sector are around 20 percent as a fraction of total incomes earned in electricity production. According to the data from the US Energy Information Administration (EIA) that we used above, we already had a worldwide share of electricity produced from renewable sources of around 19 percent (15 percent in the EU, 9 percent in the US, and 19 percent across the OECD) in 2004, and this share increased to almost 21 percent by 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 approaching or already beyond the threshold in many jurisdictions. Returning to the German example of section 2, we have $\psi_C = 0.549$.[26]

Wrapping up, tax-funding always performs better in terms of emissions than levy-funding. In addition, the advantage is increasing in the relative size (as defined in terms of income earned) of the green electricity sector. Importantly, raising the FIT under levy-funding can actually *increase* emissions–a «green paradox» in the way defined above.

If environmental performance of the FIT scheme is a policy objective, these results have important practical implications. First, governments planning the introduction of a FIT scheme are well advised to fund it 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 cap-and-trade scheme.[27] Second, governments already having a levy-financed FIT scheme in place, such as the UK, Germany or Australia, are well advised to switch if they want to avoid causing an increase in emissions: the larger the green electricity sector already has grown, the more a switch improves the environmental performance of the scheme.

5.2 Electricity as an input

In practice, electricity is not only demanded by households as a consumption good (or household production input) but also by industries as a factor or production. A general way to model this setting is to adjust the production function in sector X to $X(L_X, E_X, Y_X)$, where Y_X is the quantity of electricity demanded by firms in sector X as an input. We analyze this setting in appendix C. Here, we focus on a more specific case in which there is, besides the conventional technology $X_D(L_X, E_X)$, a (decreasing returns) conversion technology $X_C(Y_X)$ that transforms electricity into output X, such that aggregate output of X is given by $X_C + X_D$. We do so for two reasons: First, the analysis of this case is simpler than the general setting while producing very similar results. Second, the specific setting has salient applications and interesting practical implications.

One interesting example with mounting practical importance is electrically powered vehicles such as plug-in hybrids or all-electric cars. A number of governments have set explicit target quotas and respective subsidy schemes to support the diffusion of such vehicles. For example, most EU members have either exemptions from motor vehicle taxes or related charges, income tax deductions, or direct subsidies on purchases,[28] and the US government offers federal tax credit of up to \$7,500 with the purchase of an electric car for personal use since 2010. Indeed, a number of car manufacturers increasingly offer such drive concepts all across their fleets. In the context of this example, X is to be interpreted as mobility, X_D as mobility produced by fossil fuel powered vehicles, and X_C as mobility by electricity powered vehicles. Further examples are power-to-gas (P2G) or power-to-heat (P2H) technologies. P2G technologies transform electrical power into hydrogen (or in a further step into methane) by application of water electrolysis, that can be used in fuel cells or gas engines. Likewise, P2H technologies transform electricity into heat, that can be used in hot water supply or to heat buildings. Policies supporting the diffusion of such fuel-to-electricity substituting technologies outside the energy sector are frequently introduced as complements to policies promoting renewable sources of electricity.

We investigate two effects in this section: First, we analyze the effect on emissions of a direct variation of X_C, leaving the FIT constant. This is meant to represent the policies just outlined above. Second, we analyze how the presence of a conversion technology moderates the leakage effect Λ of a FIT variation.

With respect to the first step, raising X_C has two intuitive effects of opposite sign: First, at constant prices output produced with the conversion technology replaces output produced with the conventional technology, decreasing emissions *ceteris paribus*. We call this *replacement effect*, denoted Υ_{RE}. This direct and fairly intuitive effect is what policy-makers presumably aim at with programs supporting electric cars, P2G or P2H.

Second, raising X_C increases demand for electricity, that is met by the marginal electricity producer; with the FIT constant this is a conventional one. This leads to an increase of the permit and electricity prices, such that consumers substitute away from electricity into X, raising emissions *ceteris paribus*. We call this *price effect*, denoted Υ_{PE}.

Formally, let $\hat{X}_C$ be an exogenously induced proportional change of output produced with the conversion technology, β_C the *ex ante* share of output X produced with technology X_C, and Υ the elasticity of sector X's emissions with respect to this variation, that is, $\hat{E}_X = \Upsilon \hat{X}_C$ and $\hat{E} = \phi \Upsilon \hat{X}_C$.

Theorem 5.2. *If output produced with the conversion technology is raised by $\hat{X}_C$, emissions will decrease ($\Upsilon \leq 0$, with equality if and only if $\sigma_{YD} = 0$), and the decline in absolute value is increasing (Υ is decreasing and convex) in σ_{YD}, and decreasing (Υ is increasing and concave) in β_C and ς. The effect Υ is decomposable into*

- *a replacement effect Υ_{RE} that decreases emissions ($\Upsilon_{\text{RE}} < 0$), and*
- *a price effect Υ_{PE} that increases emissions ($\Upsilon_{\text{PE}} \geq 0$ with equality if and only if $\varsigma = 0$).*

Proof. Appendix A.13. □

The price effect dampens the emission reducing quantity effect, but always remains of second order (since it is a movement along the electricity demand curve), such that the total effect is never positive. This has two practical implications. First, the price effect rolls back some portion of the initial (out-of-equilibrium) emission reduction stemming from the replacement of fossil fuel powered technology by electricity powered one. This feedback effect through the electricity price has to be taken into account when estimating the effect on emissions of a particular subsidy scheme, otherwise the estimates will be biased upwards (estimates are too large compared to the true reduction).

Second, however, the electricity price will never increase so strongly that the initial demand impulse is reversed, such that the price effect can never be greater than the replacement effect. Hence, the qualitative working hypothesis that policies supporting conversion technologies reduce emissions is supported by the analysis.

We now turn to our second objective: How does the presence of a conversion technology moderate the leakage effect Λ of a FIT variation? The intuition is quite simple: electricity demand in sector X responds virtually in the same way to changes of the electricity price as the households' demand. Since raising the FIT induces a decline of the electricity price, demand for electricity to be converted into X increases, such that there is an additional component in the ITTE. *En passant* the FIT raise has the effect of expanding the conversion sector.

Formally, if we replace $\hat{X}$ by $\hat{X}_C$ in lemma 4.2, and by $\hat{X}_D$ in lemma 4.3 (and corollary 4.1), then lemmas 4.1 through 4.7 still hold. On top of this, we need to add a result that describes behavior of the conversion sector:

Lemma 5.3. *Let σ_{XC} denote the elasticity of electricity demand with respect to real factor cost, and θ_{XC} the elasticity of output with respect to electricity input in the conversion sector. Then $\hat{Y}_X = -\sigma_{XC}\hat{p}_Y$, and $\hat{X}_C = -\theta_{XC}\sigma_{XC}\hat{p}_Y$ with $\theta_{XC} < 1$.*

Proof. Appendix A.14. □

Hence, the conversion sector demands less (respectively more) electricity and produces less (respectively more) output if the electricity price increases (respectively decreases).

Lemma 4.8 still holds in essence, but we need to recognize that the permit price adjustment will be different in size compared to the benchmark case, because of the additional demand for electricity stemming from sector X. We denote the adjustment parameter $\mathring{\gamma}$ to indicate that it is different from γ, but note that $\mathring{\gamma}$ has essentially the same properties to the ones stated in lemma 4.8. Important for the present purposes is the following

Lemma 5.4. *$\mathring{\gamma} < \gamma$, and the difference $\gamma - \mathring{\gamma}$ is strictly increasing in β_C.*

Proof. Appendix A.15. □

Figure 4a illustrates this result using the parameter values from the previous section.

We are now ready to adjust theorem 4.1 to the setting considered in this section, with a circle above a variable indicating that it differs from the baseline setting studied in the previous section. Specifically, let $\mathring{\Lambda}$ denote the elasticity of sector X's emissions with respect to the FIT, that is, $\hat{E}_X = \mathring{\Lambda}\hat{t}$ and (by lemma 4.1) $\hat{E} = \phi\mathring{\Lambda}\hat{t}$, when there is an additional technology in sector X that uses Y as input.

Theorem 5.3. *If the FIT is raised by $\hat{t}$, emissions will decrease ($\mathring{\Lambda} \leq 0$ with equality if and only if $\sigma_{YC} = 0$). The effect $\mathring{\Lambda}$ is decomposable into*

- *a direct abatement resource effect $\mathring{\Lambda}_{\text{DARE}}$ that decreases emissions ($\mathring{\Lambda}_{\text{DARE}} \leq 0$ with equality if and only if $\sigma_{YC} = 0$), and is larger in absolute size if there is a conversion technology than if there is no such technology ($\mathring{\Lambda}_{\text{DARE}} \leq \Lambda_{\text{DARE}}$ with equality if and only if $\sigma_{YC} = 0$),*

- *an indirect abatement resource effect $\mathring{\Lambda}_{\text{IARE}}$ that increases emissions ($\mathring{\Lambda}_{\text{IARE}} \geq 0$ with equality if and only if $\sigma_{YC} = 0$ or $\sigma_{YD} = 0$ or both), and is smaller in absolute size if there is a conversion technology than if there is no such technology ($\mathring{\Lambda}_{\text{IARE}} \leq \Lambda_{\text{IARE}}$ with equality if and only if $\sigma_{YC} = 0$ or $\sigma_{YD} = 0$ or both),*

- *a consumption-induced indirect terms-of-trade effect $\mathring{\Lambda}^H_{\text{ITTE}}$ that decreases emissions ($\mathring{\Lambda}^H_{\text{ITTE}} \leq 0$ with equality if and only if $\sigma_{YC} = 0$ or $\varsigma = 0$ or both), and is smaller in absolute size if there is a conversion technology than if there is no such technology ($\mathring{\Lambda}^H_{\text{ITTE}} \geq \Lambda_{\text{ITTE}}$ with equality if and only if $\sigma_{YC} = 0$ or $\varsigma = 0$ or both), and*

- *a production-induced indirect terms-of-trade effect Λ^X_{ITTE} that decreases emissions ($\Lambda^X_{\text{ITTE}} \leq 0$ with equality if and only if $\sigma_{XC} = 0$),*

- $\mathring{\Lambda} \leq 0$ *with equality if and only if* $\sigma_{YC} = 0$, *and* $\Lambda \geq \mathring{\Lambda}$ *with the difference* $\Lambda - \mathring{\Lambda}$ *being increasing in* β_C.

Furthermore, a change of the FIT always produces less emissions if there is a conversion technology than if there is no such technology ($\Lambda \geq \mathring{\Lambda}$)*, and the difference* $\Lambda - \mathring{\Lambda}$ *is increasing in* β_C*, the the ex ante share of output X produced with technology* X_C.

Proof. Appendix A.16. □

This result is illustrated in figure 4, using the parameter values from the previous section, setting $\theta_{XC} = \theta_{YC} = 0.853$, and drawing on the evidence on the industrial electricity demand elasticities to set $\sigma_{XC} = 0.4$ (Espey & Espey, 2004; Simmons-Süer et al., 2011). Given this calibration, figure 4a shows that $\mathring{\gamma}$ is monotonically (albeit weakly in magnitude) decreasing in the relative size of the conversion sector (parameter β_C), such that $\mathring{\gamma} < \gamma$ for all $\beta_C > 0$. Thus, the larger the conversion sector, the smaller the permit price adjustment for a given FIT variation, and hence the closer the indirect effects IARE and household-ITTE are to zero. But the larger the conversion sector, the more distant the DARE and particularly the conversion-ITTE are from zero. For this reason, $\mathring{\Lambda}$ is monotonically decreasing and hence the difference $\Lambda - \mathring{\Lambda}$ monotonically increasing in the size of the conversion sector, as illustrated in figures 4b and 4c. Hence, a given FIT raise always performs better in terms of emissions reductions if electricity is an input in sector X compared to a setting in which electricity is only a consumption good. Furthermore, the size of this advantage is increasing in the size of the conversion sector.

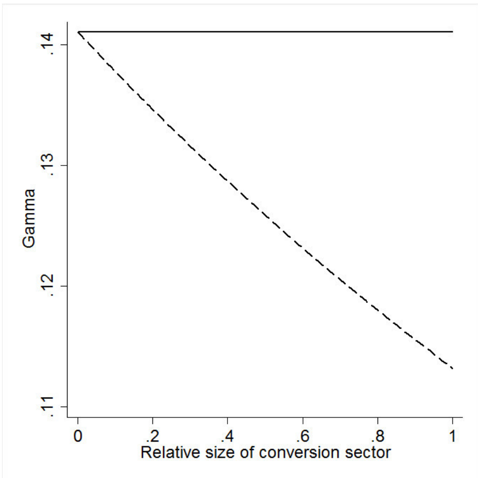
Summing up, the analysis in this subsection shows that policies supporting technologies that use electricity instead of fossil fuels outside the electricity sector, and policies supporting renewables in electricity generation are complementary in three respects: First, the former policies reduce GHG emissions directly. Second, they reinforce the emission reducing effect of the FIT scheme. Third, which is an interesting result on its own, the conversion sector grows (respectively declines) in response of a raise (respectively cut) of the FIT. This means that the FIT has wider technology adoption effects beyond the electricity sector: it does not only incentivize investment in green electricity generation technologies but also in, for example, electric cars, power-to-gas or power-to-heat facilities.

5.3 The role of technical efficiency in electricity consumption

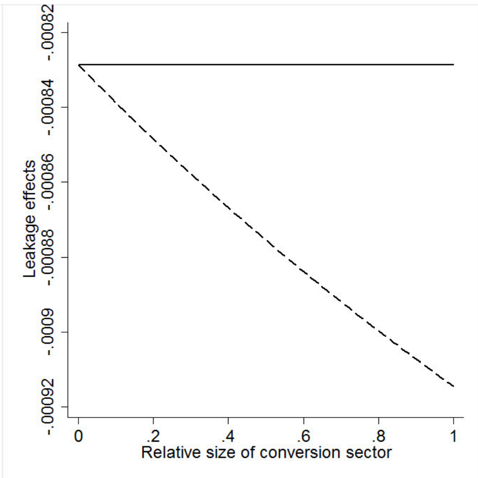
Besides regulatory instruments targeted at the generation of electricity, many jurisdictions also have various measures aimed at improving the efficiency of distribution and final consumption.[29] For example, in October 2012 the EU adopted the so-called Energy Efficiency Directive (2012/27/EU), comprising a bundle of measures for the promotion of energy efficiency within the Union in order to ensure the achievement of the Union's 2020 20-percent headline target on energy efficiency. Its aim is to remove barriers in the energy market and promote efficiency

Figure 4: Differences between the baseline setting and a setting in which electricity is used as an input in sector X. Panel (a) shows γ (solid) and $\mathring{\gamma}$ (dashed) as functions of β_C, panel (b) Λ (solid) and $\mathring{\Lambda}$(dashed) as a functions of β_C, and panel (c) the difference $\Lambda - \mathring{\Lambda}$ as a function of β_C.

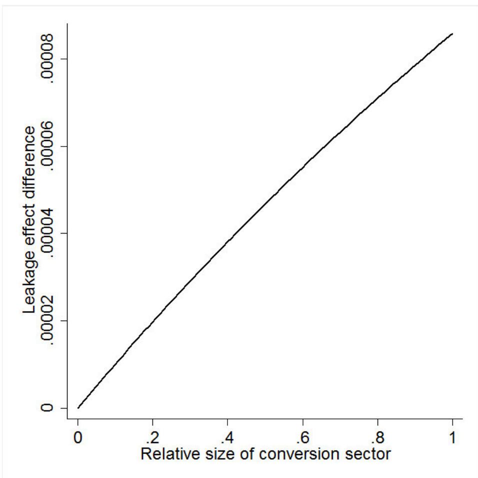
(a)



(b)



(c)



all along the energy chain, not only in the supply (transformation and distribution) but also the final consumption of energy. Primary instruments are information devices, such as labels and performance certificates, on the one hand, and compulsory efficiency standards on the other.[30] Covered are *inter alia* electric appliances, air-conditioning, consumer electronics and communication devices (amending Directive 2006/32/EC on energy end-use efficiency and energy services), as well as buildings (amending Directive 2010/31/EU on the energy performance of buildings). Many member states have further reaching national programs, such as the Green Deal in the UK, the Danish Energy Agreement, or Sweden's Climate and Energy Policy Framework. Similar measures have been adopted in the United States under major policy frameworks, such as the 2013 US Climate Action Plan, and more specific programs such as the GreenChill Advanced Refrigeration Partnership or the Assisted Housing Stability and Energy and Green Retrofit Investments Program.

We investigate two related questions with respect to such policies: First, how do measures to raise technical efficiency impact on GHG emissions alone, i.e. with the FIT fixed? Second, how do such measures interact with the FIT scheme?

We begin by being somewhat more specific about the consumption of good Y: we assume households do not consume electricity directly but services produced with electricity. Good Y is therefore a household production input, whose marginal product depends on the household production technology. Raising technical efficiency thus amounts to a raise of marginal utility derived from electricity, and accordingly a decline of the marginal rate of substitution. At constant prices households will respond by substituting away from X into Y. We model this parsimoniously by adjusting the substitution condition in lemma 4.6 to

$$\hat{X} - \hat{Y} = \varsigma \hat{p}_Y - \hat{e}$$

where $\hat{e}$ represents the growth of technical efficiency. We now can address both questions simultaneously:

Theorem 5.4. *Let both the FIT and technical efficiency in using good Y be exogenously variable, then the change of sector X's emissions are*

$$\hat{E}_X = \Lambda \hat{t} + \underbrace{(\Phi_{\text{EE}} + \Phi_{\text{PE}})}_{\Phi} \hat{e}$$

whereas $\Phi_{\text{EE}} < 0$, $\Phi_{\text{PE}} \geq 0$ *with equality if and only if* $\varsigma = 0$, *and* $\Phi < 0$.

Proof. Appendix A.17. □

With respect to our first question emissions unambiguously decline ($\hat{E} = \phi \Phi \hat{e} < 0$) in response to an increase in technical efficiency ($\hat{e} > 0$) with the FIT fixed ($\hat{t} = 0$). The effect can be decomposed into two components of opposite sign: First, raising technical efficiency induces households to substitute from X into Y. All else equal, this tends to expand electricity production and curtail production of good X, and hence emissions. We call this component *efficiency effect*, denoted Φ_{EE}. However, increased demand for electricity is met by the marginal producers, that are conventional ones, raising the permit and electricity prices. This creates a countervailing incentive for households to substitute back from Y into X, raising emissions. We call this *price effect*, denoted Φ_{PE}. The size of this effect depends on the elasticity of substitution, but does never completely eat up the efficiency effect (because it is a movement along the electricity demand curve), such that the total effect is always negative.

Now, if only the FIT is raised ($\hat{t} > 0$) with technical efficiency constant ($\hat{e} = 0$), we are apparently back in the baseline setting of section 4. Since both Λ and Φ are negative, raising the FIT and raising technical efficiency supplement each other in reducing emissions. This also works backwards, suggesting a notable practical implication: A recurring issue in discourses about FITs are phase-out scenarios– our result suggests that a phase-out of the FIT scheme (which raises emissions) can in principle be compensated by simultaneous stimuli of technical efficiency.

5.4 On the bias of virtual emission reduction estimates

Governments using FITs as part of their climate policy portfolio often gauge the impact of the intervention by a «virtual emission reductions» (VER) statistic. The virtual emission reduction approach essentially assumes that each kWh of green electricity replaces one kWh of conventional electricity, and the VER is the counterfactual quantity of emissions that would have been generated if the the additional amount of green electricity were supplied by conventional means (AGEE-Stat, 2013; 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. To see why, we develop an exact definition of VER in terms of our model. Suppose green electricity output increases by dY_C^{shock}, or equivalently in relative terms by $\hat{Y}_C^{\text{shock}}$. Emissions per unit of output in conventional electricity production are E_Y/Y_D, such that the VER associated with the shock are

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

For a raise $\hat{t}$ of the FIT, we have $\hat{Y}_C^{\text{shock}} = \theta_{YC} \sigma_{YC} \hat{t}$, and hence

$$\mathrm{VER}(\hat{t}) = \frac{Y_C E_Y \theta_{YC} \sigma_{YC}}{Y_D} \hat{t}$$

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

$$\widehat{\text{VER}}(\hat{t}) = \frac{Y_C E_Y \theta_{YC} \sigma_{YC}}{Y_D E} \hat{t} = (1-\phi) \frac{\alpha_C}{\alpha_D} \theta_{YC} \sigma_{YC} \hat{t}$$

Using the parameter values from the previous section, a ten percent raise of the FIT yields a virtual emissions reduction of 0.23 percent.

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 sector 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 sector. Specifically, if the electricity sector is subject to a cap-and-trade system, then emissions produced under the system are not reduced at all, but the VER statistic indicates a reduction.[31]

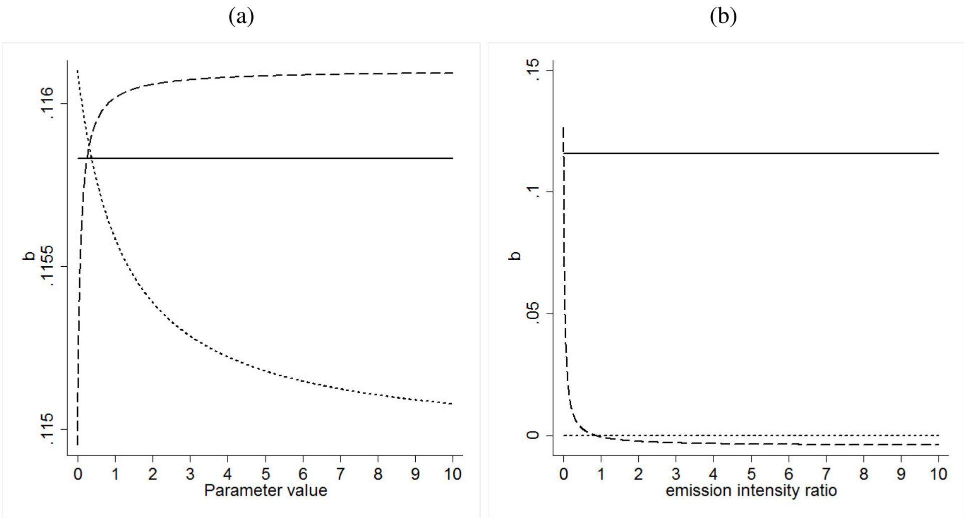
Third, the VER statistic ignores inter-sectoral leakage effects. Indeed, we showed above that such effects exist. A natural question is how the VER statistic performs relative to the true effect identified above, that accounts for those issues. We find the following:

Theorem 5.5. *The VER statistic is generally biased relative to the true effect of a variation of the FIT. Specifically, define B as the difference between the VER and the actual emission reduction, such that $B > 0$ indicates an overestimation and $B < 0$ an underestimation. Then $B = b\sigma_{YC}\hat{t}$, whereas $b \gtreqless 0$ and increasing and concave in σ_{YD}, decreasing and convex in ς, decreasing in the emission intensity in sector X, and increasing in the emission intensity in sector Y.*

Proof. Appendix A.18. □

Using the parameter values from above, figure 3b 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 $b = 0.1158$ (depicted by the solid lines in the figure) and $B = 0.0232\hat{t}$. The dashed and dotted curves in figure 5a show how b depends on the two elasticity parameters σ_{YD} and ς on a large domain from zero to ten. Note that their effects on b are very small. The dashed curve in figure 5b shows how b depends on the ratio of the emission intensities in sectors X and Y, respectively. b gets negative at a ratio of about 0.88, which means that the emission intensity in the non-capped sector X is almost as high as in the capped (electricity) sector Y. Since any real-world cap-and-trade system 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).

Figure 5: Numerical illustrations of the bias parameter 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_{YD} (dashed) and ς (dotted). Panel (b) shows the value of b as a function of the emission intensity ratio.



5.5 What if the cap is adjusted?

To start with, adjusting the cap is exactly the type of intervention that Baylis et al. (2013, 2014) consider: relaxing the cap directly decreases the permit price, tightening the cap increases it. Thus, a cap adjustment just overlays the FIT-induced leakage effects with the cap-induced leakage effects ARE and TTE identified by Baylis et al. (2013, 2014) and replicated in appendix B. Tightening the cap induces a negative ARE and a positive TTE, relaxing the cap results in a positive ARE and a negative 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. For example, if the FIT is increased by some amount such that the ITTE tends to decrease emissions and the IARE tends to increase them, tightening the cap such that the permit price increases back to its *ex ante* level neutralizes the two effects by a ITTE and a IARE of the same absolute size and opposite sign, leaving the DARE which is always negative (decreases emissions). 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); if it is the other way around, tightening the cap will carry an opportunity cost in the form of a roll-back of a negative net indirect leakage effect.

6 Conclusion

In the present paper we inspected the widely held tenet that renewable energy promotion policies have no effect on total greenhouse gas (GHG) emissions if the power sector is subject to a cap-and-trade scheme. By means of a parsimonious general equilibrium model designed to understand the impact (on total emissions) of a feed-in tariff overlapping a cap-and-trade scheme that covers only one of the two sectors, we find that, contrary to this hypothesis, that such variations *do* have a net impact on GHG emissions through inter-sectoral leakage effects.

Specifically, we show the following. First, if the subsidy scheme is tax-funded, then raising the FIT unambiguously reduces emissions. The principal reason is that the growing green electricity sector bids away factors of production from industries outside the cap-and-trade scheme, that in turn reduce output and emissions. Second-order effects due to (ii) households substituting into electricity because of falling prices and (iii) conventional electricity producers increasing their carbon intensity perturb the first-order effect but never reverse its direction.

Second, a levy-funded FIT always performs worse in terms of emissions than a tax-funded one, and the disadvantage is increasing in the relative size of the green electricity sector. This is because the levy creates a direct incentive for consumers to substitute *into* goods that are produced outside the cap-and-trade scheme. If this effect is sufficiently large, then raising the FIT can *increase* emissions under a levy-funded scheme. Thus, governments are well advised to fund a FIT scheme from general tax revenues instead of a levy on electricity consumption, in particular if the green electricity sector has grown beyond negligible size.

Third, policies supporting technologies that use electricity instead of fossil fuels outside the cap-and-trade system, and policies supporting renewables inside the system are complementary: Not only do the former policies reduce GHG emissions directly, but they reinforce the emission reducing effect of a FIT. Furthermore, the FIT has wider technology adoption effects beyond the electricity sector: it does not only incentivize investment in green electricity generation technologies but also in, for example, electric cars, power-to-gas or power-to-heat facilities.

Fourth, policies supporting the technical efficiency of electricity consumption supplement the FIT scheme in reducing emissions, because they induce a direct incentive for consumers to substitute into electricity, and hence away from goods produced outside the cap-and-trade system.

Fifth, we make explicit a set of assumptions underlying the virtual emission reductions (VER) statistic, a commonly used measure to gauge the impact of renewable energy policies, and show that it is a biased estimate of actual emission reductions in response to a FIT raise, because it (i) assumes that aggregate electricity output remains constant, and ignores (ii) the cap and (iii) leakage effects.

Finally, we comment on the possibility that the cap may be adjusted after a given FIT variation. We argue 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. We leave the rigorous investigation of such long-term feedback dynamics between FIT variations and cap adjustments for future research.

Notes

[1]For example, the EU Renewables Directive (2009/28/EC) aims at a share of 20 percent of the EU energy consumption to be supplied from renewables in 2020, and in 2014 the target of 27 percent renewables in 2030 was agreed upon. Similar national (e.g. the 2005 Energy Policy Act, the Wind Powering America Initiative, or the the Solar America Initiative) and state level programs (in particular Renewable Electricity Standards reaching from 10 percent in Michigan, South Dakota, Vermont, and Wisconsin to 40 percent in Hawaii) are in place in the United States.

[2]The cost of Germany's *Energiewende* (its transformation to a renewables-based electricity system) is around USD 21 billion per year–China, the United States and the European Union spend together around USD 140 billion per year on subsidizing renewable energy. In constrast, other instruments, such as helping developing countries phase out CFCs under the Montreal protocol (USD 2.4 billion between 1990-2010) or the Amazon Fund that fights deforestation in Brazil (USD 760 Million over 11 years), The The Economist (2014) pointed out, induced impressive GHG emissions reductions at considerably lower cost.

[3]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.

[4]See e.g. Babiker (2005), Eichner & Pethig (2011), Burniaux & Martins (2012), and Martin et al. (2014).

[5]In this this stream of literature, however, the focus is on changes in the cap itself rather than on the effect of overlapping instruments.

[6]Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont

[7]Before the Electricity Feed-In Act there was one FIT introduced in the United States by the Public Utility Regulatory Policies Act (PURPA), a part of the 1978 National Energy Act (NEA).

[8]Consumers have to pay VAT on the levy, which adds a further 19 percent or 1.19 cents per kWh.

[9]According to estimates of the International Energy Agency (IEA, 2013, p. 11), electricity and heating accounts for about 44 percent of global carbon dioxide emissions in 2011, and transportation for about 22 percent. The rest is emitted in the industrial (21 percent), residential (6 percent), and other sectors (8 percent) including agriculture. In addition, there has been a strongly increasing trend between 1990 and 2011: emissions from electricity and heating increased by around 70 percent during that period, emissions from transportation by around 60 percent.

[10]Assuming Betrand-competition, two firms in each sector are enough.

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

[12]The latter assumption assures that factor demand is not infinite for a price of zero, which is relevant because we allow for a zero carbon price below.

[13]The case where $t < p^Y$ is of no theoretical and empirical relevance because the FIT would not be binding. Green electricity producers would fare better by selling at the market price instead of the tariff.

[14]Since labor-capital is numeraire, it holds that $w = 1$.

[15]Note that lemmas 4.1 through 4.3, and 4.5 through 4.7 hold for any exogenous shock with the cap binding.

[16]Of course, the result does *not* hold if the cap is not fixed. This premise is plausible in a short-mid-term perspective but questionable in a long-term view. We further comment on this issue below.

[17]But of course lemma 4.1 also holds if the policy targets sector X or a new sector that transforms Y into X. We consider such a case in the next section.

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

[19]This result continues to hold qualitatively if labor-capital supply is not perfectly inelastic, as long as it is not perfectly elastic.

[20]Note that if the FIT is reduced, the converse happens.

[21]Baylis et al. (2014) adopt the data on labor, capital, and output from Elliott et al. (2010), and supplement it by hypothetical payments for carbon emissions based on actual emission data for that year and a price of USD 15 per ton of emissions.

[22]Allocating nuclear power to one of the two electricity sub-sectors is clearly an issue. On the one hand, it is virtually carbon emission free. On the other hand, it is usually not subsidized by FITs. Excluding nuclear power from the «green» electricity sector, we have $\alpha_C = 0.150$ for the EU, $\alpha_C = 0.092$ for the US, $\alpha_C = 0.161$ for the OECD, and $\alpha_C = 0.188$ for the world. Including nuclear power, we get $\alpha_C = 0.462$ for the EU, $\alpha_C = 0.291$ for the US, $\alpha_C = 0.388$ for the OECD, and $\alpha_C = 0.345$ for the world. Since our focus in on FITs, we allocate nuclear power to the conventional electricity sector.

[23]Of course, the elasticity depends on the time frame considered, and specifically whether the elasticity of capacity or the elasticity of output with a given capacity is considered.

[24]The empirical literature on electricity demand is vast. Espey & Espey (2004) did a meta-analysis of over 126 individual studies published in the period between 1971 and 2000 and report average price and income elasticities of electricity demand for both the short and the long term. They find a mean households' price elasticity of -0.35 (median -0.28) in the short run and -0.85 (median -0.81) in the long run. Evaluating the studies published after 2000 against this benchmark, Simmons-Süer et al. (2011) observe the application of more sophisticated statistical methods and more extensive robustness checking in this period. Overall the estimates are somewhat lower: Here the mean households' price elasticity is -0.21 (median -0.22) in the short run and -0.58 (median -0.55) in the long run. In sum, in a short-to-mid-run view corresponding to our model, a value of around -0.4 appears as a sensible choice.

[25]The indirect effects are so small because of the very small value of σ_{YC}: the smaller the elasticity σ_{YC}, the smaller the carbon price adjustments.

[26]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 percent in 2011, yielding $\psi_C = 0.549$.

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

[28]For example, in the UK all electric vehicles are exempt from annual motor vehicle tax, and buyers of electric vehicles (incl. rechargeable hybrid cars) are entitled to 25 per cent reduction off list price of the vehicle, with maximum reduction of €5,900. In Germany, electric vehicles are exempt from annual motor vehicle tax for five years, starting from the date of first registration. In Spain, buyers of an electric vehicle receive a subsidy up to 20 percent off the vehicle sale price (max. €6,000).

[29]For a steadily updated overview, see the Energy Efficiency Policies and Measures Database of the International Energy Agency (IEA).

[30]The phase-out of incandescent light bulbs also falls under the latter category. Similar bans are in place, for example, in the US, Canada, Australia and China.

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

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A Proofs

A.1 Proof of lemma 4.1

By construction $E = E_X + E_Y$. Totally differentiating, dividing both sides by E, expanding the first term on the right-hand side by $\frac{E_X}{E_X}$ and the second term by $\frac{E_Y}{E_Y}$ yields

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

Defining $\phi := E_X/E$ and recognizing $E = E_X + E_Y$, the equation can be equivalently expressed by

$$\hat{E} = \phi \hat{E}_X + (1-\phi)\hat{E}_Y \tag{A.1.1}$$

In equilibrium the permit market must clear, $E_Y = \bar{E}$. Totally differentiating this condition and dividing both sides by yields $\hat{E}_Y = 0$, such that equation A.1.1 reduces to

$$\hat{E} = \phi \hat{E}_X$$

A.2 Proof of lemma 4.2

In sector X, each firm demands an input bundle (L_X, E_X) and supplies output quantity X to maximize profit subject to the technology constraint, taking the price vector (p_X, w, τ) as given:

$$(L_X, E_X, X) \in \arg \max_{(\widetilde{L}_X, \widetilde{E}_X, \widetilde{X})} \mathscr{L}_X\left(\widetilde{L}_X, \widetilde{E}_X, \widetilde{X}\right)$$

where $\mathscr{L}_X(\cdot)$ is the Lagragian function

$$\mathscr{L}_X\left(\widetilde{L}_X, \widetilde{E}_X, \widetilde{X}\right) = p_X\tilde{X} - w\tilde{L}_X - \tau\tilde{E}_X + \lambda_X\left(\tilde{X} - X\left(\widetilde{L}_X, \widetilde{E}_X\right)\right)$$

and a tilde above a variable indicates a choice variable.

The first-order conditions of this program are

$$\begin{aligned}
\lambda_X &= -p_X \\
-\lambda_X \frac{\partial X(\cdot)}{\partial L_X} &= w \\
-\lambda_X \frac{\partial X(\cdot)}{\partial E_X} &= \tau \\
X &= X(L_X, E_X)
\end{aligned} \tag{A.2.1}$$

Totally differentiate the fourth FOC, and use the first three to get

$$dX = \frac{w}{p_X}dL_X + \frac{\tau}{p_X}dE_X$$

Divide both sides by X, and expand the right-hand side terms by $\frac{L_X}{L_X}$ and $\frac{E_X}{E_X}$, respectively, to obtain

$$\underbrace{\frac{dX}{X}}_{\hat{X}} = \underbrace{\frac{dL_X}{L_X}}_{\hat{L}_X} \frac{wL_X}{p_X X} + \underbrace{\frac{dE_X}{E_X}}_{\hat{E}_X} \frac{\tau E_X}{p_X X} \tag{A.2.2}$$

Consider the definition of scale elasticity

$$\theta_X := \underbrace{\frac{\partial X(\cdot)}{\partial L_X} \frac{L_X}{X}}_{\theta_{XL}} + \underbrace{\frac{\partial X(\cdot)}{\partial E_X} \frac{E_X}{X}}_{\theta_{XE}}$$

where θ_{XL} and θ_{XE} are the elasticities of output with respect to the individual factors. By the first-order conditions A.2.1 it holds in a profit maximum (and hence in equilibrium) that

$$\theta_{XL} = \frac{wL_X}{p_X X}$$
$$\theta_{XE} = \frac{\tau E_X}{p_X X} \tag{A.2.3}$$

i.e. the elasticity parameters are equal to the respective factor claims as shares of total revenues.

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

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

Using again the first-order conditions A.2.1 it follows

$$X(\cdot) = \frac{w}{p_X} L_X + \frac{\tau}{p_X} E_X \Leftrightarrow p_X X = wL_X + \tau E_X \tag{A.2.4}$$

that is, profits are zero. By the zero-profit condition A.2.4 we have $\theta_{XL} + \theta_{XE} = 1$ and thus by definition $\theta_X = 1$. Furthermore, by A.2.3 the elasticity parameters are also equal to the respective factor claims as shares of total costs.

Combining those results with A.2.2 yields

$$\underbrace{\frac{dX}{X}}_{\hat{X}} = \underbrace{\frac{dL_X}{L_X}}_{\hat{L}_X} \underbrace{\frac{wL_X}{p_X X}}_{\theta_{XL}} + \underbrace{\frac{dE_X}{E_X}}_{\hat{E}_X} \underbrace{\frac{\tau E_X}{p_X X}}_{\theta_{XE}} \tag{A.2.5}$$

Return to the first-order conditions A.2.1. Using the first three conditions, profit maximizing behavior of firms in sector X is characterized by

$$\underbrace{\frac{\frac{\partial X(\cdot)}{\partial L_X}}{\frac{\partial X(\cdot)}{\partial E_X}}}_{:=\rho_X} = \frac{w}{\tau} \tag{A.2.6}$$

where the left-hand side is the marginal rate of technical substitution and the right-hand side the input price ratio. Using the definition of the elasticity of technical substitution

$$\sigma_X := \frac{d\left(\frac{E_X}{L_X}\right)}{\frac{E_X}{L_X}} \left(\frac{d\rho_X}{\rho_X}\right)^{-1}$$

we can express the condition alternatively by

$$\frac{d\left(\frac{E_X}{L_X}\right)}{\frac{E_X}{L_X}} = \sigma_X \frac{d\left(\frac{w}{\tau}\right)}{\frac{w}{\tau}}$$

Transforming in growth rates yields

$$\underbrace{\frac{dE_X}{E_X}}_{\hat{E}_X} - \underbrace{\frac{dL_X}{L_X}}_{\hat{L}_X} = \sigma_X \left(\underbrace{\frac{dw}{w}}_{\hat{w}} - \underbrace{\frac{d\tau}{\tau}}_{\hat{\tau}}\right) \tag{A.2.7}$$

Since $\hat{w} = 0$ (since labor-capital is numeraire) and $\hat{\tau} = 0$ (by construction), this condition simplifies to

$$\hat{E}_X = \hat{L}_X \tag{A.2.8}$$

i.e. since the factor price ratio is constant, input quantities must change in equal proportion. Combining A.2.8 with A.2.5 yields $\hat{X} = \hat{E}_X$.

A.3 Proof of lemma 4.3

By lemma 4.2 we have $\hat{E}_X = \hat{X}$, and by condition A.2.8 we have $\hat{E}_X = \hat{L}_X$, such that the first part of the result immediately follows.

In equilibrium the labor-capital market must clear: $L_X + L_{YD} + L_{YC} = 1$. Totally differentiating and expanding each term on the left-hand side by $\frac{L_i}{L_i}$ yields

$$\underbrace{\frac{dL_X}{L_X}}_{\hat{L}_X} L_X + \underbrace{\frac{dL_{YD}}{L_{YD}}}_{\hat{L}_{YD}} L_{YD} + \underbrace{\frac{dL_{YC}}{L_{YC}}}_{\hat{L}_{YC}} L_{YC} = 0 \tag{A.3.1}$$

Rearranging yields the the second part of the result.

A.4 Proof of lemma 4.4

Each green electricity producer demands input quantity L_{YC} and supplies output quantity Y_C to maximize profit subject to the technology constraint, taking the price vector (t, w) as given:

$$(L_{YC}, Y_C) \in \arg \max_{\left(\widetilde{L}_{YC}, \widetilde{Y}_C\right)} \mathscr{L}_{YC}\left(\widetilde{L}_{YC}, \widetilde{Y}_C\right)$$

where $\mathscr{L}_{YC}(\cdot)$ is the Lagragian function

$$\mathscr{L}_{YC}\left(\widetilde{L}_{YC},\widetilde{Y}_C\right) = t\tilde{Y}_C - w\tilde{L}_{YC} + \lambda_{YC}\left(\tilde{Y}_C - Y_C\left(\widetilde{L}_{YD}\right)\right)$$

and a tilde above a variable indicates a choice variable.

The first-order conditions of this program are

$$\begin{aligned}\lambda_{YC} &= -t \\ -\lambda_{YC}\frac{\partial X(\cdot)}{\partial L_{YC}} &= w \\ Y_C &= Y_C(L_{YC})\end{aligned}$$

By the first two FOCs profit maximizing behavior of firms in the green electricity sector is characterized by

$$\frac{dY_C(\cdot)}{dL_{YC}} = \frac{w}{t} \tag{A.4.1}$$

Define the elasticity of labor-capital demand

$$\sigma_{YC} := \frac{\frac{dL_{YC}}{L_{YC}}}{\frac{d\left(\frac{w}{t}\right)}{\frac{w}{t}}}$$

such that

$$\frac{dL_{YC}}{L_{YC}} = \sigma_{YC}\frac{d\left(\frac{w}{t}\right)}{\frac{w}{t}}$$

or in growth rate notation

$$\hat{L}_{YC} = \sigma_{YC}(\hat{t} - \hat{w})$$

By $\hat{w} = 0$ we have $\hat{L}_{YC} = \sigma_{YC}\hat{t}$.

Now, totally differentiate the third FOC $Y_C = Y_C(L_{YC})$ and use condition A.4.1 to get

$$dY_C = \frac{w}{t}dL_{YC}$$

Divide both sides by Y_C and expand the right-hand side by $\frac{L_{YC}}{L_{YC}}$, yielding

$$\underbrace{\frac{dY_C}{Y_C}}_{\hat{Y}_C} = \frac{wL_{YC}}{tY_C}\underbrace{\frac{dL_{YC}}{L_{YC}}}_{\hat{L}_{YC}} \tag{A.4.2}$$

Consider the definition of scale elasticity (which in this case is equal to the elasticity of output with respect to labor-capital, since this is the only factor of production)

$$\theta_{YC} := \frac{\partial Y_C(\cdot)}{\partial L_{YC}}\frac{L_{YC}}{Y_C}$$

Use again condition A.4.1 to obtain

$$\theta_{YC} = \frac{wL_{YC}}{tY_C} \tag{A.4.3}$$

such that we have (by equations A.4.2 and A.4.3) $\hat{Y}_C = \theta_{YC}\hat{L}_{YC}$. Plugging in $\hat{L}_{YC} = \sigma_{YC}\hat{t}$ finally yields $\hat{Y}_C = \theta_{YC}\sigma_{YC}\hat{t}$.

It remains to show that $\theta_{YC} < 0$. Since the green electricity sector operates under decreasing returns, we have $Y_C(nL_{YC}) = n^k Y_C(L_{YC})$ with $k < 1$ for any $n > 0$, and therefore by Euler's homogenous function theorem and condition A.4.1

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

Since $k < 1$, this equation can only be true if $tY_C > wL_{YC}$, that is, green electricity producers make a profit. Using this condition in equation A.4.3 yields $\theta_{YC} < 1$.

A.5 Proof of lemma 4.5

In sector Y_D, each firm demands an input bundle (L_{YD}, E_Y) and supplies output quantity Y_D to maximize profit subject to the technology constraint, taking the price vector (p_Y, w, r) as given:

$$(L_{YD}, E_Y, Y_D) \in \arg \max_{\left(\widetilde{L}_{YD}, \widetilde{E}_Y, \widetilde{Y}_D\right)} \mathscr{L}_{YD}\left(\widetilde{L}_{YD}, \widetilde{E}_Y, \widetilde{Y}_D\right)$$

where $\mathscr{L}_{YD}(\cdot)$ is the Lagragian function

$$\mathscr{L}_{YD}\left(\widetilde{L}_{YD}, \widetilde{E}_Y, \widetilde{Y}_D\right) = p_Y\widetilde{Y}_D - w\tilde{L}_{YD} - r\tilde{E}_Y + \lambda_{YD}\left(\tilde{Y}_D - Y_D\left(\widetilde{L}_{YD}, \widetilde{E}_Y\right)\right)$$

and a tilde above a variable indicates a choice variable.

The first-order conditions of this program are

$$\begin{aligned} \lambda_{YD} &= -p_Y \\ -\lambda_{YD}\frac{\partial Y_D(\cdot)}{\partial L_{YD}} &= w \\ -\lambda_{YD}\frac{\partial Y_D(\cdot)}{\partial E_Y} &= r \\ Y_D &= Y_D(L_{YD}, E_Y) \end{aligned} \tag{A.5.1}$$

Totally differentiate the fourth FOC, and use the first three to get

$$dY_D = \frac{w}{p_Y}dL_{YD} + \frac{r}{p_Y}dE_Y$$

Divide both sides by Y_D, and expand the right-hand side terms by $\frac{L_{YD}}{L_{YD}}$ and $\frac{E_Y}{E_Y}$, respectively, to obtain

$$\underbrace{\frac{dY_D}{Y_D}}_{\hat{Y}_D} = \underbrace{\frac{dL_{YD}}{L_{YD}}}_{\hat{L}_{YD}}\frac{wL_{YD}}{p_YY_D} + \underbrace{\frac{dE_Y}{E_Y}}_{\hat{E}_Y}\frac{rE_Y}{p_YY_D} \tag{A.5.2}$$

Consider the definition of scale elasticity

$$\theta_{YD} := \underbrace{\frac{\partial Y_D(\cdot)}{\partial L_{YD}} \frac{L_{YD}}{Y_D}}_{\theta_{YDL}} + \underbrace{\frac{\partial Y_D(\cdot)}{\partial E_Y} \frac{E_Y}{Y_D}}_{\theta_{YDE}}$$

where θ_{YDL} and θ_{YDE} are the elasticities of output with respect to the individual factors. By the first-order conditions A.5.1 it holds in a profit maximum (and hence in equilibrium) that

$$\theta_{YDL} = \frac{wL_{YD}}{p_Y Y_D}$$
$$\theta_{YDE} = \frac{rE_Y}{p_Y Y_D} \tag{A.5.3}$$

i.e. the elasticity parameters are equal to the factor claims as shares of total revenues.

Now, by constant returns to scale $Y_D(L_{YD}, E_Y)$ is linearly homogenous, such that it follows from Euler's homogenous function theorem that

$$Y_D(\cdot) = \frac{\partial Y_D(\cdot)}{\partial L_{YD}} L_{YD} + \frac{\partial Y_D(\cdot)}{\partial E_Y} E_Y$$

Using again the first-order conditions A.5.1 it follows

$$Y_D(\cdot) = \frac{w}{p_Y} L_{YD} + \frac{r}{p_Y} E_Y \Leftrightarrow p_Y Y_D = wL_{YD} + rE_Y \tag{A.5.4}$$

i.e. profits are zero. By the zero-profit condition A.5.4 we have $\theta_{YDL} + \theta_{YDE} = 1$ and thus by definition $\theta_{YD} = 1$. Furthermore, by A.5.3 the elasticity parameters are also equal to the respective factor claims as shares of total costs.

Combining those results with A.5.2 yields

$$\underbrace{\frac{dY_D}{Y_D}}_{\hat{Y}_D} = \underbrace{\frac{dL_{YD}}{L_{YD}}}_{\hat{L}_{YD}} \underbrace{\frac{wL_{YD}}{p_Y Y_D}}_{\theta_{YDL}} + \underbrace{\frac{dE_Y}{E_Y}}_{\hat{E}_Y} \underbrace{\frac{rE_Y}{p_Y Y_D}}_{\theta_{YDE}} \tag{A.5.5}$$

Return to the first-order conditions A.5.1. Using the first three conditions, profit maximizing behavior of firms in sector Y_D is characterized by

$$\underbrace{\frac{\frac{\partial Y_D(\cdot)}{\partial L_{YD}}}{\frac{\partial Y_D(\cdot)}{\partial E_Y}}}_{:=\rho_{YD}} = \frac{w}{r} \tag{A.5.6}$$

where the left-hand side is the marginal rate of technical substitution and the right-hand side the input price ratio. Using the definition of the elasticity of technical substitution

$$\sigma_{YD} := \frac{d\left(\frac{E_Y}{L_{YD}}\right)}{\frac{E_Y}{L_{YD}}} \left(\frac{d\rho_{YD}}{\rho_{YD}}\right)^{-1}$$

we can express the condition alternatively by

$$\frac{d\left(\frac{E_Y}{L_{YD}}\right)}{\frac{E_Y}{L_{YD}}} = \sigma_{YD}\frac{d\left(\frac{w}{r}\right)}{\frac{w}{r}}$$

Transforming in growth rates yields

$$\underbrace{\frac{dE_Y}{E_Y}}_{\hat{E}_Y} - \underbrace{\frac{dL_{YD}}{L_{YD}}}_{\hat{L}_{YD}} = \sigma_{YD}\left(\underbrace{\frac{dw}{w}}_{\hat{w}} - \underbrace{\frac{dr}{r}}_{\hat{r}}\right)$$

Since $\hat{w} = 0$ (labor-capital is numeraire), this condition simplifies to

$$\hat{L}_{YD} - \hat{E}_Y = \sigma_{YD}\hat{r} \tag{A.5.7}$$

The permit market clearing condition $E_Y = \bar{E}$ must hold in equilibrium. Totally differentiating this condition and dividing both sides by E_Y yields

$$\underbrace{\frac{dE_Y}{E_Y}}_{\hat{E}_Y} = 0 \tag{A.5.8}$$

Using this equation to substitute $\hat{E}_Y$ in equation A.5.7 gives us

$$\hat{L}_{YD} = \sigma_{YD}\hat{r} \tag{A.5.9}$$

Using equations A.5.8 and A.5.9 to substitute $\hat{L}_{YD}$ and $\hat{E}_Y$ in condition A.5.5 yields

$$\hat{Y}_D = \theta_{YDL}\sigma_{YD}\hat{r}$$

A.6 Proof of lemma 4.6

Households spend their incomes M by demanding quantity x of good X and quantity y of good Y, taking as given all market prices. By the assumptions stated in section 3, their behavior is described by

$$(x,y) \in \arg\max_{(\tilde{x},\tilde{y})} \mathscr{L}(\tilde{x},\tilde{y})$$

where $\mathscr{L}(\tilde{x},\tilde{y})$ is the Lagragian function

$$\mathscr{L}(\tilde{x},\tilde{y}) = u(\tilde{x},\tilde{y}) + \lambda_H(p_X x + p_Y y - M)$$

and a tilde above a variable indicates a choice variable, whereas incomes

$$M = w + (\Pi_X + \Pi_{YD} + \Pi_{YC}) + G$$

are earned as labor-capital supplier (the wage w), as residual claimants of the production firms (the bracketed term), and as receiver of the government rebate (G). Profits are

$$\Pi_X = p_X X - wL_X - \tau E_X$$
$$\Pi_{YD} = p_Y Y_D - wL_{YD} - rE_Y$$
$$\Pi_{YC} = tY_C - wL_{YC}$$

The government rebate is given by the sum of the carbon pricing revenues, less the subsidy payments:

$$G = \tau E_X + rE_Y - (t - p_Y)Y_C$$

Combining those five equations and rearranging yields

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

The program yields the first-order conditions

$$\begin{aligned} \frac{\partial u(\cdot)}{\partial x} + \lambda_H p_X &= 0 \\ \frac{\partial u(\cdot)}{\partial y} + \lambda_H p_Y &= 0 \\ p_X x + p_Y y &= p_X X + p_Y (Y_D + Y_C) + w(1 - L_X - L_{YD} - L_{YC}) \end{aligned} \tag{A.6.1}$$

Rearranging the the budget condition yields

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

which is true by the market clearance conditions.

Rearranging the first two first-order conditions yields

$$\underbrace{\frac{\frac{\partial u(\cdot)}{\partial x}}{\frac{\partial u(\cdot)}{\partial y}}}_{:=\rho_u} = \frac{p_X}{p_Y}$$

where the left-hand side is the marginal rate of substitution. By using the definition of elasticity of substitution

$$\varsigma := \frac{d\left(\frac{y}{y}\right)}{\frac{y}{x}} \left(\frac{d\rho_u}{\rho_u}\right)^{-1}$$

we can express the first-order condition alternatively by

$$\frac{d\left(\frac{y}{x}\right)}{\frac{y}{x}} = \varsigma \frac{d\left(\frac{p_X}{p_Y}\right)}{\frac{p_X}{p_Y}}$$

Transforming in growth rates yields

$$\underbrace{\frac{dy}{y}}_{\hat{y}} - \underbrace{\frac{dx}{x}}_{\hat{x}} = \varsigma \left(\underbrace{\frac{dp_X}{p_X}}_{\hat{p}_X} - \underbrace{\frac{dp_Y}{p_Y}}_{\hat{p}_Y} \right) \tag{A.6.2}$$

Now, totally differentiating the final-good market clearance conditions $x = X$ and $y = Y$ and dividing both sides by the respective quantity yields

$$\begin{aligned} \hat{x} &= \hat{X} \\ \hat{y} &= \hat{Y} \end{aligned} \tag{A.6.3}$$

Totally differentiate the zero profit condition A.2.4 to get

$$dp_X X + dX p_X = dw L_X + dL_X w + d\tau E_X + dE_X \tau$$

Divide both sides by $p_X X$ and expand the first right-hand-side term by $\frac{w}{w}$, the second by $\frac{L_X}{L_X}$, the third by $\frac{\tau}{\tau}$, and the fourth by $\frac{E_X}{E_X}$ to obtain

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

By equations A.2.3 this expression is equal to

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

Using equation A.2.5 to substitute $\hat{X}$ and recognizing $\hat{w} = 0$ (labor-capital is numeraire) and $\hat{\tau} = 0$ (by construction) yields $\hat{p}_X = 0$: no change in input prices implies no change in the break-even output price.

Using conditions A.6.3 to substitute $\hat{y}$ and $\hat{x}$ in equation A.6.2 and recognizing $\hat{p}_X = 0$ yields the result.

A.7 Proof of lemma 4.7

Totally differentiate the zero profit condition A.5.4 to get

$$dp_Y Y_D + dY_D p_Y = dw L_{YD} + dL_{YD} w + dr E_Y + dE_Y r$$

Divide both sides by $p_Y Y_D$ and expand the first right-hand-side term by $\frac{w}{w}$, the second by $\frac{L_{YD}}{L_{YD}}$, the third by $\frac{r}{r}$, and the fourth by $\frac{E_Y}{E_Y}$ to obtain

$$\frac{dp_Y}{p_Y} + \frac{dY_D}{Y_D} = \frac{wL_{YD}}{p_Y Y_D}\left(\frac{dw}{w} + \frac{dL_{YD}}{L_{YD}}\right) + \frac{wE_Y}{p_Y Y_D}\left(\frac{dr}{r} + \frac{dE_Y}{E_Y}\right)$$

By equations A.5.3 this expression is equal to

$$\hat{p}_Y + \hat{Y}_D = \theta_{YDL}\left(\hat{w} + \hat{L}_{YD}\right) + \theta_{YDE}\left(\hat{r} + \hat{E}_Y\right)$$

Using equation A.5.5 to substitute $\hat{Y}_D$, condition A.5.8 to substitute $\hat{E}_Y$, and recognizing $\hat{w} = 0$ (labor-capital is numeraire) yields the result.

A.8 Proof of lemma 4.8

By construction it holds that $Y = Y_D + Y_C$. Totally differentiate this condition, divide both sides by Y, and the expand the right-hand-side terms by $\frac{Y_D}{Y_D}$ and $\frac{Y_C}{Y_C}$, respectively, to get

$$\underbrace{\frac{dY}{Y}}_{\hat{Y}} = \underbrace{\frac{Y_D}{Y}}_{\alpha_D}\underbrace{\frac{dY_D}{Y_D}}_{\hat{Y}_D} + \underbrace{\frac{Y_C}{Y}}_{\alpha_C}\underbrace{\frac{dY_C}{Y_C}}_{\hat{Y}_C} \tag{A.8.1}$$

By lemma 4.6 it holds that $\hat{X} = \varsigma \hat{p}_Y + \hat{Y}$. Use condition A.8.1 to substitute $\hat{Y}$ and lemma 4.7 to substitute $\hat{p}_Y$ to get

$$\hat{X} = \varsigma \theta_{YDE}\hat{r} + \alpha_D \hat{Y}_D + \alpha_C \hat{Y}_C \tag{A.8.2}$$

Now use lemma 4.4 to substitute $\hat{Y}_C$ and lemma 4.5 to substitute $\hat{Y}_D$:

$$\hat{X} = (\varsigma \theta_{YDE} + \alpha_D \theta_{YDL}\sigma_{YD})\,\hat{r} + \alpha_C \theta_{YC}\sigma_{YC}\hat{t} \tag{A.8.3}$$

Finally, using lemma 4.3 to substitute $\hat{X}$, and in turn lemmas 4.4 and 4.5 to substitute $\hat{L}_{YC}$ and $\hat{L}_{YD}$, respectively, yields after rearrangement

$$\hat{r} = -\underbrace{\left[\frac{(L_X \alpha_C \theta_{YC} + L_{YC})\,\sigma_{YC}}{(L_X \alpha_D \theta_{YDL} + L_{YD})\,\sigma_{YD} + L_X \theta_{YDE}\varsigma}\right]}_{:=\gamma}\hat{t} \tag{A.8.4}$$

Since all parameters in the expression in brackets are non-negative, it holds that $\gamma \geq 0$. Furthermore, by the exclusion of boundary-equilibria we have

Lemma A.1. $0 < L_i < 1$ *for* $i = X, YC, YD$, $0 < \alpha_j < 1$ *for* $j = C, D$, *and* $0 < \alpha_k < 1$ *for* $k = YDL, YDE, YC, XL, XE$.

such that $\gamma = 0$ if and only if $\sigma_{YC} = 0$. Furthermore, the term in brackets is increasing in σ_{YC} (since it is in the numerator) and decreasing in σ_{YD} and ς (since they are in the denominator), with $\gamma \to 0$ for $\sigma_{YD} \to 0$ or $\varsigma \to 0$ or both.

A.9 Proof of theorem 4.1

Consider equation A.8.2. By equations A.4.2, A.4.3, A.5.5 and A.5.8 this becomes

$$\hat{X} = \varsigma \theta_{YDE}\hat{r} + \alpha_D \theta_{YDL}\hat{L}_{YD} + \alpha_C \theta_{YC}\hat{L}_{YC}$$

Using the labor-capital market clearance condition A.3.1 to substitute $\hat{L}_{YD}$ and $\hat{L}_{YC}$, and recognizing $\hat{X} = \hat{L}_X = \hat{E}_X$ (lemmas 4.2 and 4.3) yields after some rearrangement

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

with $\delta > 0$ by lemma A.1. Finally, using lemma 4.4 to substitute $\hat{L}_{YC}$, lemma 4.5 to substitute $\hat{L}_{YD}$, lemma 4.8 to substitute $\hat{r}$, and rearranging yields

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

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

$$\Lambda = \frac{[(L_{YD} \alpha_C \theta_{YC} - L_{YC} \alpha_D \theta_{YDL}) \sigma_{YD} - L_{YC} \theta_{YDE} \varsigma] \sigma_{YC}}{(L_X \alpha_D \theta_{YDL} + L_{YD}) \sigma_{YD} + L_X \theta_{YDE} \varsigma} \tag{A.9.1}$$

It remains to determine the signs of the effects and to show how they depend on the elasticity parameters.

Lemma A.2. $\Lambda_{\text{DARE}} \leq 0$ *with equality if and only if* $\sigma_{YC} = 0$*.* Λ_{DARE} *is strictly decreasing and linear in* σ_{YC}*, and independent from* σ_{YD} *and* ς*.*

Proof. The DARE is given by

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

Since by lemma A.1 all parameters in brackets are strictly positive, the negative sign out front implies that Λ_{DARE} is strictly negative whenever $\sigma_{YC} > 0$, and zero if and only if $\sigma_{YC} = 0$. Differentiating Λ_{DARE} with respect to the elasticity parameters yields

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

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

proving the remaining claims in the lemma. □

Lemma A.3. $\Lambda_{\text{ITTE}} \leq 0$ *with equality if and only if* $\sigma_{YC} = 0$ *or* $\varsigma = 0$ *(or both).* Λ_{ITTE} *is decreasing and linear in* σ_{YC}*, increasing, concave, and convergent to zero in* σ_{YD}*, and decreasing and convex in* ς*.*

Proof. Substituting γ using equation A.8.4, the ITTE is given by

$$\Lambda_{\text{ITTE}} = - \frac{\theta_{YDE} (L_X \alpha_C \theta_{YC} + L_{YC}) \sigma_{YC} \varsigma}{(1+\delta) [(L_X \alpha_D \theta_{YDL} + L_{YD}) \sigma_{YD} + L_X \theta_{YDE} \varsigma]}$$

If $\sigma_{YC} = 0$ or $\varsigma = 0$, then $\Lambda_{\text{ITTE}} = 0$. If $\sigma_{YC} > 0$ and $\varsigma > 0$, then by lemma A.1 $\Lambda_{\text{ITTE}} < 0$ even if $\sigma_{YD} = 0$. For clarity, substitute

$$\theta_{YDE} (L_X \alpha_C \theta_{YC} + L_{YC}) := A$$

$$(1+\delta)\left(L_X\alpha_D\theta_{YDL}+L_{YD}\right):=B$$

$$(1+\delta)\,L_X\theta_{YDE}:=C$$

for the the present proof, and observe that by lemma A.1 all three elements are strictly positive. Differentiating Λ_{ITTE} with respect to the elasticity parameters yields

$$\frac{\partial\Lambda_{\text{ITTE}}}{\partial\sigma_{YC}}=-\frac{A\varsigma}{B\sigma_{YD}+C\varsigma}\leq 0 \qquad \frac{\partial^2\Lambda_{\text{ITTE}}}{\partial\sigma_{YC}^2}=0$$

$$\frac{\partial\Lambda_{\text{ITTE}}}{\partial\sigma_{YD}}=\frac{AB\sigma_{YC}\varsigma}{\left(B\sigma_{YD}+C\varsigma\right)^2}\geq 0 \quad \frac{\partial^2\Lambda_{\text{ITTE}}}{\partial\sigma_{YD}^2}=-\frac{2AB^2\sigma_{YC}\varsigma}{\left(B\sigma_{YD}+C\varsigma\right)^3}\leq 0$$

$$\frac{\partial\Lambda_{\text{ITTE}}}{\partial\varsigma}=-\frac{AB\sigma_{YC}\sigma_{YD}}{\left(B\sigma_{YD}+C\varsigma\right)^2}\leq 0 \quad \frac{\partial^2\Lambda_{\text{ITTE}}}{\partial\varsigma^2}=\frac{2ABC\sigma_{YC}\sigma_{YD}}{\left(B\sigma_{YD}+C\varsigma\right)^3}\geq 0$$

proving the remaining claims in the lemma. □

Lemma A.4. $\Lambda_{\text{IARE}}\geq 0$ *with equality if and only if* $\sigma_{YC}=0$ *or* $\sigma_{YD}=0$ *(or both).* Λ_{IARE} *is increasing and linear in* σ_{YC}*, increasing and concave in* σ_{YD}*, and decreasing, convex, and convergent to zero in* ς*.*

Proof. Substituting γ using equation A.8.4, the IARE is given by

$$\Lambda_{\text{IARE}}=\frac{\alpha_C\theta_{YC}L_{YD}\left(L_X\alpha_C\theta_{YC}+L_{YC}\right)\sigma_{YC}\sigma_{YD}}{(1+\delta)\left[L_{YC}\left(L_X\alpha_D\theta_{YDL}+L_{YD}\right)\sigma_{YD}+L_{YC}L_X\theta_{YDE}\varsigma\right]}$$

If $\sigma_{YC}=0$ or $\sigma_{YD}=0$, then $\Lambda_{\text{IARE}}=0$. If $\sigma_{YC}>0$ and $\sigma_{YD}>0$, then by lemma A.1 $\Lambda_{\text{IARE}}>0$ even if $\varsigma=0$. For clarity, substitute

$$\alpha_C\theta_{YC}L_{YD}\left(L_X\alpha_C\theta_{YC}+L_{YC}\right):=A$$

$$(1+\delta)\,L_{YC}\left(L_X\alpha_D\theta_{YDL}+L_{YD}\right):=B$$

$$(1+\delta)\,L_{YC}L_X\theta_{YDE}:=C$$

for the the present proof, and observe that by lemma A.1 all three elements are strictly positive. Differentiating Λ_{IARE} with respect to the elasticity parameters yields

$$\frac{\partial\Lambda_{\text{IARE}}}{\partial\sigma_{YC}}=\frac{A\varsigma}{B\sigma_{YD}+C\varsigma}\geq 0 \qquad \frac{\partial^2\Lambda_{\text{IARE}}}{\partial\sigma_{YC}^2}=0$$

$$\frac{\partial \Lambda_{\text{IARE}}}{\partial \sigma_{YD}} = \frac{AC\sigma_{YC}\varsigma}{(B\sigma_{YD}+C\varsigma)^2} \geq 0 \quad \frac{\partial^2 \Lambda_{\text{IARE}}}{\partial \sigma_{YD}^2} = -\frac{2ABC\sigma_{YC}\varsigma}{(B\sigma_{YD}+C\varsigma)^3} \leq 0$$

$$\frac{\partial \Lambda_{\text{IARE}}}{\partial \varsigma} = -\frac{AC\sigma_{YC}\sigma_{YD}}{(B\sigma_{YD}+C\varsigma)^2} \leq 0 \quad \frac{\partial^2 \Lambda_{\text{IARE}}}{\partial \varsigma^2} = \frac{2AC^2\sigma_{YC}\sigma_{YD}}{(B\sigma_{YD}+C\varsigma)^3} \geq 0$$

proving the remaining claims in the lemma. □

Lemma A.5. $\Lambda \leq 0$ *with equality if and only if* $\sigma_{YC} = 0$. Λ *is decreasing and linear in* σ_{YC}, *increasing and concave in* σ_{YD}, *and decreasing, convex in* ς.

Proof. Consider the total leakage effect in the form of equation A.9.1. If $\sigma_{YC} = 0$, then $\Lambda = 0$. If $\sigma_{YC} > 0$, then (since the denominator is positive by lemma A.1) $\Lambda \geq 0$ if and only if the expression in square brackets in the numerator is greater or equal to zero. Rearranging this condition yields

$$\frac{\varsigma}{\sigma_{YD}} \leq \frac{L_{YD}\alpha_C\theta_{YC} - L_{YC}\alpha_D\theta_{YDL}}{L_{YC}\theta_{YDE}} \tag{A.9.2}$$

Using equations A.4.3, A.5.3, and A.8.1 to substitute the parameters on the right-hand side back into the fundamental variables, we have equivalently

$$\frac{\varsigma}{\sigma_{YD}} \leq \frac{wL_{YD}Y_D}{rE_YY}\left(\frac{p_Y}{t} - 1\right) \tag{A.9.3}$$

By assumption $t > p_Y$ the right-hand side is strictly negative. Since by $\varsigma \geq 0$ and $\sigma_{YD} \geq 0$ the left-hand side is non-negative, the condition is never true, such that $\Lambda \geq 0$ is impossible. Conversely, if $\sigma_{YC} > 0$, then $\Lambda < 0$ if

$$\frac{\varsigma}{\sigma_{YD}} > \frac{wL_{YD}Y_D}{rE_YY}\left(\frac{p_Y}{t} - 1\right) \tag{A.9.4}$$

which is by $t > p_Y$, $\varsigma \geq 0$, and $\sigma_{YD} \geq 0$ always true. This concludes the proof of the first claim in the lemma.

It remains to analyze how Λ depends quantitatively on the three elasticity parameters. Consider the easy cases first. Differentiating Λ with respect to σ_{YD} yields

$$\frac{\partial \Lambda}{\partial \sigma_{YD}} = \underbrace{\frac{\partial \Lambda_{\text{DARE}}}{\partial \sigma_{YD}}}_{=0} + \underbrace{\frac{\partial \Lambda_{\text{IARE}}}{\partial \sigma_{YD}}}_{\geq 0} + \underbrace{\frac{\partial \Lambda_{\text{ITTE}}}{\partial \sigma_{YD}}}_{\geq 0} \geq 0$$

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

i.e. Λ is increasing and concave in parameter σ_{YD}. Differentiating Λ with respect to ς yields

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

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

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

Finally, consider the properties of Λ with respect to σ_{YC}. First, we have

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

such that Λ is definitely linear in σ_{YC}. To identify the slope, differentiate expression A.9.1

$$\frac{\partial\Lambda}{\partial\sigma_{YC}} = \frac{(L_{YD}\alpha_C\theta_{YC} - L_{YC}\alpha_D\theta_{YDL})\,\sigma_{YD} - L_{YC}\theta_{YDE}\varsigma}{(L_X\alpha_D\theta_{YDL} + L_{YD})\,\sigma_{YD} + L_X\theta_{YDE}\varsigma} \tag{A.9.5}$$

Since the denominator is positive by lemma A.1) 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 A.9.2 (or equivalently condition A.9.3), which is never true, as shown above. Thus, Λ cannot be increasing in σ_{YC}. Conversely, expression A.9.5 is negative if A.9.4 is true, which is always the case, as shown above as well: Λ is unambiguously decreasing in σ_{YC}. □

A.10 Proof of lemma 5.1

Let $P_Y = p_Y + s$ denote the gross price of Y. The households' problem changes to

$$(x,y) \in \arg\max_{(\tilde{x},\tilde{y})} \mathscr{L}(\tilde{x},\tilde{y}) = u(\tilde{x},\tilde{y}) + \lambda_H (p_X x + P_Y y - M)$$

with income

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

The program yields the first-order conditions

$$\begin{aligned} \frac{\partial u(\cdot)}{\partial x} + \lambda_H p_X &= 0 \\ \frac{\partial u(\cdot)}{\partial y} + \lambda_H P_Y &= 0 \\ p_X x + P_Y y = p_X X + p_Y Y_D + tY_C &+ w(1 - L_X - L_{YD} - L_{YC}) \end{aligned} \tag{A.10.1}$$

Rearranging the the budget condition yields

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

which is true by the market clearance conditions.

Rearranging the first two first-order conditions yields by the same steps as in section A.6

$$\hat{X}-\hat{Y}=\varsigma\hat{P}_Y \tag{A.10.2}$$

Now, totally differentiate the definition $P_Y=\alpha_D p_Y+\alpha_C t$, divide both sides by P_Y, use again the identity $P_Y=\alpha_D p_Y+\alpha_C t$ on the right-hand side, and expand the terms by $\frac{p_Y}{p_Y}$ and $\frac{t}{t}$, respectively, yields

$$\underbrace{\frac{dP_Y}{P_Y}}_{\hat{P}_Y}=\underbrace{\frac{p_Y Y_D}{p_Y Y_D+tY_C}}_{\psi_D}\underbrace{\frac{dp_Y}{p_Y}}_{\hat{p}_Y}+\underbrace{\frac{tY_C}{p_Y Y_D+tY_C}}_{\psi_C}\underbrace{\frac{dt}{t}}_{\hat{t}}$$

Using this equation to substitute $\hat{P}_Y$ in equation A.10.2 yields the result. By the exclusion of boundary-equilibria we have

Lemma A.6. $\psi_C>0$ *and* $\psi_D>0$.

A.11 Proof of lemma 5.2

By lemma 5.1 it holds that $\hat{X}=\varsigma(\psi_D\hat{p}_Y+\psi_C\hat{t})+\hat{Y}$. Use condition A.8.1 to substitute $\hat{Y}$ and lemma 4.7 to substitute $\hat{p}_Y$ to get

$$\hat{X}=\varsigma(\psi_D\theta_{YDE}\hat{r}+\psi_C\hat{t})+\alpha_D\hat{Y}_D+\alpha_C\hat{Y}_C \tag{A.11.1}$$

Now use lemma 4.4 to substitute $\hat{Y}_C$ and lemma 4.5 to substitute $\hat{Y}_D$:

$$\hat{X}=(\varsigma\psi_D\theta_{YDE}+\alpha_D\theta_{YDL}\sigma_{YD})\hat{r}+(\varsigma\psi_C+\alpha_C\theta_{YC}\sigma_{YC})\hat{t}$$

Finally, using lemma 4.3 to substitute $\hat{X}$, and in turn lemmas 4.4 and 4.5 to substitute $\hat{L}_{YC}$ and $\hat{L}_{YD}$ yields after rearrangement

$$\hat{r}=-\underbrace{\left[\frac{(L_X\alpha_C\theta_{YC}+L_{YC})\sigma_{YC}+L_X\psi_C\varsigma}{(L_X\alpha_D\theta_{YDL}+L_{YD})\sigma_{YD}+L_X\theta_{YDE}\psi_D\varsigma}\right]}_{:=\tilde{\gamma}}\hat{t} \tag{A.11.2}$$

Since all parameters in the expression in brackets are non-negative, it holds that $\tilde{\gamma}\geq 0$, and by lemmas A.1 and A.6 we have $\tilde{\gamma}=0$ if and only if $\sigma_{YC}=0$ and $\varsigma=0$. Furthermore, $\tilde{\gamma}$ is increasing in σ_{YC} (since it is in the numerator) and decreasing in σ_{YD} (since they are in the denominator), with $\tilde{\gamma}\to 0$ for $\sigma_{YD}\to 0$. Furthermore, we have

$$\frac{\partial\tilde{\gamma}}{\partial\varsigma}=\frac{L_X\psi_C\sigma_{YD}(L_X\alpha_D\theta_{YDL}+L_{YD})+L_X^2\psi_C\psi_D\theta_{YDE}\left(\varsigma-\varsigma^2\right)}{\left[(L_X\alpha_D\theta_{YDL}+L_{YD})\sigma_{YD}+L_X\theta_{YDE}\psi_D\varsigma\right]^2}\geq 0$$

i.e. $\tilde{\gamma}$ is increasing 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 A.11.2 becomes identical to equation A.8.4, that is, $\tilde{\gamma} = \gamma$. However, this case is ruled out: by lemma A.6 it holds that $\psi_C > 0$ such that (because $\tilde{\gamma}$ is increasing in ψ_C) it follows that $\tilde{\gamma} > \gamma$.

A.12 Proof of theorem 5.1

Consider equation A.11.1. By equations A.4.2, A.4.3, A.5.5 and A.5.8 this becomes

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

Using the labor-capital market clearance condition A.3.1 to substitute $\hat{L}_{YD}$ and $\hat{L}_{YC}$, recognizing $\hat{X} = \hat{L}_X = \hat{E}_X$ (lemmas 4.2 and 4.3), and using the definition of δ (section A.9) yields

$$\hat{E}_X\left(1+\delta\right) = \varsigma\left(\psi_D \theta_{YDE} \hat{r} + \psi_C \hat{t}\right) - \frac{L_{YC}}{L_{YD}} \alpha_D \theta_{YDL} \hat{L}_{YC} - \frac{L_{YD}}{L_{YC}} \alpha_C \theta_{YC} \hat{L}_{YD}$$

Finally, using lemma 4.4 to substitute $\hat{L}_{YC}$, lemma 4.5 to substitute $\hat{L}_{YD}$, lemma 4.8 to substitute $\hat{r}$, and rearranging yields

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

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

$$\tilde{\Lambda} = \frac{\left[\left(L_{YD}\alpha_C\theta_{YC} - L_{YC}\alpha_D\theta_{YDL}\right)\sigma_{YD} - \psi_D L_{YC}\theta_{YDE}\varsigma\right]\sigma_{YC} + \psi_C L_{YD}\sigma_{YD}\varsigma}{\left(L_X\alpha_D\theta_{YDL} + L_{YD}\right)\sigma_{YD} + \psi_D L_X \theta_{YDE}\varsigma} \tag{A.12.1}$$

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

$$\tilde{\Lambda} = \frac{\psi_C L_{YD} \sigma_{YD} \varsigma}{\left(L_X \alpha_D \theta_{YDL} + L_{YD}\right)\sigma_{YD} + \psi_D L_X \theta_{YDE} \varsigma} > 0$$

which is by lemmas A.1 and A.6 unambiguously positive. Generally, if $\sigma_{YC} = 0$ and $\varsigma = 0$, then $\tilde{\Lambda} = 0$. Otherwise, (since the denominator is positive by lemmas A.1 and A.6) $\Lambda \geq 0$ if and only if the the numerator of A.12.1 is greater or equal to zero. Rearranging this condition yields

$$\psi_C \geq \frac{\left(L_{YC}\theta_{YDE}\varsigma + \left(L_{YC}\alpha_D\theta_{YDL} - L_{YD}\alpha_C\theta_{YC}\right)\sigma_{YD}\right)\sigma_{YC}}{\left(L_{YC}\theta_{YDE}\sigma_{YC} + L_{YD}\sigma_{YD}\right)\varsigma} \tag{A.12.2}$$

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

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

$$\begin{aligned}
\tilde{\Lambda} - \Lambda &= \left(\tilde{\Lambda}_{\text{IARE}} + \tilde{\Lambda}_{\text{ITTE}} + \Lambda_{\text{DARE}} + \Lambda_{\text{DITTE}}\right) - \left(\Lambda_{\text{IARE}} + \Lambda_{\text{ITTE}} + \Lambda_{\text{DARE}}\right) \\
&= \left(\tilde{\Lambda}_{\text{IARE}} - \Lambda_{\text{IARE}}\right) + \left(\tilde{\Lambda}_{\text{ITTE}} - \Lambda_{\text{ITTE}}\right) + \Lambda_{\text{DITTE}} \\
&= (\tilde{\gamma} - \gamma) \frac{\alpha_C \theta_{YC} L_{YD}}{(1+\delta) L_{YC}} \sigma_{YD} + (\gamma - \tilde{\gamma}\psi_D) \frac{\theta_{YDE}}{(1+\delta)} \varsigma + \frac{\psi_C}{(1+\delta)} \varsigma \\
&= \frac{\tilde{\gamma} - \gamma}{\gamma} \Lambda_{\text{IARE}} - \frac{\gamma - \tilde{\gamma}\psi_D}{\gamma} \Lambda_{\text{ITTE}} + \Lambda_{\text{DTTE}} \\
&= \frac{\tilde{\gamma} - \gamma}{\gamma} \Lambda_{\text{IARE}} + \left(\frac{\tilde{\gamma}\psi_D}{\gamma} - 1\right) \Lambda_{\text{ITTE}} + \Lambda_{\text{DTTE}} \qquad \text{(A.12.3)}
\end{aligned}$$

Now, first observe that if $\psi_C = 0$ we have $\tilde{\gamma} = \gamma$ by lemma 5.2 and hence $\tilde{\Lambda} - \Lambda = 0$. For any $\psi_C > 0$, we have $\tilde{\gamma} > \gamma$ by lemma 5.2. Specifically, if $\psi_C = 1$ we have

$$\tilde{\Lambda} - \Lambda = \frac{\tilde{\gamma} - \gamma}{\gamma} \Lambda_{\text{IARE}} - \Lambda_{\text{ITTE}} + \frac{\varsigma}{(1+\delta)} > 0$$

Since $\frac{\tilde{\gamma}}{\gamma} \geq 0$, all terms in equation A.12.3 are positive for $\psi_C > 1$, and $\tilde{\Lambda} - \Lambda$ is strictly increasing in ψ_C.

A.13 Proof of theorem 5.2

By construction it holds that $X = X_D + X_C$. Totally differentiate this condition, divide both sides by X, and the expand the right-hand-side terms by $\frac{X_D}{X_D}$ and $\frac{X_C}{X_C}$, respectively, to get

$$\underbrace{\frac{dX}{X}}_{\hat{X}} = \underbrace{\frac{X_D}{X}}_{\beta_D} \underbrace{\frac{dX_D}{X_D}}_{\hat{X}_D} + \underbrace{\frac{X_C}{X}}_{\beta_C} \underbrace{\frac{dX_C}{X_C}}_{\hat{X}_C} \qquad \text{(A.13.1)}$$

By the exclusion of boundary-equilibria we have

Lemma A.7. *$\beta_C > 0$ and $\beta_D > 0$.*

By lemma 4.6 it holds that $\hat{X} = \varsigma \hat{p}_Y + \hat{Y}$. Use condition A.8.1 to substitute $\hat{Y}$, and condition A.13.1 to substitute $\hat{X}$ to get

$$\beta_D \hat{X}_D = \varsigma \hat{p}_Y + \alpha_D \hat{Y}_D + \alpha_C \hat{Y}_C - \beta_C \hat{X}_C \qquad \text{(A.13.2)}$$

Now use lemma 4.4 to substitute $\hat{Y}_C$, lemma 4.5 to substitute $\hat{Y}_D$, lemma 4.7 to substitute $\hat{p}_Y$, and recognize that $\hat{t} = 0$ by construction:

$$\beta_D \hat{X}_D = (\varsigma \theta_{YDE} + \alpha_D \theta_{YDL} \sigma_{YD}) \hat{r} - \beta_C \hat{X}_C$$

Using lemma 4.3 with $\hat{X}$ replaced by $\hat{X}_D$ to substitute $\hat{X}_D$, and in turn lemmas 4.4 and 4.5 to substitute $\hat{L}_{YC}$ and $\hat{L}_{YD}$, respectively, yields after rearrangement

$$\hat{r} = \underbrace{\left[\frac{\beta_C}{\theta_{YDE}\varsigma + \left(\alpha_D\theta_{YDL} + \beta_D\frac{L_{YD}}{L_X}\right)\sigma_{YD}}\right]}_{:=\upsilon}\hat{t} \tag{A.13.3}$$

Now, return to A.13.2. By $\hat{X}_D = \hat{L}_X = \hat{E}_X$ (lemmas 4.2 and 4.3) equations A.3.1, A.4.3, A.5.5, A.5.8, A.13.3, and lemmas 4.4 and 4.5 we get

$$\hat{E}_X = \left[\underbrace{\frac{\upsilon\theta_{YDE}}{\beta_D + \alpha_D\theta_{YDL}\frac{L_{YD}}{L_X}}\varsigma}_{\Upsilon_{\text{PE}}} \underbrace{- \frac{\beta_C}{\beta_D + \alpha_D\theta_{YDL}\frac{L_{YD}}{L_X}}}_{\Upsilon_{\text{RE}}}\right]\hat{X}_C$$

The term in brackets is the total effect Υ.

From lemmas A.1 and A.7 it follows that $\Upsilon_{\text{RE}} < 0$. By replacing

$$\alpha_D\theta_{YDL}\frac{L_{YD}}{L_X} := A$$

and recognizing $A > 0$ by lemma A.1, we have

$$\frac{\partial\Upsilon_{\text{QE}}}{\partial\beta_C} = -\frac{1+A}{(1-\beta_C+A)^2} < 0 \qquad \frac{\partial^2\Upsilon_{\text{QE}}}{\partial\beta_C^2} = -\frac{2(1+A)}{(1-\beta_C+A)^3} < 0$$

i.e. the replacement effect is decreasing and concave in β_C. Furthermore, it is directly apparent from the expression that the effect is independent from the elasticity parameters σ_{YC}, σ_{YD} and ς.

Plugging υ into Υ_{PE} and simplifying yields

$$\Upsilon_{\text{PE}} = \frac{B\beta_C\varsigma}{(C+B\beta_D)\varsigma + (\beta_D(\beta_D L_X L_{YD} + D) + E)\sigma_{YD}}$$

with

$$L_X^2\theta_{YDE} := B$$

$$L_X L_{YD}\alpha_D\theta_{YDE}\theta_{YDL} := C$$
$$\alpha_D\theta_{YDL}\left(L_X^2 + L_{YD}^2\right) := D$$

$$L_X L_{YD}\alpha_D^2\theta_{YDL} := E$$

From lemmas A.1 and A.7 it follows that $\Upsilon_{\text{PE}} = 0$ only if $\varsigma = 0$, else $\Upsilon_{\text{PE}} > 0$. Differentiating with respect to β_C yields

$$\frac{\partial\Upsilon_{\text{PE}}}{\partial\beta_C} > 0 \qquad \frac{\partial^2\Upsilon_{\text{PE}}}{\partial\beta_C^2} < 0$$

with respect to ς

$$\frac{\partial \Upsilon_{\text{PE}}}{\partial \varsigma} > 0 \qquad \frac{\partial^2 \Upsilon_{\text{PE}}}{\partial \varsigma^2} < 0$$

and with respect to σ_{YD}

$$\frac{\partial \Upsilon_{\text{PE}}}{\partial \sigma_{YD}} < 0 \qquad \frac{\partial^2 \Upsilon_{\text{PE}}}{\partial \sigma_{YD}^2} > 0$$

Now, observe that

$$\Upsilon = \frac{\beta_C}{\beta_D + \alpha_D \theta_{YDL} \frac{L_{YD}}{L_X}} \left(\frac{\theta_{YDE}\varsigma}{\theta_{YDE}\varsigma + \left(\alpha_D \theta_{YDL} + \beta_D \frac{L_{YD}}{L_X}\right) \sigma_{YD}} - 1 \right)$$

Since the first term is positive (by lemmas A.1 and A.7) and the first term in brackets is smaller or equal than one, it follows that $\Upsilon \leq 0$. Furthermore, the term in brackets is zero if and only if $\sigma_{YD} = 0$, else it is strictly negative. Differentiating with respect to β_C yields

$$\frac{\partial \Upsilon}{\partial \beta_C} > 0 \qquad \frac{\partial^2 \Upsilon}{\partial \beta_C^2} < 0$$

with respect to ς

$$\frac{\partial \Upsilon}{\partial \varsigma} > 0 \qquad \frac{\partial^2 \Upsilon}{\partial \varsigma^2} < 0$$

and with respect to σ_{YD}

$$\frac{\partial \Upsilon}{\partial \sigma_{YD}} < 0 \qquad \frac{\partial^2 \Upsilon}{\partial \sigma_{YD}^2} > 0$$

A.14 Proof of lemma 5.3

Each converter demands input quantity Y_X and supplies output quantity X_C to maximize profit subject to the technology constraint, taking the price vector (p_X, p_Y) as given:

$$(Y_X, X_C) \in \arg \max_{\left(\tilde{Y}_X, \tilde{X}_C\right)} \mathscr{L}_{XC}\left(\tilde{Y}_X, \tilde{X}_C\right)$$

where $\mathscr{L}_{XC}(\cdot)$ is the Lagragian function

$$\mathscr{L}_{XC}\left(\tilde{Y}_X, \tilde{X}_C\right) = p_X \tilde{X}_C - p_Y \tilde{Y}_X + \lambda_{XC}\left(\tilde{X}_C - X_C\left(\tilde{Y}_X\right)\right)$$

The first-order conditions of this program are

$$\begin{aligned} \lambda_{XC} &= -p_X \\ -\lambda_{XC} \frac{\partial X_C(\cdot)}{\partial Y_X} &= p_Y \\ X_C &= X_C(Y_X) \end{aligned}$$

By the first two FOC profit maximizing behavior is characterized by

$$\frac{dX_C(\cdot)}{dY_X} = \frac{p_Y}{p_X} \tag{A.14.1}$$

Define the elasticity of electricity demand

$$\sigma_{XC} := \frac{\frac{dY_X}{Y_X}}{\frac{d\left(\frac{p_Y}{p_X}\right)}{\frac{p_Y}{p_X}}}$$

such that

$$\frac{dY_X}{Y_X} = \sigma_{XC} \frac{d\left(\frac{p_Y}{p_X}\right)}{\frac{p_Y}{p_X}}$$

or in growth rate notation

$$\hat{Y}_X = \sigma_{XC}(\hat{p}_X - \hat{p}_Y)$$

Since $\hat{\tau} = 0$ (by construction) and $\hat{w} = 0$ (w is numeraire) $\hat{p}_X = 0$ holds, such that we have $\hat{Y}_X = -\sigma_{XC}\hat{p}_Y$.

Now, totally differentiate the third FOC and use condition A.14.1 to get

$$dX_C = \frac{p_Y}{p_X} dY_X$$

Divide both sides by X_C and expand the right-hand side by $\frac{Y_X}{Y_X}$, yielding

$$\underbrace{\frac{dX_C}{X_C}}_{\hat{X}_C} = \frac{p_Y Y_X}{p_X X_C} \underbrace{\frac{dY_X}{Y_X}}_{\hat{Y}_X} \tag{A.14.2}$$

Consider the definition of scale elasticity (which in this case is equal to the elasticity of output with respect to electricity, since this is the only factor of production)

$$\theta_{XC} := \frac{\partial X_C(\cdot)}{\partial Y_X} \frac{Y_X}{X_C}$$

Use again condition A.14.1 to obtain

$$\theta_{XC} = \frac{p_Y Y_X}{p_X X_C} \tag{A.14.3}$$

such that we have (by equations A.14.2 and A.14.3) $\hat{X}_C = \theta_{XC}\hat{Y}_X$. Plugging in $\hat{Y}_X = -\sigma_{XC}\hat{p}_Y$ finally yields $\hat{X}_C = -\theta_{XC}\sigma_{XC}\hat{p}_Y$.

It remains to show that $\theta_{XC} < 0$. Since the conversion sector operates under decreasing returns, we have $X_C(nY_X) = n^k X_C(Y_X)$ with $k < 1$ for any $n > 0$, and therefore by Euler's homogenous function theorem and condition A.14.1

$$kX_C(Y_X) = \frac{p_Y}{p_X} Y_X \Leftrightarrow p_X k X_C(Y_X) = p_Y Y_X$$

Since $k < 1$, this equation can only be true if $p_X X_C > p_Y Y_X$. Using this condition in equation A.14.3 yields $\theta_{XC} < 1$.

A.15 Proof of lemma 5.4

By lemma 4.6 it holds that $\hat{X} = \varsigma \hat{p}_Y + \hat{Y}$. Use condition A.8.1 to substitute $\hat{Y}$, and condition A.13.1 to substitute $\hat{X}$ to get

$$\beta_D \hat{X}_D + \beta_C \hat{X}_C = \varsigma \hat{p}_Y + \alpha_D \hat{Y}_D + \alpha_C \hat{Y}_C \tag{A.15.1}$$

Now use lemma 4.4 to substitute $\hat{Y}_C$, lemma 4.5 to substitute $\hat{Y}_D$, lemma 5.3 to substitute $\hat{X}_C$, and lemma 4.7 to substitute $\hat{p}_Y$:

$$\beta_D \hat{X}_D = (\varsigma \theta_{YDE} + \beta_C \theta_{XC} \sigma_{XC} \theta_{YDE} + \alpha_D \theta_{YDL} \sigma_{YD})\,\hat{r} + \alpha_C \theta_{YC} \sigma_{YC} \hat{t}$$

Finally, using the adjusted lemma 4.3 to substitute $\hat{X}_D$, and in turn lemmas 4.4 and 4.5 to substitute $\hat{L}_{YC}$ and $\hat{L}_{YD}$, respectively, yields after rearrangement

$$\hat{r} = -\underbrace{\left[\frac{(L_X \alpha_C \theta_{YC} + \beta_D L_{YC})\,\sigma_{YC}}{(L_X \alpha_D \theta_{YDL} + \beta_D L_{YD})\,\sigma_{YD} + (\varsigma + \beta_C \theta_{XC} \sigma_{XC})\,L_X \theta_{YDE}}\right]}_{:=\mathring{\gamma}} \hat{t} \tag{A.15.2}$$

By the same arguments as in section A.8 it is straightforward to show that $\mathring{\gamma}$ has the same properties as γ stated in lemma 4.8. Furthermore, for $\beta_C = 0$ (i.e. there is effectively no conversion sector, such that we are back in the benchmark case) we have $\mathring{\gamma} = \gamma$. Differentiating $\mathring{\gamma}$ yields

$$\frac{\partial \mathring{\gamma}}{\partial \beta_C} = A^{-1} L_X \sigma_{YC} \left[(L_X \alpha_C \theta_{YC} - L_X \alpha_D \theta_{YDL}) - B - C \right]$$

with

$$A := (L_X \alpha_D \theta_{YDL} + \beta_D L_{YD})\,\sigma_{YD} + (\varsigma + \beta_C \theta_{XC} \sigma_{XC})\,L_X \theta_{YDE}$$

$$B := L_{YC} \theta_{YDE} \varsigma$$

$$C := \sigma_{XC} \left(\theta_{XC} \theta_{YDE} \left(L_{YC} + L_X \alpha_C \theta_{YC} \right) \right)$$

From lemmas A.1 and A.7 it follows that $A > 0$, such that derivative is greater or equal to zero if

$$L_X \alpha_C \theta_{YC} - L_X \alpha_D \theta_{YDL} \geq B + C$$

or after some rearrangement

$$\frac{\varsigma}{\sigma_{YD}} \leq \frac{L_{YD} \alpha_C \theta_{YC} - L_{YC} \alpha_D \theta_{YDL}}{L_{YC} \theta_{YDE}} - \frac{C}{L_{YC} \theta_{YDE} \sigma_{YD}}$$

By lemma A.1 the second quotient on the right-hand side is non-negative, and the rest of the expression is identical to condition A.9.2. By the same argument as in section A.9 the right-hand side is strictly negative and the left-hand side non-negative. such that the inequality is never true but the reverse. It follows that $\mathring{\gamma}$ is strictly decreasing in β_C, such that $\mathring{\gamma} < \gamma$, and (since γ is independent from β_C) the difference $\gamma - \mathring{\gamma}$ is strictly increasing in β_C.

A.16 Proof of theorem 5.3

Consider equation A.15.1. By equations A.4.2, A.4.3, A.5.5, A.5.8 and lemma 5.3 this becomes

$$\beta_D \hat{X}_D = (\varsigma - \beta_C \theta_{XC} \sigma_{XC})\, \hat{p}_Y + \alpha_D \theta_{YDL} \hat{L}_{YD} + \alpha_C \theta_{YC} \hat{L}_{YC}$$

Using the labor-capital market clearance condition A.3.1 to substitute $\hat{L}_{YD}$ and $\hat{L}_{YC}$, and recognizing $\hat{X}_D = \hat{L}_X = \hat{E}_X$ (lemmas 4.2 and 4.3) yields after some rearrangement

$$\hat{E}_X (\beta_D + \delta) = (\varsigma - \beta_C \theta_{XC} \sigma_{XC})\, \theta_{YDL} \hat{r} - \frac{L_{YC}}{L_{YD}} \alpha_D \theta_{YDL} \hat{L}_{YC} - \frac{L_{YD}}{L_{YC}} \alpha_C \theta_{YC} \hat{L}_{YD}$$

Finally, using lemma 4.4 to substitute $\hat{L}_{YC}$, lemma 4.5 to substitute $\hat{L}_{YD}$, equation A.15.2 to substitute $\hat{r}$, and rearranging yields

$$\hat{E}_X = \left[\underbrace{\mathring{\gamma} \frac{\alpha_C \theta_{YC} L_{YD}}{(\beta_D + \delta) L_{YC}} \sigma_{YD}}_{\mathring{\Lambda}_{\text{IARE}}} \underbrace{- \mathring{\gamma} \frac{\theta_{YDE}}{(\beta_D + \delta)} \varsigma}_{\mathring{\Lambda}^H_{\text{ITTE}}} \underbrace{- \mathring{\gamma} \frac{\beta_C \theta_{XC} \theta_{YDE}}{(\beta_D + \delta)} \sigma_{XC}}_{\Lambda^X_{\text{ITTE}}} \underbrace{- \frac{\alpha_D \theta_{YDL} L_{YC}}{(\beta_D + \delta) L_{YD}} \sigma_{YC}}_{\mathring{\Lambda}_{\text{DARE}}} \right] \hat{t}$$

The term in brackets is the total leakage effect.

Comparing the expressions for $\mathring{\Lambda}_{\text{DARE}}$ and Λ_{DARE}, it is immediately apparent that $\mathring{\Lambda}_{\text{DARE}} = \Lambda_{\text{DARE}}$ only if $\beta_C = 0$ or $\sigma_{YC} = 0$, and

$$\frac{\partial \mathring{\Lambda}_{\text{DARE}}}{\partial \beta_C} < 0$$

such that by lemma A.7 $\mathring{\Lambda}_{\text{DARE}} \leq \Lambda_{\text{DARE}}$ with equality only if $\sigma_{YC} = 0$. Likewise, we have $\mathring{\Lambda}_{\text{IARE}} = \Lambda_{\text{IARE}}$ only if $\beta_C = 0$ or $\sigma_{YC} = 0$ or $\sigma_{YD} = 0$ and

$$\frac{\partial \mathring{\Lambda}_{\text{IARE}}}{\partial \beta_C} < 0$$

such that by lemma A.7 $\mathring{\Lambda}_{\text{IARE}} \leq \Lambda_{\text{IARE}}$ with equality only if $\sigma_{YC} = 0$ or $\sigma_{YD} = 0$. Finally, we have $\mathring{\Lambda}^H_{\text{ITTE}} = \Lambda_{\text{ITTE}}$ only if $\beta_C = 0$ or $\sigma_{YC} = 0$ or $\varsigma = 0$ and

$$\frac{\partial \mathring{\Lambda}^H_{\text{ITTE}}}{\partial \beta_C} > 0$$

such that by lemma A.7 $\mathring{\Lambda}^H_{\text{ITTE}} \geq \Lambda_{\text{ITTE}}$ with equality only if $\sigma_{YC} = 0$ or $\varsigma = 0$.

In completely resolved form, the total leakage effect is given by

$$\mathring{\Lambda} = \frac{[A\sigma_{YD} - B\varsigma - C\sigma_{XC}]\, \sigma_{YC}}{D\,[\theta_{YDE} (\varsigma + \theta_{XC} \sigma_{XC}) + \alpha_D \theta_{YDL} \sigma_{YD}]} \tag{A.16.1}$$

with

$$A := \alpha_C^2\theta_{YC}^2L_{YD}^2 - \alpha_D^2\theta_{YDL}^2L_{YC}^2$$
$$B := L_{YC}\theta_{YDE}\left(\alpha_C L_{YD}\theta_{YC} + \alpha_D L_{YC}\theta_{YDL}\right)$$
$$C := L_{YC}\theta_{YDE}\theta_{XC}\left(\beta_C\alpha_C L_{YD}\theta_{YC} + \alpha_D L_{YC}\theta_{YDL}\right)$$
$$D := \left(\alpha_C L_X L_{YD}\theta_{YC} + \alpha_D L_X\theta_{YDL} + \beta_D L_{YD}\right)L_{YC}$$

From lemmas A.1 and A.7 it follows that the denominator is positive, such that $\mathring{\Lambda} \geq 0$ if and only if either $\sigma_{YC} = 0$ (with equality) or

$$\left[A\sigma_{YD} - B\varsigma - C\sigma_{XC}\right]\sigma_{YC} \geq 0 \Leftrightarrow \frac{\varsigma}{\sigma_{YD}} + \frac{C\sigma_{XC}}{B\sigma_{YD}} \geq \frac{A}{B}$$

The left-hand side is positive (by lemmas A.1 and A.7). Substituting the parameters on the right-hand side back into their fundamental variables and rearranging yields

$$\frac{wL_{YD}Y_D}{rE_YYt}\left(\frac{p_Y}{1+\frac{t}{p_Y}} - \frac{t}{1+\frac{p_Y}{t}}\right) < 0 \tag{A.16.2}$$

from assumption $t > p_Y$, such that $\mathring{\Lambda} > 0$ is ruled out and $\mathring{\Lambda} \leq 0$ holds (with equality only if $\sigma_{YC} = 0$).

Now, observe that for $\beta_C = 0$

$$\mathring{\Lambda} = \gamma\frac{\alpha_C\theta_{YC}L_{YD}}{(1+\delta)L_{YC}}\sigma_{YD} - \gamma\frac{\theta_{YDE}}{(1+\delta)}\varsigma - \frac{\alpha_D\theta_{YDL}L_{YC}}{(1+\delta)L_{YD}}\sigma_{YC} = \Lambda$$

Differentiating $\mathring{\Lambda}$ with respect to β_C yields

$$\frac{\partial\mathring{\Lambda}}{\partial\beta_C} = -\frac{L_{YC}L_{YD}H\left(F+V+Z\right)}{\left(GH+\beta_D L_{YC}L_{YD}H\right)^2}$$

with

$$V := -\left(A\sigma_{YD} - B\varsigma\right)\sigma_{YC}$$

which is positive by condition A.16.2, and

$$F := L_{YC}^2\alpha_D\theta_{XC}\theta_{YDE}\theta_{YDL}$$

$$G := \left(\alpha_C L_{YD}\theta_{YC} + \alpha_D\theta_{YDL}\right)L_X L_{YC}$$
$$H := \theta_{YDE}\left(\varsigma + \theta_{XC}\sigma_{XC}\right) + \alpha_D\theta_{YDL}\sigma_{YD}$$
$$Z := \alpha_C L_{YC}L_{YD}\theta_{YC}\theta_{YDE}\sigma_{XC}\sigma_{YC}$$

which are all non-negative by lemma A.1, such that the derivative is non-positive. It follows that $\Lambda > \mathring{\Lambda}$ for all $\beta_C > 0$, and that the difference $\Lambda - \mathring{\Lambda}$ is increasing in β_C.

A.17 Proof of theorem 5.4

By the adjusted lemma 4.6 it holds that $\hat{X} = \varsigma \hat{p}_Y + \hat{Y} - \hat{e}$. Use condition A.8.1 to substitute $\hat{Y}$ and lemma 4.7 to substitute $\hat{p}_Y$ to get

$$\hat{X} = \varsigma \theta_{YDE} \hat{r} + \alpha_D \hat{Y}_D + \alpha_C \hat{Y}_C - \hat{e}$$

Now use lemma 4.4 to substitute $\hat{Y}_C$ and lemma 4.5 to substitute $\hat{Y}_D$:

$$\hat{X} = (\varsigma \theta_{YDE} + \alpha_D \theta_{YDL} \sigma_{YD}) \hat{r} + \alpha_C \theta_{YC} \sigma_{YC} \hat{t} - \hat{e}$$

Finally, using lemma 4.3 to substitute $\hat{X}$, and in turn lemmas 4.4 and 4.5 to substitute $\hat{L}_{YC}$ and $\hat{L}_{YD}$, respectively, yields after rearrangement

$$\hat{r} = \underbrace{\left[\frac{L_X}{(L_X \alpha_D \theta_{YDL} + L_{YD}) \sigma_{YD} + L_X \theta_{YDE} \varsigma} \right]}_{:=\varepsilon} \hat{e} - \gamma \hat{t} \tag{A.17.1}$$

By the adjusted lemma 4.6 it holds that $\hat{X} = \varsigma \hat{p}_Y + \hat{Y} - \hat{e}$. Using lemma 4.7 to substitute $\hat{p}_Y$ and equation A.8.1 to substitute $\hat{Y}$, we get

$$\hat{X} = \varsigma \theta_{YDE} \hat{r} + \alpha_D \hat{Y}_D + \alpha_C \hat{Y}_C - \hat{e}$$

By equations A.4.2, A.4.3, A.5.5 and A.5.8 this becomes

$$\hat{X} = \varsigma \theta_{YDE} \hat{r} + \alpha_D \theta_{YDL} \hat{L}_{YD} + \alpha_C \theta_{YC} \hat{L}_{YC} - \hat{e}$$

Using the labor-capital market clearance condition A.3.1 to substitute $\hat{L}_{YD}$ and $\hat{L}_{YC}$, and recognizing $\hat{X} = \hat{L}_X = \hat{E}_X$ (lemmas 4.2 and 4.3) yields after some rearrangement

$$\hat{E}_X (1+\delta) = \varsigma \theta_{YDE} \hat{r} - \frac{L_{YC}}{L_{YD}} \alpha_D \theta_{YDL} \hat{L}_{YC} - \frac{L_{YD}}{L_{YC}} \alpha_C \theta_{YC} \hat{L}_{YD} - \hat{e}$$

with $\delta > 0$ by lemma A.1. Finally, using lemma 4.4 to substitute $\hat{L}_{YC}$, lemma 4.5 to substitute $\hat{L}_{YD}$, lemma 4.8 to substitute $\hat{r}$, and rearranging yields

$$\hat{E}_X = \Lambda \hat{t} + \left[\underbrace{\varepsilon \frac{\theta_{YDE}}{(1+\delta)} \varsigma}_{\Phi_{\text{PE}}} - \underbrace{\varepsilon \frac{\alpha_C \theta_{YC} L_{YD}}{(1+\delta) L_{YC}} \sigma_{YD} - \frac{1}{(1+\delta)}}_{\Phi_{\text{EE}}} \right] \hat{e}$$

The total effect on emissions of an increase in technical efficiency is the term in bracket. Note that

$$\varepsilon \frac{\theta_{YDE}}{(1+\delta)} \varsigma - \frac{1}{(1+\delta)} = \frac{1}{(1+\delta)} \left[\frac{L_X \theta_{YDE} \varsigma}{(L_X \alpha_D \theta_{YDL} + L_{YD}) \sigma_{YD} + L_X \theta_{YDE} \varsigma} - 1 \right] < 0$$

such that $\Phi < 0$.

A.18 Proof of theorem 5.5

Specifically, define the concept of *actual emission reduction* (in relative terms) as

$$\widehat{\text{AER}} := -\hat{E}$$

which is by lemma 4.1 and theorem 4.1 equal to $-\phi\Lambda\hat{t}$.

Define the bias of the VER statistic as

$$B := \widehat{\text{VER}} - \widehat{\text{AER}}$$

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

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

Substituting Λ using equation A.9.1, we get

$$B = \underbrace{\left[(1-\phi)\frac{\alpha_C}{\alpha_D}\theta_{YC} + \phi\frac{[(L_{YD}\alpha_C\theta_{YC} - L_{YC}\alpha_D\theta_{YDL})\,\sigma_{YD} - L_{YC}\theta_{YDE}\varsigma]}{(L_X\alpha_D\theta_{YDL} + L_{YD})\,\sigma_{YD} + L_X\theta_{YDE}\varsigma}\right]}_{b}\sigma_{YC}\hat{t} \tag{A.18.1}$$

Thus, the bias is a linear function of $\hat{t}$ and σ_{YC}, which proves the third statement of the theorem.

By direct application of theorem 4.1, b is strictly increasing and concave in σ_{YD}, and strictly decreasing and convex in ς, which proves the second statement of the theorem. Furthermore, substituting the parameters in expression A.18.1 using equations A.4.3, A.5.3, A.8.1, and definition $\phi = E_X/E$, it holds that $b \leq 0$ (i.e. consistent underestimation) if

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

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 either σ_{YC} or b is zero (assuming $\hat{t} > 0$, otherwise the analysis is meaningless), otherwise $B \neq 0$, which gives rise to the first statement of the theorem.

Rearranging the term Q yields

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

with

$$Q_1 = \frac{p_Y Y_D w L_X}{t Y_C} > 0$$

and

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

i.e. the lower the emission intensity in sector X the more likely Q is positive.
Rearranging the term R yields

$$R = \left(t Y_C w L_Y \frac{Y_C}{r} - \frac{E_X}{w L_X} \right) R_1$$

with

$$R_1 = r E_Y w L_X > 0$$

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

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

Baylis et al. (2013, 2014) 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 4.6 it holds that $\hat{X} = \varsigma \hat{p}_Y + \hat{Y}$. Using lemma 4.2 to substitute $\hat{X}$, lemma 4.7 to substitute $\hat{p}_Y$, equation A.8.1 to substitute $\hat{Y}$, and assumption $\hat{t} = 0$ we get

$$\hat{E}_X = \varsigma \theta_{YDE} \hat{r} + \alpha_D \hat{Y}_D \tag{B.0.2}$$

Now, by equations A.5.5 and A.5.7 it holds that

$$\hat{Y}_D = \hat{L}_{YD} - \theta_{YDE} \sigma_{YD} \hat{r}$$

Using lemmas 4.2 and 4.3 to substitute $\hat{L}_{YD}$, and assumption $\hat{t} = 0$ we get

$$\hat{Y}_D = -\frac{L_X}{L_{YD}} \hat{E}_X - \theta_{YDE} \sigma_{YD} \hat{r} \tag{B.0.3}$$

Using equation B.0.3 to substitute $\hat{Y}_D$ in equation B.0.2 yields

$$\hat{E}_X = \beta \left[\varsigma - \alpha_D \sigma_{YD} \right] \theta_{YDE} \hat{r} = \left[\underbrace{\beta \varsigma \theta_{YDE}}_{\text{TTE}} - \underbrace{\beta \alpha_D \sigma_{YD} \theta_{YDE}}_{\text{ARE}} \right] \hat{r} \tag{B.0.4}$$

with

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

Expression B.0.4 is the analogue to expression 11 in Baylis et al. (2013, 2014). 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 sector Y_D substitute from carbon into labor-capital for abatement (to an extent that depends on the elasticity of technical substitution σ_{YD}) and thus bid labor-capital away from sector X. Alone, it would decrease the output of X and emissions E_X (because of constant factor prices firms in that sector choose not to substitute but reduce the input of both factors), and is therefore a negative leakage term.

But note that in Baylis et al. (2013, 2014) setting we have at the same time $\hat{E}_Y < 0$, that is, emissions in sector 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.

C Electricity as an input: alternative setting

Adjust the model such that the production function in sector X is $X(L_X, E_X, Y_X)$, where Y_X is the quantity of good Y demanded by firms in sector X as an input. Thus, in equilibrium production of good Y must meet demand from households and firms in sector X, $Y = y + Y_X$.

Lemma 4.1 remains true in this setting, but lemma 4.2 must be modified as follows:

Lemma C.1. *Let $\hat{Y}_X$ be the growth of demand for good Y, and θ_{XL} the elasticity if output with respect to factor Y in sector X. Then $\hat{E}_X = \frac{1}{1-\theta_{XY}}\left(\hat{X} - \theta_{XY}\hat{Y}_X\right)$, where θ_{XY} is equal to the factor Y payroll share of total costs and thus* $0 < \theta_{XY} < 1$.

The proof is equal to section A.2 but with the new production function. This means that emissions in sector X are not only driven by changes in output but also by a substitution between electricity and the other two factors. This substitution is, of course, driven by changes in the electricity price:

Lemma C.2. *Let σ_{XY} be the elasticity of technical substitution between factor Y and labor-capital or emissions. Then $\hat{E}_X - \hat{Y}_X = \sigma_{XY}\hat{p}_Y$ or equivalently $\hat{L}_X - \hat{Y}_X = \sigma_{XY}\hat{p}_Y$.*

The proof is again equal to section A.6 with the respective indices replaced.

Those two results are the key differences to the benchmark setting, and given what we know about the structure of the leakage effects, it is readily apparent where they are going to bring us: in essence, firms in sector X will respond to electricity price changes just as households do. If the price increases, they will substitute away from electricity into labor-capital and emissions, and vice versa. Since the electricity price will fall in response to a raise of the FIT, firms in sector X will substitute into electricity, lowering their emissions, *ceteris paribus*. This, the consumer induced ITTE is supplemented by an industry induced ITTE.

The formal derivation is rather straightforward. First, we recognize that the permit price adjustment will be different in size compared to the benchmark case. We replace lemma 4.8 by

Lemma C.3. *$\hat{r} = -\check{\gamma}\hat{t}$, where $\check{\gamma} = 0$ if and only if $\sigma_{YC} = 0$, and for $\sigma_{YC} > 0$*

- *$\check{\gamma} > 0$*
- *$\check{\gamma}$ is strictly increasing and linear in σ_{YC}*
- *$\check{\gamma}$ is strictly decreasing and concave in σ_{YD}, σ_{XY} and ς, with $\gamma \to 0$ for either $\sigma_{YC} \to \infty$ or $\sigma_{XY} \to \infty$ or $\varsigma \to \infty$ or both.*

This implies that the indirect effects will be different to the benchmark case as well.

Theorem C.1. *Let $\check{\Lambda}$ denote the elasticity of sector X's emissions with respect to the FIT, that is, $\hat{E}_X = \check{\Lambda}\hat{t}$ and (by lemma 4.1) $\hat{E} = \phi\check{\Lambda}\hat{t}$. Then*

$$\check{\Lambda} = \Lambda_{\text{DARE}} + \check{\Lambda}_{\text{IARE}} + \underbrace{\check{\Lambda}^{H}_{\text{ITTE}} + \Lambda^{X}_{\text{ITTE}}}_{\check{\Lambda}_{\text{ITTE}}}$$

whereas

- *$\check{\Lambda}_{\text{DARE}} \leq 0$ and $\check{\Lambda}_{\text{DARE}} \leq \Lambda_{\text{DARE}}$ with equality, respectively, if and only if $\sigma_{YC} = 0$,*
- *$\check{\Lambda}_{\text{IARE}} \geq 0$ and $\check{\Lambda}_{\text{IARE}} \leq \Lambda_{\text{IARE}}$ with equality, respectively, if and only if $\sigma_{YC} = 0$ or $\sigma_{YD} = 0$ (or both),*
- *$\check{\Lambda}^{H}_{\text{ITTE}} \leq 0$ and $\check{\Lambda}^{H}_{\text{ITTE}} \geq \Lambda_{\text{ITTE}}$ with equality, respectively, if and only if $\sigma_{YC} = 0$ or $\varsigma = 0$ (or both),*
- *$\Lambda^{X}_{\text{ITTE}} \leq 0$ with equality if and only if $\sigma_{XY} = 0$,*
- *$\check{\Lambda} \leq 0$ with equality if and only if $\sigma_{YC} = 0$, and $\Lambda \geq \check{\Lambda}$ with the difference $\Lambda - \check{\Lambda}$ being increasing in β_C.*

The proof is a straightforward adjustment of section A.16, so we avoid repetition here.