Subsidizing Renewable Energy: The Case of Budget-Neutrality

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ABSTRACT

A growing need for fiscal consolidation and the aspiration to support renewable energy may pave the way for budget-neutral tax-subsidy schemes within the energy sector. This paper evaluates the feasibility of subsidies to renewable energy financed by taxing conventional energy and derives the implication for the energy price. The three main findings are as follows: first, there exists an upper limit on the subsidy for renewable energy that can be financed budget-neutrally; second, the energy price might not necessarily increase for sufficiently small subsidy increases, but the likelihood becomes higher for stronger deteriorations of the production efficiency; and third, pre-existing taxes on conventional energy and/or subsidies for renewable energy decrease the scope for budget-neutral additional support to renewable energy and make increasing energy prices more likely. The results are strengthened if convex instead of linear marginal cost functions are considered. Critical thoughts about the welfare implications of such policy interventions are raised in the final part of the paper.

KEYWORDS: renewable energy subsidy, carbon tax, government budget, energy price

JEL: Q48, Q42, H23, H62

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1. Introduction

Fiscal problems of highly indebted states and the growing need for action against the imminent climate change will create a conflict laden policy environment in the still-young decade. Thus, the adoption of measures to promote renewable energy might in the future depend even more strongly on the feasibility of financing them budget-neutrally, which would in practice imply the financing of subsidies for renewable energy by taxing conventional energy—in particular fossil energy. In Germany, for instance, this is the applied method of financing the expenses for feed-in tariffs for renewable energy (known as the *EEG* cost apportionment), and it is similarly used in Switzerland in the form of a cost covering fee to finance the subsidy to electricity from renewable energy.

This paper aims at shedding light on this issue by explaining the scope for budget-neutral subsidies to renewable energy and by deriving the implications of this policy for energy price. At first view, one could expect energy prices to increase when a budget-neutral tax-subsidy scheme is implemented as the resultant electricity generation would not satisfy production efficiency, and one could expect that part of the inefficiency would be borne by consumers. This, however, is not simply the case since energy is supplied from a set of sources and a total supply increase (yielding a price decline) is possible if the subsidized energy sources expand supply more than the taxed ones shrink.

The starting points of the analysis are the models by Fischer (2009), Böhringer and Rosendahl (2010), and Fischer and Preonas (2010), which, among other questions, analyze how the introduction of or an increase in subsidy to renewable electricity affects the electricity market outcome. Fischer (2009) shows that the introduction of a system of tradable green certificates (TGC) is equivalent to a subsidy to producers of electricity from renewable energy combined with a tax on all other electricity producers. One finding is that it is the relative elasticities of supply that determine whether the electricity price will increase or decrease when the TGC system is implemented. Böhringer and Rosendahl (2010) confirm the result of Fischer (2009) and add, for instance, that a price decrease is more likely when an emissions quota is in place as well. This is because the implicit tax on fossil electricity due to the TGC is partly counterbalanced by a decline in the emissions price, which in itself has a stimulating effect on fossil electricity generation and implies a tendency for the electricity price to decline. A similar intuition is given by Kemfert and Traber (2009) in their quantitative analysis of the effect of Germany's tax-financed feed-in tariff for renewable energy on electricity prices in Europe.

This paper contributes to the literature in three ways. First, it explicitly defines the scope for budget-neutral tax-subsidy schemes, in particular pointing out that there exists an upper limit on the subsidy to renewable electricity that can be financed by only taxing conventionally generated electricity. Second, it shows that the electricity price might not necessarily increase for sufficiently small budget-neutral subsidy increases, but the likelihood of price rise becomes higher for stronger deteriorations in production efficiency. Third, the analysis illustrates that pre-existing taxes on conventionally generated electricity and/or subsidies to renewable electricity decrease the scope for additional budget-neutral support to renewable energy, and that at the same time increasing electricity prices become more likely. The results are strengthened if convex instead of linear marginal cost functions are considered.

The remainder of the paper is organized as follows: Section 2 introduces the general idea of the model and derives the electricity market equilibrium. In section 3, tax-subsidy schemes that satisfy the condition of budget-neutrality are specified, whereas in section 4 the effect on electricity price is derived. Differing pre-existing policy schemes and their impact on the feasibility of further renewable electricity promoting measures are evaluated in section 5. In section 6, the validity of the previously derived results in case of convex marginal cost functions is shown. The paper ends with a conclusion and a discussion of welfare implications in section 7.

2. Utility firm optimum and the market equilibrium

The model consists of two players, the national government and a representative utility firm. At the first stage, the government implements a renewable electricity subsidy and a corresponding fossil electricity tax, which together—taking into account the reaction of the utility firm—satisfy a budget-neutrality condition. At the second stage, the representative utility firm optimizes its electricity generation mix, taking the implemented policy as given. The model is solved by backward induction.

At stage two, the representative utility firm maximizes its profit Π from electricity generated from fossil energy, E^F, and from renewable energy, E^W:

$$\max_{E^F,E^W} \Pi = [p - \tau] \cdot E^F + [p + \sigma] \cdot E^W - K^F(E^F) - K^W(E^W) \qquad (1)$$

The retail electricity price is determined on a competitive market and defined by p, whereas τ and σ are the fossil electricity tax and renewable electricity subsidy, respectively, that were in place *before* this government had acted. Finally, K^i are the associated cost functions ($K^{i'} > 0$, $K^{i''} > 0$, $i = F, W$). The first order conditions for an inner optimal solution are:

$$p - \tau = K^{F'}(E^F) \qquad (2)$$

$$p + \sigma = K^{W'}(E^W) \qquad (3)$$

In equilibrium, the price p^* equates the electricity demand $D(p)$, $D' < 0$, with total electricity supply. The market clearing condition is:

$$D(p^*) = E^F(p^*, \tau) + E^W(p^*, \sigma) \qquad (4)$$

As the aim is to analyze the reaction to a new tax-subsidy scheme (that can differ from the pre-existing one), total differentiation of equations $(2) - (4)$ is required. Solving for dp yields

$$dp = s^D \cdot (dE^F + dE^W) \qquad (5)$$

where $s^D \equiv 1/D'$ is the slope of the inverse demand function. Defining, for the purpose of simpler notation, $s^i \equiv K^{i''}$, where s^i is the slope of the inverse supply curve of electricity generation possibility i, then the corresponding quantity reactions to changes in the pre-existing tax-subsidy scheme are:

$$dE^F = \frac{dp - d\tau}{s^F} \qquad (6)$$

$$dE^W = \frac{dp + d\sigma}{s^W} \qquad (7)$$

Substituting equations (6) and (7) in (5) and solving for the price change in case of a change in the tax-subsidy scheme yields

$$dp = -d\sigma \cdot \omega^W + d\tau \cdot \omega^F \qquad (8)$$

where $\omega^W \equiv \frac{1}{1+\frac{s^W}{|s^D|}+\frac{s^W}{s^F}}$ and $\omega^F \equiv \frac{1}{1+\frac{s^F}{|s^D|}+\frac{s^F}{s^W}}$, for which it holds that $0 < \omega^W, \omega^F < 1$ and $\omega^W + \omega^F \leq 1$. The variables ω^W and ω^F determine, ceteris paribus, the extent to which the price changes when a change in the renewable electricity subsidy and/or the fossil electricity tax is implemented such that a new equilibrium on the electricity market is attained.

Finally, it should be noted that the validity of the results, in principle, would be limited to inframarginal variations of the tax and the subsidy, or to the case in which the marginal cost functions are linear in the relevant segment. The implications of relaxing this restriction, however, are discussed in section 6.

3. Tax-subsidy schemes under the condition of budget-neutrality

At stage one, the government decides on the subsidy for renewable electricity and the corresponding tax on fossil electricity. Assuming for the moment that currently neither a tax nor a subsidy is in place, the budget-neutrality condition for the proposed tax-subsidy scheme is

$$\underbrace{d\tau \cdot (E^F + dE^F)}_{(additional)\ tax\ revenues} = \underbrace{d\sigma \cdot (E^W + dE^W)}_{(additional)\ subsidy\ expenses} \qquad (9)$$

where E^F and E^W are the quantities of fossil and renewable electricity, respectively, before the policy was changed.

Substituting (8) in (6) and (7), and then substituting the resulting equations for dE^F and dE^W in (9) gives a relationship between the change in the fossil electricity tax and the renewable energy subsidy that—accounting for the reactions of the utility firm—yields budget-neutrality. The resulting condition can after some re-arranging be written as an equation of a conic section of the form

$$A \cdot (d\sigma^*)^2 + B \cdot d\sigma^* \cdot d\tau^* + C \cdot (d\tau^*)^2 + d\sigma^* \cdot E^W - d\tau^* \cdot E^F = 0 \qquad (10)$$

where $A = \frac{1-\omega^W}{s^W} > 0$, $B = \frac{\omega^W}{s^F} + \frac{\omega^F}{s^W} > 0$, $C = \frac{1-\omega^F}{s^F} > 0$, and the scheme $(d\sigma^*, d\tau^*)$ is its solution. As the discriminant is $B^2 - 4 \cdot A \cdot C < 0$, equation (10) describes a real ellipse.[1, 2] The roots of equation (10) are $\{d\tau_1^* = 0, d\tau_2^* = E^F/C > 0\}$ and $\{d\sigma_1^* = 0, d\sigma_2^* = -E^W/A < 0\}$.

Thus, an ellipse as in Figure 1 represents all possible schemes $(d\sigma^*, d\tau^*)$ that solve equation (10). The tax-subsidy schemes leading to a budget surplus lie within the ellipse, all schemes outside the ellipse imply a budget deficit.

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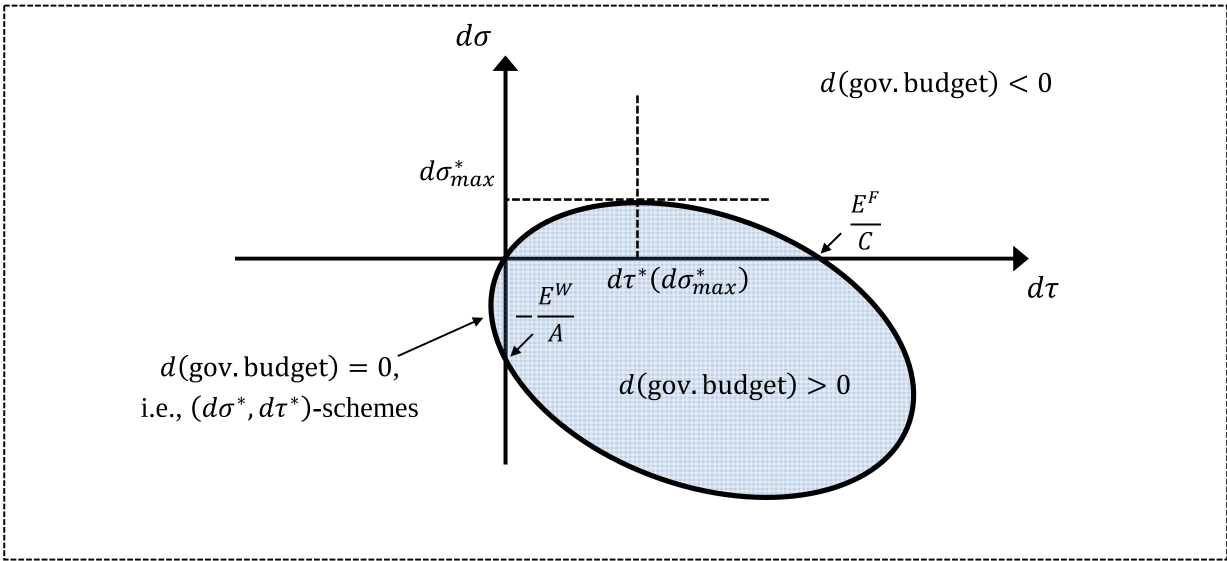
[1] $B^2 - 4 \cdot A \cdot C = -\frac{4}{s^F \cdot s^W + |s^D| \cdot (s^W + s^F)} < 0$.

[2] Note that it is not a circle since $\det\begin{pmatrix} A & B/2 & E^W/2 \\ B/2 & C & -E^F/2 \\ E^W/2 & -E^F/2 & 0 \end{pmatrix} < 0$, that is, it is a non-degenerate case.

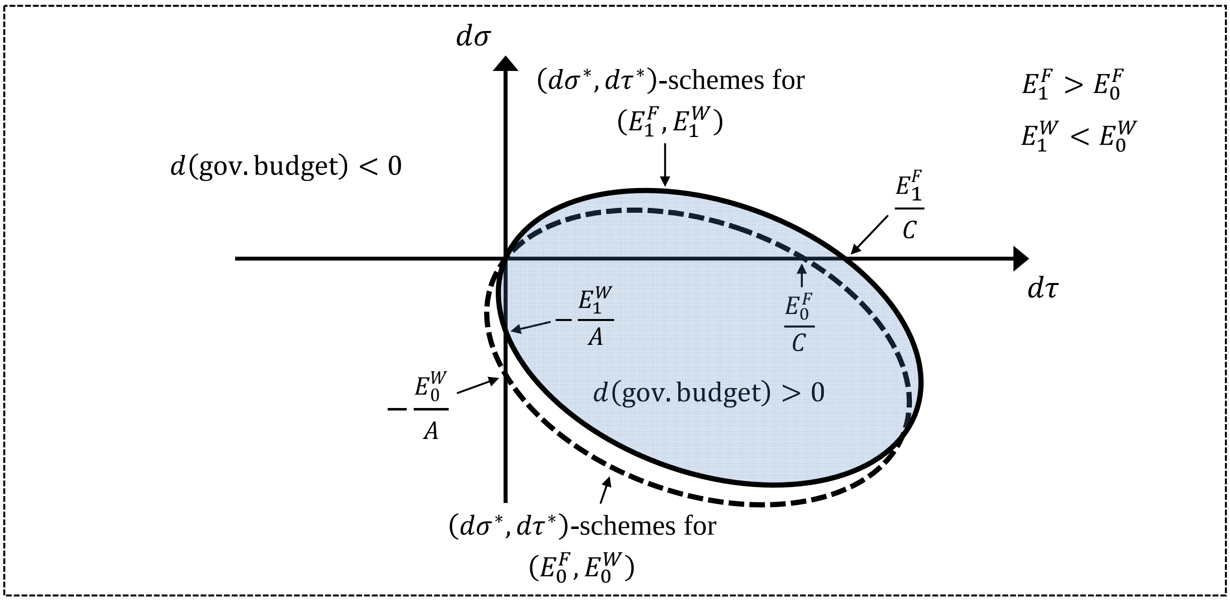
Obviously, from the policy perspective, the relevant subset of all $(d\sigma^*, d\tau^*)$-schemes is $\left[(0,0), \left(d\sigma^*_{max}, d\tau^*(d\sigma^*_{max})\right)\right]$ as in these cases a given budget-neutral subsidy increase is achieved with the minimum tax on fossil electricity. The combinations to the right of $d\tau^*(d\sigma^*_{max})$ that imply a positive $d\sigma^*$ can be interpreted similarly to the inefficient branch of a Laffer-curve. All combinations $(d\sigma^*, d\tau^*)$ with $d\sigma^* < 0$, $d\tau^* > 0$ are undesirable *per se*. Moreover, although not being further considered here, a subsidy for fossil electricity *cum* tax on renewable electricity could be studied similarly (third quadrant in Figure 1).

Fig. 1 Schemes $(d\sigma^*, d\tau^*)$ leading to budget-neutrality



An important implication from equation (10) and Figure 1 is that the scope for budget-neutral subsidies for renewable electricity is limited. More specifically, there exists a maximum subsidy that can be financed budget-neutrally, which depends on E^F—the initial fossil electricity quantity—and E^W—the initial renewable electricity quantity. A larger E^F implies a larger tax base and hence the possibility to raise more tax revenues. Since the subsidy increase does not apply only to the additional renewable electricity but also to the initial quantity, a larger E^W decreases the possibility for increasing the per unit subsidy without a budget deficit. Thus, the most ample scope for budget-neutral subsidizing of renewable electricity exists when E^F is large and E^W small. In graphical terms, the non-zero root $d\tau^*_2$ increases with increasing E^F, whereas $d\sigma^*_2$ increases (i.e., becomes less negative) when E^W decreases, which translates into a shift of the budget-neutrality ellipse.[3] In fact, the ellipse increases in size when E^F or E^W increases, and shrinks in the opposite case.[4] Evaluating the slope of the ellipse at $(d\sigma^*, d\tau^*) = (0{,}0)$, ensures that the ellipse takes the form illustrated by Figure 2 after changes in E^F and E^W. The slope at $(d\sigma^*, d\tau^*) = (0{,}0)$ is $\frac{d(d\sigma^*)}{d(d\tau^*)} = \frac{E^F}{E^W}$, hence it increases with E^F and decreases with E^W, proving that the scope for budget-neutral subsidies increases with E^F and decreases with E^W.[5]

Fig. 2 Scope for budget-neutral subsidy increases for different E^F and E^W



4. Effect on the electricity price of budget-neutral tax-subsidy schemes

The electricity price changes according to equation (8). Considering those $(d\tilde{\sigma}, d\tilde{\tau})$-combinations that lead to $dp = 0$ yields[6]

$$d\tilde{\sigma} = d\tilde{\tau} \cdot \frac{s^W}{s^F} \quad (13)$$

which is a straight line through the origin with a positive slope s^W/s^F. Moreover, for the case of $dp = 0$, the budget-neutrality condition stated in equation (10) can be reformulated to

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[3] $\frac{\partial(d\tau_2^*)}{\partial E^F} = \frac{s^F}{1-\omega^F} > 0$, $\frac{\partial(d\sigma_2^*)}{\partial E^W} = -\frac{s^W}{1-\omega^W} < 0$.

[4] See Appendix A for the derivation of the size of the ellipse.

[5] See Appendix B for the derivation of the slope of the ellipse.

[6] Equation (13) directly follows from $d\tilde{\sigma} = d\tilde{\tau} \cdot \frac{\omega^F}{\omega^W}$.

$$d\tau^* \cdot \left(E^F + \underbrace{\frac{1}{s^F} \cdot d\tau^*}_{-dE^F|_{dp=0}} \right) = d\sigma^* \cdot \left(E^W + \underbrace{\frac{1}{s^W} \cdot d\sigma^*}_{dE^W|_{dp=0}} \right) \quad (14)$$

as $-dE^F|_{dp=0} = \frac{d\tau}{s^F}$ and $dE^W|_{dp=0} = \frac{d\sigma}{s^W}$. Substituting (13) in (14), those $(d\hat{\tau}, d\hat{\sigma})$-schemes which imply budget-neutrality and at the same time no price change can be found to be $\{d\hat{\tau}_1 = 0, d\hat{\sigma}_1 = 0\}$ and $\left\{d\hat{\tau}_2 = \frac{E^F \cdot s^F - E^W \cdot s^W}{1 + \frac{s^W}{s^F}}, d\hat{\sigma}_2 = \frac{E^F \cdot s^F - E^W \cdot s^W}{1 + \frac{s^W}{s^F}} \cdot \frac{s^W}{s^F}\right\}$.

Since (13) is a straight line, there are at most two intersections of (13) and (10), the trivial solution being $(d\hat{\sigma}, d\hat{\tau}) = (0,0)$ and possibly another one with either $(d\hat{\sigma} > 0, d\hat{\tau} > 0)$ or $(d\hat{\sigma} < 0, d\hat{\tau} < 0)$. There is only one solution if the slope of (13) is equal to the slope of the ellipse at $(d\sigma, d\tau) = (0,0)$, which is the case when:[7]

$$E^F \cdot s^F - E^W \cdot s^W = 0 \leftrightarrow \frac{s^W}{s^F} = \frac{E^F}{E^W} \quad (15)$$

Fig. 3 Effect on the electricity price of budget-neutral schemes $(d\sigma^*, d\tau^*)$

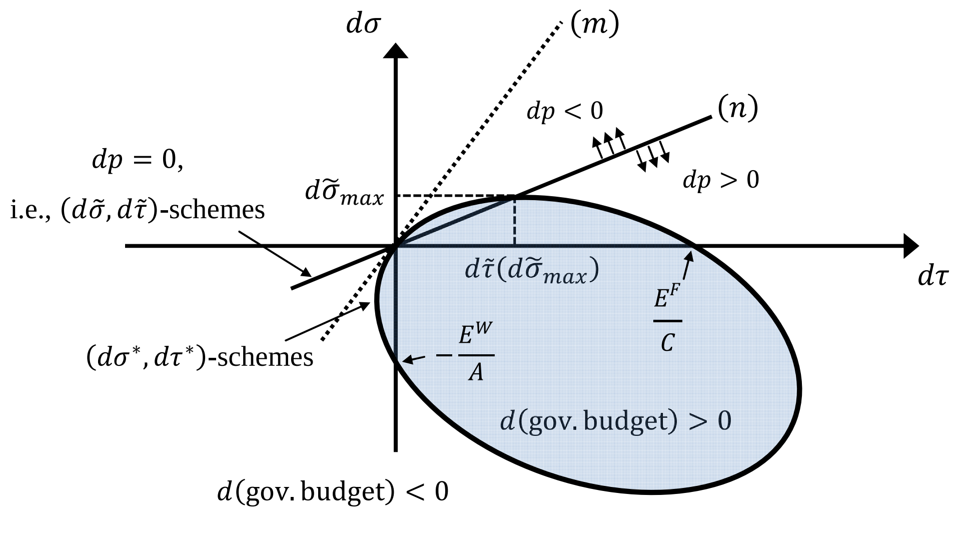


Figure 3 shows two examples of price-neutral $(d\tilde{\sigma}, d\tilde{\tau})$-combinations. While in case (n), there exists a set of budget-neutral subsidy increases that results in $dp < 0$, all $(d\sigma^*, d\tau^*)$-schemes lead to $dp > 0$ in case (m). Intuitively, budget-neutral subsidy increases which lower the price of

[7] See Appendix B for the slope of the ellipse.

electricity through increase in the quantity of electricity generated, are feasible when a high tax revenue can be generated with low crowding out and when the corresponding subsidy leads to a sufficiently large supply expansion. This is the case when the initial tax base E^F and the slope of the supply function of fossil electricity are relatively large, whereas the initial subsidy base E^W and the slope of the supply function of renewable electricity need to be sufficiently small.

Interestingly, it can be shown that case (m) results if both fossil electricity and renewable electricity have a quadratic cost function, that is, $K^i\left(E^i\right) = k^i \cdot \left(E^i\right)^2$ with $k^i > 0$. In this case all budget-neutral subsidy increases would lead to an electricity price increase. This case is discussed in more detail in Appendix C.

5. Changing existing tax-subsidy schemes under the condition of budget-neutrality

So far the scope for budget-neutral subsidy increases to renewable electricity and the consequences for the electricity price were analyzed given that neither a tax nor a subsidy is in place initially. In this section, this idea is extended to some arbitrary initial fossil electricity tax $\tau \geq 0$ and renewable energy subsidy $\sigma \geq 0$. The constraint implying budget-neutrality is then:

$$d\tau \cdot E^F + (d\tau + \tau) \cdot dE^F = d\sigma \cdot E^W + (\sigma + d\sigma) \cdot dE^W \quad (16)$$

which, after substituting for dE^F and dE^W gives

$$A \cdot (d\sigma^*)^2 + B \cdot d\sigma^* \cdot d\tau^* + C \cdot (d\tau^*)^2 + d\sigma^* \left(E^W + \tau \cdot \frac{\omega^W}{s^F} + \sigma \cdot A\right) - d\tau^* \left(E^F - \tau \cdot C - \sigma \cdot \frac{\omega^F}{s^W}\right) = 0 \quad (17)$$

Equation (17) is a real ellipse with roots $\left\{d\tau_1^* = 0, d\tau_2^* = \left(E^F - \tau \cdot C - \sigma \cdot \frac{\omega^F}{s^W}\right)/C \leq E^F/C\right\}$ and $\left\{d\sigma_1^* = 0, d\sigma_2^* = -\left(E^W + \tau \cdot \frac{\omega^W}{s^F} + \sigma \cdot A\right)/A \leq -E^W/A\right\}$. It is easy to see that both $d\tau_2^*$ and $d\sigma_2^*$ decrease with increasing initial τ and σ. Moreover, by considering the slope of the new ellipse at $(d\sigma^*, d\tau^*) = (0,0)$ and comparing it with the respective slope of the ellipse corresponding to $(\sigma, \tau) = (0,0)$, the shape and position of the new ellipse with $(\sigma > 0, \tau > 0)$ can be determined. By totally differentiating (17) and setting $(d\sigma^*, d\tau^*) = (0,0)$, the resulting slope is[8]

[8] See Appendix D.

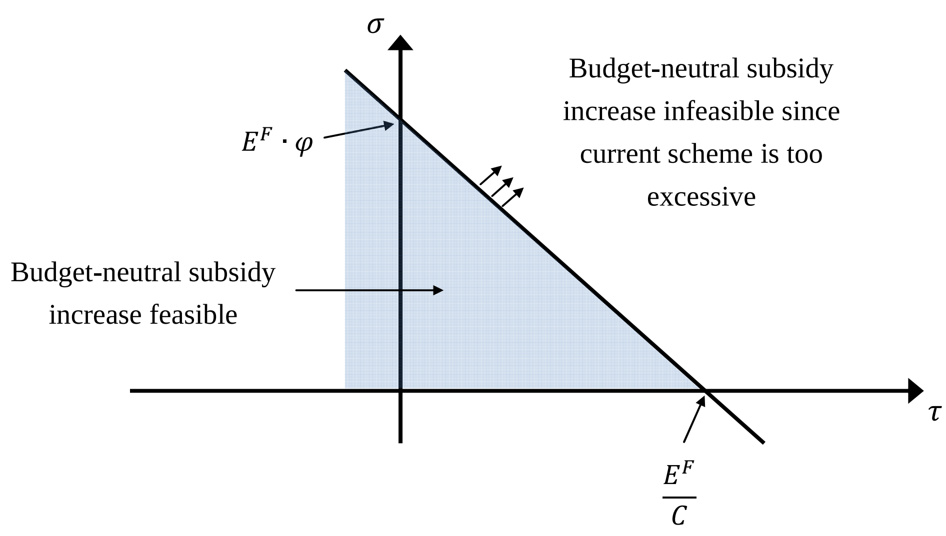
$$\frac{d(d\sigma^*)}{d(d\tau^*)} = \frac{E^F - \tau \cdot C - \sigma \cdot \frac{\omega^F}{s^W}}{E^W + \tau \cdot \frac{\omega^W}{s^F} + \sigma \cdot A} \qquad (18)$$

The slope of the ellipse given by equation (17) at $(d\sigma^*, d\tau^*) = (0,0)$ decreases when τ and σ increase. This holds for all τ and σ implying positive slopes, whereby eventually the slope might even become zero or negative, meaning that in this case no positive subsidy increase can be achieved budget-neutrally. The threshold for when this occurs is

$$\sigma = \varphi \cdot (E^F - \tau \cdot C) \qquad (19)$$

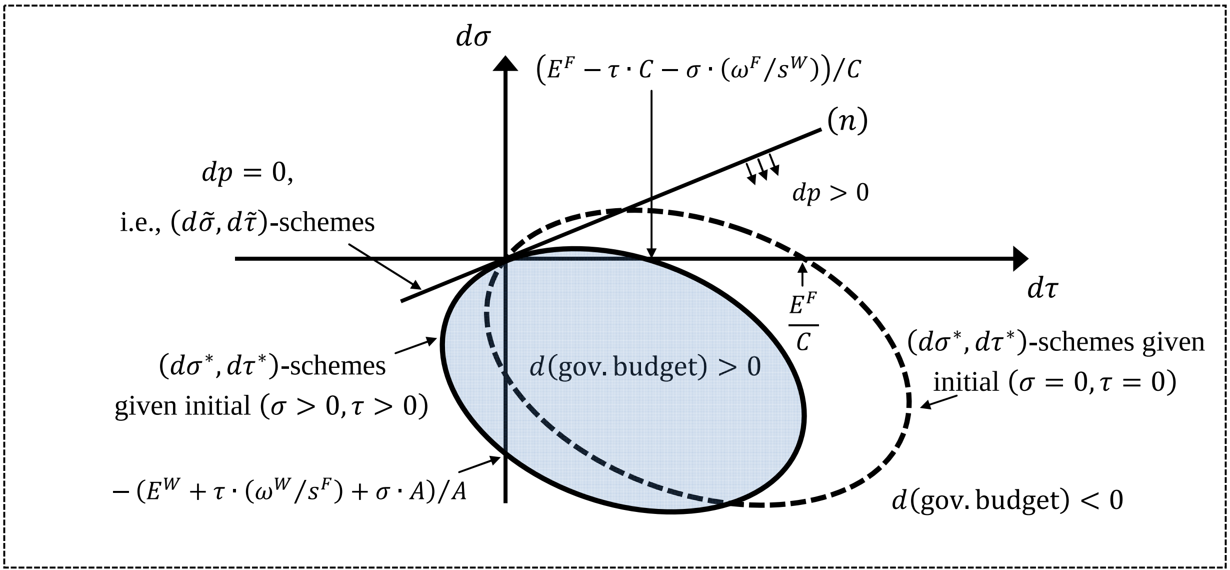
with $\varphi = \frac{s^F \cdot s^W}{|s^D|} + s^W + s^F > 0$. This relationship is illustrated in Figure 4. A negative slope of the ellipse at $(d\sigma^*, d\tau^*) = (0,0)$ implies that τ and σ are already so large that *reducing* the tax on fossil electricity and *increasing* the subsidy to renewable electricity would be feasible budget-neutrally.

Fig. 4 Feasibility of budget-neutral subsidy increases depending on σ and τ



The increase in renewable electricity quantity due to an increase in the subsidy leads to subsidy expenses of $(\sigma + d\sigma) \cdot dE^W$ which are higher for a given increase in the subsidy, the higher the pre-existing subsidy σ is. The reason is that the additional quantity not only receives the change in the subsidy, but also the level of the pre-existing subsidy. Similarly, tax revenues decrease more strongly due to a quantity reduction of fossil electricity generated when there is already a tax τ in place. This is because tax revenues of the amount $\tau \cdot dE^F$ disappear when the quantity of fossil electricity is reduced. In summary, higher existing tax-subsidy schemes additionally limit the scope for budget-neutral subsidy increases for renewable electricity; moreover, they make it more likely that the electricity price will increase. The latter is illustrated in Figure 5. Since the slope of the ellipse at $(d\sigma^*, d\tau^*) = (0,0)$ decreases and the scope for budget-neutral subsidies to renewable electricity shrinks, some—possibly all—with $(\sigma = 0, \tau = 0)$ feasible subsidy increases that would have led to a non-increasing electricity price become infeasible.

Fig. 5 Effect on the electricity price given initial $(\sigma > 0, \tau > 0)$



6. Non-linear marginal cost functions[9]

In the previous sections, it was (implicitly) assumed that the marginal cost functions of fossil electricity and renewable electricity are linear in the relevant segment. If this were not the case, the analysis would have been limited to inframarginal variations of the tax and/or the subsidy. This section discusses the implications of relaxing this assumption.

Suppose the marginal cost functions were not linear, but convex. A first implication would be that equation (6) would underestimate the decrease of fossil electricity generation for a tax increase since s^F falls as the quantity decreases if the marginal cost curve were strictly convex. Second, equation (7) would overestimate the increase in renewable electricity generation for a

[9] See Appendix E for more details.

subsidy increase since s^W increases as the quantity increases. Including in equations (6) and (7) a term that captures the convexity gives

$$dE^F = g\left(s^{F\prime}\right) \cdot \frac{dp - d\tau}{s^F} \qquad (20)$$

$$dE^W = h\left(s^{W\prime}\right) \cdot \frac{dp + d\sigma}{s^W} \qquad (21)$$

where

$$g = \begin{cases} g\left(s^{F\prime}\right) > 1 & \text{if } dp - d\tau < 0 \\ 0 < g\left(s^{F\prime}\right) < 1 & \text{if } dp - d\tau > 0 \end{cases} \qquad (22)$$

$$h = \begin{cases} h\left(s^{W\prime}\right) > 1 & \text{if } dp + d\sigma < 0 \\ 0 < h\left(s^{W\prime}\right) < 1 & \text{if } dp + d\sigma > 0 \end{cases} \qquad (23)$$

are the convexity adjustments to be added for which it is assumed that $g', h' > 0$. Using equation (5) the electricity price change then becomes

$$dp = -d\sigma \cdot \psi^W + d\tau \cdot \psi^F \qquad (24)$$

where $\psi^W = \frac{1}{1+\frac{s^W}{|s^D| \cdot h\left(s^{W\prime}\right)}+\frac{g\left(s^{F\prime}\right) \cdot s^W}{h\left(s^{W\prime}\right) \cdot s^F}}$, $\psi^F = \frac{1}{1+\frac{s^F}{|s^D| \cdot g\left(s^{F\prime}\right)}+\frac{h\left(s^{W\prime}\right) \cdot s^F}{g\left(s^{F\prime}\right) \cdot s^W}}$ with $0 < \psi^W, \psi^F < 1$.

Consequently, the budget-neutrality conditions in equations (9) and (16) also change. With convex marginal cost function, equation (16) can be rewritten as

$$d\tau \cdot E^F + (d\tau + \tau) \cdot \underbrace{g\left(s^{F\prime}\right) \cdot \frac{dp - d\tau}{s^F}}_{dE^F} = d\sigma \cdot E^W + (\sigma + d\sigma) \cdot \underbrace{h\left(s^{W\prime}\right) \cdot \frac{dp + d\sigma}{s^W}}_{dE^W} \qquad (25)$$

The resulting budget-neutrality ellipse becomes:

$$0 = (d\sigma)^2 \cdot a + d\tau \cdot d\sigma \cdot b + (d\tau)^2 \cdot c + d\sigma \cdot d - d\tau \cdot f \qquad (26)$$

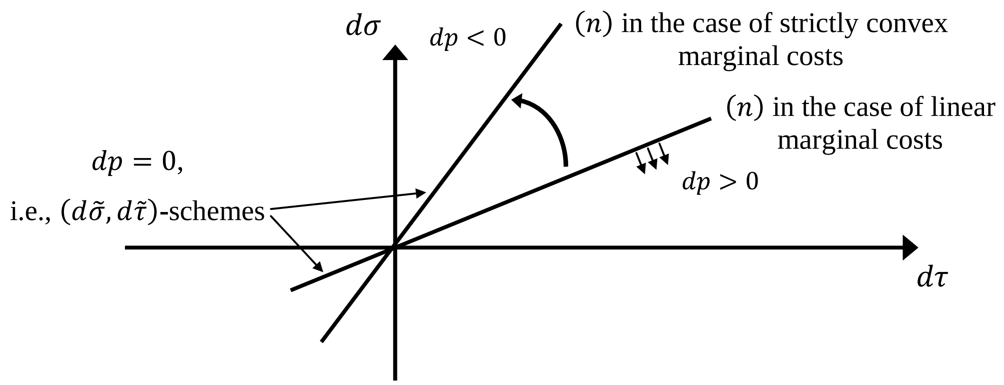
with $a = h \cdot \frac{(1-\psi^W)}{s^W}$, $b = h \cdot \frac{\psi^F}{s^W} + g \cdot \frac{\psi^W}{s^F}$, $c = g \cdot \frac{(1-\psi^F)}{s^F}$, $d = E^W + \sigma \cdot h \cdot \frac{(1-\psi^W)}{s^W} + \tau \cdot g \cdot \frac{\psi^W}{s^F}$, $f = E^F - \tau \cdot g \cdot \frac{(1-\psi^F)}{s^F} - \sigma \cdot h \cdot \frac{\psi^F}{s^W}$.

It is ambiguous how the scope for budget-neutral subsidy increases is affected as a given scheme not only leads to lower tax revenues, but also to lower subsidy expenses compared with the case of linear marginal costs. It is, however, clear that the scope shrinks for tax-subsidy increases that imply a decrease in electricity price. Thus, if the same budget-neutral subsidy increase was feasible in both cases, the linear and the convex, it will more likely lead to an electricity price increase if the marginal cost functions are convex as total electricity generation is lower than in the linear case. This can be derived from setting $dp = 0$ in equation (24). The equation determining the price-neutral $(d\tilde{\sigma}, d\tilde{\tau})$-combinations is now

$$d\tilde{\sigma} = d\tilde{\tau} \cdot \frac{g\left(s^{F'}\right) \cdot s^W}{h\left(s^{W'}\right) \cdot s^F} \qquad (27)$$

whereby a tax increase implies $g\left(s^{F'}\right) > 1$ and a subsidy increase implies $0 < h\left(s^{W'}\right) < 1$ if the price did not change. The function specified by equation (27) becomes steeper, the more convex the marginal cost functions are, which is illustrated in Figure 6. The more convex the marginal cost functions, the more difficult is finding tax-subsidy increases that do not lead to an electricity price increase.

Fig. 6 Effect of more convex marginal cost functions



7. Conclusions and discussion

The analysis has shown that finding budget-neutral subsidy schemes for promoting renewable electricity might not be simple. In particular, it becomes more difficult if excessive support schemes for renewable electricity or high taxes on conventional electricity already exist. At the same time, it becomes less likely that budget-neutral subsidies to renewable electricity will lead to an electricity price decrease if stronger policies are already in place. The latter problem intensifies if the marginal cost functions of the different electricity generation possibilities are more convex.

Even though public interest is often centered on the price of electricity, from an economic perspective, welfare implications should be evaluated before a policy scheme is implemented. In this respect, the effect of budget-neutral support to renewable electricity depends on several conditions. The most fundamental one is the existence of an externality. In the absence of an externality, any distortion of the production efficiency through taxes and subsidies would reduce the sum of consumer and producer surplus. If an externality exists, for instance when fossil electricity generation contributes to the process of global warming, there is in principle a rational for intervention in the form of a Pigouvian tax on fossil electricity. This, however, in itself does not imply that the best use of the resulting revenues lies in subsidizing renewable energy, but depends on the existence of other externalities. An example would be that renewable electricity generation carries a positive learning or spill-over externality, which could be internalized by an R&D subsidy. Irrespective of this, from a more general point of view it needs to be evaluated whether tax revenues from fossil electricity achieve the highest welfare gains by being used as subsidies to renewable electricity, or whether there is some other positive externality in another sector of the economy with higher welfare returns to subsidies. Moreover, climate change is a global public bad and unilateral policies, as discussed here, would only have an impact if the emissions reduction were not diminished by an increase in emission in the rest of the world, commonly known as carbon leakage (see for example, Eichner and Pethig, 2011; or Sinn, 2008). Finally, the effectiveness of taxing fossil electricity and supporting renewable electricity could be strongly limited by the existence of other policy instruments. A prominent example is the EU Emission Trading System, which imposes a cap on the emissions from the energy and industrial sectors, so that any unilateral emissions reduction would imply an emissions increase of another country on a one-to-one basis as long as the price of the emissions remains positive. All of this needs to be taken into account in order to gain a full picture of how budget-neutral subsidy schemes for renewable electricity affect national welfare.

References

Böhringer, C. and K. E. Rosendahl (2010), "Green Promotes the Dirtiest: On the Interaction between Black and Green Quotas in Energy Markets", *Journal of Regulatory Economics* 37, 316-325.

Eichner, T. and R. Pethig (2011), "Carbon Leakage, the Green Paradox and Perfect Future Markets", *International Economic Review* 52, 767-805.

Fischer, C. (2010), "Renewable Portfolio Standards: When do they Lower Energy Prices?", *The Energy Journal* 31, 101-120.

Fischer, C. and L. Preonas (2010), "Combining Policies for Renewable Energy: Is the Whole Less than the Sum of its Parts?", *International Review of Environmental and Resource Economics* 4, 51-92.

Kemfert, C. and T. Traber (2009), "Impacts of the German Support for Renewable Energy on Electricity Prices, Emissions and Firms", *The Energy Journal* 30, 155-178.

Sinn, H. W. (2008), "Public Policies Against Global Warming: A Supply Side Approach", *Int Tax and Public Finance* 15, 360-394.

Appendix A: Size of the ellipse defined by equation (10)

An ellipse that passes through the origin and has the general form

$$A \cdot (d\sigma^*)^2 + B \cdot d\sigma^* \cdot d\tau^* + C \cdot (d\tau^*)^2 + d\sigma^* \cdot G + d\tau^* \cdot F = 0 \quad (A1)$$

has the non-zero roots $d\tau_2^* = -F/C$ and $d\sigma_2^* = -G/A$, whereas the length of the major semi-axis is:

$$L_a = \sqrt{\frac{1}{2} \cdot \frac{C}{\Theta}} \cdot \Gamma \quad (A2)$$

and the length of the minor semi-axis is determined by:

$$L_b = \sqrt{\frac{1}{2} \cdot \frac{C}{\Omega}} \cdot \Gamma \quad (A3)$$

where

$$\Gamma = \sqrt{A \cdot C \cdot (d\tau_2^*)^2 + A^2 \cdot (d\sigma_2^*)^2 - B \cdot C \cdot d\tau_2^* \cdot d\sigma_2^*} (A4)$$

As the sign of the discriminant $B^2 - 4 \cdot A \cdot C$ of an ellipse is negative, it follows that

$$\Theta = \underbrace{\left({B^2}/_4 - A \cdot C\right)}_{<0} \cdot \underbrace{\left(\sqrt{(A-C)^2 - B^2} - (A+C)\right)}_{<0} > 0 \qquad (A5)$$

$$\Omega = \underbrace{\left({B^2}/_4 - A \cdot C\right)}_{<0} \cdot \underbrace{\left(-\sqrt{(A-C)^2 - B^2} - (A+C)\right)}_{<0} > \Theta > 0 \qquad (A6)$$

Since the roots of the ellipse given by equation (10), are $d\tau_2^* = E^F/C > 0$ and $d\sigma_2^* = -E^W/A < 0$, it holds for $j = \{a, b\}$ that

$$\underbrace{\frac{\partial L_j}{\partial \Gamma}}_{>0} \cdot \underbrace{\frac{\partial \Gamma}{\partial (d\tau_2^*)}}_{>0} \cdot \underbrace{\frac{\partial (d\tau_2^*)}{\partial E^F}}_{>0} > 0 \qquad (A7)$$

$$\underbrace{\frac{\partial L_j}{\partial \Gamma}}_{>0} \cdot \underbrace{\frac{\partial \Gamma}{\partial (d\sigma_2^*)}}_{<0} \cdot \underbrace{\frac{\partial (d\sigma_2^*)}{\partial E^W}}_{<0} > 0 \qquad (A8)$$

Thus, the length of both semi-axes increases with E^F and E^W, respectively.

Appendix B: Slope of the ellipse defined by equation (10)

The slope of an ellipse given by

$$A \cdot (d\sigma^*)^2 + B \cdot d\sigma^* \cdot d\tau^* + C \cdot (d\tau^*)^2 + d\sigma^* \cdot F + d\tau^* \cdot G = 0 \qquad (B1)$$

can be found by totally differentiating $(B1)$:

$$2 \cdot A \cdot d\sigma^* \cdot d(d\sigma^*) + B \cdot d(d\sigma^*) \cdot d\tau^* + B \cdot d\sigma^* \cdot d(d\tau^*) + 2 \cdot C \cdot d\tau^* \cdot d(d\tau^*) + d(d\sigma^*) \cdot F + d(d\tau^*) \cdot G = 0$$

and solving for $\frac{d(d\sigma^*)}{d(d\tau^*)}$, which gives

$$\frac{d(d\sigma^*)}{d(d\tau^*)} = -\frac{B \cdot d\sigma^* + 2 \cdot C \cdot d\tau^* - G}{2 \cdot A \cdot d\sigma^* + B \cdot d\tau^* - F} \qquad (B2)$$

Thus, the slope at $d\tau^* = 0$, $d\sigma^* = 0$ is

$$\frac{d(d\sigma^*)}{d(d\tau^*)} = -\frac{G}{F} \qquad (B3)$$

For the ellipse given by equation (10), where $G = -E^F$ and $F = E^W$, it is

$$\frac{d(d\sigma^*)}{d(d\tau^*)} = \frac{E^F}{E^W} \qquad (B4)$$

with

$$\frac{\partial\left(\frac{d(d\sigma^*)}{d(d\tau^*)}\right)}{\partial E^F} = \frac{1}{E^W} > 0 \qquad (B5)$$

$$\frac{\partial\left(\frac{d(d\sigma^*)}{d(d\tau^*)}\right)}{\partial E^W} = -\frac{E^F}{(E^W)^2} < 0 \qquad (B6)$$

Appendix C: The case of quadratic cost functions

There exists an obvious relationship between the quantity produced and the slope of the marginal cost function for the case of a quadratic cost function and a given market clearing price p^*. If p^* is such a price and s^i is the slope of the marginal cost function, then $E^i = p^*/s^i$. Substituting this in (13) gives $\frac{s^W}{s^F} = \frac{s^W}{s^F}$, that is, quadratic cost functions lead to the case in which only one budget-neutral tax-subsidy corresponds to no price change, and this is the trivial solution without a tax change and without a subsidy change. Note that this is independent of p^*. In Figure 2, this example is illustrated by the straight line (m) that is tangent to the ellipse. As all points to the right of (m) imply an increase in the price of electricity, there is no positive budget-neutral tax-subsidy scheme that does not lead to an increase in the electricity price.

If the cost functions were, however, linear-quadratic, the relationship between the quantity and the slope of the marginal cost function would be $E^i = \left(p^* - K^{i\prime}(0)\right)/s^i$. In this case, equation (15) would become

$$\frac{s^W}{s^F} = \frac{\left(p^* - K^{W\prime}(0)\right)\cdot s^W}{\left(p^* - K^{F\prime}(0)\right)\cdot s^F} \quad \leftrightarrow \quad K^{W\prime}(0) = K^{F\prime}(0) \qquad (C1)$$

Thus, if the linear term is the same for renewable electricity and fossil electricity, any increase in budget-neutral subsidy changes the electricity price.

Appendix D: Slope of the ellipse defined by equation (17)

In Appendix B, the slope of the ellipse defined by equation (10) was derived. Taking equation $(B3)$ and modifying it by substituting $G = -E^F + \sigma \cdot \frac{\omega^F}{s^W} + \tau \cdot C$ and $F = E^W + \tau \cdot \frac{\omega^W}{s^F} + \sigma \cdot A$ and evaluating the slope at $d\tau^* = 0$ and $d\sigma^* = 0$ gives

$$\frac{d(d\sigma^*)}{d(d\tau^*)} = \frac{E^F - \sigma \cdot \frac{\omega^F}{s^W} - \tau \cdot C}{E^W + \tau \cdot \frac{\omega^W}{s^F} + \sigma \cdot A} \qquad (D1)$$

Appendix E: Non-linear marginal cost functions

Totally differentiating equation (2) gives $dp - d\tau = K^{F''} dE^F$ with $K^{F''} \equiv s^F$. If the marginal cost function is non-linear, this solution is only a first order Taylor polynomial, thus being a valid approximation only for inframarginal dE^F. To make the analysis applicable for non-inframarginal changes, in principle a higher order Taylor polynomial would be required. This degree of complexity is, however, not needed here to derive the results. For a monotonically increasing (strictly) convex function $f(x)$, the first order Taylor approximation $f^T(x)$ at any $\bar{x}$ returns for any $dx \neq 0$, $f^T(\bar{x} + dx) < f(\bar{x} + dx)$. In this case, it means that for $dp - d\tau > 0$, the increase of E^F is overestimated by the first order Taylor approximation, that is, the true dE^F is smaller. In the other direction, that is, for $dp - d\tau < 0$, the first order Taylor approximation underestimates the decrease of E^F. Similar arguments apply to dE^W for $dp + d\sigma \lesseqgtr 0$. Thus, functions $g\left(s^{F'}(E^F), \boldsymbol{y}\right)$ and $h\left(s^{W'}(E^W), \boldsymbol{z}\right)$ can be introduced which on the one hand contain information about the degree of convexity at the initial E^F and E^W, and on the other hand include vectors $\boldsymbol{y}$ and $\boldsymbol{z}$ such that any functional form of the marginal cost functions can be replicated. Without loss of generality, the notation is simplified to $g = g\left(s^{F'}\right)$ and $h\left(s^{W'}\right)$. Hence, using these functions, equations (20) and (21) can be rewritten as

$$dE^F = g\left(s^{F'}\right) \cdot \frac{dp - d\tau}{s^F} \qquad (E1)$$

$$dE^W = h\left(s^{W'}\right) \cdot \frac{dp + d\sigma}{s^W} \qquad (E2)$$

where

$$g = \begin{cases} g\left(s^{F'}\right) > 1 & \text{if } dp - d\tau < 0 \\ 0 < g\left(s^{F'}\right) < 1 & \text{if } dp - d\tau > 0 \end{cases} \qquad (E3)$$

$$h = \begin{cases} h\left(s^{W'}\right) > 1 & \text{if } dp + d\sigma < 0 \\ 0 < h\left(s^{W'}\right) < 1 & \text{if } dp + d\sigma > 0 \end{cases} \qquad (E4)$$

Using this in equation (5), the new equation for the price change can be obtained:

$$dp = s^D \cdot \left(g\left(s^{F'}\right) \cdot \frac{dp - d\tau}{s^F} + h\left(s^{W'}\right) \cdot \frac{dp + d\sigma}{s^W} \right) \qquad (E5)$$

$$\leftrightarrow dp = -d\sigma \cdot \psi^W + d\tau \cdot \psi^F \qquad (E6)$$

where $\psi^W = \frac{1}{1 + \frac{s^W}{|s^D| \cdot h\left(s^{W'}\right)} + \frac{g\left(s^{F'}\right) \cdot s^W}{h\left(s^{W'}\right) \cdot s^F}}$, $\psi^F = \frac{1}{1 + \frac{s^F}{|s^D| \cdot g\left(s^{F'}\right)} + \frac{h\left(s^{W'}\right) \cdot s^F}{g\left(s^{F'}\right) \cdot s^W}}$ with $0 < \psi^W, \psi^F < 1$.

Budget-neutrality then implies that

$$d\tau \cdot E^F + (d\tau + \tau) \cdot g\left(s^{F'}\right) \cdot \frac{dp - d\tau}{s^F} = d\sigma \cdot E^W + (\sigma + d\sigma) \cdot h\left(s^{W'}\right) \cdot \frac{dp + d\sigma}{s^W} \qquad (E6)$$

which can be modified to

$$0 = (d\sigma)^2 \cdot h \cdot \frac{(1 - \psi^W)}{s^W} + d\tau \cdot d\sigma \cdot \left(h \cdot \frac{\psi^F}{s^W} + g \cdot \frac{\psi^W}{s^F} \right) + (d\tau)^2 \cdot g \cdot \frac{(1 - \psi^F)}{s^F}$$

$$+ d\sigma \cdot \left(E^W + \sigma \cdot h \cdot \frac{(1 - \psi^W)}{s^W} + \tau \cdot g \cdot \frac{\psi^W}{s^F} \right) - d\tau \cdot \left(E^F - \tau \cdot g \cdot \frac{(1 - \psi^F)}{s^F} - \sigma \cdot h \cdot \frac{\psi^F}{s^W} \right)$$

or,

$$0 = (d\sigma)^2 \cdot a + d\tau \cdot d\sigma \cdot b + (d\tau)^2 \cdot c + d\sigma \cdot d - d\tau \cdot f$$

with $a = h \cdot \frac{(1-\psi^W)}{s^W}$, $b = h \cdot \frac{\psi^F}{s^W} + g \cdot \frac{\psi^W}{s^F}$, $c = g \cdot \frac{(1-\psi^F)}{s^F}$, $d = E^W + \sigma \cdot h \cdot \frac{(1-\psi^W)}{s^W} + \tau \cdot g \cdot \frac{\psi^W}{s^F}$, $f = E^F - \tau \cdot g \cdot \frac{(1-\psi^F)}{s^F} - \sigma \cdot h \cdot \frac{\psi^F}{s^W}$.