# Efficient Management of Insecure Fossil Fuel Imports through Taxing (!) Domestic Green Energy?

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## Abstract

A small open economy produces a consumer good, green and black energy, and imports fossil fuel at an uncertain price. Unregulated competitive markets are shown to be inefficient. The implied market failures are due to the agents' attitudes toward risk, to risk shifting and the uniform price for both types of energy. Under the plausible assumptions that consumers are prudent and at least as risk averse as the producers of black energy, the risk can be efficiently managed by taxing emissions and green energy. The need to tax (!) green energy contradicts the widespread view that subsidization of green energy is an appropriate means to enhance energy security in countries depending on risky fossil fuel imports.


JEL-Code: F18, Q42, Q48.

Keywords: price uncertainty, black energy, green energy, fossil fuel.

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# 1 Introduction

Many countries, notably the Annex I countries of the Kyoto Protocol, take action to curb carbon dioxide emissions, and many OECD countries also have policies to promote energy from renewable energy sources (OECD/IEA 2008). From the economists' perspective, such regulation is warranted, if it serves to correct for significant market imperfections. While the case is strong for using carbon cutting policies to cope with global change externalities, the economic rationale for supporting the (domestic) production of green energy is less clear. The theoretical *economic* literature on green energy support focuses on learning-by-doing and technological spillovers (e.g. Fischer and Newell 2008, Fischer 2008) as well as on externalities combined with various other imperfections such as imperfect property rights or information (e.g. Bennear and Stavins 2007). Yet there appears to be little agreement on whether such market imperfections are empirically relevant enough to provide a convincing rationale for promoting green energy.

Nonetheless, the *political* support for promoting green energy is still strong in many countries, if not growing. The reasons policymakers put forward for that support tend to differ from the economists' arguments alluded to above. For example, in the recently amended German Renewable Energies Act, the purpose of that act is described as the sustainable development of energy provision especially in the interest of using fossil resources carefully and *reducing the dependence from energy imports*.[1] The European Commission (Com 2007) acknowledges serious energy challenges concerning security of supply and import dependence and argues that the promotion of renewable energies plays a part in securing energy supply. The EU Renewable Energies Roadmap aims at enabling the EU to meet the 'twin objectives' of increasing security of energy supply and reducing greenhouse gas emissions.

As for the objective of fighting global change, green energy promotion as well as emissions reduction schemes clearly curb emissions and thus both of them contribute to climate stabilization. However, there is ample evidence and theoretical support for the proposition that promoting green energy is less cost-effective as a means of fighting climate change than the reduction of carbon emissions through instruments targeting those emissions directly (Fischer and Newell 2008). Consequently, if fighting global change is considered the only political goal, there is no role for green energy promotion.[2] In the present paper we will

[1] Federal Government of Germany/Bundesregierung (2008), Gesetz zur Förderung erneuerbarer Energien im Wärmebereich, Bundesgesetzblatt Jg. 2008 Teil I Nr. 36 vom 18.8.2008.

[2] In a report to the German Federal Ministry of Affairs in 2004 the scientific council to that ministry recommended discontinuing the promotion of green energy in Germany on the grounds that the introduction of the European emissions trading scheme has turned the promotion of green energy into an ecologically

consider, as many policymakers do, energy security as a political goal in its own right (in countries that heavily depend on the import of fossil energy resources). It is then clear that this goal is also promoted by both types of instruments, i.e. by green energy promotion as well as by emissions reduction schemes. Yet the decisive questions are whether the degree of energy security is inefficiently low in the absence of regulation and if so which instrument is more effective in correcting for that inefficiency. If supporting green energy should turn out to be necessary for efficient risk management, one would have found a theoretical foundation for the observed green energy promotion with a rationale different from fighting global change and from other reasons mentioned above.

The present paper aims at exploring the role and effectiveness of curbing emissions and promoting green energy as alternative or joint instruments for the efficient management of risk from energy insecurity in countries that depend on fossil fuel imports. To our knowledge that issue has not yet been addressed in the analytical literature which is remarkable given the prominence policymakers assign to the energy security goal and their confidence that green energy needs to be supported for promoting that goal. A key feature of our analytical approach will be uncertainty with respect to the price of imported fossil fuels. Among the various reasons for such uncertainties are political instability in fuel-exporting countries, market power or cartels of these countries and perhaps sharp price fluctuations due to large-scale speculation.[3]

To tackle fossil fuel price uncertainty we consider a small open economy which imports fossil fuel at an uncertain price to produce black energy. In addition to black energy the economy produces green energy. We neither include in our model carbon emission externalities nor R&D and R&D externalities in green energy production. The first part of the paper characterizes allocative efficiency depending on the representative consumer's attitude toward risk and studies how the efficient allocation changes when the price risk increases. Following Feder, Just and Schmitz (1977) we assume that the social planner makes all decisions on production, consumption and trade before the uncertainty about the fossil fuel price is resolved. The social planner accounts for the consumer's risk attitude. In contrast, in the competitive market economy it is the producer of black energy who faces input price uncertainty.[4] Again, decisions (now producers' and consumers') on production,

useless and economically expensive instrument.

[3]Outstanding empirical examples of such price uncertainty (and volatility) are the massive supply-side induced oil price shocks in the 1970s. Quantity uncertainty, i.e. the risk of delivery falling short of ordered fossil fuel imports (which currently appears to exist, e.g., with respect to Russian natural gas exports) is another aspect of energy insecurity. However, with fully flexible prices quantity uncertainty necessarily translates into price uncertainty. The present paper focuses on flexible prices.

[4]Our treatment of the competitive firm under price uncertainty goes back to Sandmo (1971) and Batra and Ullah (1974).

consumption and trade are made before the true value of the international fossil fuel price is known (see also Batra and Russel 1974). In doing so, we implicitly assume there does not exist a future market for the input and hence there is no hedging opportunity for producers.

When economic agents, or the social planner, make decisions under uncertainty, the resultant allocations depend on the agents' attitudes toward risk. We focus on risk aversion and risk neutrality in alternative scenarios and show that it crucially depends on the assumptions regarding the agents' risk attitutes whether taxes or subsidies on imported fossil fuels and/or on domestic green production are effective means of risk management. In general, regulation of black and green energy is shown to be necessary for efficient risk management. If we take the scenario, where producers are less risk averse than consumers and consumers are prudent as the most relevant one, the striking message of the present paper is that efficient risk management requires

(i) curbing fossil fuel imports (and thus curbing carbon emissions) and

(ii) taxing (!) rather than subsidizing green energy production.

Taxing carbon emissions appears to be reasonable as a means to cope with price uncertainty of fossil fuel imports because that tax reduces fuel imports directly and with it the size of risk. The emissions tax also stimulates the production of green energy, but the promotion of green energy would, of course, be more effective by subsidizing green energy. The tax on green energy required for efficient management counteracts the impact of the emissions tax on both emissions and green energy. It turns out, however, that the emissions tax is dominant in the sense that as compared with the no-policy scenario the *net* effect of both taxes is an emissions reduction. On the other hand, green energy production may either decline or it may increase despite the green-energy tax.

For a better understanding of the nature of the market failures (to be corrected with two fiscal instruments) we also briefly consider the case where black energy is not produced domestically from imported fossil fuel, but where, instead, consumers purchase black energy directly on the world market at an uncertain price. We find that now the competitive economy is efficient without any tax or subsidy for two reasons. First, no risk shifting takes place and second, the market provides the correct differentiation between the prices for green and black energy. In our model with black energy production, the price of both types of energy is uniform because they are homogeneous products *and* are considered perfect substitutes by the consumers.

The paper is organized as follows. Section 2 outlines the model. In Section 3 we derive the properties of the efficient allocation and present the comparative statics of the price risk on the efficient allocation. Sections 4 and 5 investigate various corrective tax-subsidy schemes in an economy where the producer of black energy faces the price uncertainty. Section 6 turns to a modified economy where the consumers are directly exposed to the price risk. Section 7 provides some concluding remarks.

# 2 The model

Consider the economy of a small open country that generates energy $z$ according to

$$b = B(e), \qquad g = G(r_g) \quad \text{and} \quad z = b + g. \tag{1}$$

Fossil fuel, $e$, is used as an input in the production of 'black' energy $b$. 'Green' energy, $g$, is produced by means of the domestic (composite) production factor $r_g$. Both kinds of energy, $b$ and $g$, are perfect substitutes. In addition to energy the country produces the amount

$$x = X(r_x) \tag{2}$$

of some (composite) consumption good $X$ with input $r_x$. The production functions $B, G$ and $X$ are increasing and strictly concave. All fossil fuel needs to be imported at the uncertain world market price $p_e + q$. The price $p_e$ is constant, whereas $q$ is a risky mark-up representing a random variable with support $[0, \infty[$, with mean $\mu_q \geq 0$ and with standard deviation $\sigma_q \geq 0$. The country pays for its imports with revenues from exporting good $X$ that is traded at the constant world market price $p_x \equiv 1$. The trade balance reads

$$x - x_d - (p_e + q)e = 0, \tag{3}$$

where $x_d$ denotes the domestic consumption of good $X$. Since the trade balance contains the random variable $q$, the consumption of good $X, x_d$, turns out to be a random variable with the moments

$$\mu_x = x - (p_e + \mu_q)e \quad \text{and} \quad \sigma_x = \sigma_q e. \tag{4}$$

Supply and demand match for both capital and energy,

$$r_g + r_x = \bar{r} \quad \text{and} \quad z = z_d, \tag{5}$$

where $\bar{r}$ denotes the country's endowment of the production factor and $z_d$ is the domestic consumption of energy. The model is closed by introducing the representative consumer's utility function

$$u = \tilde{U}(x_d, z_d) = \mathcal{V}(x_d) + \mathcal{U}(z_d), \tag{6}$$

where the subutility functions $\mathcal{V}$ and $\mathcal{U}$ are increasing in their argument and concave. In (6) the consumer derives utility from consuming good $X$ and energy. We can think of energy consumed by households in various alternative forms, e.g. electricity or natural gas and/or oil for heating or gazoline/diesel for automobiles. The function $b = B(e)$ is interpreted as technology transforming imported fossil energy sources, like crude oil, into secondary energy, like electricity or gazoline.

Since the set of distributions of the random variable $x_d$ implied by (4) forms a linear class, expected utility and mean-variance preferences are perfect substitutes (Meyer 1987). It follows that any given von Neumann-Morgenstern function $\mathcal{V}$ can be represented in terms of mean-variance preferences without loss of generality. Therefore, we write the expected utility from the random variable $x_d$ in terms of mean $\mu_x$ and standard deviation $\sigma_x$ as

$$\mathbf{E}\mathcal{V}(x_d) = \int_a^b \mathcal{V}(\mu_x + \sigma_x n)\mathrm{d}F(n) =: V(\mu_x, \sigma_x), \tag{7}$$

where $a$ and $b$ define the interval containing the support of the standardized random variable $n$, and $F$ is the distribution function of $n$. Due to that standardization, the mean and the standard deviation of $n$ are, respectively, zero and one. Denoting by $A(x_d) := -\frac{\mathcal{V}_{xx}(x_d)}{\mathcal{V}_x(x_d)}$ the Arrow-Pratt measure of absolute risk aversion and by $M(\mu_x, \sigma_x) := -\frac{V_\sigma(\mu_x,\sigma_x)}{V_\mu(\mu_x,\sigma_x)}$ the marginal rate of substitution between $\mu_x$ and $\sigma_x$, Meyer (1987) and Lajeri and Nielsen (2000) have shown that the identity (7) gives rise to the following equivalences between von Neumann-Morgenstern utility functions and two-parameter functions[5]:

$$\mathcal{V}_x(x_d) > 0 \quad \Longleftrightarrow \quad V_\mu(\mu_x, \sigma_x) > 0, \tag{8a}$$

$$\mathcal{V}_{xx}(x_d) < 0 \quad \Longleftrightarrow \quad V_\sigma(\mu_x, \sigma_x) < 0, \tag{8b}$$

$$\Longleftrightarrow \quad V_{\mu\mu} < 0, V_{\sigma\sigma} < 0, V_{\mu\mu}V_{\sigma\sigma} - V_{\mu\sigma}^2 > 0, \tag{8c}$$

$$\mathcal{V}_{xxx}(x_d) \gtreqless 0 \quad \Longleftrightarrow \quad V_{\mu\sigma} \gtreqless 0, \tag{8d}$$

$$A_x(x_d) \gtreqless 0 \quad \Longleftrightarrow \quad M_\mu \gtreqless 0 \tag{8e}$$

for all $\mu_x$ and $\sigma_x \geq 0$. (8b) reflects risk aversion which also corresponds to the concavity of $V(\mu_x, \sigma_x)$, see (8c). Following Kimball (1990) we call an agent[6] prudent [imprudent] if and only if her preferences display $\mathcal{V}_{xxx} > [<]0$. In view of (8d) and as identified by Lajeri and Nielsen (2000) prudence translates into $V_{\mu\sigma} > 0$ for mean-variance preferences. Finally, an agent is said to be decreasing [increasing] absolute risk averse if her mean-variance preferences exhibit $M_\mu < [>]0$. Decreasing absolute risk aversion (DARA) and prudence

[5] For notational convenience we suppress the arguments of the function $V(\mu_x, \sigma_x)$ when there is no risk of confusion.

[6] An agent is prudent if adding a zero-mean risk to her future wealth raises the optimal savings in an intertemporal consumption problem (Kimball 1990).

are related as follows:

$$M_\mu = -\frac{V_{\sigma\mu}V_\mu - V_\sigma V_{\mu\mu}}{V_\mu^2} < 0 \quad\iff\quad -\frac{V_{\mu\sigma}}{V_{\mu\mu}} > -\frac{V_\sigma}{V_\mu}. \tag{9}$$

In case of risk neutrality, the von Neumann-Morgenstern utility function is linear, and it is straightforward to show

$$\mathcal{V}_{xx} = 0 \quad\iff\quad V_\sigma = V_{\mu\sigma} = V_{\mu\mu} = V_{\sigma\sigma} \equiv 0. \tag{10}$$

# 3 The efficient allocation

Consider a benevolent planner who maximizes the representative consumer's expected utility

$$\mathbf{E}\tilde{U}(x_d, z_d) \equiv V(\mu_x, \sigma_x) + \mathcal{U}(z_d)$$

subject to (1), (2), (4), (5). Solving the associated Lagrangian

$$\begin{aligned} \mathcal{L} &= V(\mu_x, \sigma_x) + \mathcal{U}(z_d) + \lambda_r(\bar{r} - r_g - r_x) + \lambda_z\left[B(e) + G(r_g) - z_d\right] \\ &+ \lambda_\mu\left[X(r_x) - (p_e + \mu_q)e - \mu_x\right] + \lambda_\sigma(\sigma_q e - \sigma_x) \end{aligned} \tag{11}$$

yields the first-order conditions listed in the first column of Table 1.

| | | Pareto efficiency<br>1 | Markets<br>2 |
|---|---|---|---|
| Consumption | 1 | $\frac{V_\sigma(\mu_x^*,\sigma_x^*)}{V_\mu(\mu_x^*,\sigma_x^*)} = \varphi_\sigma$ | |
| | 2 | $\frac{\mathcal{U}_z(z_d^*)}{V_\mu(\mu_x^*,\sigma_x^*)} = \varphi_z$ | $\frac{\mathcal{U}_z(z_d^m)}{\mathcal{V}_x(x_d^m)} = p_z$ |
| Production | 3 | $X_r(r_x^*) = \varphi_r$ | $X_r(r_x^m) = p_r$ |
| Energy | 4 | $\varphi_z G_r(r_g^*) = \varphi_r$ | $(p_z - s)G_r(r_g^m) = p_r$ |
| Production | 5 | $\varphi_z B_e(e^*) + \varphi_\sigma\sigma_q = p_e + \mu_q$ | $p_z B_e(e^m) + \frac{W_\sigma(\mu_\pi,\sigma_\pi)}{W_\mu(\mu_\pi,\sigma_\pi)}\sigma_q = p_e + \mu_q + t$ |

Table 1: Efficiency and markets with producer price uncertainty
(Notation: $\varphi_z = \lambda_z/\lambda_\mu$, $\varphi_r = \lambda_r/\lambda_\mu$ and $\varphi_\sigma = \lambda_\sigma/\lambda_\mu$)

Combined with (1), (2), (4), (5), the first-order conditions determine the efficient allocation $(e^*, b^*, g^*, r_g^*, r_x^*, x^*, \mu_x^*, \sigma_x^*, z^*, z_d^*)$. The terms in column 1 can be rearranged to read

$$\frac{X_r^*}{G_r^*} = \frac{\mathcal{U}_z^*}{V_\mu^*} = \frac{p_e + \mu_q}{B_e^*} - \frac{V_\sigma^*\sigma_q}{V_\mu^* B_e^*}. \tag{12}$$

The first term in (12) is the marginal rate of transformation between $x$ and $g$. Since $x_s^* = X(r_x^*) = X(\bar{r} - r_g^*) = X[\bar{r} - G^{-1}(g^*)]$, the value of $X_r^*/G_r^*$ uniquely determines $x^*$ and $g^*$. Suppose (12) (with stars attached) represents the optimality condition for $\sigma_q > 0$ and denote by

$$\frac{X_r^n}{G_r^n} = \frac{\mathcal{U}_z^n}{V_\mu^n} = \frac{p_e + \mu_q}{B_e^n}$$

the optimality condition in the absence of risk ($\sigma_q = 0$). $X_r^n/G_r^n$ clearly determines $x^n$ and $g^n$ which gives rise to the question whether $g^*$ is greater or smaller than $g^n$. Simple calculations show that

$$g^* \gtreqless g^n \quad \Longleftrightarrow \quad \frac{X_r^*}{G_r^*} \gtreqless \frac{X_r^n}{G_r^n} \quad \Longleftrightarrow \quad B_e(e^n) - B_e(e^*) \gtreqless \frac{V_\sigma^* \sigma_q B_e(e^n)}{(p_e + \mu_q) V_\mu^*} (< 0). \tag{13}$$

Hence there is $\tilde{e} > e^n$ such that $g^* \gtreqless g^n \Longleftrightarrow e^* \gtreqless \tilde{e}$. To interpret that result consider mean preserving spreads of the random variable $q$. As long as in the transition from $\sigma_q = 0$ to $\sigma_q > 0$ the reduction in the use of fossil fuel is not too strong (i.e. as long as $e^* > \tilde{e} > e^n$) it is optimal to produce more green energy under uncertainty than under certainty. Yet we cannot infer from (13) whether $e$ is decreasing and $g$ is increasing in risk. These mappings may as well be non-monotone because general equilibrium effects need to be accounted for and the sign and size of second derivatives of the utility function $V$ may play a role. To further clarify the impact of risk on the optimal allocation we carry out a full-scale comparative-static analysis (Appendix A) and report the results in

**Proposition 1 .** *If the efficient allocation of the model (1), (2), (4)-(6) is disturbed by a small variation in the risk parameter $\sigma_q$, the direction of change in the efficient values $e, r_g, r_x, x$ is as shown in Table 2. The direction of change in all other variables is ambiguous.*

| | $\frac{\mathrm{d}b}{\mathrm{d}\sigma_q}, \frac{\mathrm{d}e}{\mathrm{d}\sigma_q}$ | $\frac{\mathrm{d}g}{\mathrm{d}\sigma_q}, \frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q}$ | $\frac{\mathrm{d}x}{\mathrm{d}\sigma_q}, \frac{\mathrm{d}r_x}{\mathrm{d}\sigma_q}$ | $\frac{\mathrm{d}z}{\mathrm{d}\sigma_q}$ |
|---|---|---|---|---|
| $V_{\mu\sigma} \geq 0$ | $-$ | ? | ? | ? |
| $-\frac{V_{\mu\sigma}}{V_{\mu\mu}} \geq -\frac{V_\sigma}{V_\mu} \geq \frac{1}{\varepsilon} \cdot \left(-\frac{V_{\mu\sigma}}{V_{\mu\mu}}\right)$ | $-$ | $+$ | $-$ | ? |

Table 2: Impact of variations in risk on the efficient allocation
(Notation: $\varepsilon := -\frac{B_e}{eB_{ee}} > 0$)

Note first that all results reported in Table 2 refer to the case of risk aversion and prudence ($V_{\mu\sigma} > 0$). Our focus on prudence is warranted because empirical evidence (Charas and Holt 1996, Guiso et al. 1996) and experimental evidence (Binswanger 1981, Levy 1994) suggest that utility functions are decreasing absolute risk averse ($M_\mu < 0$) which in turn implies prudence ($V_{\mu\sigma} > 0$).[7] Unfortunately, in Proposition 1 the only clear-cut and intuition-conforming information about an efficient response to increasing risk is that fuel imports need to be reduced. As the change in the provision of green energy can assume either sign we get no answer to our central question whether expanding green energy is an efficient response to increasing risk.[8] Under additional sufficient conditions listed in the second row of Table 2 we attain the clear result $\mathrm{d}g/\mathrm{d}\sigma_q > 0$. These conditions do not seem to be very restrictive. In view of (9) the first inequality $-\frac{V_{\mu\sigma}}{V_{\mu\mu}} > -\frac{V_\sigma}{V_\mu}$ turns out to be DARA which is not a controversial assumption in the pertaining literature. The second inequality, $-\frac{V_\sigma}{V_\mu} \cdot \varepsilon > \left(-\frac{V_{\mu\sigma}}{V_{\mu\mu}}\right)$, is satisfied if the price elasticity of demand for black energy is sufficiently large, i.e. if the production function $B(e)$ has little curvature. A large value of $\varepsilon$ can be considered an approximation to linear cost functions (with setup costs) of power plants, an assumption that is not uncommon in the energy economics literature. The observation that $\mathrm{d}g/\mathrm{d}\sigma_q > 0$ for sufficiently large $\varepsilon$ nicely reconfirms the last inequality in (13). We know from (13) that the difference $B_e(e^n) - B_e(e^*)$ tends to zero for $\varepsilon \to \infty$ and hence renders positive the difference $g^* - g^n$.

For the sake of more specific results we parametrize the utility function and the production function by

$$\mathcal{V}(x_d) = -\frac{1}{a}\exp^{-ax_d}, \tag{14}$$
$$B(e) = e^\theta, \tag{15}$$

where $a > 0$ and $\theta \in ]0,1[$. The utility function (14) belongs to the class of hyperbolic absolute risk averse functions and displays constant absolute risk aversion (CARA). Since utility functions of type (14) are mathematically convenient representations and simplify comparative static analyses considerably, they are the most commonly used functional forms in the expected utility approach (for applications see Cass and Stiglitz 1970, Hens et al. 2002 or Gollier and Schlesinger 2003). Wagener (2005) shows that the utility function (14) translates into the mean-variance utility function

$$V(\mu,\sigma) = -\frac{1}{a}H(\sigma)\exp^{-a\mu}, \tag{16}$$

with $H(0) = 1$, and $H_\sigma > 0$ for all $\sigma > 0$. It is worth mentioning that prudence is not only necessary for DARA functions but also for CARA functions (16). Hence the result $\mathrm{d}e/\mathrm{d}\sigma_q < 0$ from Table 2 is valid for CARA functions. In addition, Appendix B proves:

[7] There is also a strong theoretical argument for prudence. Menegatti (2001) has proven that $\mathcal{V}_x > 0$, $\mathcal{V}_{xx} < 0$ and sign $\mathcal{V}_{xxx}$ being the same for all $x_d \geq 0$ is sufficient for $\mathcal{V}_{xxx} > 0$ for all $x_d \geq 0$.

[8] It is interesting to note that even if $\mathrm{d}g/\mathrm{d}\sigma_q < 0$ in case of $V_{\mu\sigma} \geq 0$, the ratio of green to black energy, $g/b$, will increase if and only if $|\mathrm{d}g/\mathrm{d}\sigma_q| < |\mathrm{d}b/\mathrm{d}\sigma_q|$. Changing the composition of total energy in favor of green energy can then be considered as an expansion of green energy in *relative* rather than in *absolute* terms.

**Proposition 2.** *Suppose the mean-variance utility function $V(\mu, \sigma)$ is speciefied by (16) and the production function $B(e)$ is specified by (15). If the efficient allocation of the model (1), (2), (4)-(6) is disturbed by a small increase in the risk parameter $\sigma_q$, then the efficient response is*

*(i) to reduce black energy production $b$,*

*(ii) to increase green energy production $g$,*

*(iii) to reduce total energy consumption $z$ and*

*(iv) to reduce consumer good consumption $x$.*

Under the conditions of Proposition 2 that are slightly more restrictive than those of Proposition 1 an efficient response to increasing energy insecurity consists in curbing black as well as total energy while expanding green energy. That involves a shift in the composition of total energy toward green energy which we have already identified in Proposition 1 under the conditions of the second row of Table 2. The observation that the use of fossil fuel is monotone decreasing in risk under conditions of both Propositions 1 *and* Proposition 2 suggests that this result appears to be quite robust.

Having characterized the social planner's efficient solution as a benchmark we will now turn to the decentralized economy with perfectly competitive markets for the consumption good, the resource and for energy. The government has at its disposal two instruments whose rates are not sign-constrained to regulate fossil-fuel use and/or green-energy production. In the remainder of the paper we seek to answer the following questions:

(i) Does the allocation of the no-tax competitive equilibrium deviate from the social planner's solution?

(ii) If it deviates, is it possible to characterize corrective tax-subsidy policies?

# 4 The competitive economy and corrective taxation

To prepare for tackling these core questions we first need to specify the competitive economy with fossil fuel price uncertainty and taxation. Then we present the main result of decentralizing the efficient allocation by prices and taxes. We denote the market prices associated with the perfectly competitive markets for the consumption good, the resource and for energy by $p_x \equiv 1, p_r$ and $p_z$, respectively. The government has at its disposal tax policies $(s, t)$ where $s$ is the rate of a tax on green energy production and $t$ is the rate of a tax on fossil fuel input;[9] both rates are unconstrained in sign.[10]

In this setup, the profits of the three industries are given by

$$\pi_g = (p_z - s)G(r_g) - p_r r_g, \quad (17a)$$

$$\pi_x = X(r_x) - p_r r_x, \quad (17b)$$

$$\pi_b = p_z B(e) - (p_e + q + t)e. \quad (17c)$$

Inspection of the profits $\pi_g, \pi_x$ and $\pi_b$ reveals that it is the producer of black energy who is exposed to and has to cope with price uncertainty while the other producers and the consumer are not subject to any uncertainty.[11] Hence the profit of the producer of black energy becomes a random variable such that she needs to determine her production plan under input price uncertainty. However, her (ex ante) supply of black energy is deterministic which means that the uncertainty is not passed on to the consumer. As will be shown below, that difference in risk management of the social planner and the agents in the market economy will lead to market failure which will then give rise to the question whether suitable taxes and/or subsidies are available to correct for those failures.

The manager of the black energy firm is assumed to be either risk neutral or risk averse. Her preferences are represented by the two-moment utility function $W(\mu_\pi, \sigma_\pi)$, with the function $W$ posessing the same properties as the function $V$ in (8a)-(8e) and (10). The manager's decision problem is

$$\max_e W(\mu_\pi, \sigma_\pi) \quad \text{s.t.} \quad \mu_\pi = p_z B(e) - (p_e + \mu_q + t)e, \quad \sigma_\pi = \sigma_q e. \quad (18)$$

For any tax policy $(s, t)$, a *competitive ex ante equilibrium* of the economy (1) - (3) and (5) is attained if the prices $p_r$ and $p_z$ are market clearing, if firms maximize profits (17a), (17b),

[9] In our simple model, this tax is equal to an import tariff as well as a carbon emissions tax.

[10] In practical policy, combinations of various fiscal instruments can be and are applied to promote green energy and/or to curb carbon emissions (e.g. taxes on total energy consumption, taxes on black energy consumption). To keep focused we refrain from characterizing all possible combinations of fiscal instruments capable of supporting allocative efficiency. In our stylized model, the incidence of the green energy subsidy ($s < 0$) is essntially the same as that of feed-in tariffs or green certificates. Similarly, the emissions tax ($t > 0$) is here equivalent to an emissions trading scheme with $t$ denoting the (endogenous) price of emission allowances. Hence $s$ and $t$ stand for the prime instruments used in practice for promoting green energy and for reducing emissions, respectively.

[11] Note the decisive difference between the risk management of the social planner and of the agents in the market economy. The former does not account for (domestic) markets and profits and thus rightly identifies the consumption of good $X$ as a random variable derived from the price uncertainty in the trade balance (see Section 3).

(18), and if the representative consumer maximizes her utility (6) subject to the budget constraint[12]

$$\phi + p_r\bar{r} = p_z z_d + x_d, \tag{19}$$

where $\phi := \mu_\pi^m + \pi_g^m + \pi_x^m + te + sg$ is a lumpsum transfer of profits and net tax revenues to the consumer. $\mu_\pi^m + \pi_g^m$ and $\pi_x^m$ denote maximum profits. The first-order conditions listed in the second column of Table 1 determine the equilibrium allocation ($e^m, b^m, g^m, r_g^m, r_x^m, x^m, z^m, z_d^m$) for some predetermined tax policy $(s,t)$, where the superscript $m$ indicates the market equilibrium. We now wish to determine that particular tax policy $(s,t)$ which makes the corresponding equilibrium allocation coincide with the social planner's optimum. To that end we compare the columns 1 and 2 of Table 1 and obtain

**Proposition 3.** *A competitive ex ante equilibrium with producer price risk exists and the pertinent equilibrium allocation is efficient, if the (endogenous) prices are given by*

$$p_r = \varphi_r \quad \text{and} \quad p_z = \frac{V_\mu(\mu_x,\sigma_x)}{\mathcal{V}_x(x_d)}\varphi_z \tag{20}$$

*and if the fiscal policy $(s,t)$ satisfies*

$$s = \frac{(V_\mu - \mathcal{V}_x)\varphi_z}{\mathcal{V}_x} \quad \text{and} \quad t = sB_e + \left(\frac{W_\sigma}{W_\mu} - \frac{V_\sigma}{V_\mu}\right)\sigma_q. \tag{21}$$

*In (20) - (21), $\varphi_r, \varphi_z, B_e, V_\mu$ and $V_\sigma$ are evaluated at the solution of (11) and $\mathcal{V}_x, W_\sigma$ and $W_\mu$ are evaluated at the agents' optimal programs in the market economy.*

# 5 The role of attitudes toward risk for corrective taxation

This section serves to discuss and interpret the results of Proposition 3 focusing on the capacity of green subsidies and black taxes as means to cope with energy insecurity under varying assumptions on attitudes toward risk.

Consider first the efficient tax/subsidy on green energy. In (21) it depends on the sign of the difference $V_\mu(\mu_x,\sigma_x) - \mathcal{V}_x(x_d)$ whether it is optimal to tax or to subsidize green energy. It is therefore useful to begin with investigating the determinants of that sign. Recall that (7) links the mean-variance utility function $V(\mu_x,\sigma_x)$ and the von Neumann-Morgenstern utility function $\mathcal{V}(x_d)$. Differentiation of (7) with respect to $\mu_x$ yields

$$V_\mu(\mu_x,\sigma_x) = \int_a^b \mathcal{V}_x(\mu_x + \sigma_x n)\mathrm{d}F(n). \tag{22}$$

[12]Observe that (19) is implied by (1) - (4) and recall that the consumer acts under certainty.

An immediate implication of (22) is $V_\mu(\mu_x, 0) = \mathcal{V}_x(\mu_x)$, which gives rise to

$$V_\mu(\mu_x, \sigma_x) \gtreqless \mathcal{V}_x(\mu_x) \quad \Longleftrightarrow \quad V_{\mu\sigma}(\mu_x, \sigma_x) \gtreqless 0. \tag{23}$$

for $\sigma_x > 0$. The right side of the equivalence (23) is linked, in turn, via (8d) to the concepts of prudence and imprudence as defined in our remarks on (8d) in Section 2. Hence we have established that taxing green energy ($s > 0$) is efficient, if and only if the consumer is prudent ($V_{\mu\sigma} > 0$), and green energy needs to be subsidized [needs to remain untaxed and unsubsidized], if and only if the consumer is imprudent [risk neutral]. These results are independent of the black energy producer's attitude toward risk.

We proceed making more transparent the implications of Proposition 3 by distinguishing the consumer's (and hence the benevolent planner's) and the black energy producer's attitudes toward risk according to whether they are risk neutral ($V_\sigma = 0, W_\sigma = 0$) or risk averse ($W_\sigma < 0, V_\sigma < 0$) *and* - in the latter case - whether the consumer's von Neumann-Morgenstern utility function displays prudence ($V_{\mu\sigma} > 0$) or imprudence ($V_{\mu\sigma} < 0$). This distinction of preference attributes gives rise to the following three scenarios:[13]

*Scenario 1*: The consumer is risk neutral ($V_\sigma = 0$) and the black energy producer is risk averse ($W_\sigma < 0$) or risk neutral ($W_\sigma = 0$).

*Scenario 2*: The consumer is risk averse ($V_\sigma < 0$) and imprudent ($V_{\mu\sigma} < 0$) and the black energy producer is risk averse ($W_\sigma < 0$) or risk neutral ($W_\sigma = 0$).

*Scenario 3*: The consumer is risk averse ($V_\sigma < 0$) and prudent[14] ($V_{\mu\sigma} > 0$) and the black energy producer is risk averse ($W_\sigma < 0$) or risk neutral ($W_\sigma = 0$).

Although these scenarios differ with respect to their empirical relevance,[15] we will explore the implications of each of them to see what drives the results. The issue of empirical relevance will be addressed later.

For Scenario 1, (21) readily yields the corrective policy

$$s = 0 \quad \text{and} \quad t = \frac{W_\sigma}{W_\mu}\sigma_q \leq 0.$$

Note first that any regulation of green energy, taxing as well as subsidizing, would render the risk management inefficient in Scenario 1. If $W_\sigma < 0$, the efficient regulation consists of subsidizing (!) fossil fuel. At first glance that result may appear puzzling but its logic is straightforward. If society, represented by the consumer, is risk neutral and the producer is risk averse, the latter needs to receive an incentive in form of a subsidy to overcome her

[13] Observe that the sign of $W_{\mu\sigma}$ is irrelevant for the qualitative results of Proposition 3.

[14] Recall that $V_{\mu\sigma} > 0$ is necessary for both CARA and DARA.

[15] Recall our remarks following Proposition 1 in Section 3.

reluctance to take some risk in production. Curbing carbon emissions ($t > 0$) would reduce rather than enhance welfare.

Suppose next that $V_\sigma = W_\sigma = 0$, i.e. that both the consumer and the black energy producer are risk neutral. The straightforward implication is that ($s = 0, t = 0$) is the optimal policy. No tax policy is needed at all to correct for allocative distortions because there is no such distortion. Although risk exists, the agents essentially behave as under certainty. Scenario 1 with $V_\sigma = W_\sigma = 0$ can therefore - and will later - be considered as the benchmark case of certainty. We conclude that in Scenario 1 neither curbing emissions via $t$ nor promoting green energy via $s$ can be rationalized as a means for enhancing energy security.

Consider next the Scenario 2 which requires

$$s = \frac{(V_\mu - \mathcal{V}_x)\varphi_z}{\mathcal{V}_x} < 0 \quad \text{and} \quad t = sB_e + \left(\frac{W_\sigma}{W_\mu} - \frac{V_\sigma}{V_\mu}\right)\sigma_q$$

as a corrective policy. In this case, promoting green energy ($s < 0$) is an appropriate means to cope with energy insecurity. To understand the rationale of that policy we first assume that $\left(\frac{W_\sigma}{W_\mu} - \frac{V_\sigma}{V_\mu}\right) = 0$. According to (23) for imprudent consumers ($V_{\mu\sigma} < 0$) the marginal utility of an additional unit of $\mu_x$ under uncertainty is lower than an additional unit of $x_\mathrm{d}(= \mu_x)$ under certainty, in formal terms $V_\mu(\mu_x, \sigma_x) < \mathcal{V}_x(\mu_x)$. With this information we infer from (20) that the market price $p_z$ is lower than the associated shadow price $\varphi_z$. Comparing column 1 and 2 in rows 4 and 5, respectively, of Table 1 and accounting for $p_z < \varphi_z$ we conclude that the producers of green and black energy receive too weak market price signals for producing energy, if $s = t = 0$. This market failure is corrected by subsidizing green energy ($s < 0$) *and* subsidizing fossil fuel ($t < 0$). The green energy subsidy stimulates the production of green energy, while the fossil fuel subsidy fosters the production of black energy.

Suppose now that $\left(\frac{W_\sigma}{W_\mu} - \frac{V_\sigma}{V_\mu}\right) \neq 0$. This term introduces an additional effect caused by the difference in the consumer's and producer's risk aversion. If the consumer is much more risk averse than the producer, fossil fuel use has to be taxed, ceteris paribus, since the producer is too lax in coping with risk. In contrast, if the consumer is less risk averse than the producer, the producer is too anxious dealing with the risk and fossil fuel use has to be subsidized. Therefore, the corrective tax rate can attain either sign irrespective of whether $W_\sigma < 0$ or $W_\sigma = 0$. $t > 0$ is the more likely the greater is the consumer's as compared to the producer's risk aversion. $\left(\left|\frac{V_\sigma}{V_\mu}\right| > \left|\frac{W_\sigma}{W_\mu}\right|\right)$. In conclusion, in Scenario 2 green energy promotion ($s < 0$) is an indispensible instrument for coping with energy insecurity in an efficient way. Under certain conditions, this holds for emissions reduction policies ($t > 0$) as well but the case of welfare-enhancing fossil fuel subsidies cannot be ruled out.

Suppose finally, Scenario 3 prevails. In that scenario the policy $(s, t)$ is corrective, if and only if

$$s = \frac{(V_\mu - \mathcal{V}_x)\varphi_z}{\mathcal{V}_x} > 0 \quad \text{and} \quad t = sB_e + \left(\frac{W_\sigma}{W_\mu} - \frac{V_\sigma}{V_\mu}\right)\sigma_q.$$

The striking result is that efficiency requires discouraging (i.e. taxing) green energy production rather than promoting (subsidizing) it. Using the same arguments as in Scenario 2 it is now straightforward to show that $p_z > \varphi_z$ for prudent consumers. Hence, if $\frac{W_\sigma}{W_\mu} - \frac{V_\sigma}{V_\mu} = 0$ both green energy and the fossil fuel use needs to be taxed in order to manage the risk in an efficient way. Accounting for $\frac{W_\sigma}{W_\mu} - \frac{V_\sigma}{V_\mu} \neq 0$, the efficient fuel tax rate is unambiguously positive, if the black energy producer is risk neutral. Otherwise it may be negative but only if the producer's risk aversion is sufficiently stronger than that of the consumer (which does not seem to be plausible).

We conclude that promoting green energy in Scenario 3 is not suitable as an instrument to cope with energy insecurity. It is even welfare reducing and therefore harmful. Moreover, except for cases of strongly risk averse black energy producers, taxing fuel is a necessary instrument for efficient risk management.

| | Instrument for efficient risk management | |
|---|---|---|
| | fossil fuel policy $(t)$ | green energy policy $(s)$ |
| Scenario 1 | $t \leq 0$ | $s = 0$ |
| Scenario 2 | $t < 0^*$ | $s < 0$ |
| Scenario 3 | $t > 0^*$ | $s > 0$ |

*under plausible conditions

Table 3: Assessment of instruments for risk management

Our preceding discussion of the Scenarios 1-3 and its summary in Table 3 show that the effectiveness of the tax instruments for an efficient risk management crucially depends on the agents' attitudes toward risk. The appropriate choice of instruments is therefore an empirical issue. Consumers use to be portrayed as being risk averse while producers are usually considered as risk neutral. If producers are risk averse they are likely less risk averse than consumers suggesting that $\left|\frac{W_\sigma}{W_\mu}\right| < \left|\frac{V_\sigma}{V_\mu}\right|$. Moreover, as we mentioned before, empirical as well as experimental studies suggest that preferences exhibiting DARA are realistic. Since DARA implies prudence, Scenario 3 appears to be more realistic than the other scenarios. We highlight that main result of our policy analysis in[16]

[16]Suppose the government has at its disposal a sign-unconstrained tax on the sales price of both black and green energy (but no emissions tax). If the consumer is prudent and more risk averse than the producer

**Proposition 4.** *Suppose consumers are prudent and at least as risk averse as producers. Then efficient risk management requires taxing both green energy and fossil fuels.*

Recall that in the Introduction of the present paper we started out on the intuition or conjecture that efficient management of risk from energy insecurity might turn out to be a rationale for subsidizing green energy. Subject to the qualification that the behavioral assumptions of Proposition 4 are empirically relevant we now find the contrary. Not only is green energy promotion ineffective as a means of coping with energy insecurity, it even renders inefficient the risk management.

The information on corrective regulation $(s^*, t^*)$ we gained in Proposition 3 and the subsequent discussion of the Scenarios 1-3 leave unanswered the question what the qualitative difference is between the no-policy allocation $(e^o, g^o)$ and the efficient allocation $(e^*, g^*)$. It is tempting to argue that $e^o \lesseqgtr e^*$ if $t^* \gtreqless 0$ and $g^o \lesseqgtr g^*$ if $s^* \gtreqless 0$. However, since both tax instruments have an impact on both fossil fuel consumption and the production of green energy, the 'backward inference' from $(s^*, t^*)$ to sign $(e^o - e^*)$ and sign $(g^o - g^*)$ is not that simple. To see this, take the puzzling observation that efficiency requires taxing green energy in Proposition 4 while according to Proposition 2 and one part of Proposition 1 the efficient production of green energy is strictly increasing in risk. For resolving that seeming 'contradiction' we ease the exposition by restricting our attention to the black energy producer being risk neutral. If in that case the consumer is risk neutral as well we get the benchmark scenario (of risk neutral agents) which yields the same market allocation as in the absence of risk. (See our discussion of Scenario 1 above). That, in turn, allows us to draw on Pethig and Wittlich (2009) who analyze the model consisting of the equations (1)-(3), (5) and (6) *in the absence of uncertainty* and characterize the equilibrium values $(e, g)$ for alternative policies $(s \leq 0, t \geq 0)$. They illustrate their result in a graph which we have reproduced here in Figure 1 and extended to include $s \geq 0$ and $t \leq 0$.

Point A in Figure 1 represents the levels of green energy, $g^o$, and fossil fuel $e^o$, in the no-policy competitive equilibrium $(s = 0, t = 0)$. If we keep $s$ constant at $s = 0$ but successively increase $t$ we move on the line AB from A toward B. During that move fuel consumption declines and the production of green energy increases. Alternatively if we keep $t$ constant at $t = 0$ and successively increase $|s|$, where $s \leq 0$, we move on the line AC from A toward C, and we thus also curb the use of fuel and expand green energy. However, in the latter case the increase in green energy is larger and the emissions reduction is smaller than in the former case.[17] Thus the area ABC in Figure 1 is the set of all equilibrium

of black energy both tax rates are positive and the rate on black energy is higher than the rate on green energy.

[17]In other words, all lines in Figure 1 with constant $t$ are steeper than the lines with constant $s$.

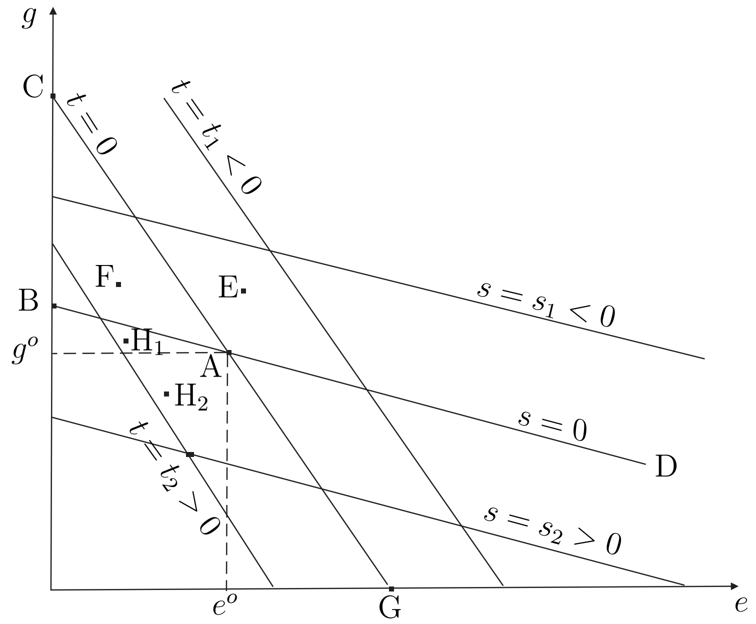


Figure 1: Allocations $(e, g)$ of fossil fuel and green energy attained through policies $(s, t)$

allocations $(e^m, g^m)$ attainable through tax policies $(s \leq 0, t \geq 0)$. Moreover, each point in that area is uniquely associated with a tuple $(s \leq 0, t \geq 0)$ that supports the corresponding competitive equilibrium.

Figure 1 is a convenient device to illustrate how the efficient allocation $(e^*, g^*)$ deviates from the no-policy market allocation $(e^o, g^o)$. Obviously, in Scenario 1 the efficient allocation coincides with the no-policy allocation in point A in Figure 1. If in Scenario 2 the corrective policy is $(s^* < 0, t^* < 0)$, the efficient allocation is a point in the area above the line CAD, e.g. point E. In this case we cannot exclude any divergence between $(e^o, g^o)$ and $(e^*, g^*)$ other than $e^* < e^o$ *and* $g^* < g^o$. If in Scenario 2 the corrective policy turns out to be $(s^* < 0, t^* > 0)$, the efficient allocation lies in the interior of the triangle ABC at a point such as F which implies $e^* < e^o$ and $g^* > g^o$. While the information on the divergence of $(e^o, g^o)$ and $(e^*, g^*)$ has been limited in the case $(s^* < 0, t^* < 0)$ of Scenario 2 we now have clear qualitative information on the kind of inefficiency of the unregulated economy. Thus in the scenario under consideration the information of Figure 1 is more specific than that from the 'marginal' comparative statics of increasing the risk $\sigma_q$ presented in Appendix A.

Finally, we turn to risk averse and prudent consumers (Scenario 3). With producers being risk neutral, the corrective policy is characterized by $(s^* > 0, t^* > 0)$ and the efficient allocation is a point below the line BAG. Inspection of Figure 1 shows that we cannot exclude any divergence between $(e^o, g^o)$ and $(e^*, g^*)$ other than $e^* > e^o$ *and* $g^* > g^o$. However, we know from Proposition 1 that in the transition from efficiency under certainty to efficiency under uncertainty the fossil fuel use decreases monotonely. Hence, the efficient tuple $(e^*, g^*)$ can only be a point in the interior of the area BA$e^o$, e.g. the point $\mathrm{H}_1$ or $\mathrm{H}_2$. As Proposition 1 shows the sign of $g^o - g^*$ remains unclear under risk aversion and prudence (first row of Table 2) so that we cannot discriminate between $\mathrm{H}_1$ and $\mathrm{H}_2$. However, with some further qualifications (second row of Table 2 and Proposition 2) we know that $(e^*, g^*)$ is a point such as $\mathrm{H}_1$ in the interior of the triangle $g^o$BA. Observe that in this case the inequality $g^* > g^o$ holds, while it is efficient, at the same time, to tax green energy ($s^* > 0$). We have thus demonstrated that $g^* > g^o$ and $s^* > 0$ is not an incompatible constellation. For prudent consumers we summarize the results of the tax incidence in

**Proposition 5.** *Suppose the preconditions of Proposition 4 hold and consider the transition from laissez-faire ($s = 0$, $t = 0$) to efficient regulation ($s^*, t^*$).*

*(i)* $e^* < e^o$ *and* $\operatorname{sign}(g^o - g^*)$ *unclear.*

*(ii) If the functions $B$ and $\mathcal{V}$ are specified by (14) and (15), respectively, then* $e^* < e^o$ *and* $g^* > g^o$.

In concluding the discussion of Proposition 3 we observe that the inefficiency of the competitive economy in the absence of fiscal policy ($s = 0$, $t = 0$) is caused by the fact that in the market economy the black energy producer is the only agent who is exposed to the price risk while the social planner (correctly) takes the consumer's risk exposure into account. Hence divergencies between $V_\mu$ (social planner) and $\mathcal{V}_x$ (consumer) are distortionary as well as differences in risk aversion ($W_\sigma/W_\mu - V_\sigma/V_\mu \neq 0$). The counter-intuitive result of a green energy tax being optimal emerges only, because the risk averse and prudent consumer is sheltered from the price risk by the black energy producer and therefore acts if there were no risk.

# 6 Market efficiency in case of direct exposure to risk of consumers

In this section we will highlight these reasons for allocative inefficiency by slightly modifying our model (1)-(7). The modification is a simplification, in fact, and consists of replacing $b = B(e)$ by $b \equiv e$. The interpretation is that fossil fuel, $e$, is not transformed into black energy by a domestic producer anymore. Instead, the consumer buys black energy directly from the world market and hence is directly exposed to the risk of the fossil fuel price. The production of green energy and of the consumption good still takes places in industries.

The associated profits are

$$\pi_g = (p_g - s)G(r_g) - p_r r_g, \quad (24a)$$

$$\pi_x = X(r_x) - p_r r_x, \quad (24b)$$

where $p_g$ denotes the price of green energy. In contrast to the previous model, the representative consumer now purchases black energy $b \equiv e$ on the world market at the uncertain price $p_e + q$ and she purchases green energy on the domestic market for green energy at the deterministic price $p_g$. The condition

$$G(r_g) = g_d \quad (25)$$

clears the green energy market.

The consumer's stochastic budget constraint is given by

$$\phi + p_r \bar{r} = p_g g_d + (p_e + q + \tau)e + x, \quad (26)$$

where $\tau$ denotes the tax rate on black energy consumption and $\phi := \pi_g^c + \pi_x^c + \tau b + sg$ is a lumpsum transfer of profits and net tax revenues to the consumer. The first-order conditions of the consumer's decision problem

$$\max_{e,g_d} V(\mu_x, \sigma_x) + \mathcal{U}(e + g_d) \quad \text{s.t.} \quad \mu_x = \phi + p_r \bar{r} - p_g g_d - (p_e + \mu_q + \tau)e, \quad \sigma_\pi = \sigma_q e, \quad (27)$$

are listed in the second column of Table 4.[18]

| | | Pareto efficiency<br>1 | Markets<br>2 |
|---|---|---|---|
| Consumption | 1 | $\frac{V_\sigma(\mu_x^*,\sigma_x^*)}{V_\mu(\mu_x^*,\sigma_x^*)} = \frac{p_e+\mu_q-\varphi_z}{\sigma_q}$ | $\frac{V_\sigma(\mu_x^c,\sigma_x^c)}{V_\mu(\mu_x^c,\sigma_x^c)} = \frac{p_e+\mu_q+\tau}{\sigma_q} - \frac{\mathcal{U}_z(e^c+g_d^c)}{\sigma_q V_\mu(\mu_x^c,\sigma_x^c)}$ |
| | 2 | $\frac{\mathcal{U}_z(z_d^*)}{V_\mu(\mu_x^*,\sigma_x^*)} = \varphi_z$ | $\frac{\mathcal{U}_z(e^c+g_d^c)}{V_\mu(\mu_x^c,\sigma_x^c)} = p_g$ |
| Production | 3 | $X_r(r_x^*) = \varphi_r$ | $X_r(r_x^c) = p_r$ |
| Energy Production | 4 | $\varphi_z G_r(r_g^*) = \varphi_r$ | $(p_g - s)G_r(r_g^c) = p_r$ |

Table 4: Efficiency and markets with consumer price uncertainty
(Notation: $\varphi_z = \lambda_z/\lambda_\mu$ and $\varphi_r = \lambda_r/\lambda_\mu$)

For given tax policy $(s, \tau)$ the competitive ex ante equilibrium is constituted by prices $(p_x \equiv 1, p_g, p_r)$ and by the allocation $(b^c, e^c, g_d^c, r_g^c, r_x^c, \mu_x^c, \sigma_x^c)$. Comparing column 1 and 2 of Table 4 yields

[18]Column 1 of Table 4 is identical to column 1 of Table 1, if we set $B_e = 1$ and eliminate $\varphi_\sigma$ in Table 1.

**Proposition 6.** *A competitive ex ante equilibrium with consumer price risk exists and the pertinent equilibrium allocation is efficient, if the (endogenous) prices are given by*

$$p_r = \varphi_r \quad \textit{and} \quad p_g = \varphi_z. \tag{28}$$

Proposition 6 shows that the laissez-faire competitive economy is efficient if the consumers face the price risk. It thus highlights that the policy conclusions of Proposition 3 are essentially driven by the risk shifting from consumers to producers as discussed at the end of Section 5. Observe also that the rows 1 and 2 in the second column of Table 4 yield $p_e + \mu_q > p_g$, if and only if the consumer is risk averse. It is then in the consumer's self interest to pay a higher price for green energy than for black energy. More generally, since the efficient equilibrium prices for green and black energy differ (unless the consumer is risk neutral), a uniform market price $p_z$ for both types of energy - as in the laissez-faire competitive economy of the Sections 4 and 5 - fails to be efficient. The tax/subsidy $s$ from (21) is needed to bring about the efficient differentiation of prices for green and black energy.[19]

To sum up, the modified model studied in the present section sheds additional light on the reasons why the laissez-faire equilibrium of our previous model is inefficient. There are two market failures. First, an inefficiency arises because it is the black energy producer instead of the consumer who is exposed to the risk. An emissions tax/subsidy is needed to correct for differences in risk aversion of the consumer and the producer. Second, because the black energy producer guards the consumer against risk the latter considers green and black energy as perfect substitutes - which they are not. Therefore the resultant uniform price, $p_z$, fails to account for the price risk related to black energy. A green energy tax/subsidy corrects for that market failure. Note that the rate $s$ as defined in the first equation in (21) also co-determines the size of the rate $t$. In that way, $s$ brings about the price differentiation for black and green energy to restore efficiency.

# 7 Concluding remarks

The present paper analyzes fossil fuel price uncertainty in a small open economy depending on fossil fuel imports. Using mean-variance preferences which in our model are equivalent to expected utility preferences we find that increases in the variance of the fossil fuel price (= increasing risk) reduce the efficient black energy production in case of prudent consumers

[19]Interestingly, although black and green energy are physically homogeneous products the consumer views them as imperfect substitutes in the present model specification, because the price of green energy is certain and that of black energy is uncertain.

and enhance the efficient green energy production for constant absolute risk averse consumers. These results are intuitive. Turning to competitive markets we get at first glance counterintuitive results. If consumers are prudent and more risk averse than producers, both fossil fuel and green energy have to be taxed to implement the efficient allocation.

That risk shifting (from the consumer in the social planner's program to the black energy producer in the competitive economy) gives rise to two market failures, the correction of which requires two fiscal instruments. If the consumer and the (black energy) producer differ with respect to their risk aversion, a tax/subsidy on fossil fuel is needed to compensate for that difference. Moreover, since the producer guards the consumer against the price risk, the latter considers black and green energy as perfect substitutes which therefore are uniformly priced in the markets. This is inefficient, however, unless the consumer is risk neutral. The tax/subsidy on green energy serves to generate the wedge between the prices for black and green energy which is a necessary condition for an efficient allocation.

While our simple analytical framework allows for a clear focus and informative results, the insights are limited due to restrictive assumptions. For example, learning spillovers in the production of green energy would obviously raise the likelihood of green energy subsidies being optimal. This is not true, however, if one would extend the model by introducing a cost-effective climate policy, say in form of a cap-and-trade scheme because green energy promotion is less effective in curbing emissions than an emissions tax. Yet that extension would have other interesting implications. To see that suppose an emissions cap is introduced that is more stringent than the emissions under efficient risk management without the emissions cap (Proposition 3). In that case the cost to society of the climate policy is smaller than the total cost of the cap-and-trade scheme in the absence of risk management because the optimal risk management also requires to curb emissions.

Our paper leaves open some various other issues. For example, it is unclear whether our results also hold for import quantity uncertainty with rigid import prices. One might also want to introduce forward markets and investigate hedging of the price risk. These topics are beyond the scope of the present paper but appear to be interesting for future research.

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## Appendix A: Proof of Proposition 1

**Comparative statics of the social planner's solution with respect to $\sigma_q$:** Maximizing $V\left[X(\bar{r}-r_g)-(p_e+\mu_q)e, e\sigma_q\right]+\mathcal{U}\left[B(e)+G(r_g)\right]$ yields the first order conditions

$$-(p_e+\mu_q)-\sigma_q M+\frac{\mathcal{U}_z}{V_\mu}B_e=0 \quad\equiv\quad \Phi, \tag{A1}$$

$$-X_r+\frac{\mathcal{U}_z}{V_\mu}G_r=0 \quad\equiv\quad \Omega, \tag{A2}$$

where $M:=-\frac{V_\sigma}{V_\mu}$. Total differentiation of (A1) and (A2) yields

$$\begin{pmatrix}\Phi_e & \Phi_{r_g}\\ \Omega_e & \Omega_{r_g}\end{pmatrix}\begin{pmatrix}\mathrm{d}e\\ \mathrm{d}r_g\end{pmatrix}=\begin{pmatrix}-\Phi_{\sigma_q}\\ -\Omega_{\sigma_q}\end{pmatrix}, \tag{A3}$$

where

$$\Phi_e \;=\; -\sigma_q^2(M_\mu M+M_\sigma)+\frac{2MM_\mu\sigma_q B_e\mathcal{U}_z}{V_\mu}+\frac{B_e^2\mathcal{U}_{zz}}{V_\mu}+\frac{B_e^2\mathcal{U}_z^2V_{\mu\mu}}{V_\mu^3}+\frac{B_{ee}U_z}{V_\mu}, \tag{A4}$$

$$\Phi_{r_g} \;=\; \sigma_q X_r M_\mu+\frac{B_eG_r\mathcal{U}_{zz}}{V_\mu}+\frac{B_e\mathcal{U}_zX_rV_{\mu\mu}}{V_\mu^2}, \tag{A5}$$

$$\Phi_{\sigma_q} \;=\; -M-\sigma_q eM_\sigma-\frac{eB_e\mathcal{U}_zV_{\mu\sigma}}{V_\mu^2}, \tag{A6}$$

$$\Omega_e \;=\; \frac{B_eG_r\mathcal{U}_{zz}}{V_\mu}+\frac{\sigma_qM_\mu G_r\mathcal{U}_z}{V_\mu}+\frac{G_rB_e\mathcal{U}_z^2V_{\mu\mu}}{V_\mu^3}, \tag{A7}$$

$$\Omega_{r_g} \;=\; X_{rr}+\frac{\mathcal{U}_zG_{rr}}{V_\mu}+\frac{G_r^2\mathcal{U}_{zz}}{V_\mu}+\frac{X_rG_r\mathcal{U}_zV_{\mu\mu}}{V_\mu^2}, \tag{A8}$$

$$\Omega_{\sigma_q} \;=\; -\frac{eG_r\mathcal{U}_zV_{\mu\sigma}}{V_\mu^2}. \tag{A9}$$

Solving the equation system (A3) by using Cramer's rule we obtain

$$\frac{\mathrm{d}e}{\mathrm{d}\sigma_q} = \frac{-\Phi_{\sigma_q}\Omega_{r_g} + \Omega_{\sigma_q}\Phi_{r_g}}{D}, \tag{A10}$$

$$\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q} = \frac{-\Phi_e\Omega_{\sigma_q} + \Omega_e\Phi_{\sigma_q}}{D}, \tag{A11}$$

where $D = \Phi_e\Omega_{r_g} - \Omega_e\Phi_{r_g} > 0$ via the assumption that the second-order condition for a maximum is satisfied. Making use of (A5), (A6), (A8), (A9) in (A10) we get after rearrangement of terms

$$\begin{aligned}\frac{\mathrm{d}e}{\mathrm{d}\sigma_q}\cdot D &= (M + \sigma_q e M_\sigma)\left(X_{rr} + \frac{\mathcal{U}_z G_{rr}}{V_\mu} + \frac{G_r^2\mathcal{U}_{zz}}{V_\mu} + \frac{X_r G_r \mathcal{U}_z V_{\mu\mu}}{V_\mu^2}\right) \\ &+ \frac{e\mathcal{U}_z V_{\mu\sigma}}{V_\mu^2}\left(B_e X_{rr} + \frac{B_e\mathcal{U}_z G_{rr}}{V_\mu} - M_\mu\sigma_q G_r X_r\right).\end{aligned} \tag{A12}$$

Accounting for $M_\sigma V_{\mu\mu} - M_\mu V_{\mu\sigma} = -\frac{1}{V_\mu}(V_{\mu\mu}V_{\sigma\sigma} - V_{\mu\sigma}^2)$ in (A12) yields

$$\begin{aligned}\frac{\mathrm{d}e}{\mathrm{d}\sigma_q}\cdot D &= (M + \sigma_q e M_\sigma)\left(X_{rr} + \frac{\mathcal{U}_z G_{rr}}{V_\mu} + \frac{G_r^2\mathcal{U}_{zz}}{V_\mu}\right) + \frac{e\mathcal{U}_z V_{\mu\sigma}}{V_\mu^2}\left(B_e X_{rr} + \frac{B_e\mathcal{U}_z G_{rr}}{V_\mu}\right) \\ &- \frac{e\sigma_q X_r G_r \mathcal{U}_z}{V_\mu^3}(V_{\mu\mu}V_{\sigma\sigma} - V_{\mu\sigma}^2).\end{aligned} \tag{A13}$$

Next, we insert (A4), (A6), (A7), (A9) into (A11) and rearrange terms to get

$$\begin{aligned}\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q}\cdot D &= \frac{\mathcal{U}_z^2 e\sigma_q B_e G_r}{V_\mu^3}(M_\mu V_{\mu\sigma} - M_\sigma V_{\mu\mu}) + \frac{\mathcal{U}_z^2}{V_\mu^3}G_r\left(eV_{\mu\sigma}B_{ee} - MB_eV_{\mu\mu}\right) \\ &- \frac{\mathcal{U}_z G_r \sigma_q^2 e}{V_\mu}\left[\frac{V_{\mu\sigma}}{V_\mu}(M_\mu M + M_\sigma) + M_\sigma M_\mu\right] - \frac{MM_\mu\sigma_q\mathcal{U}_z G_r}{V_\mu} \\ &- \frac{(M + e\sigma_q M_\sigma)\mathcal{U}_{zz}B_e G_r}{V_\mu}.\end{aligned} \tag{A14}$$

Observe that $M_\mu V_{\mu\sigma} - M_\sigma V_{\mu\mu} = \frac{1}{V_\mu}(V_{\mu\mu}V_{\sigma\sigma} - V_{\mu\sigma}^2)$ and $\frac{V_{\sigma\mu}}{V_\mu}(MM_\mu + M_\sigma) + M_\sigma M_\mu = \frac{M}{V_\mu^2}(V_{\mu\mu}V_{\sigma\sigma} - V_{\mu\sigma}^2)$. Using this information in (A14) we get

$$\begin{aligned}\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q}\cdot D &= \left(\frac{\mathcal{U}_z^2 e\sigma_q B_e G_r}{V_\mu^4} - \frac{M\mathcal{U}_z G_r\sigma_q^2 e}{V_\mu^3}\right)(V_{\mu\mu}V_{\sigma\sigma} - V_{\mu\sigma}^2) \\ &+ \frac{\mathcal{U}_z^2 G_r}{V_\mu^3}(eV_{\mu\sigma}B_{ee} - MB_eV_{\mu\mu}) - \frac{MM_\mu\sigma_q\mathcal{U}_z G_r}{V_\mu} \\ &- \frac{(M + e\sigma_q M_\sigma)\mathcal{U}_{zz}B_e G_r}{V_\mu}.\end{aligned} \tag{A15}$$

Finally, using the first-order condition (A1) in (A15) establishes

$$\begin{aligned}\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q}\cdot D &= \frac{\mathcal{U}_z^2\sigma_q e G_r}{V_\mu^3}(p_e + \mu_q)(V_{\mu\mu}V_{\sigma\sigma} - V_{\mu\sigma}^2) \\ &+ \frac{\mathcal{U}_z^2 B_e G_r V_{\mu\mu}}{V_\mu^3}\left(\frac{V_{\mu\sigma}}{V_{\mu\mu}}\frac{B_{ee}\cdot e}{B_e} + \frac{V_\sigma}{V_\mu}\right) - \frac{MM_\mu\sigma_q\mathcal{U}_z G_r}{V_\mu} \\ &- (M + e\sigma_q M_\sigma)\frac{\mathcal{U}_{zz}B_e G_r}{V_\mu}.\end{aligned} \tag{A16}$$

According to (9) prudence ($V_{\mu\sigma} > 0$) implies decreasing absolute risk aversion ($M_\mu < 0$). In addition, the concavity of $V$ ($V_{\mu\mu}V_{\sigma\sigma} - V_{\mu\sigma}^2$) implies convex indifference curves, i.e. $M_\sigma + MM_\mu > 0$. Then $V_{\mu\sigma} > 0$ and the concavity of $V$ are sufficient for $M_\sigma > 0$. Using these properties in (A13) we immediately get $\mathrm{d}e/\mathrm{d}\sigma_q < 0$ if $V_{\mu\sigma} > 0$. Closer inspection of (A16) reveals that all sum terms on the right side of (A16) are positive for $V_{\mu\sigma} > 0$ except for $\frac{\mathcal{U}_z^2 B_e V_{\mu\mu}}{V_\mu^3}\left(\frac{V_{\mu\sigma}}{V_{\mu\mu}}\frac{B_{ee}e}{B_e} + \frac{V_\sigma}{V_\mu}\right)$. To ensure that this term is also non-negative it must hold

$$-\frac{V_{\mu\sigma}}{V_{\mu\mu}} \cdot \frac{1}{\varepsilon} \leq -\frac{V_\sigma}{V_\mu}, \tag{A17}$$

where $\varepsilon := -\frac{B_e}{eB_{ee}} > 0$, and hence we get $\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q} > 0$. Next, observe that

$$\frac{\mathrm{d}b}{\mathrm{d}\sigma_q} = B_e\frac{\mathrm{d}e}{\mathrm{d}\sigma_q}, \quad \frac{\mathrm{d}g}{\mathrm{d}\sigma_q} = G_r\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q}, \quad \frac{\mathrm{d}x}{\mathrm{d}\sigma_q} = -X_r\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q}, \quad \frac{\mathrm{d}r_x}{\mathrm{d}\sigma_q} = -\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q}. \tag{A18}$$

The comparative static effect $\mathrm{d}z/\mathrm{d}\sigma_q$ is ambiguous in sign.

## Appendix B: Proof of Proposition 2

Observe that the utility function (16) satisfies $M_\mu = 0$ or equivalently $-\frac{V_\sigma}{V_\mu} = -\frac{V_{\sigma\mu}}{V_{\mu\mu}}$. Hence, it holds $V_{\mu\sigma} > 0$ and using the same arguments as in the proof of Proposition 1 we get $\frac{\mathrm{d}e}{\mathrm{d}\sigma_q} < 0$ and $\frac{\mathrm{d}b}{\mathrm{d}\sigma_q} < 0$. Next, observe that $\varepsilon = \frac{1}{1-\theta} > 1$ ensures that (A17) holds and we obtain $\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q} > 0$ and $\frac{\mathrm{d}g}{\mathrm{d}\sigma_q} > 0$. Finally, we insert (A13) and (A15) in

$$\frac{\mathrm{d}z}{\mathrm{d}\sigma_q} = B_e\frac{\mathrm{d}e}{\mathrm{d}\sigma_q} + G_r\frac{\mathrm{d}r_g}{\mathrm{d}\sigma_q}, \tag{B1}$$

use $\frac{eB_{ee}}{B_e} = \theta - 1$, $X_r = \frac{U_z}{V_\mu}G_r$ and rearrange terms to get

$$\begin{aligned}\frac{\mathrm{d}z}{\mathrm{d}\sigma_q} \cdot D &= (M + \sigma_q e M_\sigma)\left(B_e X_{rr} + \frac{\mathcal{U}_z B_e G_{rr}}{V_\mu}\right) - \frac{MM_\mu \sigma_q \mathcal{U}_z G_r^2}{V_\mu} \\ &\quad -\frac{M\mathcal{U}_z G_r \sigma_q^2 e}{V_\mu^3}(V_{\mu\mu}V_{\sigma\sigma} - V_{\mu\sigma}^2) + \frac{eB_e^2 U_z V_{\mu\sigma}}{V_\mu^2}\left(X_{rr} + \frac{\mathcal{U}_z G_{rr}}{V_\mu}\right) \\ &\quad +\frac{\mathcal{U}_z^2 G_r^2 V_{\mu\sigma}\theta}{V_\mu^3}.\end{aligned} \tag{B2}$$

Accounting for $M_\mu = 0$ and $V_{\mu\sigma} > 0$ establishes $\frac{\mathrm{d}z}{\mathrm{d}\sigma_q} < 0$.

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