Addressing the Climate Problem

Choice between Allowances, Feed-in Tariffs and Taxes

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Abstract

Instruments chosen to pursue climate related targets are not always efficient. In this paper we consider an economy with three climate related targets for its electricity generation: a given share of "green" electricity, a given expansion of "green" electricity, and a given reduction of "black" (fossil based) electricity. At its disposal the country has three instruments: an allowance system (tradable green certificates), a subsidy system (feed-in tariffs) and a Pigouvian fossil tax. Each of these instruments may be used to attain any of the given targets. Within the setting of the model it is verified that each kind of the target has only a single efficient instrument under certainty, and that there is a deadweight loss of using other instruments to achieve the target. Similarly, there is also an analysis of instrument choice when several targets are to be attained at the same time. The paper also discusses the case of simultaneous targets as well as the relevance of the various targets.

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1. Introduction

Many countries have targets and measures to address the climate change problem. The targets come in different forms: targets on greenhouse gas reduction, targets on shares of renewable energy (e.g. Denmark) and targets on green energy generation (e.g. Norway and Sweden). Along with these targets several measures and instruments are proposed and put into use: CO_2 taxes (or emission permits), allowances (tradable green certificates[5]) and feed- in tariffs/ feed-in premiums. In principle, each of these instruments may be applied to attain each of the targets, but they are not necessarily equally efficient. In an analytic model designed for an electricity market, we show that each target has only one single efficient instrument. Hence, choosing the wrong instrument to attain a target will result in a loss to society. These are basic and straightforward results that should not be forgotten in deciding on which instruments to use. However, the results need to be verified and the objectives of the targets need to be evaluated. An analysis of this kind seems relevant for many economies both within the EU, the USA and for large economies such as China and India.

Within the EU and the EEA, targets on greenhouse gas emission, share of renewables and green energy generation are generally governed by the specific EU 2020 and 2030 policies on energy use. Hence, for 2020 the target is to reduce CO2 emission by 20% compared to the level of 1990 and to increase the share of renewables to 20% (EU-COM, 2010). For 2030 the corresponding numbers are 40% and 27%, respectively (EU-Com, 2014)[6]. For the electricity market all EU member states and participating EEA countries are included in a common emission permit market for CO2, the EU emission trading system (ETS). With respect to the targets on green electricity the EU/EEA member states are at liberty of choosing a share target or a specific green generation capacity target and to decide which instruments to use to attain those targets. Some countries focus mainly on the renewable share target (e.g. Denmark) while others use quantitative expansion of green generation capacity (e.g. Norway and Sweden). With respect to the instruments applied some countries use a

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[5] Green certificate systems are in use in several countries, e.g., the UK ("Renewable Obligation Certificates", Norway and Sweden ("elsertifikater") and the US ("Renewable Portfolio Standards"),

[6] In addition the EU has common targets on energy efficiency and energy savings both for the period up to 2020 and up to 2030. However, no country specific targets or instruments are determined.

single instrument (e.g. the common allowance system for Norway and Sweden) while some countries combine several instruments (e.g. the UK).[7]

A similar picture to that of the EU is valid for the USA. For instance, California has a target of 40% reduction of greenhouse gases by 2030 as compared with 1990 and a target of 50% share of renewables in electricity generation by 2030 (California Government, 2015, Senate Bill 350). To achieve those targets both emission permits (cap and trade programs) and tradable green certificates (renewable portfolio standards) are in use. Otherwise, regional cooperation between states is important. California cooperates with British Columbia, Ontario, Quebec and Manitoba through the Western Climate Initiative to develop harmonized cap and trade programs. Similar programs are also in use in several Northeast Eastern states through the so-called Regional Greenhouse Gas Initiative (RGGI).

According to China's Nationally Determined Contribution (NDC) plan submitted to the UNFCCC for the Paris Agreement China has targets of peaking CO_2 emissions by 2030, lowering the carbon intensity of GDP by 60%−65% below 2005 levels by 2030, and increasing the share of non-fossil energy to around 20% by that time. Measures and instruments in use are primarily specific plans to restrict coal consumption and specific support to increase renewable capacity. However, an initiative to develop a nationwide carbon emission trading market is also taken. According to India's NDC India has targets to lower the emissions intensity of GDP by 33% to 35% by 2030 below 2005 levels, and to increase the share of non-fossil based power generation capacity to 40% of installed electric power capacity by 2030 (equivalent to 26–30% of generation in 2030). India's measures and instruments to achieve the targets are mainly in the category of production plans and direct investments, but India has also

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[7] In the UK, the generation of electricity from renewable sources is supported through a combination of a feed-in tariff system, Contracts for Difference system, a quota system in terms of a quota obligation and a certificate system and a tax mechanism. In Germany, electricity from renewable sources is mainly supported through a market premium determined through a tendering scheme, while smaller plants can benefit from a feed-in tariff. In France, electricity from renewable sources is promoted through a feed-in tariff, a premium tariff as well as through tenders for the definition of the premium tariff level. Additionally, tax benefits are also available.

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an emerging cap and trade market and a green certificate market (a Renewable Energy Certificate trading system).

Hence, many economies around the world have similar climate related targets as well as make use of similar instruments. The instruments in question are well investigated. There exists an abundant literature on the functioning of black certificate (emission permit) systems (see, e.g., Ellerman, 2010). In addition, a sizable literature on green certificate system has emerged. Some of the literature addresses the interplay between the green certificate market and the electricity market (e.g. Nese, 2003; Amundsen, Baldursson and Mortensen, 2006; Fischer, 2009; Amundsen and Nese, 2009; Fischer and Preonas, 2010), while some consider the electricity market, the black certificate market and the green certificate market (e.g., Amundsen and Mortensen, 2001, 2002; Unger and Ahlgren, 2005; Böhringer and Rosendahl, 2010). Furthermore, some analyze the coexistence between an electricity market, a black certificate market and feed-in tariffs. Recently, some literature has emerged addressing all certificate systems taken together (Meran and Wittmann, 2012). Feed-in tariffs and feed-in premiums are also well analyzed, e.g. Traber and Kemfert (2009) analyze the relationship between feed-in tariffs and the CO2 permit market, while Dressler (2016) investigates how feed-in tariffs and feed-in premiums interplay with electricity market with respect to market power exertion.

Hence, how these instruments function is well known, but what we seek here is to investigate how the instruments perform with respect to achieving the targets at least cost to society. The plan of the paper is as follows. Section 2 introduces an analytical model and section 3 presents the targets and analyzes what characterizes the socially first best solutions. Section 4 presents the instruments and section 5 studies how each of the targets may be obtained by using each of the instruments while calculating the social surplus. Section 6 discusses the results and the objectives of the targets, whereas section 7 concludes and summarizes the paper.

2. Basic model

In order to analyze the relationship between targets and instruments, we consider a basic model for an electricity market. It is assumed that electricity producers supply a common wholesale market within which a single wholesale electricity price is

established. Electricity generation is based on both fossil fuel ("black" electricity) and on renewable sources ("green" electricity). Retailers purchase electricity on the wholesale market. The electricity is further distributed to end-users and a single end-user price is established. For simplicity distribution is assumed to be costless. Perfect competition is assumed to prevail all around with many producers of black and green electricity, many retailers and many end-users of electricity. Hence, all agents treat the various prices as given by the market.

We apply the following symbols and functional relationships.

$p =$ End-user price of electricity

$q =$ Wholesale price of electricity

$y =$ Generation of "black" electricity

$z =$ Generation of "green" electricity

$x =$ Total consumption of electricity, where $x = y + z$

$p(x)$: Inverse demand function of electricity, where $(\partial p(x) / \partial x) = p' < 0$

$c = c(y)$: Industry cost function[8] for black electricity, where $\dfrac{\partial c}{\partial y} = c'(y) > 0$ and

$$\frac{\partial^2 c}{\partial y^2} = c''(y) \geq 0$$

$h = h(z)$: Industry cost function for green electricity, where $\dfrac{\partial h}{\partial z} = h'(z) > 0$ and

$$\frac{\partial^2 h}{\partial z^2} = h''(z) > 0\text{ [9]}.$$

$\Pi = \Pi(.)$: Profit function

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[8] The industry cost function is derived by "horizontal addition" of individual cost functions i.e. cost minimization of aggregate market supply. The reason for using the industry cost function is that we avoid messy notation for describing individual decisions. Our prime interest is with the equilibrium market solution and not with individual decisions as such. However, not very much is lost by this approach as individual first order conditions for electricity producers correspond directly to those derived in the analysis.

[9] Black electricity plants (e.g. coal fired power plants) may well be replicated at constant cost whereas green electricity generation from e.g. wind power typically is restricted by Nature's varying supply of good sites for wind mills. For this reason we assume an increasing marginal industry cost function for green electricity plants. Observe that short run marginal cost of wind power is close to zero (i.e. from existing plants). However in this paper we consider new capacity for green electricity generation.

Base case

Without any targets and instruments the producers act as if they jointly maximize

$$\Pi(y,z) = q(y+z) - c(y) - h(z).$$

The first order condition for black electricity and green electricity generation is $q = c'(y)$ and $q = h'(z)$, respectively. Hence, this is the very basic case where marginal generation costs should be the same for the two generation technologies. As there are no distribution costs by assumption we have: $p(x) = c'(y) = h'(z)$. For later use we denote the optimal solution of this basic problem by x_0^*, y_0^*, z_0^*.

3. Targets

In the following we consider optimal social solutions for a planner facing each of three targets: a share target, a target of green electricity expansion and a target of black electricity reduction.

Target of a given share of green electricity

Assume the objective of a social planner is to attain a target of a given share $\overline{\alpha}$ of renewable energy and - to have an interesting problem- that $z_0^* < \overline{\alpha} x_0^*$ at the outset. The social planner's problem is then to maximize:

$$\Pi(y,z) = p(x)x - c(y) - h(z), \text{ subject to: } z = \overline{\alpha}x, \ y = (1-\overline{\alpha})x$$

Upon substitution, the first order condition for this maximization problem is seen to be equal to

(1) $p(x) = (1-\overline{\alpha})c'(y) + \overline{\alpha}h'(z)$

This condition says that the end user price should be equal to a linear (or convex) combination of marginal costs with the percentage target as a weight. For later use we denote the optimal solution for this target by $x_{\overline{\alpha}}^*, y_{\overline{\alpha}}^*, z_{\overline{\alpha}}^*$. Observe, that with the assumed functional forms and the constraints $z = \overline{\alpha}x$ and $y = (1-\overline{\alpha})x$, the solution

$x_{\bar{\alpha}}^*, y_{\bar{\alpha}}^*, z_{\bar{\alpha}}^*$ is a unique solution to this optimization problem. The social surplus[10] for this target is

$$W_{\bar{\alpha}}^* = \int_0^{x_{\bar{\alpha}}^*} \{p(x) - [(1-\bar{\alpha})c'((1-\bar{\alpha})x) + \bar{\alpha}h'(\bar{\alpha}x))]\}dx = \int_0^{x_{\bar{\alpha}}^*} p(x)dx - c((1-\bar{\alpha})x_{\alpha}^*) - h(\bar{\alpha}x_{\alpha}^*)$$

Target of a given expansion of green electricity

Assume the objective of the social planner is to attain a target of a given quantity $\bar{z}$ of renewable energy and assume that the unregulated quantity of green electricity is less than the regulator's target (i.e. $z_0^* < \bar{z}$). The social planner's problem is then to maximize:

$\Pi(y,z) = p(x)x - c(y) - h(z)$, subject to: $z \geq \bar{z}$.

Denoting the shadow price of the constraint by λ the first order condition is equal to

(2) $p(x) = c'(y) = h'(\bar{z}) - \lambda$

As $\lambda > 0$ for a binding constraint, the marginal cost for green electricity should exceed that of black electricity. We denote the optimal solution for this target by $x_{\bar{z}}^*$, $y_{\bar{z}}^*, z_{\bar{z}}^* = \bar{z}, \lambda_{\bar{z}}^*$. Observe that with the assumed functional forms and the constraint this solution is a unique solution to this optimization problem. The social surplus for this target is

$$W_{\bar{z}}^* = \int_0^{x_{\bar{z}}^*} p(x)dx - c(x_{\bar{z}}^* - \bar{z}) - h(\bar{z})$$

Target of a given reduction of black electricity

Assume that the objective of the social planner is to reduce the emission of CO_2 stemming from the generation of black electricity to a certain level and, for simplicity, that there is a one to one relationship between the generation of black electricity and the emission of CO_2. Let further $\bar{y}$ denote the corresponding target of black electricity

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[10] The social surpluses calculated in the following do not include the possible social gains of the regulation (e.g. the value of the internalization of a negative externality). For a given target such a gain will be the same for all instruments that attain that target.

generation, and assume that the unregulated quantity of black electricity is larger than the regulator's target (i.e. $y_0^* > \bar{y}$). The social planner's problem is then to maximize:

$\Pi(y, z) = p(x)x - c(y) - h(z)$, subject to: $y \le \bar{y}$.

Denoting the shadow price of the constraint by γ the first order condition is equal to

$$(3) \quad p(x) = c'(y) + \gamma = h'(z)$$

As $\gamma > 0$ for a binding constraint, the marginal cost for black electricity should be smaller than that of green electricity. We denote the optimal solution for this target by $x_{\bar{y}}^*$, $y_{\bar{y}}^* = \bar{y}$, $z_{\bar{y}}^*$, $\gamma_{\bar{y}}^*$. Observe that with the assumed functional forms and the constraint this solution is a unique solution to this optimization problem. The social surplus for this target is

$$W_{\bar{y}}^* = \int_0^{x_{\bar{y}}^*} p(x)dx - c(\bar{y}) - h(x_{\bar{y}}^* - \bar{y})$$

4. Instruments

In order to attain the targets the social planner is assumed to have three instruments at disposal: a tradable green certificates system denoted, TGC, a unit subsidy (feed-in tariff) denoted, σ, and a unit tax on black electricity denoted, τ. The functioning of the last two instruments are well known, but the nature of the first mentioned instrument needs some explanation.

Tradable Green Certificates (TGC)

As for any other market the markets for TGCs consist of suppliers and buyers. Suppliers are the producers of green electricity that receive an amount of TGCs corresponding to the amount of green electricity they generate. The suppliers thus may sell these TGCs on the TGC market. Hence, the producers receive in this way both the wholesale price and the TGC price per MWh green electricity generated. Buyers of TGCs are the retailers/consumers that are obliged by the government to keep a certain share ("the percentage requirement", α) of TGCs out of total electricity consumed (i.e. the sum of green and black electricity). Thus, the demand for TGCs is

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simply derived as a percentage of the total end use demand for electricity. On the basis of supply and demand a single TGC price, denoted, s, is established. With a large number of retailers the equilibrium established in the market (i.e. the competitive equilibrium) must be characterized by:

$$(4)\ p = q + \alpha s \quad .$$

We assume the amount of TGCs is measured in the same units as the amount of green electricity. Thus, the demand of TGCs is given by $g^d = \alpha x$ and the supply of TGCs is given by $g^s = z$.

5. Attaining a single target by various instruments

In this section we consider how the targets may be attained by applying the various instruments.

5.1 Target of a given share of green electricity

In this case the objective of the social planner is to attain a target of a given share α of renewable electricity. From expression 1) we know that the optimality condition for this case is that price should be equal to a linear combination of the marginal generation costs of the two technologies with the share $\overline{\alpha}$ as weight.

Using a TGC-system to attain the share target

With this instrument the producers act as if they seek to maximize

$$\Pi(x) = qy + [q + s]z - c(y) - h(z) .$$

The first order condition for black and green electricity generation is: $q = c'(y)$ and $q + s = h'(z)$, respectively. Denoting the market solution of this case by $x^*_{\overline{\alpha}TGC}, y^*_{\overline{\alpha}TGC}, z^*_{\overline{\alpha}TGC}, q^*_{\overline{\alpha}TGC}, s^*_{\overline{\alpha}TGC}$ the equilibrium of the two markets is thus characterized by

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(5) $\quad p(x^*_{\bar{\alpha}TGC}) = q^*_{\bar{\alpha}TGC} + \bar{\alpha}s^*_{\bar{\alpha}TGC}$.

(6) $\quad x^*_{\bar{\alpha}TGC} = y^*_{\bar{\alpha}TGC} + z^*_{\bar{\alpha}TGC} = \dfrac{z^*_{\bar{\alpha}TGC}}{\bar{\alpha}}$.

(7) $\quad q^*_{\bar{\alpha}TGC} = c'(y^*_{\bar{\alpha}TGC})$.

(8) $\quad q^*_{\bar{\alpha}TGC} + s^*_{\bar{\alpha}TGC} = h'(z^*_{\bar{\alpha}TGC})$.

Inserting 6), 7) and 8) in 5), we find that the end-user price in equilibrium may be written as a linear combination of the marginal cost of black and green electricity:

$$(9) \quad p(x^*_{\bar{\alpha}TGC}) = (1-\bar{\alpha})c'(y^*_{\bar{\alpha}TGC}) + \bar{\alpha}h'(z^*_{\bar{\alpha}TGC}) \quad .$$

From (6) we see that $z^*_{\bar{\alpha}TGC} = \alpha x^*_{\bar{\alpha}TGC}$ and that $y^*_{\bar{\alpha}TGC} = (1-\bar{\alpha})x^*_{\bar{\alpha}TGC}$. Also we see that (9) is exactly equal to (1), wherefore we conclude that the TGC system is an optimal instrument for attaining the target of a given share of renewables (i.e. $x^*_{\bar{\alpha}TGC} = x^*_{\bar{\alpha}}, y^*_{\bar{\alpha}TGC} = y^*_{\bar{\alpha}}, z^*_{\bar{\alpha}TGC} = z^*_{\bar{\alpha}}$). Therefore, denoting the social surplus for this target when using the TGC instrument by $W^*_{\bar{\alpha}TGC}$, we must have $W^*_{\bar{\alpha}TGC} = W^*_{\bar{\alpha}}$.

Using a feed–in tariff to attain the share target

In this case a feed-in tariff σ is given per unit of green electricity generated in order to attain the share target. The effect of a feed-in tariff is to make green electricity more profitable and black electricity relatively less profitable such that a substitution takes place in production and makes the share of green electricity higher. In this case the producers act as if they seek to maximize

$$\pi_{\bar{\alpha}\sigma} = p(x)x - c(y) - h(z) + \sigma_{\bar{\alpha}}z$$

We denote the market solution of this case by $x^*_{\bar{\alpha}\sigma}, y^*_{\bar{\alpha}\sigma}, z^*_{\bar{\alpha}\sigma}, \sigma^*_{\bar{\alpha}}$, where the symbol $\sigma^*_{\bar{\alpha}}$ signifies the subsidy necessary to increase the share of renewables such that the α-target is attained. The first order conditions of this solution is

$$(10) \quad p(x^*_{\bar{\alpha}\varsigma}) = c'(y^*_{\bar{\alpha}\sigma}) = h'(z^*_{\bar{\alpha}\sigma}) - \sigma^*_{\bar{\alpha}}$$

Clearly, this condition does not satisfy (1). To see this, observe that

$$p(x^*_{\bar{\alpha}\sigma}) = c'(y^*_{\bar{\alpha}\sigma}) = h'(z^*_{\bar{\alpha}\sigma}) - \sigma^*_{\bar{\alpha}} = (1-\bar{\alpha})c'(y^*_{\bar{\alpha}\sigma}) + \bar{\alpha}(h'(z^*_{\bar{\alpha}\sigma}) - \sigma^*_{\bar{\alpha}}) \neq (1-\bar{\alpha})c'(y^*_{\bar{\alpha}\sigma}) + \bar{\alpha}h'(z^*_{\bar{\alpha}\sigma})$$

Hence, the first order necessary condition for obtaining a given share of renewables in an optimal way (efficiently) is not satisfied when using a feed-in tariff. In fact, it turns out that too much electricity is generated by using such a subsidy system as compared with what is socially optimal in order to attain the share target, i.e.: $x^*_{\bar{\alpha}\sigma} > x^*_{\bar{\alpha}}, y^*_{\bar{\alpha}\sigma} > y^*_{\bar{\alpha}}, z^*_{\bar{\alpha}\sigma} > z^*_{\bar{\alpha}}$. To see this, assume the opposite, i.e. $x^*_{\bar{\alpha}\sigma} \leq x^*_{\bar{\alpha}}$ and seek a contradiction. Observe that this assumption also implies $y^*_{\bar{\alpha}\sigma} \leq y^*_{\bar{\alpha}}, z^*_{\bar{\alpha}\sigma} \leq z^*_{\bar{\alpha}}$, as the $\bar{\alpha}$-share is satisfied with both instruments. As $p'(x) < 0$, it then follows that $p(x^*_{\alpha\sigma}) \geq p(x^*_{\alpha})$. Next, observe again that $p(x^*_{\bar{\alpha}\sigma}) = (1-\bar{\alpha})c'(y^*_{\bar{\alpha}\sigma}) + \bar{\alpha}(h'(z^*_{\bar{\alpha}\sigma}) - \sigma^*_{\bar{\alpha}})$ and from (1) that $p(x^*_{\bar{\alpha}}) = (1-\bar{\alpha})c'(y^*_{\bar{\alpha}}) + \alpha h(z^*_{\bar{\alpha}})$. Hence, the contradictory assumption implies that $p(x^*_{\bar{\alpha}\sigma}) = (1-\bar{\alpha})c'(y^*_{\bar{\alpha}\sigma}) + \bar{\alpha}(h'(z^*_{\bar{\alpha}\sigma}) - \sigma^*_{\bar{\alpha}}) \geq p(x^*_{\bar{\alpha}}) = (1-\bar{\alpha})c'(y^*_{\bar{\alpha}}) + \bar{\alpha}h'(z^*_{\bar{\alpha}})$.

Rearranging terms we find that $(1-\bar{\alpha})(c'(y^*_{\bar{\alpha}\sigma}) - c'(y^*_{\bar{\alpha}})) + \bar{\alpha}(h'(z^*_{\bar{\alpha}\sigma}) - h'(z^*_{\bar{\alpha}})) - \alpha\sigma^*_{\bar{\alpha}} \geq 0$. However, this is a contradiction due to the assumed convexity of the cost functions and the contradictory assumption that $y^*_{\bar{\alpha}\sigma} \leq y^*_{\bar{\alpha}}, z^*_{\bar{\alpha}\sigma} \leq z^*_{\bar{\alpha}}$ (implying $c'(y^*_{\bar{\alpha}\sigma}) \leq c'(y^*_{\bar{\alpha}})$ and $h'(z^*_{\bar{\alpha}\sigma}) < h'(z^*_{\bar{\alpha}})$). Hence, we must have $x^*_{\alpha\sigma} > x^*_{\bar{\alpha}}, y^*_{\bar{\alpha}\sigma} > y^*_{\bar{\alpha}}, z^*_{\bar{\alpha}\sigma} > z^*_{\bar{\alpha}}$. For this solution the social surplus is

$$W^*_{\alpha\sigma} = \int_0^{x^*_{\bar{\alpha}\sigma}} \left\{ p(x) - \left[(1-\bar{\alpha})c'((1-\bar{\alpha})x) + \bar{\alpha}(h'(\bar{\alpha}x) - \sigma^*_{\bar{\alpha}})\right]\right\}dx - l^*_{\bar{\alpha}\sigma}$$

The symbol $l^*_{\bar{\alpha}\sigma}$ represents the lump sum value of the total subsidy (i.e. $l^*_{\bar{\alpha}\sigma} = \sigma^*_{\bar{\alpha}}z^*_{\bar{\alpha}\sigma}$) that comes from outside of the electricity sector and therefore has to be subtracted in calculating the social surplus using this instrument. Rewriting the expression for the social surplus we find

$$W^*_{\bar{\alpha}\sigma} = \int_0^{x^*_{\bar{\alpha}\sigma}} p(x)dx - c((1-\bar{\alpha})x^*_{\bar{\alpha}\sigma}) - h(\bar{\alpha}x^*_{\bar{\alpha}\sigma})$$

We know that $x = x^*_{\alpha}$ maximizes this expression. Therefore, as $x^*_{\bar{\alpha}\sigma} > x^*_{\bar{\alpha}}$, we must have $W^*_{\bar{\alpha}\sigma} < W^*_{\bar{\alpha}}$.

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Using a tax to attain the share target

In this case a tax τ is levied per unit of the black electricity generated in order to attain the share target. The effect of a tax on black electricity is to make green electricity relatively more profitable and black electricity relatively less profitable such that a substitution takes place in production and makes the share of green electricity higher. In this case the producers act as if they seek to maximize

$$\pi_{\overline{\alpha}\tau} = p(x)x - c(y) - h(z) - \tau_{\overline{\alpha}} y$$

We denote the market solution of this case by $x^*_{\overline{\alpha}\tau}, y^*_{\overline{\alpha}\tau}, z^*_{\overline{\alpha}\tau}, \tau^*_{\overline{\alpha}}$, where the symbol $\tau^*_{\overline{\alpha}}$ signifies the tax necessary to reduce the share of black electricity such that the α-target is attained. The first order condition of this solution is

$$(11) \quad p(x^*_{\overline{\alpha}\tau}) = c'(y^*_{\overline{\alpha}\tau}) + \tau^*_{\overline{\alpha}} = h'(z^*_{\overline{\alpha}\tau})$$

Clearly, this condition does not satisfy (1). To see this, observe that

$$p(x^*_{\overline{\alpha}\tau}) = c'(y^*_{\overline{\alpha}\tau}) + \tau^*_{\overline{\alpha}} = h'(z^*_{\overline{\alpha}\tau}) = (1-\overline{\alpha})(c'(y^*_{\overline{\alpha}\tau}) + \tau^*_{\overline{\alpha}}) + \overline{\alpha}h'(z^*_{\overline{\alpha}\tau}) \neq (1-\overline{\alpha})c'(y^*_{\overline{\alpha}\tau}) + \alpha h'(z^*_{\overline{\alpha}\tau})$$

Hence, the first order necessary condition for obtaining a given share of renewables in an optimal way (efficiently) is not satisfied when using a tax. In fact, it turns out that too little electricity is generated by using a tax system as compared with what is socially optimal in order to attain the share target, i.e.: $x^*_{\overline{\alpha}\tau} < x^*_{\overline{\alpha}}, y^*_{\overline{\alpha}\tau} < y^*_{\overline{\alpha}}, z^*_{\overline{\alpha}\tau} < z^*_{\overline{\alpha}}$.

To see this, seek a contradiction and assume the opposite, i.e. $x^*_{\overline{\alpha}\tau} \geq x^*_{\overline{\alpha}}$. Observe that this assumption also implies $y^*_{\overline{\alpha}\tau} \geq y^*_{\overline{\alpha}}, z^*_{\overline{\alpha}\tau} \geq z^*_{\overline{\alpha}}$, as the α-share is satisfied using both instruments. As $p'(x) < 0$, it follows that $p(x^*_{\overline{\alpha}\tau}) \leq p(x^*_{\overline{\alpha}})$. Next, observe again that

$p(x^*_{\overline{\alpha}\tau}) = c'(y^*_{\overline{\alpha}\tau}) + \tau^*_{\overline{\alpha}} = h'(z^*_{\overline{\alpha}\tau}) = (1-\overline{\alpha})(c'(y^*_{\overline{\alpha}\tau}) + \tau^*_{\overline{\alpha}}) + \overline{\alpha}h'(z^*_{\overline{\alpha}\tau})$, and from (1) that

$p(x^*_{\overline{\alpha}}) = (1-\overline{\alpha})c'(y^*_{\overline{\alpha}}) + \overline{\alpha}h(z^*_{\overline{\alpha}})$. Hence, the contradictory assumption implies that

$p(x^*_{\overline{\alpha}\tau}) = (1-\overline{\alpha})(c'(y^*_{\overline{\alpha}\tau}) + \tau^*_{\overline{\alpha}}) + \overline{\alpha}(h'(z^*_{\overline{\alpha}\sigma}) \leq p(x^*_{\overline{\alpha}}) = (1-\overline{\alpha})c'(y^*_{\overline{\alpha}}) + \overline{\alpha}h'(z^*_{\overline{\alpha}})$. Rearranging terms we find that $(1-\overline{\alpha})(c'(y^*_{\overline{\alpha}\tau}) - c'(y^*_{\overline{\alpha}})) + \overline{\alpha}(h'(z^*_{\overline{\alpha}\tau}) - h'(z^*_{\overline{\alpha}})) + (1-\overline{\alpha})\tau^*_{\overline{\alpha}} \leq 0$. However, this is a contradiction due to the assumed convexity of the cost functions and the contradictory assumption that $y^*_{\overline{\alpha}\tau} \geq y^*_{\overline{\alpha}}, z^*_{\overline{\alpha}\tau} \geq z^*_{\overline{\alpha}}$ (implying $c'(y^*_{\overline{\alpha}\tau}) \geq c'(y^*_{\overline{\alpha}})$ and

$h'(z_{\overline{\alpha}\tau}^*) \geq h'(z_{\overline{\alpha}}^*))$ Hence, we must have $x_{\overline{\alpha}\tau}^* < x_{\overline{\alpha}}^*, y_{\overline{\alpha}\tau}^* < y_{\overline{\alpha}}^*, z_{\overline{\alpha}\tau}^* < z_{\overline{\alpha}}^*$. For this solution the social surplus is

$$W_{\overline{\alpha}\tau}^* = \int_0^{x_{\overline{\alpha}\tau}^*} \left\{ p(x) - \left[(1-\overline{\alpha})c'((1-\overline{\alpha})x + \tau_{\overline{\alpha}}^*) + \overline{\alpha}h'(\overline{\alpha}x) \right] \right\} dx + l_{\overline{\alpha}\tau}^*$$

The symbol $l_{\alpha\tau}^*$ represents the lump sum value of the total tax (i.e. $l_{\overline{\alpha}\tau}^* = \tau_{\overline{\alpha}\tau}^* z_{\overline{\alpha}\tau}^*$) subtracted from the electricity sector and that therefore has to be added in calculating the social surplus using this instrument. Rewriting the expression for the social surplus we find

$$W_{\overline{\alpha}\tau}^* = \int_0^{x_{\overline{\alpha}\tau}^*} p(x)dx - c((1-\overline{\alpha})x_{\overline{\alpha}\tau}^*) - h(\overline{\alpha}x_{\overline{\alpha}\tau}^*)$$

We know that $x = x_{\overline{\alpha}}^*$ maximizes this expression. Therefore, as $x_{\overline{\alpha}\tau}^* < x_{\overline{\alpha}}^*$, we must have $W_{\overline{\alpha}\tau}^* < W_{\overline{\alpha}}^*$.

5.2. *Target of a given expansion of green electricity*

In this case the objective of the social planner is to attain a target of a given quantity $\overline{z}$ of renewable energy. From expression 2) we know that the optimality condition for this case is that price should be equal to the marginal cost of green electricity minus a shadow price of the constraint and also equal to the marginal cost of black electricity.

Using a TGC-system to attain the target of a given expansion of green electricity

For this instrument the problem of the social planner is to determine the size of the percentage requirement α that induces the market to achieve a quantity of green electricity that is equal to $\overline{z}$.[11] We denote this percentage requirement by $\alpha_{\overline{z}}^*$ and the market solution using this instrument by $x_{\overline{z}TGC}^*, y_{\overline{z}TGC}^*, z_{\overline{z}TGC}^* = \overline{z}, q_{\overline{z}TGC}^*, s_{\overline{z}TGC}^*$. From section 5.1., we know that the market solution for this instrument must be characterized by the following optimality conditions

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[11] The idea is that green electricity may be stimulated by increasing the size of the percentage requirement. However, further assumptions on the functional forms of both the generation costs and the demand function are needed to ensure this (see Amundsen and Mortensen, 2001). These assumptions are reasonable and realistic when considering specific electricity markets (see Amundsen and Bye, 2016 for the case of the Norwegian electricity market).

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$$(12) \quad p(x^*_{\bar{z}TGC}) = (1 - \alpha^*_{\bar{z}})c'(y^*_{\bar{z}TGC}) + \alpha^*_{\bar{z}}h'(\bar{z})$$

We also know that $\bar{z} = \alpha x^*_{\bar{z}TGC}$ and that $y^*_{\bar{z}TGC} = (1 - \alpha)x^*_{\bar{z}TGC}$.

Clearly, condition (12) does not satisfy the optimality condition as seen from the point of view of the social planner, i.e. condition (2). In fact we will have

$$p(x^*_{\bar{z}TGC}) = (1 - \alpha^*_{\bar{z}})c'(y^*_{\bar{z}TGC}) + \alpha^*_{\bar{z}}h'(\bar{z}) \quad > p(x^*_{\bar{z}}) = c'(y^*_{\bar{z}}) = h'(\bar{z}) - \lambda^*_{\bar{z}}$$

From this it also follows that $x^*_{\bar{z}TGC} < x^*_{\bar{z}}$. To see this, assume that the opposite is true and seek a contradiction, i.e. assume

$$(1 - \alpha^*_{\bar{z}})c'(y^*_{\bar{z}TGC}) + \alpha^*_{\bar{z}}h'(\bar{z}) \quad \leq c'(y^*_{\bar{z}}) = h'(\bar{z}) - \lambda^*_{\bar{z}}$$

This assumption also implies $x^*_{\bar{z}TGC} \geq x^*_{\bar{z}}$ and $y^*_{\bar{z}TGC} \geq y^*_{\bar{z}}$. Rearrange this expression and find

$$c'(y^*_{\bar{z}TGC}) - c'(y^*_{\bar{z}}) + \alpha^*_{\bar{z}}(h'(\bar{z}) - c'(y_{\bar{z}TGC}^*)) \quad \leq 0$$

Inspection of signs show that this is a contradiction as the left hand side of the expression is strictly positive i.e. $c'(y^*_{\bar{z}TGC}) \geq c'(y^*_{\bar{z}})$ and $h'(\bar{z}) - c'(y_{\bar{z}TGC}^*) = s^*_{\bar{z}TGC} > 0$. Hence, we must have $x^*_{\bar{z}TGC} < x^*_{\bar{z}}$ and $y^*_{\bar{z}TGC} < y^*_{\bar{z}}$. With this solution the social surplus may be written

$$W^*_{\bar{z}TGC} = \int_0^{x^*_{\bar{z}TGC}} p(x)dx - c((1 - \alpha^*_{\bar{z}})x^*_{\bar{z}TGC}) - h(\alpha^*_{\bar{z}TGC}x^*_{\bar{z}TGC}) = \int_0^{x^*_{\bar{z}TGC}} p(x)dx - c(x^*_{\bar{z}TGC} - \bar{z}) - h(\bar{z})$$

We know that $x = x^*_{\bar{z}}$ maximizes this expression. Therefore, as $x^*_{\bar{z}TGC} < x^*_{\bar{z}}$ it follows that $W^*_{\bar{z}TGC} < W^*_{\bar{z}}$.

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Using a feed-in tariff to attain the target of a given expansion of green electricity

In this case a feed-in tariff σ is given per unit of the green electricity generated in order to attain the target. We denote the market solution by $x_{\bar{z}\sigma}^*, y_{\bar{z}\sigma}^*, z_{\bar{z}\sigma}^* = \bar{z}, \sigma_{\bar{z}}^*$, where the symbol $\sigma_{\bar{z}}^*$ signifies the feed-in tariff necessary to increase the quantity of green electricity such that the $\bar{z}$-target is attained. We know from earlier that the market solution must be characterized by

$$(13) \quad p(x_{\bar{z}\varsigma}^*) = c'(y_{\bar{z}\sigma}^*) = h'(\bar{z}) - \sigma_{\bar{z}}^*$$

Comparing (13) with (2) we see that a feed-in tariff $\sigma_{\bar{z}}^*$ equal to the shadow price $\lambda_{\bar{z}}^*$ will efficiently induce the optimal solution as seen from the point of view of the social planner, i.e. $x_{\bar{z}\sigma}^* = x_{\bar{z}}^*, y_{\bar{z}\sigma}^* = y_{\bar{z}}^*, z_{\bar{z}\sigma}^* = z_\sigma^* = \bar{z}$. Hence, not unexpectedly, we find that a feed-in tariff on green electricity generation will efficiently achieve the target of expanding the generation of green electricity. Denoting the social surplus using this instrument by $W_{\bar{z}\sigma}^*$, we find that $W_{\bar{z}\sigma}^* = W_{\bar{z}}^*$.

Using a tax on black electricity to attain the target of a given expansion of green electricity

In this case a tax τ is levied per unit of the black electricity generated in order to attain the target. The effect of a tax on black electricity is to make green electricity relatively more profitable and black electricity relatively less profitable such that a substitution takes place in production and stimulates green electricity generation[12]. We denote the market solution by $x_{\bar{z}\tau}^*, y_{\bar{z}\tau}^*, z_{\bar{z}\tau}^*, \tau_{\bar{z}}^*$, where the symbol $\tau_{\bar{z}}^*$ signifies the tax necessary to increase the quantity of green electricity such that the $\bar{z}$-target is attained. We know from earlier that the market solution must be characterized by

$$(14) \quad p(x_{\bar{z}\tau}^*) = c'(y_{\bar{z}\tau}^*) + \tau_{\bar{z}}^* = h'(\bar{z})$$

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[12] Formally, we need to show that a tax on black electricity will actually increase the quantity generated of green electricity and not only increase the relative share. It turns out that the condition for having a positive increase of green electricity is: $(c''(z) + h''(y) - c''(y)h''(z)/p'(x)) > 0$. This condition is satisfied under the assumptions of the model.

Comparing (14) with (2), we see that $p(x^*_{\bar{z}\tau}) = h'(\bar{z}) > p(x^*_{\bar{z}}) = h'(\bar{z}) - \lambda^*_{z*}$. Hence, using a tax to attain the target does not give rise to the optimal solution as seen from the point of view of view of the social planner. Clearly, we find that both total electricity generation as well as the generation of black electricity is too small as compared what is regulatory optimal, i.e. $x^*_{\bar{z}\tau} < x^*_{\bar{z}}$ and $y^*_{\bar{z}\tau} < y^*_{\bar{z}}$. After adding the lump sum value of the total tax revenue to compensate for the tax take, the social surplus using this instrument is equal to

$$W^*_{\bar{z}\tau} = \int_0^{x^*_{\bar{z}\tau}} p(x)dx - c(x^*_{\bar{z}\tau} - \bar{z}) - h(\bar{z})$$

We know that $x = x^*_{\bar{z}}$ maximizes this expression. Therefore, as $x^*_{\bar{z}\tau} < x^*_{\bar{z}}$, we must have $W^*_{\bar{z}\tau} < W^*_{\bar{z}}$.

5.3. *Target of a given reduction of black electricity*

In this case the objective of the social planner is to reduce the generation of black electricity to attain a level $\bar{y}$ of renewable energy. From expression 3) we know that the optimality condition for this case is that price should be equal to the marginal cost of black electricity plus the shadow price of the constraint and also equal to the marginal cost of green electricity.

Using a TGC-system to attain the target of a given reduction of black electricity
For this instrument the problem of the social planner is to determine the size of the percentage requirement α that induces the market to achieve a quantity of black electricity that is equal to $\bar{y}$.[13] We denote this percentage requirement by $\alpha^*_{\bar{y}}$ and the market solution using this instrument by $x^*_{\bar{y}TGC}, y^*_{\bar{y}TGC} = \bar{y}, z^*_{\bar{y}TGC}, q^*_{\bar{y}TGC}, s^*_{\bar{y}TGC}$. From section 5.1., we know that the market solution for this instrument must be characterized by the following optimality conditions

$$(15) \quad p(x^*_{\bar{y}TGC}) = (1 - \alpha^*_{\bar{y}})c'(\bar{y}) + \alpha^*_{\bar{y}}h'(z^*_{\bar{y}TGC})$$

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[13] Under the assumptions of the model it is a clear cut result that the generation of black electricity will fall as the size of the percentage requirement is increasing (see Amundsen and Mortensen, 2002).

We also know that $z^*_{\bar{y}TGC} = \alpha x^*_{\bar{y}TGC}$, and that $\bar{y} = (1-\alpha)x^*_{\bar{y}TGC}$.

Generally, condition (15) does not satisfy the optimality condition as seen from the point of view of the social planner, i.e. condition (3). In fact we will have

$$p(x^*_{\bar{y}TGC}) = (1-\alpha^*_{\bar{y}})c'(\bar{y}) + \alpha^*_{\bar{y}}h'(z^*_{\bar{y}TGC}) < p(x^*_{\bar{y}}) = c'(\bar{y}) + \gamma^*_{\bar{y}} = h'(z^*_{\bar{y}})$$

From this it also follows that $x^*_{\bar{y}TGC} > x^*_{\bar{y}}$ and $z^*_{\bar{y}TGC} > z^*_{\bar{y}}$. To see this, assume the opposite is true and seek a contradiction, i.e. assume

$$p(x^*_{\bar{y}TGC}) = c'(\bar{y}) + \alpha^*_{\bar{y}}(h'(z^*_{\bar{y}TGC}) - c'(\bar{y})) \ge p(x^*_{\bar{y}}) = c'(\bar{y}) + h'(z^*_{\bar{y}}) - c(\bar{y})$$

This assumption also implies that $x^*_{\bar{y}TGC} \le x^*_{\bar{y}}$ and $z^*_{\bar{y}TGC} \le z^*_{\bar{y}}$. As this implies $h'(z^*_{\bar{y}TGC}) \le h'(z^*_{\bar{y}})$ and as $0 < \alpha^*_{\bar{y}} < 1$, we clearly have a contradiction. Hence, we must have $x^*_{\bar{y}TGC} > x^*_{\bar{y}}$ and $z^*_{\bar{y}TGC} > z^*_{\bar{y}}$. With this solution the social surplus may be written

$$W^*_{\bar{y}TGC} = \int_0^{x^*_{\bar{y}TGC}} p(x)dx - c((1-\alpha^*_{\bar{y}})x^*_{\bar{y}TGC}) - h(\alpha^*_{\bar{y}TGC}x^*_{\bar{y}TGC}) = \int_0^{x^*_{zTGC}} p(x)dx - c(\bar{y}) - h(x^*_{\bar{y}TGC} - \bar{y})$$

We know that $x = x^*_{\bar{y}}$ maximizes this expression. Therefore, as $x^*_{\bar{y}TGC} > x^*_{\bar{y}}$ it follows that $W^*_{\bar{y}TGC} < W^*_{\bar{y}}$.

Using a feed-in tariff on green electricity to attain the target of a given reduction of black electricity

In this case a feed-in tariff σ is given per unit of the green electricity generated in order to attain the target. We denote the market solution by $x^*_{\bar{y}\sigma}, y^*_{\bar{y}\sigma} = \bar{y}, z^*_{\bar{y}\sigma}, \sigma^*_{\bar{y}}$, where the symbol $\sigma^*_{\bar{y}}$ signifies the feed-in tariff necessary to increase the quantity of

green electricity such that the $\bar{y}$-target is attained. We know from earlier that the market solution must be characterized by

(16) $p(x^*_{\bar{y}\sigma}) = c'(\bar{y}) = h'(z^*_{\bar{y}\sigma}) - \sigma^*_{\bar{y}}$

Comparing (16) with (3) we see that $p(x^*_{\bar{y}\sigma}) = c'(\bar{y}) < p(x^*_{\bar{y}}) = c'(\bar{y}) + \gamma^*_{\bar{y}}$. Hence, using a feed-in tariff to attain the target does not give rise to the optimal solution as seen from the point of view of the social planner. Clearly, we find that both total electricity generation as well as the generation of green electricity is too large as compared what is socially optimal, i.e. $x^*_{\bar{y}\tau} > x^*_{\bar{y}}$ and $z^*_{\bar{y}\tau} > y^*_{\bar{y}}$. After subtracting the lump sum value of the total subsidy to compensate for the subsidy given to the electricity market, the social surplus using this instrument is equal to

$$W^*_{\bar{y}\sigma} = \int_0^{x^*_{\bar{z}\sigma}} p(x)dx - c(\bar{y}) - h(x^*_{\bar{y}\sigma} - \bar{y})$$

We know that $x = x^*_{\bar{y}}$ maximizes this expression. Therefore, as $x^*_{\bar{y}\tau} > x^*_{\bar{y}}$ we must have $W^*_{\bar{y}\sigma} < W^*_{\bar{y}}$.

Using a tax on black electricity to attain the target of a given reduction of black electricity

In this case a tax τ is levied per unit of the black electricity generated in order to attain the target. We denote the market solution by $x^*_{\bar{y}\tau}, y^*_{\bar{y}\tau} = \bar{y}, z^*_{\bar{y}\tau}, \tau^*_{\bar{y}}$, where the symbol $\tau^*_{\bar{y}}$ signifies the tax necessary to reduce the quantity of black electricity such that the $\bar{y}$-target is attained. We know from earlier that the market solution must be characterized by

(16) $p(x^*_{\bar{y}\tau}) = c'(\bar{y}) + \tau^*_{\bar{y}} = h'(\bar{z}_{\bar{y}\tau})$

Comparing (16) with (3), we see that a tax $\tau^*_{\bar{y}}$ set equal to the shadow price $\gamma^*_{\bar{y}}$ will efficiently induce the optimal solution as seen from the point of view of the social planner, i.e. $x^*_{\bar{y}\tau} = x^*_{\bar{y}}, y^*_{\bar{y}\tau} = \bar{y}, z^*_{\bar{z}\sigma} = z^*_{\bar{y}}$. Hence, not unexpectedly, we find that a tax

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on black electricity generation will efficiently achieve the target of reducing the generation of black electricity. Hence, denoting the social surplus using this instrument by $W_{\bar{y}\tau}^*$, we must have $W_{\bar{y}\tau}^* = W_{\bar{y}}^*$.

6. Simultaneously attaining several targets by various instruments

Next, we turn to the case of simultaneously attainment of the proposed targets. Hence, we assume that the generation of green electricity should be at least as large as a given target, $\bar{z}$ and simultaneously that the generation of black electricity should not be larger than a given target, $\bar{y}$.

The social planner's optimization problem is

$$\max \Pi(y,z) = p(x)x - c(y) - h(z), \text{ subject to: } z \geq \bar{z} \text{ and } y \leq \bar{y}$$

Denoting the shadow prices of green and black electricity by φ and μ, respectively, the following first order conditions must simultaneously be satisfied

$$(17) \quad p(x) = c'(y) + \mu = h'(z) - \varphi$$

We denote the optimal solution for these targets by: $x_{\overline{zy}}^*, y_{\overline{zy}}^* = \bar{y}, z_{\overline{zy}}^* = \bar{z}, \varphi_{\overline{zy}}^*, \mu_{\overline{zy}}^*$.

Clearly, attaining both targets with a single instrument is not generally feasible (Tinbergen, 1952). A subsidy of green electricity could be designed to achieve the green target, but could only by chance attain the black target at the same time, just as a tax on black electricity could be designed to attain the target on black electricity but only by chance attain the green target (i.e. depending on a specific constellation of parameters). Hence, normally two targets call for two instruments.

Still, one may wonder whether a TGC system alone with an announced percentage requirement of $\bar{\alpha} = \bar{z}/(\bar{y} + \bar{z})$ could attain the two targets. The answer is that it will (generally) not. To see this, consider equation (9). From this we have

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$$(18) \quad p(x^*_{\overline{\alpha}TGC}) = (1-\overline{\alpha})c'(y^*_{\overline{\alpha}TGC}) + \overline{\alpha}h'(z^*_{\overline{\alpha}TGC}) \qquad .$$

From (6) we also have $z^*_{\overline{\alpha}TGC} = \overline{\alpha}x^*_{\overline{\alpha}TGC}$ and that $y^*_{\overline{\alpha}TGC} = (1-\overline{\alpha})x^*_{\overline{\alpha}TGC}$. To see that, generally, $x^*_{\overline{\alpha}TGC} \neq x^*_{\overline{zy}} = \overline{y} + \overline{z}, y^*_{\overline{\alpha}TGC} \neq y^*_{\overline{zy}} = \overline{y}, z^*_{\overline{\alpha}TGC} \neq z^*_{\overline{zy}} = \overline{z}$, apply (17) to obtain

$$(19) \quad \begin{aligned} p(x^*_{\overline{zy}}) &= (1-\overline{\alpha})(c'(\overline{y}) + \mu^*_{\overline{zy}}) + \overline{\alpha}(h'(\overline{z}) - \varphi^*_{\overline{zy}}) \\ &= (1-\overline{\alpha})c'(\overline{y}) + \overline{\alpha}h'(\overline{z}) + (1-\overline{\alpha})\mu^*_{\overline{zy}} - \overline{\alpha}\varphi^*_{\overline{zy}} \end{aligned}$$

Hence, we see that only if: $(1-\overline{\alpha})\mu^*_{\overline{zy}} = \overline{\alpha}\varphi^*_{\overline{zy}}$, will

$x^*_{\overline{\alpha}TGC} = x^*_{\overline{zy}} = \overline{y} + \overline{z}, y^*_{\overline{\alpha}TGC} = \overline{y}, z^*_{\overline{\alpha}TGC} = \overline{z}$. Otherwise if: $(1-\overline{\alpha})\mu^*_{\overline{zy}} > \overline{\alpha}\varphi^*_{\overline{zy}}$, then

$x^*_{\overline{\alpha}TGC} < x^*_{\overline{zy}} = \overline{y} + \overline{z}, y^*_{\overline{\alpha}TGC} < \overline{y}, z^*_{\overline{\alpha}TGC} < \overline{z}$ and if: $(1-\overline{\alpha})\mu^*_{\overline{zy}} < \overline{\alpha}\varphi^*_{\overline{zy}}$, then

$x^*_{\overline{\alpha}TGC} > x^*_{\overline{zy}} = \overline{y} + \overline{z}, y^*_{\overline{\alpha}TGC} > \overline{y}, z^*_{\overline{\alpha}TGC} > \overline{z}$.

Searching for two instruments that may optimally attain the two targets, a combination of a tax and a subsidy seems to be a natural choice. Denoting the tax by $\tau_{\overline{zy}}$ and the subsidy by $\sigma_{\overline{zy}}$ the optimization problem reads

$$\max \Pi(y, z) = p(x)x - c(y) - h(z) - \tau_{\overline{zy}}y + \sigma_{\overline{zy}}z$$

The first order conditions related to this problem is

$$p(x^*_{\overline{zy}\tau\sigma}) = c'(y^*_{\overline{zy}\tau\sigma}) + \tau_{\hat{z}y} = h'(z^*_{\overline{zy}\tau\sigma}) - \sigma_{\overline{zy}}$$

Clearly by setting $\tau_{\overline{yz}} = \mu^*_{\overline{zy}}$ and $\sigma_{\overline{yz}} = \varphi^*_{\overline{zy}}$, the above first order conditions are seen to be identical to the social optimality conditions. Hence, we must have $y^*_{\overline{zy}\tau\sigma} = \overline{y}$ and $z^*_{\overline{zy}\tau\sigma} = \overline{z}$ i.e. the combination of a tax and a subsidy may optimally achieve the targets on black and green electricity[14].

7. Discussion

The main message of this paper is that each kind of environmental target has a single optimal instrument, and that there is a deadweight loss of using other instruments to

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[14] It turns out that a combination of a TGC-system and a tax may also achieve the targets simultaneously, if the percentage requirement is set to $\alpha = \overline{\alpha} = \overline{z}/(\overline{z} + \overline{y})$, and the tax is equal to

$\tau^*_{\alpha\overline{zy}} = \mu^*_{\overline{zy}} - (\overline{\alpha}/(1-\overline{\alpha}))\varphi^*_{\overline{zy}}$.

achieve the target. (See summary of results in Table 1.).Yet, many countries apply instruments that are not optimal in relation to the stated targets. For example Norway uses a system of tradable green certificates (jointly with Sweden) to attain a quantity target of new capacity installation of green electricity.[15] Clearly, according to the analysis it would be better to use a feed-in system. Furthermore, Denmark uses a feed-in premium system financed by a PSO[16] system to basically attain a share target on renewables[17]. From the analysis it would be better to use an allowance system based on tradable certificates. However, many countries have not only one climate related target, but several targets that they seek to attain by using several instruments at the same time.[18] This raises the question as to what the purposes of the targets are and which market failures they are intended to address.

Table1. Optimal solutions of applying various instruments to achieve various targets

	Share target: α	Green target: $\bar{z}$	Black target: $\bar{y}$
Allowances: TGC	$W^*_{\alpha TGC} = W^*_\alpha$, $x^*_{\alpha TGC} = x^*_\alpha$ $y^*_{\alpha TGC} = y^*_\alpha$, $z^*_{\alpha TGC} = z^*_\alpha$	$W^*_{\bar{z} TGC} < W^*_{\bar{z}}$, $x^*_{\bar{z} TGC} < x^*_{\bar{z}}$ $y^*_{\bar{z} TGC} < y^*_{\bar{z}}$, $z^*_{\bar{z} TGC} = \bar{z}$	$W^*_{\bar{y} TGC} < W^*_{\bar{y}}$, $x^*_{\bar{y} TGC} > x^*_{\bar{y}}$ $y^*_{\bar{y} TGC} = \bar{y}$, $z^*_{\bar{y} TGC} > z^*_{\bar{y}}$
Green subsidy: σ	$W^*_{\alpha\sigma} < W^*_\alpha$, $x^*_{\alpha\sigma} > x^*_\alpha$ $y^*_{\alpha\sigma} > y^*_\alpha$, $z^*_{\alpha\sigma} > z^*_\alpha$	$W^*_{\bar{z}\sigma} = W^*_{\bar{z}}$, $x^*_{\bar{z}\sigma} = x^*_{\bar{z}}$ $y^*_{\bar{z}\sigma} = y^*_{\bar{z}}$, $z^*_{\bar{z}\sigma} = \bar{z}$	$W^*_{\bar{y}\sigma} < W^*_{\bar{y}}$, $x^*_{\bar{y}\sigma} > x^*_{\bar{y}}$ $y^*_{\bar{y}\sigma} = \bar{y}$, $z^*_{\bar{y}\sigma} > z^*_{\bar{y}}$
Black tax: τ	$W^*_{\alpha\tau} < W^*_\alpha$, $x^*_{\alpha\tau} < x^*_\alpha$ $y^*_{\alpha\tau} < y^*_\alpha$, $z^*_{\alpha\tau} < z^*_\alpha$	$W^*_{\bar{z}\tau} < W^*_{\bar{z}}$, $x^*_{\bar{z}\tau} < x^*_{\bar{z}}$ $y^*_{\bar{z}\tau} < y^*_{\bar{z}}$, $z^*_{\bar{z}\tau} = \bar{z}$	$W^*_{\bar{y}\tau} = W^*_{\bar{y}}$, $x^*_{\bar{y}\tau} = x^*_{\bar{y}}$ $y^*_{\bar{y}\tau} = \bar{y}$, $z^*_{\bar{y}\tau} = z^*_{\bar{y}}$

The stated purposes for adopting the various regulatory instruments may be many and range from the regulation of market failures to environmental preservation, job

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[15] The joint Norwegian-Swedish target is to attain new renewable capacity of 28.4 TWh by 2020.

[16] The Danish feed-in premium system amounts to giving new renewable energy - mainly offshore wind power projects - a guaranteed price, i.e. if the wholesale price of electricity is low, the necessary feed-in premium will be high and vice versa. The system is financed by a PSO (Public Service Obligation) system that charges the electricity consumers with a varying unit fee to be paid over the electricity bill. The fee varies with the wholesale price of electricity. However, Denmark is about to abandon the PSO-system because the EU has determined that the PSO system gives rise to unfair competition with respect to foreign electricity producers.

[17] For 2020 Denmark's target for renewables is 30 percent out of total energy use.

[18] For instance, towards 2020, all member states of the EU has to fulfill a country specific share target for renewables, as well as fulfill a percentage target on the reduction of greenhouse gases in the non-ETS sectors of the economy. For the 2030 policy the country specific targets on the share of renewables will be abandoned. In addition to this they have to participate in the joint ETS-system. Also, the EU has a common target on energy savings that the member states have to address.

creation and innovation with a consideration of distributional equity and political feasibility (Weitzman, 1974; Goulder and Parry, 2008; Fischer and Preonas, 2010).

While the target of reducing the generation of fossil energy is well founded by the market failure related to climate change, it is not equally obvious why one needs specific targets on shares of renewables and on quantities of green energy (and on energy savings as in the EU). As illustrated by the analysis, it is true that a target on the share of green electricity or a specific increase of the quantity of green electricity may correspond to a given reduction of black electricity when TGCs and subsidies are applied. However, if the main objective is to reduce the generation of black electricity, then a Pigouvian tax or an emission permit system would be better. It should also be noted that a Pigouvian tax on black electricity will itself lead to an increase of the share of green electricity as well as of the quantity of green electricity generated. The question then is whether there are other kinds of market failures that are taken care of by the share target and the target of expanding the quantity of green electricity.

One argument, frequently heard is that subsidies on green energy will create new jobs and give a country that engage in such a practice a first mover advantage in developing a "green" industry that may grow into a profitable export industry. However, lack of jobs and unprofitable industries are not normally a result of a market failure in the proper meaning of the term (i.e. a failure that not even a perfect competitive organization of the market will make go away), but rather of short and intermediate term economic situations. Anyhow, if the target is to stimulate the employment, it would be better to use more general economic instruments (e.g. budgetary and monetary policies) rather than to give subsidies to specific industries.

Along the same lines, subsidies are considered beneficial as they are assumed to stimulate the research and development of new green technologies. In part, this is true and there is a basic economic argument for why the government should promote research. Technological progress benefits all and not only those who make the inventions and develop the technology, but also the rest of the economy that adopts the new technologies. Hence, society is benefitted through so-called knowledge spill-over effects. (see e.g. Jaffe, 1986, Jaffe et al., 1993). Therefore, there is a danger that

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too little research would take place if research is left to the private sector alone, acting only in their own interest without considering the positive spill-over effects to society. However, stimulation of research is good for any new technological development, not only within the energy sector. Furthermore, the subsidies for green energy are also given to producers making use of established technologies where the argument of stimulating spill-over effects is no longer valid. Hence, this is an argument for general subsidies to research and not for support of a specific industry as such.[19] Furthermore, it should be noted that a Pigouvian tax on fossil based electricity also will stimulate research in renewable energy through so-called "induced" technological change (see e.g. Newell et al. , 1999, Popp, 2002 and Goulder and Mathai, 2000).

Yet another argument put forward for having targets on shares of renewables and of subsidizing green energy is that these targets may increase the security of supply. The point is that a country with a large dependency on imported fossil energy (coal, oil and natural gas) is very vulnerable if the supply of energy should disappear or become considerably reduced within a short interval of time. Such shocks may have a sizeable negative effect on the economy, just as it happened after the OPEC oil embargo in 1973/74 (see Kilian 2008, 2009, and Löschel et al., 2010) The resulting increase of energy prices following from a supply chock of the mentioned kind may be amplified by imperfections in other markets (e.g. the labour market) and give rise to considerable negative effects on the economy (see Baumeister et al., 2010) Stimulating the generation of green energy within the country as well as diversifying the use of energy types (possibly by trade) may lessen the dependency and increase the security of supply. However, uncertain and short time fluctuating energy prices as such do not necessarily call for governmental intervention in the energy sector. Uncertain and short time fluctuating prices are typical for many traded inputs and goods, and in general the government may deal with the more severe consequences of such problems by making use of budgetary policies to stabilize the economy, rather than to intervene in the energy market itself.

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[19] A study of the knowledge spillover effects from private research in Denmark investigated whether such spillover effects were larger within the energy sector (thus calling for larger subsidies) as compared with other sectors of the economy (Bjørner and Machenhauer, 2011). The study found that this was not the case. In fact, the study suggested that the spillover effects were lower for the energy sector.

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Furthermore, another meaning of the term "security of supply" needs to be mentioned, namely the degree of which one can make sure that "the light will stay on". In this sense the increasing dependency on intermittent power (i.e. from wind energy), will worsen the security of supply situation within the electricity sector, rather than improving it (Hirth, 2015). The increasing share of renewable energy in electricity generation will induce additional costs in terms of increased reserve capacity that can be ramped quickly possibly through new capacity markets (see e.g. Cramton et al. 2013).

The fact that many countries pursue several targets[20] (whether they are economically well founded or not) implies that several instruments must be applied in order to achieve a maximal social surplus given the attainment of these targets. Just as the number of independent linear equations must be equal to the number of unknowns in a uniquely determined equation system, the number of instruments should ideally be equal to the number of targets (see Tinbergen, 1952)[21]. Instruments and targets are interconnected in the sense that each instrument may affect all targets and, consequently, each target may be affected by all instruments. Some of the instruments may be compatible while others may be outright counteractive (e.g. subsidizing green electricity will help reaching the share target for renewables, but will at the same time run counter to a target of increasing energy savings, through the price lowering effect). Also, targets may themselves be incompatible, e.g. the target on renewable expansion, and the target of fossil energy reduction may not necessarily correspond to the share target.

It should be stressed that if the single overriding target is to reduce the emission of greenhouse gases from using fossil energy (and the other targets are set with the intention to promote this superior target), then, clearly, there will be a social loss from using several instruments to also attain the subordinate targets (i.e. too many irrelevant constraints). This does, however, not mean that it is always bad to use several instruments to attain a single target. As shown by e.g. Roberts and Spence (1976) and Kwerel (1977) it may be optimal from the point of view of society to

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[20] Indeed, this is true for many countries around the world, including the USA, China and India.
[21] More precisely Jan Tinbergen's rule can be stated in the following way: The number of goals a policymaker can pursue can be no greater than the number of instruments the policymaker can control.

combine a certificate system with an additional instrument such as floor and ceiling prices (a so-called "hybrid system") when faced with uncertainty. Also, more recently Pizer (2003), Jacoby and Ellerman (2004), Burtraw and Palmer (2006), Goulder and Parry (2008) show how a system of "safety valves" (ceilings and floors prices) under uncertainty may increase the efficiency of a dynamic emissions certificates systems that allows banking.[22]

Otherwise, the reasons for applying several instruments even though only the target of fossil energy reduction is at the forefront may generally be found within the realm of political economy. For example, a part of the carbon tax burden may be taken away from the fossil intensive industries, if subsidies to green energy do a part of the job of reducing the emission of CO_2. Hence, the combination of instruments is not particularly cost effective but it is an answer to a political wish of "distributional equity", and possibly also, to ideas of green job creation and first mover advantages (Goulder and Parry, 2008).

7. Summary and conclusion

In order to attain a given climate related target a social planner may choose among several instruments. Using a standard analytic model for an electricity market, this paper verifies that each kind of target (i.e. target on black or green electricity generation; or percentages of the two) has only a single efficient instrument (under certainty), and that there is a deadweight loss of using other instruments to achieve the target. With the same logic, the paper confirms that several simultaneous targets on green and black electricity generation call for several instruments. In particular, it is shown that a system of tradable green certificates cannot generally alone attain simultaneous targets on black and green electricity generation. Generally, it is a problem that many countries use instruments that are not optimal for the stated targets, wherefore there is a loss in terms of wasted resources.

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[22] The logic of this result is recently adopted in the Market Stability Reserve of EU ETS, becoming active as of January 2019. According to this mechanism EU ETS quotas will enter into a reserve if quota prices tends to go below a floor price, while quotas from the reserve will be released if the quota price tends to rise above a given price cap.

This paper also discusses the relevance of the various climate targets that a country may have i.e. what kind of market failure they are intended to deal with. The discussion reveals that the economic rationales for the stated targets are not at always obvious. The paper also points out that there is loss to society of trying to achieve targets that are irrelevant as compared with an overriding target e.g. to curtail the emission of greenhouse gases.

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Appendix: A simple illustrative model with numbers

Assumptions: $p(x) = a - bx$, $c(y) = \dfrac{y^2}{2}$, $h(z) = k\dfrac{z^2}{2} + gz$, where a, b, k, g are all strictly positive constants. For optimization problems and first order conditions, see main text.

Solution: No targets

$$y^* = \frac{ak + gb}{(1+b)(k+b) - b^2}, \quad z^* = \frac{a - (1+b)g}{(1+b)(k+b) - b^2}$$

Target: a given share of green electricity, $\overline{\alpha}$.

Optimal social solution: $y_{\overline{\alpha}}^* = (1 - \overline{\alpha})\dfrac{a - \overline{\alpha}g}{(1-\overline{\alpha})^2 + k\overline{\alpha}^2 + b}$, $z_{\overline{\alpha}}^* = \overline{\alpha}\dfrac{a - \overline{\alpha}g}{(1-\overline{\alpha})^2 + k\overline{\alpha}^2 + b}$

Using a TGC system: $y_{\overline{\alpha}TGC}^* = (1 - \overline{\alpha})\dfrac{a - \overline{\alpha}g}{(1-\overline{\alpha})^2 + k\overline{\alpha}^2 + b}$,

$z_{\overline{\alpha}TGC}^* = \overline{\alpha}\dfrac{a - \overline{\alpha}g}{(1-\overline{\alpha})^2 + k\overline{\alpha}^2 + b}$, $s_{\overline{\alpha}}^* = \left[k\overline{\alpha} - (1-\overline{\alpha})\right]\dfrac{a - \overline{\alpha}g}{(1-\overline{\alpha})^2 + k\overline{\alpha}^2 + b} + g$

Using a subsidy: $y_{\overline{\alpha}\sigma}^* = (1 - \overline{\alpha})\dfrac{a}{1 + b - \overline{\alpha}}$, $z_{\overline{\alpha}\sigma}^* = \overline{\alpha}\dfrac{a}{1 + b - \overline{\alpha}}$,

$\sigma_{\alpha}^* = \dfrac{(k\overline{\alpha} - (1-\overline{\alpha}))a + (1 + b - \overline{\alpha})g}{1 + b - \overline{\alpha}}$

Using a tax: $y_{\overline{\alpha}\tau}^* = (1 - \overline{\alpha})\dfrac{a - g}{\overline{\alpha}k + b}$, $z_{\overline{\alpha}\tau}^* = \overline{\alpha}\dfrac{a - g}{\overline{\alpha}k + b}$,

$\tau_{\overline{\alpha}}^* = \dfrac{(\overline{\alpha}k - (1-\overline{\alpha}))a + (1 + b - \overline{\alpha})g}{\overline{\alpha}k + b}$

Target: a given level of green electricity, $\overline{z}$.

Optimal social solution: $y_{\overline{z}}^* = \dfrac{a - b\overline{z}}{1 + b}$, $z_{\overline{z}}^* = \overline{z}$

Using a TGC system: $y_{\overline{z}TGC}^* = \dfrac{(1 - \alpha_{\overline{z}}^*)\overline{z}}{\alpha_{\overline{z}}^*}$, $z_{\overline{z}TGC}^* = \overline{z}$, $\alpha_{\overline{z}}^*$: numerically determined (quadratic equation)

Using a subsidy: $y_{\overline{z}\sigma}^* = \dfrac{a - b\overline{z}}{1 + b}$, $z_{\overline{z}\sigma}^* = \overline{z}$, $\sigma_{\overline{z}}^* = \dfrac{(k\overline{z} + g)(1 + b) + b\overline{z} - a}{1 + b}$

Using a tax: $y^*_{\bar{z}\tau} = \dfrac{a-(b+k)\bar{z}-g}{b}$, $z^*_{\bar{z}\tau} = \bar{z}$, $\tau^*_{\bar{z}} = \dfrac{(b+bk+k)\bar{z}+(1+b)g-a}{b}$

Target: a given level of black electricity, $\bar{y}$.

Optimal social solution: $y^*_{\bar{y}} = \bar{y}$, $z^*_{\bar{y}} = \dfrac{a-g-b\bar{y}}{b+k}$

Using a TGC system: $y^*_{\bar{y}TGC} = \bar{y}$, $z^*_{\bar{y}TGC} = \dfrac{\alpha\bar{y}}{(1-\alpha)}$, $\alpha^*_{\bar{y}}$: numerically determined (quadratic equation)

Using a subsidy: $y^*_{\bar{y}\sigma} = \bar{y}$, $z^*_{\bar{y}\sigma} = \dfrac{a-(1+b)\bar{y}}{b}$, $\sigma^*_{\bar{y}} = \dfrac{ak+bg-(b+bk+k)\bar{y}}{b}$

Using a tax: $y^*_{\bar{y}\tau} = \bar{y}$, $z^*_{\bar{y}\tau} = \dfrac{a-g-b\bar{y}}{b+k}$, $\tau^*_{\bar{y}} = \dfrac{a-g-(2b+k)\bar{y}}{b+k}$

Table A. Example: Optimal solutions of applying various instruments to achieve various targets

	Share target: $\bar{\alpha}=0,6$	Green target: $\bar{z}=25$	Black target: $\bar{y}=20$
Social optimum	$y^*_{\bar{\alpha}}=20,6, z^*_{\bar{\alpha}}=31,0$ $W^*_{\bar{\alpha}}=2502,4$	$y^*_{\bar{z}}=37,5, z^*_{\bar{z}}=25,0$ $W^*_{\bar{z}}=2843,8$	$y^*_{\bar{y}}=20,0, z^*_{\bar{y}}=25,0$ $W^*_{\bar{y}}=2537,5$
Allowances: TGC	$y^*_{\bar{\alpha}TGC}=20,6, z^*_{\bar{\alpha}TGC}=31,0$ $W^*_{\bar{\alpha}TGC}=2502,4, s^*_{\bar{\alpha}}=46,3$	$y^*_{\bar{z}TGC}=33,1, z^*_{\bar{z}TGC}=25,0$ $W^*_{\bar{z}TGC}=2824,7$, $s^*_{\bar{z}}=21,8$	$y^*_{\bar{y}TGC}=20,0, z^*_{\bar{y}TGC}=31,3$ $W^*_{\bar{y}TGC}=2478,3, s^*_{\bar{y}}=47,6$
Green subsidy: σ	$y^*_{\bar{\alpha}\sigma}=28,6, z^*_{\bar{\alpha}\sigma}=42,9$ $W^*_{\bar{\alpha}\sigma} 2132,7, \sigma^*_{\bar{\alpha}}=62,1$	$y^*_{\bar{z}\sigma}=37,5, z^*_{\bar{z}\sigma}=25,0$ $W^*_{\bar{z}\sigma}=2843,8, \sigma^*_{\bar{z}}=17,5$	$y^*_{\bar{y}\sigma}=20,0, z^*_{\bar{y}\sigma}=60,0$ $W^*_{\bar{y}\sigma}=700,0, \sigma^*_{\bar{y}\sigma}=105$
Black tax: τ	$y^*_{\bar{\alpha}\tau}=17,3, z^*_{\bar{\alpha}\tau}=25,9$ $W^*_{\bar{\alpha}\tau}=2435,8, \tau^*_{\bar{\alpha}}=39,5$	$y^*_{\bar{z}\tau}=20,0, z^*_{\bar{z}\tau}=25,0$ $W^*_{\bar{z}\tau} 2537,5, \tau^*_{\bar{z}}=35,0$	$y^*_{\bar{y}\tau}=20,0, z^*_{\bar{y}\tau}=25,0$ $W^*_{\bar{y}\tau}=2537,5, \tau^*_{\bar{z}\tau}=35$

No targets: $y^*=18,0, z^*=41,0, W^*=2905,0$. Parameter values applied:
$a=100, b=1, k=2, g=5,$