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Alternate solutions in mixing energy tax/subsidy and emission control policies

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Abstract

In this article, we look at the combination of several market-based climate and energy policies and compare them with first best solution, i.e., a perfectly designed emission tax or emission cap level. It is shown that in the case an emission control policy is imperfect designed or implemented, its performance can be improved by an energy (output) tax/subsidy scheme, where the subsidy is given only to renewable generators or for energy efficiency improvements. This combination can bring the production levels and energy price to the optimum level. The emission level is also decreased by this combination, but not to the optimum level. Thus it may be considered as a second-best policy set. However, other targets on renewables share or energy efficiency level are improved instead, although they are bounded by an optimum level. The policy combination needs to be applied globally to have its best effect and heterogeneous implementation (i.e. different levels of tax/subsidy for various regions) makes welfare loss, but still adding a global emission control policy to a set of existing different local output tax/subsidy policies may be beneficial**.**

Keywords: Climate change mitigation, environmental policy, instrument mixes, economic efficiency, environmental taxes and subsidies

JEL Codes: C61, D60, H21, H23, Q41, Q48

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1 Introduction

Environmental policies has been subject of many studies by now (for example see Bohm and Russell (1985), Goulder and Parry (2008), Zylicz (2009), Aldy and Stavins (2012), or Taylor, Pollard, Rocks, and Angus (2012)). Dating back to Tinbergen's 'one policy (instrument) per target' rule (Tinbergen, 1952), over time, many economic models has been developed to analyze the markets' general equilibrium and dynamic performance, and especially on market failures, that justifies additional policies to remove or reduce their impacts on economic efficiency.

Climate change impacts are one of the most important environmental challenges, and it is mainly attributed to GHG emissions, mostly caused by fossil fuels burning. The problem roots in market failures, that is, low price of fossil fuels (that cause negative externality) and the public-good nature of environmental commodities. Properly setting the emission price is a theoretical solution for this issue, as approached by carbon tax or Emission Trading System (ETS) in some countries (see World Bank (2014) page, which includes a map). In addition to non-environmental reasons for policies, our environmental targets are more than just GHG emissions control. So we may need more than one instrument related to energy sector and they will interact with GHG control policy. Such targets are discussed in many articles, and we can name among them reducing dependency to fossil fuels (security of supply), energizing the slow diffusion rate of renewable energies, improving energy efficiency, and management of uncertainty in climate dynamics, technology advancement, social development and economic growth (see for example Lecuyer and Quirion (2013), Lehmann and Gawel (2013), IEA (2011), or OECD (2007)). Another dimension of complexity is that the targets may not be independent and the market failures may not be completely removed.[1] The set of policy measures may affect each other in positive or negative way, and may cause gain or loss in social welfare. All in all, these points make study and complete analysis of policy sets very complicated.

Theoretical models for policy mixes are normally formulated with many assumptions and simplifications, giving the first-best solution an abstract nature especially in a static general equilibrium model. Partial equilibrium models (e.g. looking only in a specific market sector) showed to have more theoretical problems following Lipsey & Lancaster's theory of second-best (Lipsey & Lancaster, 1956) and critics following it. However, this approach is still used and is widely acceptable.

In this article, we consider a simplified model of the energy sector, and look at some selected policies interactions and possible improvements by their overlapping through an analytical partial equilibrium model. The emission control policy (either by tax or emission quota) is assumed to be in place, but the point is to try to have remedies for its possible inefficiency (i.e. less-than-optimum setting) by adding some other policies and look at their interaction outcome. Considering the fossil fuels as the cause for GHG emissions, the next correction point after emission itself can be the fossil

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[1] Tinbergen rule assumptions are not met in this case.

fuels consumption. The additional policies interactions should be investigated, also keep in mind that it comes at extra institutional cost. As will be discussed later, it is also important to consider the policies time precedence, i.e. what is the old institution and what will be added to it.

The structure of this article is as follows: We'll introduce some general findings and research examples in the next section. A summary of points on policies of interest (i.e. taxes, subsidies, and emission quota) will come at the end of it, showing the researched area and highlighting the uncovered possibility. Then we introduce our analysis framework and list policy set scenarios in the third. The detailed analysis is done in the fourth section, and consists of an analytic setup, a comparative static analysis (without specific assumption on cost functions), and a detailed analysis with specific cost functions for each scenario. The last part concludes the article and includes additional comments and points for further works.

2 A brief review of emission control policies interaction analysis

Analyzing the effect of single policies and comparison between them normally starts by classification of policies (regulations, market-based, informative, etc.) and giving a short description on them and their applications (see for example Goulder and Parry (2008) or Taylor et al. (2012)). The market-based policies are generally more welcomed due to their inherent economic efficiency, and they are basically composed of emission tax or trading permit system, fuel taxes, Renewable Energy (RE) subsidies or special feed-in tariffs, and other clean energy support policies like renewable portfolio standards (RPS). The energy efficiency (EE) policies are recently added to this set, especially after introduction of EU 20/20/20 environmental target set[2]and its further amendments.

But the literature on interactions of co-existing policies is more recent and not that rich. Generally speaking, we have some works that try to establish general qualitative or descriptive frameworks for climate & energy policy interactions either via previous literature review (Oikonomou & Jepma, 2008), or by matching lessons from various case studies (OECD, 2007). In the former article they list various criteria (for policy mix evaluation) under categories of effectiveness, efficiency, price impact, societal impact, and innovation. They then discuss each criterion in more detail by indicative subtitles for evaluation. For example, the effectiveness heading is detailed by static/dynamic effectiveness, energy effectiveness, security of supply, free-rider effect, rebound effect, and a few others. They ask for quantitative evaluation of each subtitle in a total matrix but do not go into further modeling. The OECD report, on the other hand, lists general recommendations to be noticed by policy mix designers, result of some individual environmental case studies in member countries. For example, some of their recommendations are:

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[2] These targets set three key objectives for 2020: i) 20% reduction in EU greenhouse gas emissions from 1990 levels; ii) Raising the share of EU energy consumption produced from renewable resources to 20%; iii) 20% improvement in the EU's energy efficiency.

- *Avoid overlapping instruments, except when they can mutually reinforce each other, or address different aspects of the environmental problem.*
- *Supplement instruments that address total pollution level with instruments that address other aspects of "multi-aspect" problems: Where, when, how, etc.*
- *Use information instruments to enhance the environmental effectiveness of any taxes, fees or charges.*
- *Put in place appropriate monitoring and enforcement mechanisms – to safeguard the environmental effectiveness of the instrument mix.(OECD, 2007, p. 221)*

The results of these works are useful to show the possible areas and outcomes of interaction, and importance of evaluation criteria for policy selection. But any specific selection still requires quantitative approach. This analysis can be done in different market spaces (from just electricity generators to the whole economy) by analytical approach or deploying numerical simulation models.

Before looking at quantitative analyses results, it is important to stress on the importance of transaction costs in evaluation of single or mix of policies. According to Lehmann (2008), failure in *private governance structures* is the reason for policy making by governments, and he names pollution externality, technological spillover, and asymmetrical information as examples of it.[3] Then he raises two reasons for a policy mix instead of a single policy on this ground: "multiple failures of private governance structures" (*ibid.,*p.5) that requires multiple correcting policies, and possibly "high transaction costs of regulation with single first-best policies" (*ibid.,* p.8) that may advantage a policy mix over a single policy. Of course, the policy mix's net welfare benefit should be positive and larger than any private governance structures or single policy for this to come true. So, talking about policy mix only without caring all of these conditions has a serious shortcoming.

However, the cost-benefit analysis (or evaluation) of a policy is just one of different aspects of policy evaluations when considering the general Oikonomou's framework. Note that even if one wants to include the cost, there are different structures and assumptions used in various models on how to calculate the policy cost (see for example Söderholm (2012) for a review on this topic). Also as pointed by Higgins (2013), under uncertainty, weighting environmental and economic targets (in a whole package of a country's political agenda) depend on policy makers subjective preferences. Maybe due to all of these problems, inclusion of policy transaction costs is absent in most of analytic policy mix researches.

Analytic treatment of economic policies is normally done through simplified models of supply and demand and producer/environmental cost functions, solved at equilibrium. The equilibrium models

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[3] By *asymmetric information* he mean giving incomplete or even false information or hiding them, in a way that result in society's welfare loss without any compensation or penalty to the actor, or lack of information at the consumer side that results in inefficient social behavior. *Knowledge spillover* refers to infiltration of knowledge (which is a public good) from its owner to other market participants. Therefore, innovators are often not get complete social return on their innovations, and it results in underinvestment in R&D, compared to social optimum.

can be viewed just parametric without specific form for cost functions, with the aim of finding the market variables sign and rate of change with policies parameters (named comparative static analysis). These models can also be solved as a complete set of equations, with or without sensitivity analysis.

Detailed simulations, on the other hand, are dynamic and show the market behavior during the whole period. Looking especially in energy and climate sector, Huppmann and Holz (2014) identify four classes of numerical models: *Integrated Assessment Model (IAM)*,*Computable General Equilibrium (CGE)* model, *Energy System Model (ESM)*, and *Sector-specific model*. As they mention, "In both IAM and CGE models, the energy sector can be embedded in the broader economy… however, due to the aggregation necessary to numerically solve such models, many details have to be omitted." (*ibid.*)[4] In contrast, ESM models are of partial-equilibrium nature, "… focus only on the energy sector…their limited focus allows for a more detailed analysis of technical-engineering aspects." (*ibid.*) *sector-specific* models only deal with specific fuel or industry/consumer sector.

Note that in each case the set of policies, type of analysis, market boundaries and assumptions, and evaluation criteria may be different. Welfare maximization is the most common criterion for policy mix evaluation, but it is not always the case and it may affect the result considerably. For example, although it is known that single complete emission tax is the first-best solution in economic efficiency, the wealth redistribution is improved in a combined emission tax and renewable subsidy, due to opposite change in wealth upon implication of different policies (Hirth & Ueckerdt, 2013).

Accepting the single emission tax/quota as the first-best solution to pollution externality, added policies may weaken it but serve other goals. For example it is shown in Palmer, Paul, and Woerman (2011) that having emission cap alone will result in most cost effective emission reduction but results in the highest energy price and lowest fossil and RE generation. Adding RE subsidy or RPS policy to it will reduce the cost effectiveness but will increase the renewable generation. Also Lecuyer and Bibas (2012) show that among the set of emission tax, emission cap, RE subsidy, and EE subsidy, emission cap is conflicting with the others as they lower the emission quota price. EE subsidy also conflicts with RE subsidy.

Looking at the literature we can see different researches trying to find the best mix to resolve market failures under certain assumptions. However, there are a few meta-analysis to construct advice on specific policy mixes. Lehmann (2008) provides a good example of such an analysis. Based on his treatment, we can derive following guidelines.

Considering the general failure of private governance structure, it can happen due to technical spillover or asymmetric information externalities. To correct for asymmetric information, mixing of

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[4] This classification is also extended in some other sources. For example, Capellán-Pérez (2013)contains two chapters introducing *Agent Based Model (ABM)* and *System Dynamics (SD)* models in addition to IAM and CGE.

emission control with information policies gives better performance than single emission control policy. Examples of information policies are labeling schemes or auditing and consultancy service.

To correct for technical spillover, it is superior to have a combination of technology support and emission control tax/permit trading policies. The technology support can be, for example, in form of a clean technologies subsidy or commanding a certain technological standard. This combination is analyzed for example in Fischer and Newell (2007). They show that among the set of emission tax, emission performance standard, fossil tax, RPS, RE subsidy, and RE R&D subsidy, emission tax has the highest single-policy efficiency but the optimal combination is emission tax + RE subsidy + RE R&D subsidy, to suppress failure of knowledge spillover. So, the RPS policy is inferior in performance to RE subsidy, and another problem with it, as mentioned for example in Fischer and Peronas (2010), is that it will cause fossil fuels generation to be bound to renewable and thus both will change in the same way.

In case of high transaction costs of regulation with single first-best policies, three possible causes are mentioned in literature and their possible second-best policy mix alternative. One reason for high transaction cost can be the spatial heterogeneity of marginal pollution damage. In this case, the first best solution is a costly *ambient tradable permit* scheme, and the alternative can be a mix of a regular emission tax/permit and a command-and-control policy that prohibits ambient pollution rising above a specific level at any point (Lehmann, 2008). Another well-known case of concern on high transaction cost is the famous *safety valve* mechanism, in which we complement an emission permit policy with a ceiling tax level (on pollution) and a floor subsidy level (on abatement) in case of high uncertainty or difficulty in finding marginal abatement cost among polluters (Jacoby & Ellerman, 2004). Other combinations under uncertainty have also been studied in literature. For example a research by Lecuyer and Quirion (2013) shows that setting emission cap according to expected abatement cost (under uncertainty) can result in large welfare loss, and it may be better to complement it with RE subsidy. Finally, if polluters' non-compliance is probable and the cost of monitoring and enforcement is too high, setting indirect taxes and subsidies on goods (like *deposit-refund systems*) can be a low-cost alternative (Lehmann, 2008).

Most of the above discussion (at least in analytic researches) is based on a presumption that there is no pre-existing policy in force. However, fuel or emission taxes or subsidies may exist beforehand, either in inefficient size (to mitigate climate change) or set for other reason than climate change. Without taking the policy costs into account, it can be concluded based on Lehmann (2010) that with a prior emission tax in place, an emission quota system is still useful to reach the optimum emission level (unless the tax is already achieved this goal). Note that as shown by Fischer and Peronas (2010), adding emission cap over emission tax will promote the dirtiest fossil technology, if we have different types of fossil technology employed. Another point is that opposite to emission quota (that seems to be easier to be implemented globally), taxes are almost always set at national level as they are imposed also as fiscal instruments. Having a heterogeneous emission tax causes some economic inefficiency in pollution control compared to a homogeneous tax. However, adding a binding emission quota over a heterogeneous emission tax will still make some gains that may cover the tax heterogeneity loss, especially if the emission quota itself is applied heterogeneously (Lehmann, 2010).

Two other points also worth to mention here. The first one is about giving subsidy to renewables, which is normally justified by technological spillover market failure and it is an indirect instrument for emission control. This subsidy (or in another form, Feed-In-Tariff scheme, which can be translated to a combination of output tax and RE subsidy) is normally analyzed in a two-period framework: period of immaturity and period of maturity. The spillover effect is only justifiable when renewables are not as matured as, e.g., fossil fuels. After they pass their immaturity period, it is out of efficiency to support them against other technologies. However, the tariff and emission prices should be updated continuously based on a complicated and costly procedure, which may put overall efficiency of this scheme under question (see Fischer and Newell (2007) or Lehmann (2010) for more information).

Another point is that a prior output tax on energy careers is much more common and in place in many countries before emission tax. Comparing these two, output tax brings some economic inefficiency in maintaining emission target. However, it can still be helpful if the emission control policies are imperfect or absent. When combine these different policies and consider subsidies for renewables, some new ideas can appear that are not discussed in previous literature. The current research aim is to have a look at this issue via an analytic research.

3 Model framework and parameters

In general, energy policies can cover a wide range of instruments due to the diversity of energy carriers and the way they are used (end-use sector). Some policies like fossil taxes can be applied generally, but for example an emission restriction policy is not easy to implement in all sectors. A complete model of all energy carriers and sectors is outside the scope of this research, and we consider only the electric power industry and its customers (denoted by EL) in our current analysis, which generates the electricity energy as a commodity. We assume that this commodity is sold in a global free market and a single price is set by market equilibrium. The electricity sector may be governed by a global emission tax (carbon tax) or emission trading system (ETS). In the ETS case, the emission is capped and the emission permit price is determined in the ETS market.

Electricity is generated using two types of resources in our model: fossil and renewable. We assume only one fossil (e.g. oil) and only one renewable (e.g. wind) at the moment. There will be a certain amount of emission by generating electricity out of fossil fuel, but it can be abated at additional cost by producers (end of pipe abatement). GHG emission due to renewables is assumed negligible in this research.

Like in any other market, we assume that electricity producers try to maximize their net benefits based on the market demand from the customers. The policy parameters are external to the producers and customers and are set by policymakers. As discussed previously, the policy parameters should be set in a way to maintain some overall criteria, and we choose the maximization of social welfare as the criterion for selection of policy parameters by policymaker.

We assume that electricity consumption is taxed independent of the source of electricity generation. This will also help to attain some energy efficiency goals. Further, we include subsidies for renewables or energy efficiency. Starting with a baseline case of no policy, the policy effects are analyzed and compared in below scenarios:

- *Scenario A:* A fixed carbon tax plus a tax on electricity consumption (energy tax) and a subsidy for renewable generation,
- *Scenario B:* An emission trading system plus a tax on electricity consumption and a subsidy for renewable generation as in Scenario A,
- *Scenario C:* A global emission cap and a set of different local taxes and subsidies,
- *Scenario D:* Adding a subsidy for energy efficiency (EE) to Scenario A/B.

Parameters and functions used to define the model in the first three scenarios are given in Table 1 (additional parameters for last scenario will be introduced later). Using this notation, we will write the market equations and do the analysis in the next section. The aim of analysis is to construct formulas for market variables behavior as a function of policy variables (in each of three mentioned scenarios). As deriving a closed form solution in a very general case of cost functions is not possible, we do the analysis in general and specific cost functions separately.

4 Analysis of policies interactions

In this section we present a summary of the analysis and important results of it for each scenario in a separate subsection. For each scenario, we first present the market functions (producers profit, demand, and social welfare) and welfare maximization conditions. Then we do a comparative static analysis, and finally solve the model for a specific set of cost functions.

4.1 Carbon tax plus energy tax and RE subsidy (scenario A)

4.1.1 Market functions and optimum solution

The whole producers profit function is written as:

$$\Pi = (P-t)f + (P-t+s)r - C_f(f) - C_r(r) - C_a(a) - \phi(\tau f - a)$$

Table 1: Parameters and functions used to define the model

Symbol	***Description***
Constants:	
T	carbon intensity for fossil fuel
Δ	marginal environmental damage
Market variables:	
F	the quantity of fossil-generated electricity
R	the quantity of renewable-generated electricity
P	electricity market price for consumers
A	amount of emission abatements by fossil generators
Q	Total generated electricity (f+r)
E	Total emission level $= \tau f - a$
Policy variables:	
t	tax on electricity consumption
ϕ/Ω	carbon price/emission cap
S	renewables subsidy
Functions:	
$C_f(f)$	EL production cost from fossil source
$C_r(r)$	EL production cost from renewable source
$C_a(a)$	fossil generators abatement cost
$APC(\phi, f, a)$	Emission allowance purchase cost = $\phi(\tau f - a)$
$dam(f,a)$	environmental damage function = $\delta(\tau f - a)$
$D(P)$	EL market demand function
$CS(P)$	EL consumers surplus function

This profit function is maximized when the producers' net marginal production cost is equal to market price (and marginal abatement cost equal to carbon price):

$P - t - \acute{C}_f(f) - \phi\tau = 0$ (for fossil-based producers, maximization w.r.t. f)
$P - t + s - \acute{C}_r(r) = 0$ (for renewable-based producers, maximization w.r.t. r)
$\acute{C}_a(a) - \phi = 0$ (for abatement, maximization w.r.t. a)

Where $\acute{C}_x = \frac{dC_x}{dx}$, and market clearing equation is (q is the total electricity production):

$$q = f + r = D(P)$$

We also define the welfare function as:

W(Policy variables) = *CS*(*P*) + ***Π***(*all variables*) – *dam*(*f*,*a*)+ *Pure transfer cancellations*

The *CS* function is generally defined on basis of the inverse demand function by below formula:

$$CS(P) = \int_0^{D(P)} D^{-1}(q)dq - P.D(P)$$

So the welfare function can be written as:

$$\boldsymbol{W} = \int_0^{D(P)} D^{-1}(q)dq - C_f(f) - C_r(r) \text{-} C_a(a) - \delta(\tau f - a)$$

"Pure transfer cancellations" will nullify the effect of tax and subsidy and emission allowance monetary exchange on consumers and producers in welfare equation, because these payments are received by another party in the same welfare system and cancel each other in the total welfare sum. Like profit maximization, we have first order conditions for optimizing welfare:

$$P - \acute{C}_f(f) - \delta\tau = 0$$
$$P - \acute{C}_r(r) = 0$$
$$\acute{C}_a(a) - \delta = 0$$

By comparing profit and welfare maximization relations derived before, we can easily conclude that:

$$t^* = s^* = \tau(\delta - \phi)$$
$$\phi^* = \delta$$

It is in accordance to the well-known rule that if the carbon tax is completely internalizing the environmental damage, we don't need any other instrument (like energy tax and subsidy). But it shows another point as well: If $\phi^* \neq \delta$, an equal level of energy tax and RE subsidy can still be used to improve welfare.

4.1.2 Comparative static analysis

Taking derivatives of above equations, we'll have:

$$dP - dt - \acute{\acute{C}}_f df - \tau d\phi = 0 \Rightarrow df = \eta_f(dP - dt - \tau d\phi)$$

$$dP - dt + ds - \acute{\acute{C}}_r dr = 0 \Rightarrow dr = \eta_r(dP - dt + ds)$$

$$\frac{d\phi}{da} = \acute{\acute{C}}_a(a) \Rightarrow da = \eta_a d\phi$$

Where $\acute{C}_f = \frac{1}{\eta_f}\acute{C}_r = \frac{1}{\eta_r}$, $\acute{C}_a = \frac{1}{\eta_a}$. We assume the demand to be linear, i.e., $r + f = i_d - \eta_D P$. Then:

$$df + dr = -\eta_D dP \Rightarrow dP = -\frac{(df + dr)}{\eta_D}$$

All $\eta_x$values assumed to be positive parameters. Solving the above set for marginal market variables in terms of marginal policy variables and other parameters, we'll have:

$$dP = \frac{(\eta_f+\eta_r)dt-\eta_r ds+\tau\eta_f d\phi}{\eta_D+\eta_f + \eta_r},\ df = \eta_f\frac{-\eta_D dt-\eta_r ds-(\eta_D+\eta_r)\tau d\phi}{\eta_D+\eta_f + \eta_r},\ dr = \eta_r\frac{-\eta_D dt+(\eta_D+\eta_f)ds+\eta_f\tau d\phi}{\eta_D+\eta_f + \eta_r}$$

$$da = \eta_a d\phi,\ dq = d(r + f) = -\eta_D dP$$

Signs of partial derivatives of market variables with respect to policy variables are summarized in Table 2 (market variables are shown in columns and policy variables in rows). It can be noted that the only policy that certainly lead to positive *dr* but negative *dq* is carbon price (ϕ). If the carbon price increases, *P* and *r* will also be increased but *q* and *f* will be decreased. To return them to their optimum level, we need to increase both *t* and *s* (changing just one of them will not correct all variables), which confirms result obtained in previous part.

Table 2: Sign of change in market variables vs. a positive change in policy variables, scenario A

	dP	dq	df	dr	da
dt	+	-	-	-	0
ds	-	+	-	+	0
$d\phi$	+	-	-	+	+

4.1.3 Market variables for specific cost functions

To have a more detailed look in market variables values, we assume some typical forms for cost functions. Production from fossil fuel is generally considered to be matured and with a constant marginal cost, while for the renewable generation, the marginal cost is increasing with production level and adding a second order term to the price equation is the normal way to simulate it. Having a second order term for abatement cost is also reasonable, because the easiest ways of abatement are utilized first and next step costs (marginal abatement cost) will increase with abatement level. So we assume:

$$C_f(f) = i_f f\ \ ,\ C_r(r) = i_r r + \frac{r^2}{2\eta_r}\ \ ,\ C_a(a) = \frac{a^2}{2\eta_a}$$

Where i_f and i_r are intercept values of fossil and renewable supply function, respectively. Writing again first order and market clearance conditions, we'll have:

$f = K_f - \eta_D t - \eta_r s - (\eta_D + \eta_r)\phi\tau$
$r = K_r + \eta_r s + \eta_r \phi\tau$
$P = i_f + t + \phi\tau$
$a = \eta_a \phi$
And:
$q = r + f = K_f + K_r - \eta_D t + \eta_D \phi\tau$
Total emissions = $e = \tau K_f - \tau\eta_D t - \tau\eta_r s - K_\phi \phi$

Where $K_f = i_d - (\eta_D + \eta_r)i_f + \eta_r i_r$, $K_r = (i_f - i_r)\eta_r$, and $K_\phi = \eta_a + \tau^2(\eta_D + \eta_r)$. Using optimum values calculated in part 4.1.1for $\phi, s,$ and t, and varying value of ϕ from 0 to δwe will have below cases:

Table 3: Market variables for specific cost functions, scenario A

Variable	$\phi = \delta, s = t = 0$	$0 < \phi < \delta, s = t = \tau(\delta - \phi)$	$\phi = 0, s = t = \delta\tau$
f	$K_f - (\eta_D + \eta_r)\delta\tau$	$K_f - (\eta_D + \eta_r)\delta\tau$	$K_f - (\eta_D + \eta_r)\delta\tau$
r	$K_r + \eta_r\delta\tau$	$K_r + \eta_r\delta\tau$	$K_r + \eta_r\delta\tau$
P	$i_f + \delta\tau$	$i_f + \delta\tau$	$i_f + \delta\tau$
a	$\eta_a\delta$	$\eta_a\phi$	0
q	$K_f + K_r - \eta_D\delta\tau$	$K_f + K_r - \eta_D\delta\tau$	$K_f + K_r - \eta_D\delta\tau$
e	$\tau K_f - (\eta_D + \eta_r)\delta\tau^2 - \eta_a\delta$	$\tau K_f - (\eta_D + \eta_r)\delta\tau^2 - \eta_a\phi$	$\tau K_f - (\eta_D + \eta_r)\delta\tau^2$

As we see, *f, r, p,* and *q* are the same in all cases, so we have the energy consumption and price level at the optimum level. However, the total emissions will increase from full carbon tax case to full fossil tax and renewable subsidy case. The full carbon tax would be a first-best solution, and complementing it with energy tax and renewable subsidy can be the second-best. Note that as a tax is implied on energy commodity regardless of its origin (fossil or renewable), this combination will not place any financial burden on government but makes some revenue for it, equal to *tf*, and the net effect of this combined equal tax and subsidy is to keep the taxing only for fossil-based part of whole electricity generation, and cancel it for the renewable-based production part. So, we'll concentrate in our subsequent analyses on this equity.

We also repeated the analysis for more complete set of cost functions, in which all of $C_f(f)$, $C_r(r)$, and $C_a(a)$ was assumed to contain first and second order terms. Although the formulas in the above tables become more complex, but the same end results was achieved in this case as well. So we keep the same set of simpler functions in future sections analysis.

4.2 Emission cap plus energy tax and RE subsidy (scenario B)

4.2.1 Market functions and optimum solution

Here the emission level ($e = \tau f - a$) will become a bounded variable. Assuming the initial permits are distributed for free and the emission limit is binding, the profit maximization will become:

$\max \Pi = (P - t)f + (P - t + s)r - C_f(f) - C_r(r)\text{-} C_a(a)$
s.t. $\tau f - a = \Omega$

Using Lagrange method and considering ϕ as shadow price for emission permit, we'll have the following first order conditions:

$$P - t - \acute{C}_f(f) - \phi\tau = 0$$
$$P - t + s - \acute{C}_r(r) = 0$$
$$\acute{C}_a(a) - \phi = 0$$
$$\tau f - a = \Omega$$

That is the same relation as we had before. The welfare function and its first order conditions also remain unchanged to 4.1.A. It means that if the emission cap is binding and set at the efficient level, say $\Omega = \Omega^*$, such that the emission permit price will reach an efficient level, i.e. $\phi^* = \delta$, then we have $t^* = s^* = 0$. Otherwise, $t^* = s^* = \tau(\delta - \phi)$.

4.2.2 Comparative static analysis

It can be shown that the equations in this case will have the following form:

$$d\phi = \frac{1}{\eta_n}\left[-\tau\eta_f\eta_D dt - \tau\eta_f\eta_r ds - \eta_\Sigma d\Omega\right]$$

$$df = \frac{1}{\eta_n}\left[-\eta_a\eta_f\eta_D dt - \eta_a\eta_f\eta_r ds + \tau\eta_f(\eta_D + \eta_r)d\Omega\right]$$

$$dr = \frac{1}{\eta_n}\left[-\eta_r\eta_D\left(\eta_a + \tau^2\eta_f\right)dt + \left(\eta_a\eta_f\eta_r + \eta_r\eta_D\left(\eta_a + \tau^2\eta_f\right)\right)ds - \tau\eta_f\eta_r d\Omega\right]$$

$$dP = \frac{1}{\eta_n}\left[\left(\eta_a\eta_f + \eta_r\left(\eta_a + \tau^2\eta_f\right)\right)dt - \eta_r\left(\eta_a + \tau^2\eta_f\right)ds - \tau\eta_f d\Omega\right]$$

$$da = \eta_a d\phi \quad , \quad = dr + df = -\eta_D dP$$

Where $\eta_\Sigma = \eta_f + \eta_r + \eta_\mathrm{D}$ and $\eta_n = \eta_a\eta_f + (\eta_r + \eta_\mathrm{D})\left(\eta_a + \tau^2\eta_f\right)$.

Like in the previous section, we can build Table 4 and look at the sign of changes in market variables.

Table 4: Sign of change in market variables vs. a positive change in policy variables, scenario B

	dP	dq	df	dr	$d\phi$	da
dt	+	-	-	-	-	-
ds	-	+	-	+	-	-
$d\Omega$	-	+	+	-	-	-

As we see, increasing all instruments variables have a negative effect on the carbon price. Total emission is fixed in this case. However, there may be a possibility to change the share of fossil and renewable by changing the tax and subsidy values. Like in the previous scenario, if the emission cap increases, *P* and *r* will also be reduced but *q* and *f* will be increased. To return them to their optimum level, we need to increase both *t* and *s* (changing just one of them will not correct all variables), which confirms the result obtained in the previous part.

4.2.3 Market variables for specific cost functions

Assuming the same cost functions as in the first case, we'll have the same equations for market variables. However, the carbon price in this case is itself a dependent variable, and we have a new equation for total emission cap (which we assume binding for this analysis). Solving for it, we'll have:

$$\phi = \frac{1}{K_\phi}(\tau K_f - \tau\eta_D t - \tau\eta_r s - \Omega)$$

$$f = \frac{1}{K_\phi}(\eta_a K_f - \eta_a\eta_D t - \eta_a\eta_r s + \tau(\eta_r + \eta_D)\Omega)$$

$$r = K_r + \frac{1}{K_\phi}(\tau^2\eta_r K_f - \tau^2\eta_r\eta_D t + \eta_r(\eta_a + \tau^2\eta_D)s - \tau\eta_r\Omega)$$

$$P = i_f + \frac{1}{K_\phi}(\tau^2 K_f + (\eta_a + \tau^2\eta_r)t - \tau^2\eta_r s - \tau\Omega)$$

$$a = \eta_a\phi$$

For the first best case we have $t^* = s^* = 0,\ \phi^* = \delta,$ and $\Omega^* = \tau K_f - \delta K_\phi$, and we'll get the same values for the variables as in the first best solution in scenario A.

If we introduce a same amount of tax and subsidy in the system (but keeping the total emission cap intact), the carbon price will decrease. In fact, the tax/subsidy will weaken the emission cap policy, but the emission is not increased as it is capped. However, contrary to scenario A, imposing a non-zero tax/subsidy here will cause other market variables (*f, r, P*, and *q*) to deviate from optimum level. So, this is not even a second-best solution. Nevertheless, the tax/subsidy introduction will reduce the fossil generation and increase the renewable, so they may help in other green targets, and it will also generate some revenue for the government.

Now we ask the previous question again: If the cap is not set at optimum level, will there be any gain of introduction of tax/subsidy?

Assuming $s = t$ and $\Omega = \Omega^*$, the above set of equations can be written as below:

$$\phi = \delta - \frac{\tau(\eta_D + \eta_r)t}{K_\phi}$$

$$f = K_f - \delta\tau(\eta_D + \eta_r) - \frac{\eta_a(\eta_D + \eta_r)t}{K_\phi}$$

$$r = K_r + \eta_r\delta\tau + \frac{\eta_r\eta_a t}{K_\phi}$$

$$P = i_f + \delta\tau + \frac{\eta_a t}{K_\phi}$$

$$a = \eta_a\phi$$

As we see, *P* is always greater than $i_f + \delta\tau$ for $t > 0$. We can introduce tax/subsidy until the carbon price reaches zero. This limit value is:

$$t_{L^*} = s_{L^*} = \frac{\delta K_\phi}{\tau(\eta_D + \eta_r)} = \delta\tau + \frac{\delta\eta_a}{\tau(\eta_D + \eta_r)}$$

Now assume that emission cap is set at higher level than optimum level, Ω^*, and we have excess emission permits. This will decrease the carbon price. Let show the carbon price reduction by ξ and assume no tax or subsidy at the moment. This carbon price corresponds to an emission cap set at $\Omega = \Omega^* + \xi K_\phi$. By this enlarged cap and reduced carbon price, we'll have more fossil fuel generation and emission. The market price is also reduced compared to the first-best case.

Now we introduce same levels of tax and subsidy to the system to do some correction. This will decrease the carbon price more, and total emission will be the same, but it will increase renewables and decreasing the fossil generation.

Like the previous case, tax/subsidy can be increased until the carbon price reaches zero. At this point we have:

$$t_L = s_L = \frac{(\delta - \xi)K_\phi}{\tau(\eta_D + \eta_r)} = (\delta - \xi)\tau + \frac{\delta\eta_a}{\tau(\eta_D + \eta_r)}$$

The market price in this case will be:

$$P = i_f + (\delta - \xi)\tau + \frac{\eta_a t}{K_\phi}$$

Interesting point is that, now P can be set to the same level as the first-best case, provided that $t = s = t_M = \frac{\tau\xi K_\phi}{\eta_a}$. For this to be possible, this value should be in the range of $(0, t_L)$. So we should have:

$$\frac{\tau\xi K_\phi}{\eta_a} < \frac{(\delta - \xi)K_\phi}{\tau(\eta_D + \eta_r)} \quad \Rightarrow \quad \xi < \frac{\delta\eta_a}{K_\phi} = \xi_L$$

So, if the over allocation of permits is not so severe ($\xi < \xi_L$) and we are not able to correct it directly, we can still do some enhancement with the help of this tax/subsidy combination to attain a second-best efficiency. In other words, the total emissions is higher than first-best, because the emission cap is set at wrong level, but the fossil and renewable production levels can be tuned by tax and subsidy at the correct (first-best) level. As shown in previous section B, this setting for tax and subsidy is welfare maximizing and it has some welfare gain over zero tax and subsidy (under inefficient cap). The above cases are summarized in Table 5 and Table 6. Note that at $\xi = \xi_L$, the second and third columns of Table 6 show the same point ($t_M = t_L = \delta\tau$).

Table 5: Market variables for specific cost functions, scenario B, optimum cap level

Variable	$e = \Omega = \Omega^*$	
	$t = s = 0$	$t = s = t_{L^*}$
ϕ	δ	0
a	$\eta_a\delta$	0
f	$K_f - (\eta_D + \eta_r)\delta\tau$	$K_f - (\eta_D + \eta_r)t_{L^*}$
r	$K_r + \eta_r\delta\tau$	$K_r + \eta_r t_{L^*}$
P	$i_f + \delta\tau$	$i_f + t_{L^*}$
q	$K_f + K_r - \eta_D\delta\tau$	$K_f + K_r - \eta_D t_{L^*}$

Table 6: Market variables for specific cost functions, scenario B, excessive cap level

Variable	$e = \Omega = \Omega^* + \xi K_\phi$		
	$t = s = 0$	$t = s = t_M$	$t = s = t_L$
ϕ	$\delta - \xi$	$\delta - \xi K_\phi / \eta_a$	0
a	$\eta_a(\delta - \xi)$	$\eta_a \delta - \xi K_\phi$	0
f	$K_f - (\eta_D + \eta_r)(\delta - \xi)\tau$	$K_f - (\eta_D + \eta_r)\delta\tau$	$K_f - (\eta_D + \eta_r)t_L$
r	$K_r + \eta_r(\delta - \xi)\tau$	$K_r + \eta_r \delta\tau$	$K_r + \eta_r t_L$
P	$i_f + (\delta - \xi)\tau$	$i_f + \delta\tau$	$i_f + t_L$
q	$K_f + K_r - \eta_D(\delta - \xi)\tau$	$K_f + K_r - \eta_D \delta\tau$	$K_f + K_r - \eta_D t_L$

Before discussing the next scenario, it may be helpful to have a closer look at the renewable share in total production. The optimum production level gives us the efficient level of *f* and *r* and changing policy values will disrupt efficiency. However, it is still possible to change the *f* and *r* levels by changing K_f, K_r, η_D, or η_r. Following options seem possible:

- If we can reduce demand function intercept (i_d), K_f is reduced as well. This will cause q and *f* to decrease but *a*, *r*, and *P* remain the same. Reducing i_d is analogous to a shift in demand, which can be done by energy efficiency measures. So in our policy arrangement, *improving energy efficiency can help the renewable share to increase.*
- Increasing η_D - i.e. price elasticity of demand – will have the same effect as above, but changing price elasticity is less probable than a linear shift in demand.
- Increasing η_r or decreasing i_r will increase *r* and reduce *f*. This corresponds to a price break in renewable energy, which can be accelerated by RE R&D support.
- Assuming fossil technology to be in mature state, its cost function coefficient (i_f) is not expected to change considerably. If it is not the case, when it goes up, it will help reducing the fossil generation and increasing renewable, and vice versa.
- Increasing η_a - i.e. reducing abatement cost - results in more abatement under emission tax. But under an emission permit policy, cap level should be adjusted for this change to be effective. Of course, it will still be possible to have some improvements by additional output tax/subsidy even if cap level cannot be adjusted.

4.3 A global emission cap and heterogeneous taxes and subsidies (scenario C)

The previous scenarios may be interesting from a scientific point of view, but imposing a global energy tax or renewable subsidy is always far out of reach. In fact, if there is enough power and will to impose a global tax, it would be easier to correct for the wrong emission cap instead and reach the optimum point with fewer policies. Even setting the global emission cap is more welcomed as the initial permits are normally distributed for free and the producers then only pay between themselves. Setting a tax requires much more justification and social acceptance.

As mentioned previously, we may have an existing heterogeneous set of energy (output) prices and taxes prior to adding subsidies or an emission cap. As discussed in Lehmann (2010), a heterogeneous tax set causes a welfare loss compared to equivalent (average) homogeneous tax, but a binding emission quota will add some gain that can cover that loss. We think this idea can be extended to our case as well.

Considering an existing heterogeneous output tax, we expect to have some gain by adding equal renewable subsidies and a global binding emission cap. Addition of renewable subsidies will help to optimize the energy carrier price and renewable to fossil share in each sector, and if the emission cap is tight enough, the gain of its addition will hopefully cover the loss of the heterogeneous output tax inefficiency loss.

If we have a prior - efficient or inefficient - emission cap, raising a local tax level for emission mitigation (even with adding subsidy level) is not justified as it will not change the emission level. The only possibility to have some gain is to have more revenue from selling the freed local emission permits to other regions than the welfare loss due to extra cost of abatement and local price increase. We will have a closer look on this issue below.

Let us consider a global emission cap plus taxes and subsidies on a local scale (e.g. on country level). Further, we name the assigned local share of emission cap Ω_{LO}. Prior to setting local tax and subsidy, the cap was assumed binding. But after imposing the tax, we have less local emission and thus some freed permits that can be sold on global market. Actually this may change the carbon price, but we assume the carbon price to be fixed at the moment (this can be a reasonable assumption if the size of the local economy is small compared to the global market).

Another point is about the environmental damage. As the GHG emissions will affect climate globally, the total damage will be the same as far as the total emission cap is the same. Even if local emissions are reduced, other countries will fill the gap. So we assume that the local share of environmental damage is fixed. We also consider any benefit resulting from freeing some permits below Ω_{LO} level (i.e. their selling price in the permits market), to be added to the welfare function.

By these assumptions, we are actually in the same situation as in the first case (a fixed carbon price plus tax and subsidy). Looking at the welfare function, the change in welfare (from zero tax and subsidy to an arbitrary value of $t = s$) is composed of a change in the CS-related term, a change in the cost of fossil generation, a change in the cost of renewable generation, with addition of the benefit of selling freed permits (the environmental damage is the same in both cases, so dropped from the difference calculation). It can be shown that the change in welfare will be:

$$\Delta W = -t\eta_D\left(i_f + \frac{t}{2} + \phi\tau\right) + i_f t(\eta_D + \eta_r) - t\eta_r\left(i_f + \frac{t}{2} + \phi\tau\right) + \phi\tau t(\eta_D + \eta_r) \qquad \Rightarrow$$

$$\Delta W = -t(\eta_D + \eta_r)\left(\frac{t}{2}\right) \leq 0$$

So any level of local tax and (equal) subsidy will cause local welfare loss. Note that we assumed a fixed carbon price, while in reality the excess permit will weaken the carbon price further. This reduced carbon price will decrease the local producers cost but also reduce the benefit of selling extra permits. So the final result is not certain, and it depends on carbon price elasticity, which is a global market specification.

4.4 Adding a subsidy for energy efficiency (scenario D)

4.4.1 Market functions and optimum solution

Now let's assume we give a subsidy w on energy efficiency, given to electricity producers for each unit of reduction they make in total demand. Despite reduced consumption, the consumers will get the same service level as before and pay the market price for each consumption unit. To look at this issue analytically, we use the approach taken by Lecuyer and Bibas (2012). If *l* is the total reduction in demand, the market clearance equation will be:

$f + r = D(P) - l$ (or $f + r + l = D(P)$)

In fact, *l* here is considered as a *good* like *f* or *r*, produced by energy efficiency investments and should make profit for producers counting the subsidy of *w*, more than what they could get by selling the same unit of electricity at the market price. Showing energy efficiency investment cost by $C_l(l)$, producers profit and welfare functions of Scenario A can be rewritten as follows:

$$\mathbf{\Pi} = (P-t)f + (P-t+s)r + (P-t+w)l - C_f(f) - C_r(r) - C_l(l) - C_a(a) - \phi(\tau f - a)$$

With first order conditions:

$$P - t - \acute{C}_f(f) - \phi\tau = 0$$
$$P - t + s - \acute{C}_r(r) = 0$$
$$P - t + w - \acute{C}_l(l) = 0$$
$$\acute{C}_a(a) - \phi = 0$$

And

$$\boldsymbol{W} = \int_0^{D(P)} D^{-1}(q)dq - C_f(f) - C_r(r) - C_l(l) - C_a(a) - \delta(\tau f - a)$$

With first order conditions:

$$P - \acute{C}_f(f) - \delta\tau = 0$$
$$P - \acute{C}_r(r) = 0$$
$$P - \acute{C}_l(l) = 0$$
$$\acute{C}_a(a) - \delta = 0$$

Comparing above set of conditions, we have a familiar result:

$$t^* = s^* = w^* = \tau(\delta - \phi) \qquad , \qquad \phi^* = \delta$$

The same result can be easily obtained with changing emission tax to emission permit. As expected, there is no need for any other measure if emission tax or permit is set at optimum level. But the additional policies can help improve the welfare if it is not the case.

4.4.2 Comparative static analysis

Due to the similarity of equations for energy efficiency and renewable production, analysis and formulas in this section are the same as in scenario B. Changes in *s* or *w* has the same effect on *P, q, f,* ϕ, and a. However, they have counter effect on each other. The sign of changes in this case would be as shown inTable 7.

Table 7: Sign of change in market variables vs. a positive change in policy variables, scenario D

	dP	dq	df	dr	dl	$d\phi$	da
dt	+	-	-	-	-	-	-
ds	-	+	-	+	-	-	-
dw	-	+	-	-	+	-	-
$d\Omega$	-	+	+	-	-	-	-

4.4.3 Market variables for specific cost functions

Because the analysis is very similar to previous scenarios, we'll not repeat it for emission tax again and only present the combination of emission cap, output tax, and two subsidies. Assuming an EE cost function of below form:

$$C_l(l) = \frac{l^2}{2\eta_l}$$

and following the same approach taken in previous sections, we'll have:

$$\phi = \frac{1}{\acute{K}_\phi}(\tau \acute{K}_f - \tau\eta_D t - \tau\eta_r s - \tau\eta_l w - \Omega)$$
$$f = \frac{1}{\acute{K}_\phi}(\eta_a \acute{K}_f - \eta_a\eta_D t - \eta_a\eta_r s - \eta_a\eta_l w + \tau(\eta_r + \eta_D + \eta_l)\Omega)$$
$$r = K_r + \frac{1}{\acute{K}_\phi}(\tau^2\eta_r \acute{K}_f - \tau^2\eta_r\eta_D t + \eta_r(\eta_a + \tau^2(\eta_D + \eta_l))s - \tau^2\eta_r\eta_l w - \tau\eta_r\Omega)$$
$$P = i_f + \frac{1}{\acute{K}_\phi}\left(\tau^2\acute{K}_f + \left(\eta_a + \tau^2(\eta_r + \eta_l)\right)t - \tau^2\eta_r s - \tau^2\eta_l w - \tau\Omega\right)$$
$$l = \eta_l i_f + \frac{1}{\acute{K}_\phi}(\tau^2\eta_l \acute{K}_f - \tau^2\eta_l\eta_D t - \tau^2\eta_l\eta_r s + \eta_l(\eta_a + \tau^2(\eta_D + \eta_r))w - \tau\eta_r\Omega)$$
$$a = \eta_a\phi$$

Where $\acute{K}_f = i_d - (\eta_D + \eta_r + \eta_l)i_f + \eta_r i_r$ and $\acute{K}_\phi = \eta_a + \tau^2(\eta_D + \eta_r + \eta_l)$.

For the first best case we have $t^* = s^* = w^* = 0,\ \phi^* = \delta,$ and $\Omega^* = \tau\acute{K}_f - \delta\acute{K}_\phi$. Like previous scenarios, introducing a tax and two subsidies will weaken the carbon price and make deviation from first or second-best solutions. Assuming $s = t = w$and $\Omega = \Omega^*$, the above set of equations can be written as below:

$$\phi = \delta - \frac{\tau(\eta_D + \eta_r + \eta_l)t}{\acute{K}_\phi}$$
$$f = \acute{K}_f - \delta\tau(\eta_D + \eta_r + \eta_l) - \frac{\eta_a(\eta_D + \eta_r + \eta_l)t}{\acute{K}_\phi}$$
$$r = K_r + \eta_r\delta\tau + \frac{\eta_r\eta_a t}{\acute{K}_\phi}$$
$$l = \eta_l i_f + \eta_l\delta\tau + \frac{\eta_l\eta_a t}{\acute{K}_\phi}$$
$$P = i_f + \delta\tau + \frac{\eta_a t}{\acute{K}_\phi}$$
$$a = \eta_a\phi$$

Again, we can introduce tax/subsidies until the carbon price reaches zero. This limit value is:

$$t_{\acute{L}^*} = s_{\acute{L}^*} = w_{\acute{L}^*} = \frac{\delta\acute{K}_\phi}{\tau(\eta_D + \eta_r + \eta_l)} = \delta\tau + \frac{\delta\eta_a}{\tau(\eta_D + \eta_r + \eta_l)}$$

Assuming the emission cap to be set at a higher level than the optimum level ($\Omega = \Omega^* + \xi K_\phi$), and following the same procedure as scenario B, tax/subsidy can be increased until the carbon price reaches zero. At this point we have:

$$t_{\acute{L}} = s_{\acute{L}} = w_{\acute{L}} = \frac{(\delta - \xi)\acute{K}_\phi}{\tau(\eta_D + \eta_r + \eta_l)} = (\delta - \xi)\tau + \frac{\delta \eta_a}{\tau(\eta_D + \eta_r + \eta_l)}$$

The market price in this case will be:

$$P = i_f + (\delta - \xi)\tau + \frac{\eta_a t}{\acute{K}_\phi}$$

And P can be set to the same level as the first-best case, provided that $t = s = w = t_{\acute{M}} = \frac{\tau \xi \acute{K}_\phi}{\eta_a}$. For this to be possible, this value should be in the range of $(0, t_{\acute{L}})$. So we should have:

$$\frac{\tau \xi \acute{K}_\phi}{\eta_a} < \frac{(\delta - \xi)\acute{K}_\phi}{\tau(\eta_D + \eta_r + \eta_l)} \quad \Rightarrow \quad \xi < \frac{\delta \eta_a}{\acute{K}_\phi} = \xi_{\acute{L}}$$

The above cases are summarized in Table 8 and Table 9.

Table 8: Market variables for specific cost functions, scenario D, optimum cap level

Variable	$e = \Omega = \Omega^*$	
	$t = s = w = 0$	$t = s = w = t_{\acute{L}^*}$
Φ	δ	0
A	$\eta_a \delta$	0
F	$\acute{K}_f - (\eta_D + \eta_r + \eta_l)\delta\tau$	$\acute{K}_f - (\eta_D + \eta_r + \eta_l)t_{\acute{L}^*}$
R	$K_r + \eta_r \delta\tau$	$K_r + \eta_r t_{\acute{L}^*}$
L	$\eta_l i_f + \eta_l \delta\tau$	$\eta_l i_f + \eta_l t_{\acute{L}^*}$
P	$i_f + \delta\tau$	$i_f + t_{\acute{L}^*}$
q (r+f+l)	$\acute{K}_f + \eta_l i_f + K_r - \eta_D \delta\tau$	$\acute{K}_f + \eta_l i_f + K_r - \eta_D t_{\acute{L}^*}$

Table 9: Market variables for specific cost functions, scenario D, excessive cap level

Variable	$e = \Omega = \Omega^* + \xi \acute{K}_\phi$		
	$t = s = w = 0$	$t = s = w = t_{\acute{M}}$	$t = s = w = t_{\acute{L}}$
Φ	$\delta - \xi$	$\delta - \xi K_\phi / \eta_a$	0
A	$\eta_a(\delta - \xi)$	$\eta_a \delta - \xi \acute{K}_\phi$	0
F	$\acute{K}_f - (\eta_D + \eta_r + \eta_l)(\delta - \xi)\tau$	$\acute{K}_f - (\eta_D + \eta_r + \eta_l)\delta\tau$	$\acute{K}_f - (\eta_D + \eta_r + \eta_l)t_{\acute{L}}$
R	$K_r + \eta_r(\delta - \xi)\tau$	$K_r + \eta_r \delta\tau$	$K_r + \eta_r t_{\acute{L}}$
L	$\eta_l i_f + \eta_l(\delta - \xi)\tau$	$\eta_l i_f + \eta_l \delta\tau$	$\eta_l i_f + \eta_l t_{\acute{L}}$
P	$i_f + (\delta - \xi)\tau$	$i_f + \delta\tau$	$i_f + t_{\acute{L}}$
q (r+f+l)	$\acute{K}_f + \eta_l i_f + K_r - \eta_D(\delta - \xi)\tau$	$\acute{K}_f + \eta_l i_f + K_r - \eta_D \delta\tau$	$\acute{K}_f + \eta_l i_f + K_r - \eta_D t_{\acute{L}}$

Note that $\acute{K}_f + \eta_l i_f = K_f$ and the last line (*q*) is actually the same as shown in Table 5 and Table 6. But the actual production is *r*+*f*, which is *l* unit less than before, and only fossil production is affected by this reduction, while renewable production remains unchanged.

One point of interest here is that $t_{\acute{L}^*} < t_{L^*}$, derived in section 4.2. So, by adding the energy efficiency policy, the government revenue will decrease while the subsidies that it should give will increase. Thus to keep the budget positive, we should keep tax (and subsidies) below a certain level. This level corresponds to the point that causes *f* to be equal to *l*. Unfortunately, calculating the formula for this limit value does not result in certainty that it will fall lower or higher than $t_{\acute{M}}$ and it should be judged by numeric evaluation of formulas in each case.

4.5 Renewable share and energy efficiency indicators

Although the emission reduction is the main aim in energy and climate policies, increasing renewables share or energy efficiency level are still important. Pursuing targets for these indicators can be done through their specific instruments, which we will not consider in our analysis. But in this section we have a look at the level of these indicators in different discussed scenarios.

We found the optimum (welfare maximizing) solutions in different cases previously. There were specific (optimum) values for fossil and renewables production. Therefore we have a specific optimum renewable share in total production. Setting a target out of this production share means economic inefficiency in production. However, welfare function may not represent all the cost and benefit portions, and it may be socially desirable to increase these values to a target beyond those calculated optimums. These values are formulated in Table 10 and are based on first-best solutions from previous sections. As you see, renewable share is increased from no policy to scenario A/B and further in scenario D.

Table 10: Optimum renewable share and efficiency level for different scenarios

Scenario	Renewable share $(\frac{r}{r+f})$	Efficiency level $(\frac{l}{r+f+l})$
No policy	$\frac{K_r}{K_f + K_r}$	0
Scenario A/B	$\frac{K_r + \eta_r \delta\tau}{K_f + K_r - \eta_D \delta\tau}$	0
Scenario D	$\frac{K_r + \eta_r \delta\tau}{K_f + K_r - \eta_D \delta\tau - \eta_l (i_f + \delta\tau)}$	$\frac{\eta_l (i_f + \delta\tau)}{K_f + K_r - \eta_D \delta\tau}$

These levels are achievable at first-best optimum. However, we can still go further (until the point that the carbon price drop to zero and emission cap become useless), which correspond to last columns of Table 5 to Table 9. The target values in this case can be simply derived by substituting $\delta\tau$ with t_L, t_{L^*},$t_{\acute{L}}$, or $t_{\acute{L}^*}$ in Table 10.

5 Conclusions and further remarks

This study showed some possibilities of constructive interaction of climate and energy policies via an analytic treatment. It is known that internalizing the emission externality via correct emission tax or emission quota is the best single policy and adding other policies will avert us from the optimum point. However, in the case of an inappropriate emission tax or quota levels, additional policies can help to recover some of deficiency.

Looking only at the EL market (and actually it is a simplified view because the emission market covers other polluting carriers as well), we have the tax applied not only to the fossil-based EL but also to the EL based on renewables. As shown in our results, the optimum setting is to have a subsidy equal to the tax for renewables. So the net effect is to have a tax only on fossil-based EL (a homogeneous output tax). If we have already an inefficient emission tax, this additional instrument can reduce fossil-based EL to its optimum (first-best) setting. This will reduce the emission as well, but not to the same level under first-best setting (complete emission tax or quota).It has also two other important effects that may justify this combination:

- Along with the reduction of fossil-based EL generation, the market price and renewable-based level will also increase to their first-best levels. So this combination is not completely neutral to renewables promotion and will enhance the renewables share as well.
- The transaction cost of setting an output tax/subsidy may be smaller than emission tax.

This result is also valid if we have a loose emission quota and output tax, instead of emission tax and output tax. Here, the total emission level cannot be changed, but again we can reduce the fossil- and renewable-based EL to their optimum levels. So, we can have some gain in adding the output tax to an inefficient emission tax or quota policy. This finding was not discussed in the previous literature on this topic. It is also possible to push fossil generation further down, by inclusion of an energy efficiency support via a subsidy.

Setting the price or quantity levels different than those obtained for the first-best solutions results in inefficiency. In fact, we have an efficient level of renewable share or output reduction, but it is not necessarily pursued or achieved in practice. For example, it is shown in a study by Fischer, Newell, and Peronas (2012) that the EU 20/20/20 targets fall considerably shorter than the optimum point attainable by an emission cap alone.

But this is the optimum in the context of a normally used social welfare function, which is defined as consumer surplus plus producer surplus minus environmental damage. It may be rational to increase renewables or energy efficiency due to other reasons (e.g. energy security, technology advancement, reducing unemployment, etc.). If we can include these terms in welfare function, we can integrate these targets into this analysis as well. But this way is not pursued normally. It may be because of difficulty and high level of uncertainty in quantifying these terms, also because resulting high levels of tax/subsidy may bring very high and unacceptable transaction cost. So, considering other targets (than just emission control) still remains very important.

Briefly speaking, additional policies may be justifiable when:

- Having additional targets over emission control.
- The combination modify some parameters of the original system in such a way that the optimum point moves closer to the new targets (e.g. lowering the renewable generation cost by R&D subsidy changes the renewables cost function and thus affect the optimum solution).
- The combination compensates for inefficiency of single instrument (like the scenarios discussed in this paper)
- They may have lower transaction cost than implementing single optimum policy
- They may provide for easier tightening of main emission control policy

By the fourth item we mean the high transaction cost of the full emission tax and less transaction cost of an incomplete emission quota plus an output tax/subsidy. By the fifth item we mean the positive effect that is discussed in Gawel, Strunz, and Lehmann (2014). As they say (and show analytically), although renewables support policies will weaken the emission trading system by lowering the allowance price and the abatement costs, they make a tighter emission cap more negotiable, which comes as a result of the bargaining process between regulators and emitters. “In conclusion, RE subsidies might be interpreted as the “political price” to pay for introducing and tightening an emission cap.” (Gawel et al., 2014)

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