Efficiency Gap and Optimal Energy Conservation Incentives

Franz Wirl[*,†]

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Abstract

Energy conservation has been for decades a public objective and is one of the pillars of climate policies (e.g. in the European Union). Distortions leading to an energy efficiency gap justify conservation initiatives but private information renders them much less effective as promised. This conclusion is strengthened if the external costs were internalized: an intervention is only justified for low costs of public funds and large payback gaps. Internalization leads to a nonstandard mechanism design problem because it depends also on aggregate performance; this extension is applicable to other areas whereaggregate (or team) performance matters.

Keywords: energy efficiency gap; payback gap; private information; principal-agent model; mechanism including aggregate performance.

JEL: D62; D86; Q40; Q50.

[*]Corresponding author: University of Vienna, Faculty of Business, Economics and Statistics, Oskar Morgenstern Platz 1, Room 4.635, 1090 Wien, AUSTRIA. Email: franz.wirl@univie.ac.at, Tel: +43 1 4277 38101.

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1 Introduction

Energy efficiency (in the following often only efficiency) has been for decades an objective of public policy interventions. At the beginning and following the Public Utility Regulatory Policy Act of 1978 (PURPA) regulatory and economic efficiency aspects were the raison d'être while the current justification is that energy use is inevitably associated with a number of environmental harms, in particular, global warming. Conservation (i.e., increasing energy efficiency) is important because both, renewable energy and technical solutions (carbon capture and storage, substitute fuels like hydrogen, fusion) lack the scale that conservation may achieve, and those which could (e.g., nuclear and geo-engineering) are questionable. Therefore, it is no surprise that the International Energy Agency (IEA 2014) considers conservation an important source of energy in its own. Increasing energy efficiency is not only seen as an important but also as a 'low cost - no regret' option. The claim of low cost builds on the so called efficiency gap, i.e., consumers bypassing profitable energy efficient appliances. Therefore, conservation appears prominently in all CO2 mitigation strategies and the European Union (EU) 'committed' to a 20% reduction in energy consumption due to higher efficiencies until 2020 (European Commission (2006, 2011)).

Energy conservation programs involve three parties: governments, utilities and consumers (households and firms). The economics literature on conservation emphasizes regulatory aspects - the interactions between regulators and utilities - but tends to neglect consumers and their private information. However, the provision of incentives, rebates, etc. will affect consumer decisions and consumers will respond strategically to incentives.

From the beginning with PURPA to the recent EU energy directive and the introduction of white certificates (in addition to those on CO2 and renewable energy), the following procedure was adopted. First, almost all conservation incentives are linked to energy efficiency improvements. That is, consumers receive a subsidy ranging from the provision of expert advice to full compensation of an efficiency upgrade. Second, the utilities are considered to play a special and helpful role because "energy markets do not operate properly ... utilities can help to overcome these barriers and do so at low cost" according to Hirst (1992). This position is still upheld, e.g. in Bertoldi et al. (2013, p337), "For the residential sector the authors believe that the utilities (mainly the energy suppliers) could be best placed to deliver energy efficiency targets, ...". Some (e.g., Lovins (1985)) even claimed that utilities can 'make gigabucks with negawatts'. These claims led to a wave of utility sponsored conservation programs in the past and recently to the introduction of white certificates in the EU, i.e., conservation mandates imposed on utilities (and large firms). However, the role of utilities as conservation angels is questionable, because 'a butcher is asked to sell fish' according to Ruff (1986). Considering utility sponsored conservation only few papers allow for private information, which is the focus of this paper. Lewis and Sappington (1992) and Chu and Sappington (2012, 2013) account for private information on the part of the utility assuming passive consumers (but Chu and Sappington (2013) accounts for the rebound) while Wirl (1999, 2016) allow for strategic consumer actions.

The need for a conservation program results from an efficiency gap originating from wrong consumer decisions (a market failure) and distorted (too low) energy prices as the external costs are not properly internalized (a policy failure). The objective should be to eliminate this gap directly at the level of consumers and not indirectly through an intermediary like the utility which faces also other and presumably counterproductive incentives. After all, they make their money from selling kWhs. Therefore, it is assumed that a benevolent government designs optimal conservation initiatives facing an efficiency gap due to distortions, private information at the level of consumers, and costs of public funds. Private information as well as one of the distortions are linked to the claim that consumers apply too short payback times when choosing the energy efficiency of an appliance. The second potential distortion is that the external costs of fossil energy are not internalized. The second case of energy prices including all external costs allows to answer whether the payback gap alone justifies an intervention. Assuming that the collected energy taxes are returned to the households leads to a nonstandard mechanism design problem because it is necessary to account for aggregates (here aggregate energy conservation that affects the energy tax revenues). This extension is transferable to other areas, like labor contracts that account for individual but also for team performance.

2 Framework

The external costs of energy consumption (not only of fossil fuels and not only due to environmental damages) are nowadays the major justification for intervening in energy markets. Of course, only market distortions and failures justify interventions like conservation programs and standards which are both part of an EU Directive for 2020 (EED (2012)). In particular, economic agents (consumers, firms, including government agencies and regulators) choose energy inefficient appliances. This misallocation, called efficiency gap, plays a central role in public debates (compare the comprehensive survey Gerarden, Newell and Stavins (2015)) and serves as justification for many policy interventions. A decision maker (consumer, firm) should buy equipment that maximizes the net present value of benefits over expenditures over the whole lifetime of the equipment using the correct discount rate. However, empirical studies since Hausman (1979) find that consumers use too high implicit discount rates when buying appliances.

The following framework accounts for the two major sources of the energy efficiency gap: First, boundedly rational consumers apply too low payback times when choosing the (energy) efficiency of an appliance; this is known as the payback gap. Too short payback times result from consumers using either too high discount rates and/or too short planning horizons. Payback time is private information of an individual, because it is unknowable to all outsiders prior to buying an appliance. Second, consumers base their decisions on energy prices that do not incorporate all external costs. Although also labeled a market failure, it is clearly a failure of politics.

2.1 Energy Demand

The following partial equilibrium analysis is based on the framework introduced in Wirl (1997, 1999). The crucial assumption is that services matter and not kWhs. Service s (e.g., thermal comfort measured by indoor temperature, lighting by lumen-hours, mobility by miles driven, etc.) is the product of the energy efficiency η (expressed in terms of the amount of service s delivered per unit of energy, e.g., miles per gallon gasoline), and energy e:

$$s = e\eta.$$

A consumer's service benefit $u(s)$ satisfies the standard assumptions: increasing, concave and the Inada conditions ensure $s > 0$. Expenditures are for energy, purchased at the unit price p, and for the investment into an appliance depending on its energy efficiency, $K(\eta)$ increasing and convex.

The ex post optimal choice of energy conditional on the ex ante choice of the efficiency η determines the flow of surplus,

$$w(\eta, p) := \max_e [u(e\eta) - ep] \Longrightarrow w_\eta = u'e > 0, \tag{1}$$

with the energy demand satisfying,

$$e = E(\eta, p) : u' = \frac{p}{\eta}. \tag{2}$$

Therefore, higher efficiencies increase the service demand which is known as rebound[1]. Although this effect should be known since Jevons' (1865) famous work on coal it was and is still ignored in most conservation initiatives and their evaluations (e.g., Bertoldi (2011), '90% of the savings delivered via projects submitted to date are of the deemed saving and engineering method variety'). Therefore, the crucial claim that higher efficiencies reduce energy consumption holds iff,

$$E_\eta = -\frac{u' + u''s}{u''\eta^2} < 0 \Longleftrightarrow -\frac{u''s}{u'} > 1 \Longleftrightarrow \frac{\partial \ln E}{\partial \ln p} = -\alpha = \frac{u'}{u''s} > -1.$$

That is, the (absolute) elasticity of marginal utility from energy services is greater than 1. Or equivalently, one must assume that the (short run or ex post) demand for energy (= service) is inelastic, $\alpha < 1$, in order to justify efficiency enhancement programs on environmental grounds. A positive side effect of this rebound is that the gross benefit from saving the last kWh $(-w_\eta/E_\eta)$ exceeds the saving of fuel costs (equal to p),

$$-\frac{w_\eta}{E_\eta} = \frac{p}{1-\alpha}. \tag{3}$$

[1] The analysis is partial equilibrium. Recent and more extensive theoretical discussions are Chan and Gillingham (2015) and Turner (2013) and of course the comprehensive treatment in Sorrell (2007).

Knowing the ex post reaction, a consumer's ex ante choice of the level of energy efficiency maximizes the net present value (NPV) of surplus minus the necessary investment expenditure,

$$\max_{\eta} W := tw(\eta, p) - K(\eta). \tag{4}$$

The parameter $t \in [\underline{t}, \bar{t}]$ denotes the subjective payback time that a consumer demands for an investment in energy efficiency; the upper bound $\bar{t}$ denotes the correct payback time based on the social discount rate and the lifetime of the equipment. Only a consumer can know the parameter t but no one else, not even a powerful government, which, however, knows the (cumulative) distribution function $F(t)$; hence, the mass of consumers is normalized to 1. It is assumed that the implied hazard rate $h = F'/(1-F)$ is monotonically increasing.

Furthermore, it is assumed that the price of energy is unaffected by the conservation program. Therefore, the argument price is suppressed in the following analysis in which it is assumed that the short-run surplus $w(\eta)$ satisfies the inequalities,

$$w' = u'E > 0, \ w'' = E'u' + \alpha u'' E^2 < 0. \tag{5}$$

The arithmetical expressions of these derivatives are derived from the above framework (they follow from differentiating, see Wirl (1997)) but only the signs are used in the following. Of course, it must be assumed that higher efficiencies reduce energy consumption, i.e., $E' < 0$, and thus that the price elasticity is less than 1.

In the absence of incentives (identified by the subscript 0), the ex ante choice of efficiency $\eta_0(t)$ follows from equating the NPV of the marginal benefit to the marginal cost of efficiency,

$$\eta_0(t) : tw' = K' \Longrightarrow \frac{p}{1-\alpha} = -\frac{K'/t}{E'}. \tag{6}$$

Using (3) allows for the simple linkage between marginal investment costs, the price elasticity α and the payback time t: the annuity of the necessary expenditure to conserve the last kWh (the rhs after the implication in (6) and based on the subjective payback time) must equal the benefit from conserving this incremental kWh. This benefit is given by the price-elasticity ratio in (3) and it exceeds the value of the conserved kWh due to the rebound effect. Substituting the laissez faire choice (6) into (4) determines the corresponding NPV of consumer surplus,

$$U_0(t) := tw(\eta_0) - K(\eta_0). \tag{7}$$

Any conservation program must guarantee the consumer the reservation price U_0, which is type dependent and increasing, $\dot{U}_0 = w > 0$, due to the envelope theorem and economically because a larger t increases the net present value of the benefit of more efficient appliances.

Remark 1: *The parameter t may reflect or include other aspects affecting a consumer's willingness to pay for efficiency. This includes behavioral biases resulting from the lack of salience, split incentives, etc. that are addressed in Gerard, Newell and Stavins (2015) and loss aversion that is added in Greene (2011).*

2.2 Government (benevolent and paternalistic)

A benevolent government maximizes the expected (with respect to the distribution of the types t) NPV of consumer plus producer surplus accounting for all costs by designing a conservation program, which consists of efficiencies $\eta(t) \geq \eta_0(t)$ backed up by subsidies $z(t)$. Assuming that energy production has constant marginal costs c that determine the (market) price p, the producer surplus vanishes and without loss in generality I normalize,

$$p = c = 1. \tag{8}$$

The government is paternalistic, because it uses the socially correct payback time $\bar{t}$ to determine the NPV. Costs beyond energy production arise from externalities and for public funds. d denotes the (constant) marginal external costs from energy consumption and δ denotes the deadweight loss associated with subsidies, i.e., the loss associated with any \$ dollar transferred; Wirl (1999) studies different opportunity costs of a paternalistic principal within a 'family'.

2.3 Example

For illustrative purposes and for concreteness, the following specification is used: CRRA utilities (θ is the absolute elasticity of marginal utility),

$$u = u_0 - As^{-(\theta-1)},\ \theta > 1, \tag{9}$$

quadratic investment cost,

$$K(\eta) = \frac{k}{2}\eta^2 \tag{10}$$

and uniformly distributed types with the hazard rate,

$$h(t) = \frac{1}{\bar{t} - t}. \tag{11}$$

Therefore, the ex post energy demand implied by (2) is,

$$E(\eta, p) = (A(\theta-1))^{\frac{1}{\theta}} p^{-\alpha} \eta^{-(1-\alpha)},\ \alpha := \frac{1}{\theta},$$

and (6) implies for the ex ante choice of efficiency,

$$\eta_0(t) = (A(\theta-1))^{\frac{1}{3\theta-1}} \left(\frac{t}{k}\right)^{\frac{\theta}{3\theta-1}} p^{\frac{\theta-1}{3\theta-1}},$$

which is increasing and concave in type and price and decreasing and convex in costs. In fact, all solutions can be given in closed analytical form (available upon request) but are suppressed because they are cumbersome.

3 Optimal conservation incentives

3.1 External costs are not internalized

A benevolent government maximizes the social surplus including all external costs. However, many governments find internalizing the external costs politically difficult if not impossible. Instead they offer conservation incentives, i.e., subsidy z for choosing a higher efficiency $\eta \geq \eta_0$. In this case, $p = c$ such that the external costs are not internalized, a benevolent and paternalistic government maximizes the expected social surplus,

$$\max_{\{\eta(t)\geq\eta_0(t),\, z(t)\}} \int_{\underline{t}}^{\bar{t}} \bar{t} \left\{ \left[w\left(\eta\left(t\right)\right) - dE\left(\eta\left(t\right)\right) \right] - K\left(\eta\left(t\right)\right) - \delta z\left(t\right) \right\} dF\left(t\right). \tag{12}$$

The expectation is take within respect to the agents private information. The social surplus consists of the NPV of consumer surplus (w) plus producer surplus (which vanishes) minus the external costs (dE); from this, one must subtract the investment costs and the deadweight loss associated with the transfer of subsidies. Paternalism means that the government uses instead of the agents subjective payback time the one based on the social discount rate and the lifetime of equipment.

A fully informed government facing no deadweight loss of transfer, i.e., $\delta = 0$, can ask everyone to choose the efficiency,

$$\eta^* : w' = \frac{K'}{\bar{t}} + dE' \Longrightarrow -\frac{w'}{E'} + d = -\frac{K'/\bar{t}}{E'}; \tag{13}$$

i.e., the (annual) costs for conserving a kWh (the term on the rhs of the implication shown in (13)) must equal the marginal consumer surplus from consuming one kWh less plus the marginal reduction of damages. Any deviation from η^* may be considered an efficiency gap. This policy is inefficient for the realistic setting of private information and costs of public funds, because the voluntary implementation of η^* requires high and constant subsidies since also the least efficient type must benefit,

$$z^* = [\underline{t}w(\eta_0(\underline{t})) - K(\eta_0(\underline{t}))] - [\underline{t}w(\eta^*) - K(\eta^*)]\,. \tag{14}$$

Accounting for private information, the maximization of the government's objective (12) is subject to two constraints. The first is incentive compatibility based on the revelation principle, i.e., an optimal contract 'forces' a consumer to report the true t instead of another type $\hat{t}$,

$$U(t) := U(t,t) > U\left(\hat{t},t\right) := tw\left(\eta\left(\hat{t}\right)\right) - K\left(\eta\left(\hat{t}\right)\right) + z\left(\hat{t}\right),\ \forall t,\hat{t} \in [\underline{t},\bar{t}] \tag{15}$$

and the second is individual rationality, $U(t) \geq U_0(t)\ \ \forall t \in [\underline{t},\bar{t}]$, i.e., no consumer must lose.

Substituting the necessary subsidy,

$$z = U + K - tw, \tag{16}$$

into (12) and using the first order optimality condition from the truth telling property (15), the following optimal control problem results (suppressing the argument type),

$$\max_{\eta \geq \eta_0} \int_{\underline{t}}^{\bar{t}} \bar{t}\left[w(\eta) - dE(\eta)\right] - K(\eta) + \delta\left[tw(\eta) - K(\eta) - U\right] dF, \tag{17}$$

$$\dot{U} = w(\eta)\,, \tag{18}$$

$$U \geq U_0 = tw(\eta_0) - K(\eta_0)\ \ \forall t \in [\underline{t},\bar{t}]\,. \tag{19}$$

Defining the Hamiltonian (using $f := F'$ to denote the density),

$$H := \{\bar{t}\left[w(\eta) - dE(\eta)\right] - K(\eta) + \delta\left[tw(\eta) - K(\eta) - U\right]\} f + \lambda w(\eta)\,, \tag{20}$$

the first order optimality conditions are,

$$H_\eta = \{\bar{t}\,[w' - dE'] - K' + \delta\,[tw' - K']\}\, f + \lambda w' = 0, \tag{21}$$

$$\dot{\lambda} = -H_U = \delta f,\ \lambda(\bar{t}) = 0 \Longrightarrow \lambda(t) = \delta(F-1), \tag{22}$$

if the individual rationality constraint (19) is ignored and the costate (λ) differential equation (22) is correspondingly integrated. Hence, the following condition must hold,

$$Tw' = (1+\delta)\,K' + \bar{t}dE', \tag{23}$$

for interior solutions ($U > U_0$, i.e. for all participating consumers). Compared to the consumer's own choice (6), the left hand side (lhs) in (23) uses instead of t,

$$T(t,\delta) := \bar{t} + \delta\left(t - \frac{1}{h}\right),\ \frac{\partial T}{\partial t} = \delta + \frac{\delta \dot{h}}{h^2} > 0, \tag{24}$$

in order to compute a consumer's net present value of marginal benefit. This term T is increasing with respect to the type due to the assumption of an increasing hazard rate. On the right side (rhs) of (23), the investment costs are inflated by the costs of public funds while the NPV of the marginal damage is subtracted using the government's payback time $\bar{t}$. Rewriting (23) for a better comparison with the laissez faire outcome (6),

$$w' = \frac{K'}{\frac{T}{1+\delta}} + \frac{\bar{t}}{T}dE', \tag{25}$$

implies that $\eta(t) > \eta_0(t)$, iff the rhs in (25) is less than the annuity used by a consumer (K'/t). That is, the government applies a modified payback time

$$\frac{T}{1+\delta} \tag{26}$$

to investments in efficiencies instead of $\bar{t}$ due to the costs of public funds and the agency costs captured by the hazard rate as a part of T. The following Lemma 1 summarizes some properties of T and of the endogenous and type dependent payback time (26) applied by the government; the implications for the uniform distribution are included with reference to the example from 2.3 and the following figures.

Lemma 1 *(i) The adjusted payback time (26) is increasing with respect to types and reaches the correct payback time at the most efficient type,*

$$\frac{T(\bar{t},\delta)}{1+\delta} = \bar{t} \Longrightarrow \frac{T}{1+\delta} < \bar{t} \text{ for } t < \bar{t}.$$

It exceeds the consumer's payback time, iff

$$\frac{T}{1+\delta} > t \Longleftrightarrow \bar{t} - t \geq \frac{\delta}{h(t)},$$

which implies for the uniform distribution

$$t < \frac{T}{1+\delta} \Longleftrightarrow \delta < 1$$

and equality for $\delta = 1$.

(ii) Higher costs of public funds lower the adjusted payback time,

$$\frac{\partial}{\partial\delta}\left(\frac{T}{1+\delta}\right) = -\frac{\bar{t} - t + 1/h}{(1+\delta)^2} < 0,$$

and can turn it (as well as T) negative for high costs of public funds since

$$\lim_{\delta\to\infty}\frac{T}{1+\delta} = \lim_{\delta\to\infty}\frac{\bar{t}/\delta + (t - 1/h(t))}{1/\delta + 1} = (t - 1/h(t))$$

and low types; in particular, for the uniform distribution,

$$\frac{T}{1+\delta} < 0 \Longleftrightarrow t < \frac{\bar{t}}{2} \wedge \delta > \frac{\bar{t}}{\bar{t} - 2t},$$

which jointly imply, $\delta > 1$.

(iii) $\bar{t}/T$ declines due to (24) and reaches at the upper bound,

$$\frac{\bar{t}}{T(\bar{t},\delta)} = \frac{1}{1+\delta} < 1,$$

but can be larger than 1 *for small types, iff* $ht < 1$; *this implies for the uniform distribution* $t < \bar{t}/2$ *(and thus* $\underline{t} < \bar{t}/2$*).*

All statements follow more or less directly, e.g.,

$$\frac{T}{1+\delta} \geq t \Longleftrightarrow \bar{t} + \delta\left(t - \frac{1}{h}\right) > t\left(1+\delta\right) \Longleftrightarrow \bar{t} - \underline{t} \geq \frac{\delta}{h\left(t\right)},$$

and thus for the uniform distribution, iff $1 \geq \delta$, or the last statement,

$$\frac{\bar{t}}{T} = \frac{\bar{t}}{\bar{t} + \delta\left(1 - \frac{1}{h}\right)} > 1 \Longleftrightarrow 0 > \left(t - \frac{1}{h}\right) \overset{F \text{ uniform}}{\Longrightarrow} 2t - \bar{t} < 0.$$

Applying Lemma 1 allows to characterize the optimal conservation program.

Proposition 1 *Given the two distortions - efficiency gap and external costs - and not too high costs of public funds (*$\delta < 1$ *is sufficient for the uniform distribution) then it is optimal for the government to subsidize energy efficiency upgrades for all,* $\eta\left(t\right) > \eta_0\left(t\right) \forall t$*. The prescription* $\eta\left(t\right)$ *is based on the trade off in (25), which can be written in terms of one kWh:*

$$-\frac{1+\delta}{T}\frac{K'}{E'} = -\frac{w'}{E'} + \frac{\bar{t}}{T}d. \tag{27}$$

That is, the annuity (based on the payback time (26)) of investment in energy efficiency that reduces energy consumption by one additional kWh (a 'negawatt') is equated to the marginal consumer surplus from this reduction of energy consumption by one kWh ($-w'/E'$ *given by the price elasticity ratio in (3)) and the associated reduction in external costs.*
A consequence of the trade-off in (27) is that higher types are asked to choose higher efficiencies (thereby satisfying the monotonicity requirement, $\dot{\eta} > 0$*) and receive larger subsidies.*

To see that $\dot{\eta} > 0$, I modify (23) into

$$w' = \frac{\bar{t}}{T}\left(K'\left(1+\delta\right) + \bar{t}E'\right) > 0$$

and the rhs must be positive for any $\eta > 0$. The rhs is lowered for higher types because $\bar{t}/T$ is declining according to Lemma 1. Therefore, the unaffected and declining lhs must cut the lowered and increasing rhs at a higher level of η.

The determination of the subsidies according to (16) requires to integrate the IC-constraint yielding,

$$z(t) = \int_{\underline{t}}^{t} w(\eta(z))\, dz + U_0(\underline{t}) + K(\eta(t)) - tw(\eta(t)).$$

Hence, the subsidies increase since

$$\dot{z} = w + K'\dot{\eta} - tw'\dot{\eta} - w = -(tw' - K')\dot{\eta} > 0$$

and $tw' < K'$ for $\eta \geq \eta_0$ and $\dot{\eta} > 0$. QED.

While the payback time for the investment decision is reduced in (27) from $\bar{t}$ to (26) due to the costs of public funds and private information, the external costs are scaled by $\bar{t}/T > 1/(1+\delta)$ and thus correctly accounted for according to (23). Therefore, the external costs are disproportionately reflected in the trade-off (27) and this effect is larger for low than for high types (since $\bar{t}/T$ is declining). The standard η^* from (13) is too ambitious even for the most efficient type and results only if transfers are costless, $\delta = 0 \Longrightarrow T = \bar{t}$. In the opposite situation - raising subsidies has high costs - only the lack of internalization may justify conservation, more precisely:

Corollary 1: *Assuming that the types are uniformly distributed and high cost of public funds, $\delta \geq 1$, then only the policy failure of not internalizing the external costs can justify a conservation program but not the consumer's payback gap.*

This claim follows immediately from (23) and Lemma 1 as $\delta > 1$ implies $t > T/(1+\delta)$ for the uniform distribution and this lower payback time of the government yields an efficiency target below the consumer's if no external costs arise (i.e., if $d = 0$); the consequences of internalization will be explored in the next subsection.

Fig. 1 shows the details of such a conservation program for an example assuming: a price elasticity of $\alpha = 1/3$ (thus an intertemporal elasticity of substitution of $\theta = 3$), external costs equal to the production costs, $d = 1$, a large variation of payback times, $t \in [2, 10]$, and $k = 1$ as investment cost parameter. The figure at the top left hand side compares the prescribed efficiencies with the laissez faire outcomes and the ideal standard η^*, the figure at the top right hand side shows the resulting levels of energy consumption and the figure at the bottom left hand side shows the necessary subsidies; all this plots have the types t as abscissa. The figure at the bottom right hand side shows how subsidies depend on efficiencies.

The first observation is that the efficiency gap based on η^* cannot be closed and remains large even for an optimal program run by a benevolent government. More precisely, only the part indicated by $\Delta\eta$ of the entire efficiency gap (= area between η^* and η_0) should be closed. There are also two unconventional properties for a mechanism design problem: First, the concavity of the agent's subsidy with respect to type and efficiency, as usually more efficient types and higher outputs (here the choice of energy efficiency) are typically rewarded disproportionately. The usual convexity applies, however, to incremental efficiency and induced energy conservation ($\Delta\eta$ an Δe shown in Fig. 1 are declining yet subsidies increase with respect to types). Second, the government may lose from high types as the costs of their subsidies exceed their gains in terms of incremental energy efficiency improvement (see Fig. 2). However, the program increases the aggregate social surplus by construction.

[Insert Figs. 1 & 2 approximately here]

3.2 External costs are internalized

The conservation initiative derived above has two potential roots: the price distortion due to not charging for the external costs and the payback gap. Since the policy failure of too low energy prices is in principle easy to correct (albeit not necessarily in the real world of politics), one may ask whether the payback gap alone justifies conservation initiatives. Therefore, it is assumed that a Pigouvian tax, $\tau = d$, is levied on energy to change consumer behavior but not to raise tax revenues; this is known as revenue neutral tax reform. As a consequence, consumers have to pay the price $(c + d)$ but are reimbursed for the average tax payment by lump sum transfers. This policy does not affect the price at the power gate: it is still identical to the constant marginal production costs c such that the producer surplus vanishes again. Using tildes to identify variables in this scenario in which the energy price internalizes all the external costs,

$$\tilde{w}(\eta) := \max_{e} [u(e\eta) - (c + d)e] \Longrightarrow e = \tilde{E}(\eta) : u'\eta = c + d, \qquad (28)$$

is a consumer's surplus if paying the higher price. Clearly, $\tilde{w}(\eta) < w(\eta)$, but $\tilde{w}'(\eta) > w'(\eta)$, i.e., higher energy prices increase the marginal consumer surplus from higher efficiencies due to (5). Therefore, the corresponding choice of efficiency ($\tilde{\eta}_0$) exceeds the one in the absence of internalizing the external costs:

$$\eta_0(t) < \tilde{\eta}_0(t) : t\tilde{w}' - K' = 0. \qquad (29)$$

As a consequence, energy consumption is reduced directly due to a higher price of energy and indirectly through a higher efficiency. In fact, the unincentivized choices of efficiency may exceed the subsidized ones from the previous section. This means that the simple policy of internalizing the external costs may trigger more conservation than the much more complex and costly conservation program characterized in Proposition 1, at least for high types.

Proposition 2 *If w' is convex with respect to the price of energy (which holds for CRRA utility (9)), then $\tilde{\eta}_0(\bar{t}) > \eta(\bar{t})$. That is, the unsubsidized choices of efficiency given internalization of the external costs exceed the subsidized ones but absent internalization (characterized in Proposition1) even at low costs of public funds (δ small), at least for t close to $\bar{t}$.*

Proof: convexity of w_η (both arguments, efficiency and price, are indicated) with respect to the price (either equal to c or $c+d$) implies,

$$\tilde{w}' = w_\eta(\eta, c+d) \geq w_\eta(\eta, c) + w_{\eta p}(\eta, c)\, d = w_\eta(\eta, c) - dE_\eta(\eta, c),$$

because $w_{\eta p} = -E_\eta$ from (5). At $t = \bar{t}$ and applying Lemma 1 yields the claim,

$$\tilde{w}' \geq w' - dE' > w' - \frac{d}{1+\delta}E' = w' - \frac{\bar{t}}{T}dE',$$

at least for $\bar{t}/T < 1$ and thus for sure for $t \to \bar{t}$, i.e., the consumer's marginal benefit from higher efficiency under energy taxes exceeds its counterpart if energy is not taxed and the reduction in marginal damage is added. The assumption of convexity holds at least for the specification (9) since

$$\frac{\partial^2 w'}{\partial p^2} = \frac{\partial w_{\eta p}}{\partial p} = \frac{\partial}{\partial p}(-E') > 0. \text{ QED.}$$

Since the benevolent government introduces the tax only to change consumer behavior and not to increase its tax revenues, they are returned to consumers as lump sum. Of course, in order to retain the tax incentive of lowering energy consumption, the lump sum transfer must be independent of individual consumption and thus, is based on the aggregate energy consumption (more precisely, the expected value = total energy consumption because the mass of consumers is normalized to 1),

$$\bar{e} := \int_{\underline{t}}^{\bar{t}} \tilde{E}\left(\tilde{\eta}\left(t\right)\right) dF\left(t\right).$$

The objective of a benevolent government is as above. It consists of the consumer surplus (after reimbursement of taxes and assuming that this transfer bears no deadweight loss[2]),

$$\bar{t}\left(\tilde{w}\left(\eta\right) + \bar{e}d\right) - K\left(\eta\right),$$

the producer surplus (which vanishes), minus the external costs,

$$\bar{t}d\int_{\underline{t}}^{\bar{t}} \tilde{E}\left(\eta\left(t\right)\right) dF\left(t\right) = \bar{t}d\bar{e},$$

which cancel the reimbursement of the tax. Summarizing, the government

$$\max_{\{\tilde{\eta}(t)\geq\tilde{\eta}_0(t),\, \tilde{z}(t)\}} \int_{\underline{t}}^{\bar{t}} \left\{\bar{t}\tilde{w}\left(\tilde{\eta}\left(t\right)\right) - K\left(\tilde{\eta}\left(t\right)\right) - \delta\tilde{z}\left(t\right)\right\} dF\left(t\right), \tag{30}$$

subject to

$$U\left(t\right) \,:\, = U\left(t,t\right) > U\left(\hat{t},t\right) := t\left[\tilde{w}\left(\tilde{\eta}\left(\hat{t}\right)\right) + \bar{e}d\right] - K\left(\tilde{\eta}\left(\hat{t}\right)\right) + \tilde{z}\left(\hat{t}\right), \tag{31}$$

$$U\left(t\right) \geq t\left[w\left(\tilde{\eta}_0\left(t\right)\right) + \bar{e}d\right] - K\left(\tilde{\eta}_0\left(t\right)\right) \;\forall t \in \left[\underline{t}, \bar{t}\right]. \tag{32}$$

Note that tildes are suppressed for U and U_0 (and also for H and λ in the Appendix) as there seems to be no danger of confusion with the analysis in the previous subsection of no internalization. Although the tax revenues and their reimbursements are not part of the objective, they

[2] Otherwiese only the fraction $(1 - \delta)$ can be returned.

appear in the two constraints above. Each consumer must receive the same reimbursement ($\bar{e}d$) independent of the own action and therefore also whether participating or not. Hence it becomes part of the agent's reservation price and also of the incentive compatibility constraint. However, the level of reimbursement includes the consequences of the incentive scheme on the aggregate energy demand, i.e., by how much the incentivized upgrades of efficiencies lower total energy consumption.

Substituting for the subsidies and suppressing the argument type, the government must solve,

$$\max_{\{\tilde{\eta}\geq\tilde{\eta}_0\}} \int_{\underline{t}}^{\bar{t}} \left\{\bar{t}\tilde{w} - K + \delta\left[t\left(\tilde{w} + \bar{e}d\right) - K - U\right]\right\} dF, \tag{33}$$

accounting for incentive compatibility,

$$\dot{U} = \tilde{w} + \bar{e}d = \tilde{w} + d\int_{\underline{t}}^{\bar{t}} \tilde{E}\left(\tilde{\eta}\left(s\right)\right) dF\left(s\right), \tag{34}$$

and individual rationality,

$$U\left(t\right) \geq U_0 := t\left[\tilde{w}\left(\tilde{\eta}_0\left(t\right)\right) + d\int_{\underline{t}}^{\bar{t}} \tilde{E}\left(\tilde{\eta}\left(s\right)\right) dF\left(s\right)\right] - K\left(\tilde{\eta}_0\left(t\right)\right). \tag{35}$$

Observe that the tax revenues ($\bar{e}d$) appear now in the objective (33) although they cancel against the damage in (30) and in the incentive compatibility (34) and individual rationality (35) constraints. This nonstandard optimal control problem with an integro-differential equation (34) and a double integral in (33) can be rearranged as a standard optimal control problem but with two more states. The derivation and the analysis of this modified control problem is relegated to the Appendix but the results are summarized below.

Proposition 3 *Given complete internalization of the external costs, the* *optimal prescriptions of energy efficiencies are*

$$\tilde{\eta}(t) = \max\left\{\tilde{\eta}^i(t), \tilde{\eta}_0(t)\right\}, \tag{36}$$

where $\tilde{\eta}^i$ *denotes the interior solution, which follows from the trade off,*

$$\tilde{\eta}^i : \tilde{w}' = \frac{K'}{\frac{T}{1+\delta}} - \frac{E_t}{T}\delta d\tilde{E}', \tag{37}$$

where E_t *denotes the average type. Since something is added on the rhs of (37) to the marginal (adjusted annuity of the) investment costs,* $\tilde{\eta}^i(\bar{t}) < \tilde{\eta}_0(\bar{t})$ *and also for* $t \to \bar{t}$ *due to continuity. Therefore, the constraint in (36) is binding and* $\tilde{\eta}(t) = \tilde{\eta}_0(t)$ *for* t *close to* $\bar{t}$.
High deadweight losses render a conservation program inefficient, in the case of the uniform distribution already for $\delta \geq 1$ *no matter how large the payback gap is.*

Proof: The interior solution (37) is derived in the Appendix. The lhs in (37) is the consumer's marginal surplus as in (25) but based on a higher energy price and is thus higher, $\tilde{w}' > w' \forall \eta$. The costs, on the rhs of (37), consist of: (i) the annuity (adjusted for agents' information rents and the deadweight loss from transfers) of the marginal investment costs, which is identical to its counterpart in (25) and thus as in Proposition 1; (ii) a term is added to the cost side in rhs in (37) but subtracted in (25) leading to the trade-off (27) in Proposition 1. Therefore, considering the most efficient type $t = \bar{t}$, the interior solution $\tilde{\eta}^i$ requires,

$$\tilde{w}' > \tilde{w}' + \frac{E_t\delta}{1+\delta}d\tilde{E}' = \frac{K'}{\bar{t}},$$

which falls short of the own and unsubsidized choice $\tilde{\eta}_0(\bar{t})$ from $\tilde{w}' = K'/\bar{t}$! The economic intuition behind $\tilde{\eta}^i < \tilde{\eta}_0$ is that the efficient type $\bar{t}$ already chooses the first best efficiency if the price of energy includes all external costs. Incentive compatibility, i.e., to deter cheating, also requires subsidies for these high types. However, the government faces a deadweight loss and thus wants to lower subsidies. The only way is to reduce its demand on efficiency as this reduces the growth in the agent's payoff (see (34)) and the necessary transfer (at least, if the impact on the level of reimbursements is ignored). Of course, it cannot make sense to pay an agent for lowering efficiency below his own choice. Since $\tilde{\eta}$ is monotonically increasing (the rhs in (37) decreases with respect to t), relatively efficient types with $\tilde{\eta}^i < \tilde{\eta}_0$ have an incentive to report a higher type, more precisely, $\hat{t} > t$ such that $\tilde{\eta}\left(\hat{t}\right) = \tilde{\eta}_0\left(t\right)$. This allows for the individually efficient choice and for a higher subsidy. Of course, types t sufficiently close to $\bar{t}$ will not find a pairing match and can only pretend $\hat{t} = \bar{t}$ and choose $\tilde{\eta}\left(\bar{t}\right)$ or even the higher $\tilde{\eta}_0\left(t\right)$. A consequence of the above calculation is that the amount of subsidies paid are higher than anticipated. Therefore the only sensible and incentive compatible mechanism is to extend the interior solution by the unsubsidized choice and to pay the incentive compatible subsidies. This leads to (36).

The proof of the last claim in Proposition 3, no conservation program is optimal for high deadweight losses, is straightforward. Consider the case of $\delta = 1$ and the uniform distribution, then $t = T/\left(1+\delta\right)$ such that the rhs is less than the consumer's own choice based on K'/t and thus for all t, no matter how small. QED.

The above comparison of the different trade-offs with and without internalization does not allow for an immediate comparison of the resulting efficiencies. The reason is that the lhs (recall $\tilde{w}' > w'$) as well as the rhs are larger than in (25). However, Proposition 2 suggests that internalization will lead to higher efficiencies and this is confirmed at least in the following examples. Fig. 3 shows how internalizing the external costs affects energy efficiency based on the example already used in Figs. 1-2. The implication of Proposition 2, internalization triggers higher efficiency (and even more energy conservation), holds not only for high types but for all types $t > 4.5$ and thus for more than 2/3; see the chart at the lhs of Fig. 3. Moreover, the ultimately crucial target, energy consumption, is substantially improved (i.e., reduced) for all types (rhs in Fig. 3). Since the payback gap is now the only reason for an intervention, the incremental efficiency improvement achieved by the optimal program is much less and zero at high types. Increasing the deadweight loss from 1/2 to 4/5, then $\tilde{\eta}^i < \tilde{\eta}_0$ even for the least efficient type, $\underline{t} = 2$. In this case, $\delta \geq 4/5$, no program makes sense in spite of very large payback gaps. Fig. 4 shows the sensitivity how the set of types that are induced to upgrade their efficiency changes with respect to model parameters. More precisely, Fig. 4 plots

$$t^{crit} : \tilde{\eta}^i (t) = \tilde{\eta}_0 (t)$$

such that only the types $t < t^{crit}$ will upgrade their efficiency. As expected and mentioned above, the costs of public funds are crucial and very sensitive beyond 1/2 (the reference case). External costs (because internalized) as well as the elasticity parameter are much less important, while reducing the agents' myopia (i.e., increasing $\underline{t}$) renders conservation programs much less effective and possibly entirely useless.

[Insert Fig. 3 and 4 approximately here]

4 Discussion

The upshot of the above analysis is that the efficiency gap based on distortions (a payback gap and too low energy prices not covering all external costs) provides a reason for correction even under private information and deadweight losses. However, it is never optimal to close the gap entirely. The reason for intervention is severely reduced if external costs are included in the price of energy and entirely eliminated for high costs of public funds, which is presumably the case in the EU with governments taking a share around and above 50%. Subsidies flow disproportionately to those who already use reasonable payback times and who will upgrade only little (and nothing at all if external costs were internalized). This is a consequence of private information as the efficient types must benefit from reporting their higher efficiency type. It also makes economic sense for the government, because giving money to people characterized by low payback times is waste from the perspective of conserving energy.

The above analysis of a benevolent government choosing efficient policies sketches the best what conservation programs can achieve. Introducing intermediaries like the utilities in the past and via white certificates nowadays in the EU can only make matters worse and also more complicated (compare Wirl (2015)). Unfortunately, past and current energy policies provide little hope that things will turn efficient. And there are precedents of inefficiently designed policies such as Joint Implementation and the Clean Development Mechanism that lead to cheating and even to fraud which anyone familiar with private information could tell ahead (Wirl, Huber and Walker (1998)). Or consider the involvement of utilities in conservation in the past and at present; or the hefty subsidies paid for electric cars (€ 4000 in Germany, even higher ones in Austria, Energiemagazin (2017)), although each additional electricity requirement, here due to an electric car, is 100% fossil fuel based (maybe except for Norway and a few sunny and windy days in Austria).

Since the ultimate objective is to reduce energy consumption it seems awkward that all conservation programs choose the indirect way of subsidizing efficiencies, in particular in light of the rebound effect. Incentivizing reductions in energy consumption directly offers control over the rebound to the government and thus seems superior. However, there are serious practical obstacles. If announced it creates incentives for 'negawatt-mills', i.e., artificially high levels of energy consumption during a reference period in order to benefit in the future from the subsidies for 'reducing' energy consumption. And how to hand out the subsidies, lump sum or annually? Subsidies linked to efficiencies have a number of advantages in this respect. First, they involve just one interaction: money is paid once for the efficiency upgrade lowering energy consumption in all following years. Second, impatient consumers prefer a lump sum to annual payments, which lowers the principal's necessary expenditure on a net present value basis. Therefore, offering a lump sum instead of annual payments is also preferable for incentives linked to reductions of energy consumption. The reason is that consumers undervalue the NPV of annual transfers (ta) compared to the government paying it $(\bar{t}a)$; and this difference is substantial for low types as empirically reported payback times can vary by a wide margin, e.g., between 2 and 10 years for a refrigerator. The alternative, to pay a lump sum at the beginning, requires a consumer's commitment to not exceed the agreed target, which seems impossible in practice, e.g., in a year with a cold winter, a change in family size, mobility, etc. Therefore, and in line with practice, the paper considered only programs targeting energy efficiency. The extension to programs tied to energy consumption is left for future research.

5 Concluding remarks

Energy efficiency investments are promoted as one of the silver bullets to mitigate climate change and it is claimed that they can do so at no cost. This claim will not materialize for a number of reasons. First, due to the rebound effect, which is substantial in all services with high energy demands, i.e., mobility, heating, air conditioning, and lighting; large rebound effects are reported in Frondel, Peters and Vance (2008) for driving and in Saunders (2015) for many services over the course of history. Second, all conservation initiatives face private information, because no outsider can observe or even guess someone's willingness to pay for efficiency that depends on an individual's psychology like discounting and patience, personal plans (to move or not affects the willingness to pay for efficient household appliances like a washing machine) and expectations. These obstacles render regulation questionable and lower the scope of conservation initiatives even assuming a benevolent government and substantial market distortions (although the lack of internalizing external costs is not a market but a policy failure).

Under these idealistic premises of a benevolent and paternalistic government, conservation programs allow to narrow the so much discussed efficiency gap but fail to close it by far. The achieved efficiency improvements come at a high price, because the bulk of the subsidies must go those who upgrade their efficiency only little. The prospects of a conservation program turn even worse if the government exercised its option of internalizing the external cost: First, subsidies must be paid to high types without increasing efficiency at all. Second, no intervention is optimal for high costs of public funds (a likely description in high tax Europe) even if the payback gap is large. Adding the high administrative costs that are unavoidable if dealing with many small consumers like households and the less than perfect record of governments' past energy policies renders such initiatives questionable. However, a policy should be judged by its results and not its intentions (© Milton Friedman) and I think that this emphasis on intentions is a major fault of the many environmental policies and in particular in the case of energy conservation.

6 Appendix: Proof of Proposition 3

Introducing additional states allows to transfer the nonstandard optimal control problem (33) subject to (35) and (34) into a standard one. The first additional state is,

$$\dot{\Sigma} = \tilde{E}f,\ \Sigma\left(\underline{t}\right) = 0, \tag{38}$$

which aggregates the energy demand up to type t. The second additional state,

$$\dot{x} = 0,\ x\left(\bar{t}\right) = \Sigma\left(\bar{t}\right), \tag{39}$$

replaces the functional $\bar{e}$ in the state differential equation. The introduction of the state Σ allows to move $\bar{e}$ out from the integrand into a 'scrap' value,

$$\int_{\underline{t}}^{\bar{t}} \delta t d\bar{e} dF = \delta d\Sigma\left(\bar{t}\right) \int_{\underline{t}}^{\bar{t}} t dF = \delta d\Sigma\left(\bar{t}\right) E_t, \tag{40}$$

which is the terminal value of the newly defined state Σ measuring aggregate energy demand times the costs of public funds, the damage parameter (equal to the tax) and the average type (E_t). Summarizing, the following control problem results,

$$\max_{\{\tilde{\eta} \geq \tilde{\eta}_0\}} \int_{\underline{t}}^{\bar{t}} \left\{\bar{t}\tilde{w} - K + \delta\left[t\tilde{w} - K - U\right]\right\} f dt + \delta d E_t \Sigma\left(\bar{t}\right) \tag{41}$$

The 'dynamic' constraints are,

$$\dot{U} = \tilde{w} + dx,\ U \geq U_0, \tag{42}$$

$$\dot{\Sigma} = \tilde{E}f,\ \Sigma\left(\underline{t}\right) = 0, \tag{43}$$

$$\dot{x} = 0,\ x\left(\bar{t}\right) = \Sigma\left(\bar{t}\right). \tag{44}$$

Defining the Hamiltonian,

$$H = \left\{\bar{t}\tilde{w} - K + \delta\left[t\tilde{w} - K - U\right]\right\} f + \lambda\left(\tilde{w} + dx\right) + \mu\tilde{E}f,$$

the first order conditions are: the Hamiltonian maximizing condition,

$$\left\{\bar{t}\tilde{w}' - K' + \delta\left[t\tilde{w}' - K'\right] + \mu\tilde{E}'\right\} f + \lambda\tilde{w}' = 0,$$

and the costate differential equations assuming that the state constraint, $U \geq U_0$, is not binding,

$$\begin{aligned}
&\dot{\lambda} = -H_U = \delta f,\ \lambda\left(\bar{t}\right) = 0 \Longrightarrow \lambda\left(t\right) = \delta\left(F - 1\right), \\
&\dot{\mu} = -H_\Sigma = 0,\ \mu\left(\bar{t}\right) = \delta dE_t \Longrightarrow \mu\left(t\right) = \delta dE_t, \\
&\dot{\nu} = -H_x = -d\lambda,\ \nu\left(\bar{t}\right)\ \text{fixed}.
\end{aligned}$$

Rearranging, combining and using the definition (24),

$$\bar{t}\tilde{w}' - K' + \delta\left[t\tilde{w}' - K'\right] + \delta dE_t\tilde{E}' = \frac{\delta\tilde{w}'}{h} \Longrightarrow \tilde{w}' = \frac{K'}{\frac{T}{1+\delta}} - \frac{E_t}{T}\delta d\tilde{E}',$$

yield the trade-off reported in Proposition 3 and in equation (37).

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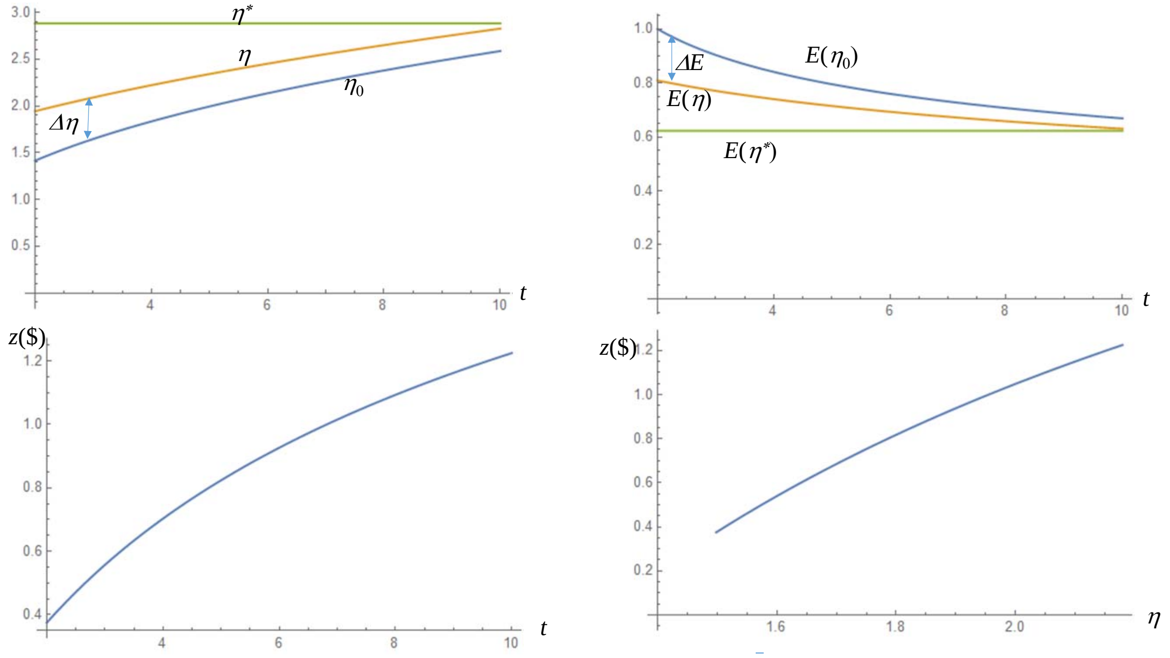

Fig. 1: Optimal conservation program, $A = 1$, $\theta = 3$, $\underline{t} = 2$, $t = 10$, $\delta = ½$, $d = 1$, $u_0 = 22^{1/4}$

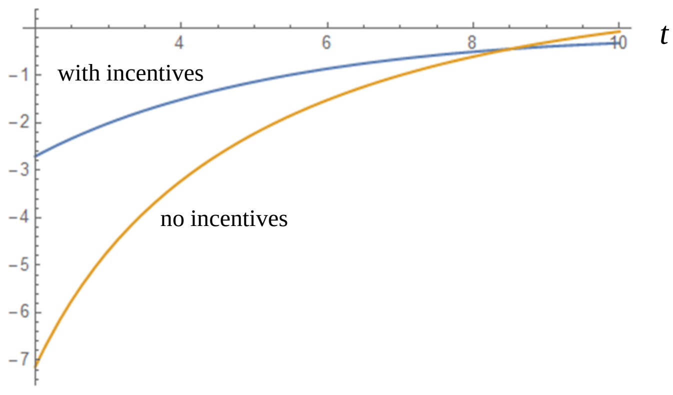

Fig. 2: Government's objective (integrand in (9)) with and without incentives with respect to types
$A = 1$, $\theta = 3$, $\underline{t} = 2$, $\bar{t} = 10$, $\delta = ½$, $d = 1$, $u_0 = 22^{1/4}$

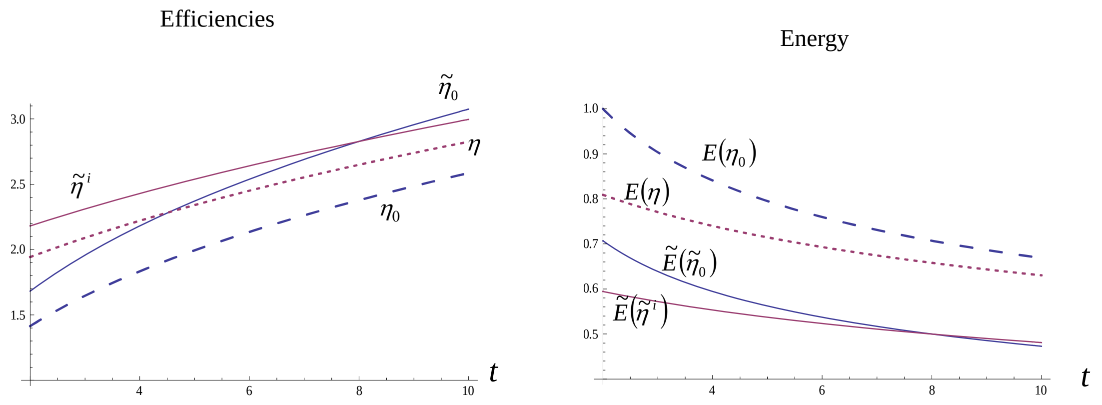

Fig. 3: Optimal conservation program with and without (dashing) internalized external costs,
$A = 1,\ \theta = 3,\ \underline{t} = 2,\ t = 10,\ \delta = ½,\ d = 1$

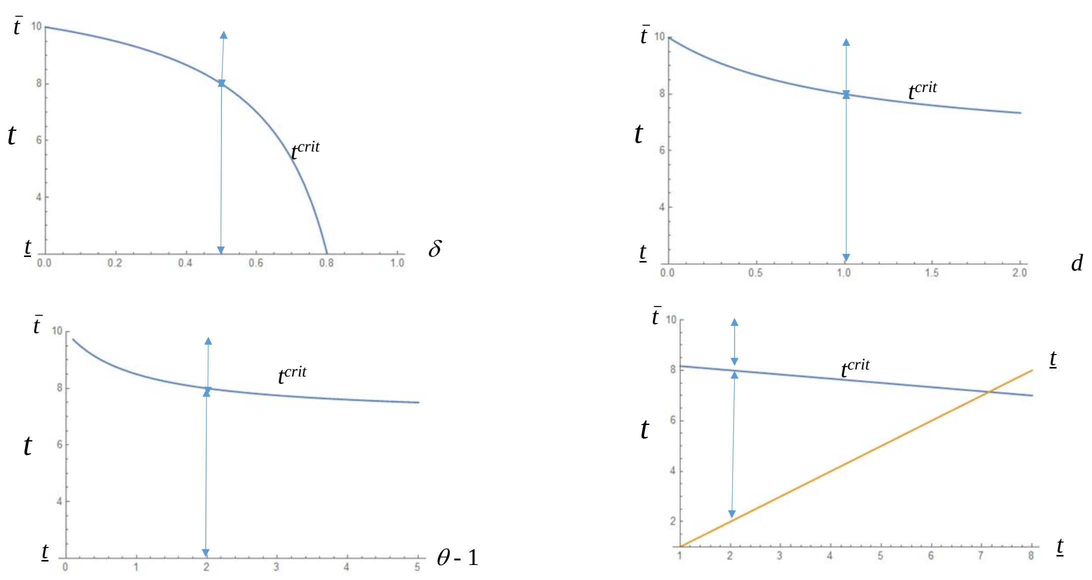

Fig. 4: Sensitivity of critical type t^{crit} for parameter variations around the reference case (at the level of the arrows): i.e., types only types $t < t^{crit}$ are asked to upgrade their efficiency as indicated by the arrows at the parameter values of the reference case.