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Long-run carbon emission implications of energy-intensive infrastructure investments with a retrofit option

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ABSTRACT

Investments in long-lived, fossil-fuel intensive infrastructure can have large effects on carbon emissions over a long future period. We simulate a 2-period model of infrastructure investment with subsequent retrofit to purge its carbon emissions, under uncertainty about climate and retrofit costs. The energy intensity chosen upon investment depends on current and expected future energy and environmental costs, and on future retrofit cost. Simulations of a simplified but realistic model indicate that energy consumption and carbon emissions can be highly excessive when future energy and climate costs are not considered at the time infrastructure investments are made, and charged at globally suboptimal rates when operated; often by more than 50% when energy costs are undervalued at this rate both ex ante and ex post. Good anticipated retrofit options reduce ex post energy costs, but lead to ex ante choice of more energy-intensive infrastructure, which could more than fully offset the energy-reducing effect of the retrofit. These results are of particular importance for emerging economies with large current and anticipated energy-related investments, where long-term climate policy goals may be seriously jeopardized by policy makers facing too low energy prices, now and in the future.

1. Introduction

Long-lasting energy-intensive infrastructure gives rise to much of the energy consumed and greenhouse gases (GHGs) emitted by modern societies. It can also tie up fossil energy consumption at high levels for long future periods, and thus potentially jeopardize important climate policy goals. Coal-fired power plants, in particular, usually have lifetimes of 40–50 years or more, locking in high carbon emissions. These can in principle be eliminated later, but only through very expensive "carbon capture and storage" (CCS) retrofits. Choosing low-carbon power technologies (solar, wind, geothermal or hydro) will by contrast lock in much less future emissions. Related energy demand effects are found in urban planning.[1] "Sprawling" cities remain car-oriented with high GHG emissions per capita. Urban structure, once established, is difficult to alter. Shorter-lasting but still important energy-consuming infrastructure locking in future emissions includes motor vehicles, household appliances, and home heating and cooling systems.[2] Such energy demand is particularly crucial for rapidly growing emerging economies with expanding cities and massive infrastructure investments. All exemplify path dependence: current choices have direct effects on the costs of implementing future policies.

This paper addresses such issues through analyzing and simulating a stylized model of energy-intensive infrastructure investments. We will study whether related carbon emissions can be eliminated by costly infrastructure "retrofits." Almost trivially, when policy makers do not fully account for energy and climate costs, energy consumption and emissions will then be excessive in both the short and the long run. Our focus is more on the degree to which emissions are excessive, through simulations on a stylized model with two periods: the "present" ("period 1"); and the "future" ("period 2"). Energy costs, and "retrofit" costs (discussed below), are unknown in period 1, but have known (or knowable) period 2 distributions in period 1. We assume that the infrastructure lasts for both periods, but may be abandoned in period 2. Fossil-fuel consumption can be modified in period 2, in two ways: (1) by a (costly)

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[1] See further discussion in Shalizi and Lecocq (2009); Glaeser and Kahn (2010); and Larson et al. (2012).

[2] A slightly different categorization, based on the longevity of the capital stock, is found in Jaccard (1997), and Jaccard and Rivers (2007).

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"retrofit" in period 2, removing all carbon emissions from the infrastructure either by using non-fossil sources or removing carbon through CCS or similar processes; (2) by then abandoning the infrastructure. The latter can be viable only when energy and retrofit costs of continued operation both turn out very high, the lower being higher than the utility value of continued operation.[3]

Our simulations illustrate excessive energy consumption from two types of inefficiency. First, investment decisions are based on too low future energy prices, but energy prices are still charged correctly at the operation stage. Secondly, energy prices are too low at both the investment and operating stages. We will sort out how much of an "overall" inefficiency is due to the investment decision alone; and how much to failing policies later.

In Section 3 we derive analytical solutions for the initial infrastructure investment decision including its (fossil) energy intensity in period 1, jointly with strategies for retrofitting and operating the infrastructure in period 2, under uncertainty — as only the future distributions of the energy and retrofit costs are known in period 1. We focus on the case where emissions are phased out completely by the retrofit; but also, more briefly (in Subsection 3.2), consider the case of incomplete phase-out. In Section 4 these solutions are simulated on a parameterized model. We identify factors behind too energy intensive infrastructure. We also study whether, and to what extent, an initially high energy intensity level can be modified later through retrofit or closedown, when energy and environmental costs are high.

A key issue on which we focus is that infrastructure decisions involving long-run climate impacts are typically non-optimal from a global perspective. Carbon emissions require a global view for their optimal control, incorporating globally correct carbon costs. This is unlikely in practical policy, except when international agreements require, and enforce, globally efficient prices (for emissions and energy, currently and in the future). The practical decision maker is usually a local or national government, who will incorporate prices, costs, discount rates etc. at the respective (local or national) decision level. We here aim to study how such a decision maker deviates from a globally optimal decision.[4]

In studying effects of uncertainty about climate or retrofit costs on infrastructure-related GHG emissions, two countervailing factors are at work. First, emissions are avoided in future periods with better retrofit and closedown options, and in states where emission costs are very high and retrofit costs low. Such states are, overall, more frequent with greater uncertainty. Higher uncertainty makes both low-cost and high-cost outcomes more likely; emissions tend to result only when emission costs are relatively low. Expected emission costs, and expected emissions, are then reduced with greater uncertainty, for a given initial infrastructure.

However, greater uncertainty and better retrofit options raise the chosen energy intensity of infrastructure. Expected future operating costs are then reduced when uncertainty is greater, since there will be more (desirable) low-cost states, and also many high-cost states but where these costs will be avoided through closedown or retrofit. This makes higher initial energy intensity attractive when uncertainty is great.[5] From our simulations, expected lifetime energy consumption may either increase or decrease when uncertainty increases. The tendency for energy consumption to be reduced due to more retrofits and closedowns often dominates; but the net effect is often small.

Infrastructure investments could be made without sufficient concern for future climate costs, but these costs are still actually incurred when the future arrives. Our simulations indicate strong "path dependence": One could end up with an initial infrastructure investment whose energy intensity is highly excessive, and is very difficult to reduce later.

When the energy cost is too low both ex ante and ex post, additional inefficiencies result as infrastructure investment and operation are both too energy intensive. The impacts on investment and operation are here compounded, and the overall effect in terms of excessive energy use and emissions can be far greater, as also illustrated in our simulations referred to in Sections 3–4. This issue is particularly important for many emerging economies today.

2. Background literature

Among earlier literature, Arthur (1983), David (1992), and Leibowitz and Margulis (1995) discuss the related issue of "path dependency". The more specific context of infrastructure choice and its implications for mitigation policy is studied only more recently. Ha-Duong et al. (1997), Wigley et al. (1996), Ha-Duong (1998), and Lecocq et al (1998) focus on infrastructure whose energy commitments can form obstacles to effective mitigation policy. A seminal contribution is Kolstad's (1996) analysis of sequentially optimal climate-related policy under uncertainty with potential irreversibilities. Shalizi and Lecocq (2009) discuss infrastructure costs and constraints which is more applied and intuitive than that provided here. Persistent effects of infrastructure choice on energy consumption and carbon emissions are discussed also by Brueckner (2000), Gusdorf and Hallegatte (2007a,b), Glaeser and Kahn (2010), Larson et al (2012), and Vogt-Schilb et. al. (2012). Gusdorf and Hallegatte (2007a) study the energy intensity of urban infrastructure for given population density, focusing on inertia resulting from established urban structure, in response to low but uncertain energy prices. Permanent energy price shocks can then lead to a long (20 years or more) and painful transition period (with high energy costs and carbon emissions), but with energy consumption eventually falling substantially. Glaeser and Kahn (2010) quantify relationships between energy consumption and spatial patterns in the U.S. One finding is much lower per-capita energy consumption and carbon emissions in central cities than in suburbs, indicating that "compact" infrastructure is less energy demanding than "less compact". Viguié and Hallegatte (2012), applying multi-criteria optimization of transport plans for Paris up to 2030, study long-run fuel consumption due to alternative transport infrastructure investments, which can be substantial. Framstad and Strand (2013) study optimal infrastructure investment in continuous time, generalizing Pindyck's (2000, 2002) analysis of optimal climate-related retrofits, where future energy prices follow a continuous stochastic process. An option value then raises the threshold for the ex post retrofit to be implemented, and thus further increases the average energy intensity of such initial infrastructure. Jaccard (1997) and Jaccard and Rivers (2007) discuss retrofit possibilities and costs more practically, with specific infrastructure categories including urban structure, buildings, and equipment. A finding is needed for strong initial considerations for future emissions even when emission prices start low but increase strongly over time.[6] Lecocq and Shalizi (2014) discuss infrastructure-related energy demand and supply more broadly, arguing that energy-intensive infrastructure involving supply is often more rigid than that involving demand; but sometimes (but not always) more prone to complete retrofit.

Our paper also relates to literature on a "low-carbon society" with high concern for infrastructure investment design (Strachan et al (2008a,b), Hourcade and Crassous (2008)).[7] Two World Development Reports from the World Bank, in 2003 ("Sustainable Development in a Dynamic World"; World Bank (2003)), and 2010 ("Development and Climate Change"; World Bank (2009)), also have "inertia in physical capital" as main theme.

[3] A more general interpretation of this case is that energy consumption and emissions in the "closedown" alternative serve as a reference point against which the "business-as-usual" and retrofit alternatives are valued.

[4] See Strand (2011) for further elaboration.

[5] This result holds when decision makers are risk neutral, which is assumed here. Under risk aversion, the utility effect of greater uncertainty could here go either way.

[6] For a complementary discussion but in the context of an overall climate policy see Wigley et al. (1996).

[7] An early champion of this line of thinking and discussion was Lovins (1977).

3. Analytical foundations

3.1. Base case: retrofit with complete carbon phase-out

Consider a two-period economy where infrastructure investments are made at the start of period 1, and can be "retrofitted" at the start of period 2.[8] When operated and not retrofitted, infrastructure gives rise to constant per-time energy consumption, set at the time of investment. Energy and climate-related costs are uncertain in period 1, but revealed at the start of period 2. When retrofitted, we assume in this sub-section that the infrastructure is purged of all fossil-fuel energy and/or all carbon emissions, while providing the same services to the public as before the retrofit (Sub-section 3.2 discusses the case of incomplete carbon phase-out). "Retrofits" represent new technology, available at the start of period 2. The infrastructure will be shut down at the start of period 2 when the utility from operation is then less than the minimum of the energy cost of operation, and the retrofit cost.

Period 1 has unit length, while period 2 has length T. Alternatively, T could represent discounted value of period 2 relative to period 1.[9]

In period 1, the unit energy cost is q_1.[10] The policy maker decides on an infrastructure investment with given capital cost K. Infrastructure type is identified solely by its energy intensity H, where energy consumption per time unit associated with the infrastructure is fixed once the infrastructure is established, and until it is possibly retrofitted or closed down. Considering only economically viable projects, an infrastructure project with higher energy content must give higher utility to the public, but is more costly to operate (as long as not being retrofitted) due to its greater fossil-fuel energy requirement. Denote current (per time unit) utility from the infrastructure when operated by $U(H)$, where $U'(H) > 0$, $U''(H) < 0$. Assume that $U(H)$ is the same in both periods.[11]

Three alternative actions may be chosen in period 2:

1. *Normal energy use*, as in period 1. This is optimal when the energy cost in period 2 turns out to be lower than both the retrofit cost and the period-2 utility level from continued operation.
2. *Retrofit* is optimal when the retrofit cost in period 2 turns out to be lower than either the energy cost, or the period-2 utility level.
3. *Closedown* is optimal when energy and retrofit costs are both higher than period 2 utility from continued operation.

The decision maker in period 1 selects an energy intensity H of the infrastructure to maximize

$$EW(1) = U(H) - q_1 H + EW(2) \tag{1}$$

where E is the expectation operator and $W(2)$ the (optimized) value function associated with the infrastructure in period 2. $EW(2)$ embeds the decision maker's optimal responses in period 2 (with no further changes from then on). Define $F(q,y)$ as the (continuous ex ante) cumulative bivariate distribution over q and y levels in period 2, with support $[0, q_M] \times [0, y_M]$, where q_M and y_M could be large.[12] y represents the retrofit costs (per unit of energy capacity to be retrofitted) in period 2. We assume that an infrastructure project, after a retrofit, incurs no energy costs nor any other current costs in period 2, apart from the retrofit cost itself (which can be "periodized" in the same way as energy cost).[13] Period 2 realizations of energy and retrofit costs are assumed in general to be correlated.[14]

Consider the choice between alternatives 1–3 in period 2. Define total utility per energy unit for installed infrastructure by $U(H) / H = y^*$. Close-down will then be chosen when the energy cost q, and the retrofit cost y, both exceed y^*. The probability of this event as viewed from period 1 is

$$P_3 = \int_{q=y*}^{\infty} \int_{y=y*}^{\infty} f(q,y)dydq, \tag{2}$$

where $f(q,y)$ is the (simultaneous) probability density function corresponding to F.

Given that $y^* < \min\{q_M, y_M\}$, and $0 < F(y^*, y^*) < 1$, there will exist some states where the infrastructure is closed down in period 2; thus $P_3 > 0$.

The probability P_1 of no action is given by:

$$P_1 = \int_{y=q}^{\infty} \int_{q=0}^{y*} f(q,y)dqdy. \tag{3}$$

The probability P_2 of retrofit equals $1 - P_1 - P_3$, but can also be found in[15]

$$P_2 = \int_{q=y}^{\infty} \int_{y=0}^{y*} f(q,y)dydq. \tag{4}$$

Considering actual realized costs, the expected "per time unit" period 2 energy and retrofit costs in period 1, given an optimal strategy in period 2, are respectively

$$E[CH(2)] = \left(\int_{q=0}^{y*} q \int_{y=q}^{\infty} f(q,y)dydq \right) H \tag{5}$$

$$E[CR(2)] = \left(\int_{y=0}^{y*} y \int_{q=y}^{\infty} f(q,y)dqdy \right) H. \tag{6}$$

Define $E[C(2)] = E[CH(2)] + E[CR(2)]$, and $Ec(2) = E[C(2)] / H$.

Ex ante expected net utility from the infrastructure when operated in period 2, denoted $EW(2)$, equals gross utility $TU(H) = Ty^*H$, with (operation) probability $1 - P_3$, minus total expected energy and retrofit costs, $T\{EC(2)\} = T\{E[CH(2)] + E[CR(2)]\}$, over states where the infrastructure is operated (without or with retrofit). We then have

$$EW(2) = \{y * (1 - P_3)H - E[CH(2)] - E[CR(2)]\}T. \tag{7}$$

The first-period problem is to maximize expected utility of the infrastructure investment in period 1, given an optimal strategy in period 2.

[8] In the model as it otherwise stands, the assumption that a retrofit can be done only at the start of period 2, and not during this period, is no limitation as, we assume, no new information (nor any new or better retrofit technology) will be forthcoming during period 2.

[9] More precisely, when unity represents the present discounted value of a current income flow of one dollar throughout period 1, T would in this case represent the present discounted value of a current income flow of one dollar throughout period 2, as evaluated from the start of period 1.

[10] In the continuation, when we say "energy cost", we mean the combined energy and environmental cost associated with normal (fossil-fuel) energy use. This would be unproblematic when all environmental costs are charged to energy use in the form of energy taxes and quota prices. It is more problematic when this is not the case; this issue is elaborated in the final section.

[11] $U(H)$ represents the current utility to the public from an infrastructure investment of size K which leads to a continuous energy consumption level of H.

[12] In simulations below we assume that F is the bivariate log-normal, in which case F is not bounded above (it is however "thin-tailed").

[13] Alternatively, the retrofit cost could be interpreted to include some energy cost. This is unproblematic as long as the retrofit cost can be periodized.

[14] Correlated energy and retrofit costs (positively or negatively) are often realistic. Negative cost correlation could occur when high energy cost in period 2 leads to great R&D efforts to develop new retrofit technologies. On the other hand, common drivers may affect both costs in the same direction, as e.g. when energy cost is correlated with general production cost; when a retrofit involves use of fossil energy; or when subsequent use of renewable energy whose marginal production cost is positively correlated with the cost of fossil fuels.

[15] We can here switch order of any double integrals applying Fubini's theorem; see e.g. Royden (1988).

The solution to this problem takes the form, using Eq. (1) and the definition $y* = \frac{U(H)}{H}$,

$$\frac{dEW(1)}{dH} = U\prime(H) - q_1 + \frac{EW(2)}{H} + [U\prime(H) - y*]\frac{d\left(\frac{EW(2)}{H}\right)}{dy*} = 0. \tag{8}$$

From Eq. (7) we may derive[16]

$$\frac{d\frac{EW(2)}{H}}{dy*} = [1 - P_3]T. \tag{9}$$

The optimal energy intensity of the infrastructure, H, is now found implicitly from

$$U\prime(H) = \frac{q_1 + \frac{E(CH(2) + E(CR(2))}{H}T}{1 + [1 - P_3]T} = \frac{q_1 + \left\{\int_{q=0}^{y*} q \int_{y=q}^{\infty} f(q,y)dydq + \int_{y=0}^{y*} y \int_{q=y}^{\infty} f(q,y)dqdy\right\}T}{1 + \left\{\int_{y=q}^{\infty}\int_{q=0}^{y*} f(q,y)dqdy + \int_{q=y}^{\infty}\int_{y=0}^{y*} f(q,y)dydq\right\}T}. \tag{10}$$

$1 + [1 - P_3]T$ is here the expected time the infrastructure will operate. $\{E(CH(2)) + E(CR(2))\}T = \{EC(2)\}T$ is the ex ante expected (energy plus retrofit) cost in period 2, which when divided by H, is scaled relative to energy intensity. The expression in the curled bracket in the numerator of Eq. (10) denotes expected energy plus retrofit cost per unit of energy consumption defined by the established infrastructure.[17]

The optimal energy intensity is chosen according to average energy cost in operating the infrastructure over its expected period of operation. For the change in y^* $(= U(H) / H)$ we find

$$\frac{dy*}{dH} \equiv y_H* = -\frac{1}{H}(y* - U\prime). \tag{11}$$

$y^* - U'$ must be positive and more so the more curved U is in the neighborhood of H. Thus we can expect $y_H^* < 0$.[18] This implies that a more energy-demanding infrastructure will have a lower threshold for operation, and will be "closed down" (or replaced) more often ex post in period 2, when energy and retrofit costs increase. This appears reasonable in our model where all infrastructure projects require the same initial investment cost: projects are distinguished solely by their ex post energy intensity.[19]

3.2. Retrofit with incomplete carbon phase-out

A weak assumption in the analysis above is that all energy consumption is always purged of the infrastructure upon a retrofit. This is very often not the case in practice, such as when introducing CCS, or transitioning from fossil fuels to biofuels. We will here rather briefly indicate how our main result, with respect to energy intensity of infrastructure, H, changes under an alternative formulation where a fraction $1 - \tau$ of the initial energy consumption remains after a retrofit. Thus, the retrofit removes a fraction τ of the initial energy consumption. The chosen H is then found from, as alternative to Eq. (10),

$$U'(H) = \frac{q_1 + \left\{(1-\tau)E(q(2)) + \tau\frac{E(CH(2) + E(CR(2)))}{H}\right\}T}{1 + [1 - P_3]T}. \tag{10a}$$

An easy generalization applies because we may split the energy cost associated with H in period 2 in two: one component with fixed energy cost having weight $1 - \tau$; and another component having variable cost as before, with weight τ. The retrofit cost term is also given weight τ. We here assume, when considering a parametric variation in τ, that the retrofit cost varies proportionately to the fraction of energy being phased out by the retrofit, τ. $E(CR(2))$ in Eq. (10a) would then be scaled down proportionately to τ, which can be represented as in Eq. (10a). This is relevant with a view to simulations in Section 4. Alternative values of τ, the fraction of carbon emissions that is phased out, should then be assumed; given CCS τ may today be, perhaps, 0.7, while given a switch to biofuels it may be lower (0.5 or below).

4. Simulations

We now simulate how expected energy consumption depends on energy prices facing policy makers; anticipated ex ante, and realized ex post. Simulations are essential to the argument in our paper. While many of the qualitative analytical results (in Section 2 and Appendix A) are, arguably, trivial (including e.g. that energy consumption will be excessive with suboptimal energy prices), the simulations can provide us more tangible results, indicating likely quantitative impacts of distortions of particular magnitudes, under alternative assumptions. Of particular interest is the degree to which energy consumption is excessive in response to low energy prices, ex ante and ex post. We simulate four variables[20]:

1) Ex ante expected probabilities of normal energy use, and retrofit, in period 2.
2) Ex ante expected energy and retrofit costs in period 2.
3) Energy intensity of the infrastructure.
4) Lifetime expected energy consumption. This combines energy intensity of infrastructure with probability that the infrastructure has normal energy use ex post.[21]

We focus on cases where the closedown option can be neglected.[22] Most of the simulations of expected energy cost in period 2 depart directly from Eqs. (5), and (6) for expected retrofit cost in period 2. For probabilities of normal operation and retrofit respectively we use Eqs. (3) and (4), and for energy intensity of infrastructure we use Eq. (10). For overall energy use, we apply the solution value for H together with the ex ante probability of normal energy use, Eq. (3).

Unless otherwise stated, the (unconditional) expected energy and retrofit costs (per unit of energy use, and retrofit investment) are assumed constant with $E(q(2)) = 2$, and $E(y(2)) = 3$. $E(q(2))$ is the unconditional expected energy/environmental cost in period 2; these would be actual expected costs given that this alternative is chosen for certain. Energy and retrofit costs are assumed both to be log-normal, and independent.[23]

16 See Appendix A1 for a proof.

17 Eq. (10) looks complicated but can be given a simple interpretation: marginal utility of increased energy intensity associated with the infrastructure (the left-hand side of Eq. (10)) should equal the average energy plus retrofit costs incurred over the lifetime of the infrastructure (the right-hand side).

18 Another way of interpreting this can be found by considering that y^* is an expression of the average utility of infrastructure per unit of H_1. $y_H^* < 0$ then simply expresses that average utility of infrastructure must exceed its marginal utility at the point of indifference between operation and closedown.

19 Appendix A1–A2 deals with comparative statics for the above model, when there are period 2 shifts in the distribution of energy costs (A1), and in the distribution of retrofit costs (A2), for a simplified case with independent costs.

20 All simulations are carried out using Matlab.

21 Further simulations, not reproduced here but available upon request, focus on cases where energy and retrofit costs are positively correlated, and on the degree of such correlation.

22 We will here argue that log-normality is robust; see e.g. Schuster (1984). For the CRRA assumption, criticism can be raised in particular to the Cobb–Douglas specification; see below.

23 We have conducted an additional set of simulations, available upon request, where q and y have a bi-lognomal distribution with a positive correlation coefficient equal to 0.5.

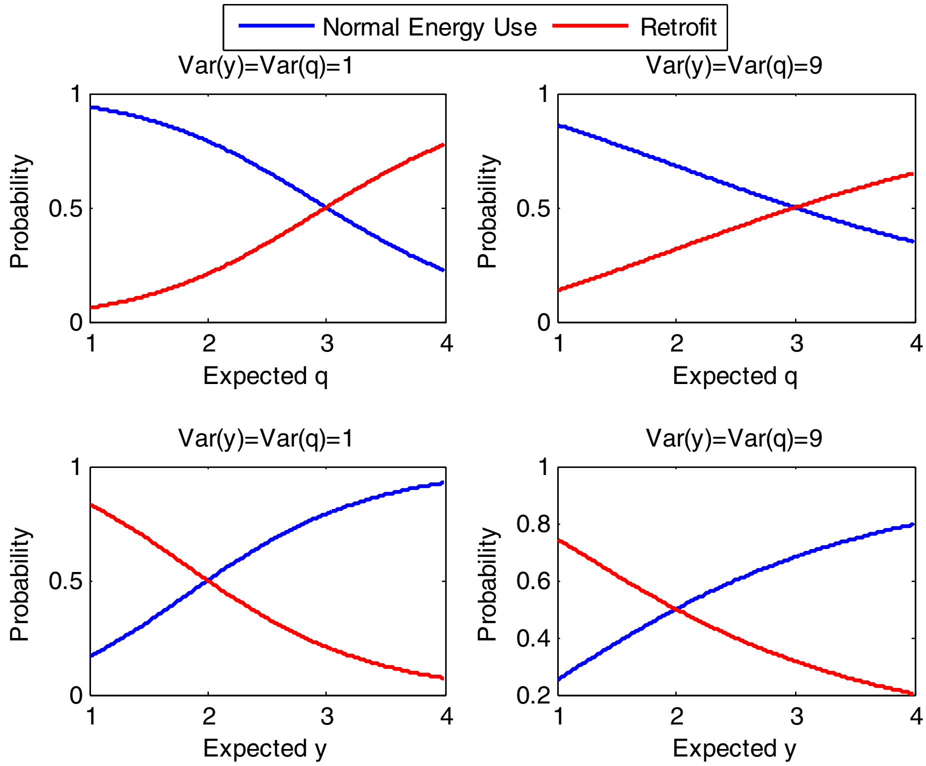

Fig. 1. Probabilities of normal energy use and retrofit as functions of unit energy cost, and unit retrofit, respectively, for independent costs.

We find our chosen parameters "realistic" in the sense of describing relevant scenarios for respective relative costs. First, over a relevant range for period 2 relative to period 1 (perhaps, 10–15 years in the future), a doubling of total energy prices (including environmental costs) in expectation seems realistic. It may also be realistic to assume that, in expectation, retrofit of an existing facility will remain a relatively expensive option (in our case, having a higher expected cost than continued normal energy use). The numerical example also recognizes the potential for these variables to be highly uncertain; this will for energy reflect compounded effects of the basic energy price, and the globally correct environmental cost of fossil energy use; with a range for the standard deviation of energy cost in our numerical examples (from period 1 to 2) of between 50% and 150% of the expected period 2 cost.

4.1. Ex ante probability of retrofit in period 2

We first consider implications for the (ex ante) probabilities to retrofit the infrastructure in period 2, as ex ante expected values of energy cost (q) and retrofit cost (y) change, where in either case the other expectational value is kep constant (with Eq = 2, and Ey = 3, respectively). We also find the impact on the retrofit probability from "incorrect" prices in period 2. Fig. 1 shows the retrofit probability given a parametric change in expected energy cost, and for 2 different levels of uncertainty about both energy and retrofit costs: with standard deviations equalling 1 and 9, respectively (which are used also in Figs. 2–4 below).[24] A low (high) *Eq* implies a low (high) retrofit probability; more so when variances are smaller.[25] Higher variances imply more attractive options to substitute out one variable for the other; and thus a smaller propensity to rely on a given factor when it becomes less expensive. Also, the uncertainty examples span out larger sets of cases as outcomes are smooth in (and roughly proportional to) respective standard deviations.

Fig. 1 also shows how probabilities change when expected energy cost is constant and expected retrofit cost changes. A similar pattern emerges except that the retrofit probability now decreases when expected retrofit cost increases: the two figures are, in important ways, mirror images of one another.[26]

4.2. Ex ante expected energy and retrofit costs in period 2

We next simulate expected energy and retrofit costs in period 2. Interpreting the figures requires some care. As *Eq* in Fig. 2 rises above 3, and *Ey* falls below 2, retrofit in both cases becomes the more efficient alternative on average.

The curves cross at $Eq = 3$ and $Ey = 2$. Higher variances reduce expected costs by opening up more options to reduce ex post costs. For our high-variance alternative in Fig. 2 ($var(q) = var(y) = 9$), conditional expected energy cost increases well beyond the crossing point 3.

4.3. Infrastructure investment choice

We next, in Fig. 3, simulate how the initial infrastructure investment decision, H, from Eq. (10), depends on the expected values of *Eq* and *Ey*, given $T = 5$ (period 2 is 5 "times as long" as period 1). Note that the probability of retrofit in period 2 is not affected by H.[27] T is found to affect H (as it affects the balance between periods 1 and 2, with generally different costs).

[24] The probability of closedown is also accounted for, but is too small to matter. With a value of continued use set at 10, this option will be exercised only when $\min(q,y) > 10$, which has exceedingly small probabilities.

[25] While this is shown in the figures only for simultaneous changes in both variances, the same basic result holds when only one of the variances at the time is changed.

[26] Further simulations, available upon request, show similar results when q and y are positively correlated with correlation coefficient = 0.5. Distributions are then similar, with the (small) change that $P(1)$ is higher for low *Eq*, and lower for high *Eq*. Positive cost correlation leaves less scope for substituting a cheaper alternative for a more costly one. Higher correlation between energy and retrofit costs, and lower variances on costs also reduces the retrofit probability given our assumption $Eq < Ey$.

[27] Conceivably, however, the decision to close down the infrastructure may be affected; see Section 4 below.

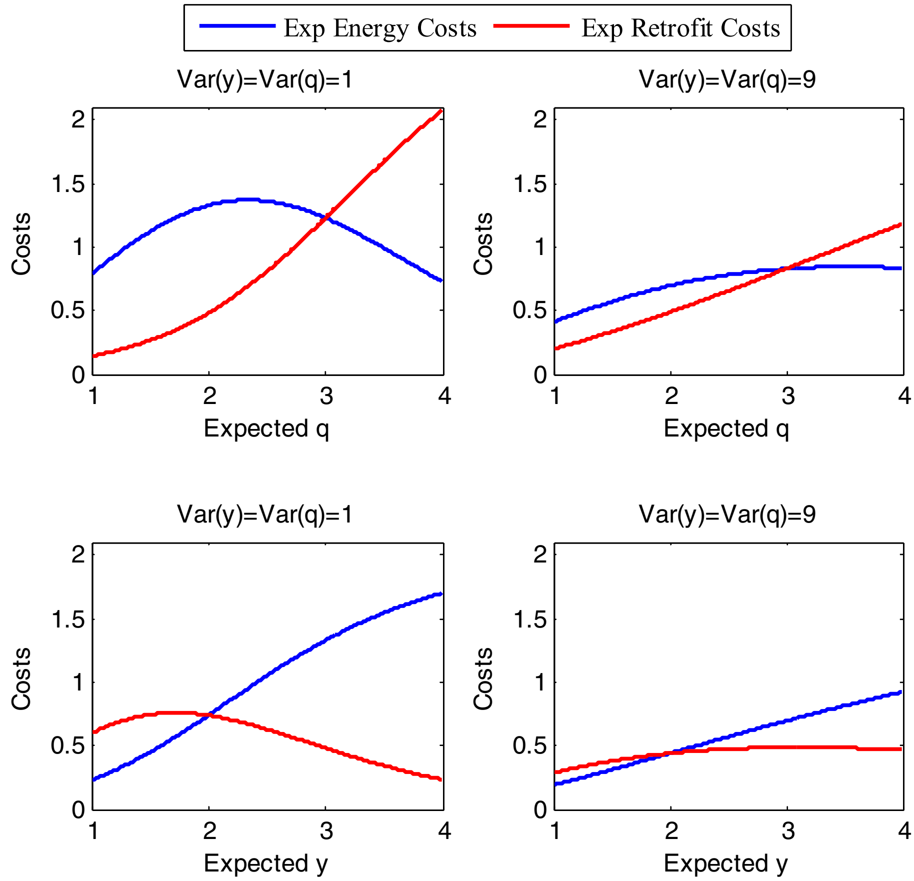

Fig. 2. Ex ante expected energy/retrofit costs in period 2 as function of unit energy costs, and unit retrofit cost, respectively, for different variances, independent costs.

The specification of the public's utility as function of the infrastructure's energy intensity, $U(H)$ from Eq. (10), here matters. We consider the class of constant relative risk aversion (CRRA) utility functions, with general form[28]

$$U(H) = A\frac{H^{1-\rho}}{1-\rho} + K. \tag{12}$$

A and K are the constants, while ρ is the (Arrow–Pratt) measure of relative risk aversion, and $\varepsilon_H = 1/\rho =$ the (absolute-valued) "elasticity of demand" for infrastructure H with respect to unit energy cost. Fig. 3 shows results for two variants of Eq. (12): the log-linear case with $\rho = \varepsilon_H = 1$; and the exponential case with $\rho = 1.5$ (thus $\varepsilon_H = 2/3$).[29] The exponential form gives the smaller variation in H when Eq changes, and in energy intensity when Eq and Ey change.

4.4. Ex ante expected energy consumption over the project lifetime

Our final simulations (Fig. 4) show how ex ante expected energy consumption varies when both ex ante expected and realized costs in period 2 vary in the same way. We now multiply the initial energy intensity by the probability of normal energy use in period 2, which is 1 in period 1, and $P(1)$ in period 2.

These calculations compound two effects: energy intensity of infrastructure investment, H; and the probability of normal energy use in period 2, $P(1)$. When Eq increases, both are reduced. The reduction in energy consumption in response to a (correctly anticipated) increase in future expected energy costs, is then larger than for either of the two alone.

The derived responses are "globally optimal" given that the decision maker faces "correct" energy costs both initially and later. When prices are instead too low both ex ante and ex post, energy consumption is excessive. This is seen by comparing expected energy costs for alternative values of Eq; see also Table 1 in Section 4 below.

Fig. 4 also shows how lifetime energy consumption from operating the infrastructure responds to an increase in (period 2) expected retrofit costs (Ey). Two impacts go in opposite directions. Ex post, energy consumption is increased as the infrastructure is retrofitted in fewer states when Ey increases. Ex ante, however, the initial energy intensity is reduced as overall (ex ante) expected costs in period 2 increase. When variances on costs are high, the latter effect may dominate, as the former effect is small (with good substitution possibilities ex post, expected ex post costs do not increase much when Ey rises). Lifetime energy use of the infrastructure then increases when retrofit costs increase.

5. Summary and final comments

This paper studies the degree to which energy consumption and carbon emissions resulting from long-lasting, energy-intensive infrastructure can be excessive, when policy makers face too low energy prices when investing in and operating the infrastructure. The issue is highly relevant today as massive infrastructure investments are being and will soon be undertaken by major emerging economies including the BRIC countries. When long-lasting and energy-demanding infrastructure investments have already been sunk, they tend to commit high energy consumption and carbon emission levels for a long future period.

[28] Remember our assumption that the size of the infrastructure investment is constant. For the problem to be meaningful economically, the public's utility of the infrastructure must then be increasing in the infrastructure's energy consumption.

[29] A third variant of Eq. (12) is the Cobb–Douglas specification, which is however less realistic and will not be detailed in the following. Simulations for this case have been made and are available upon request.

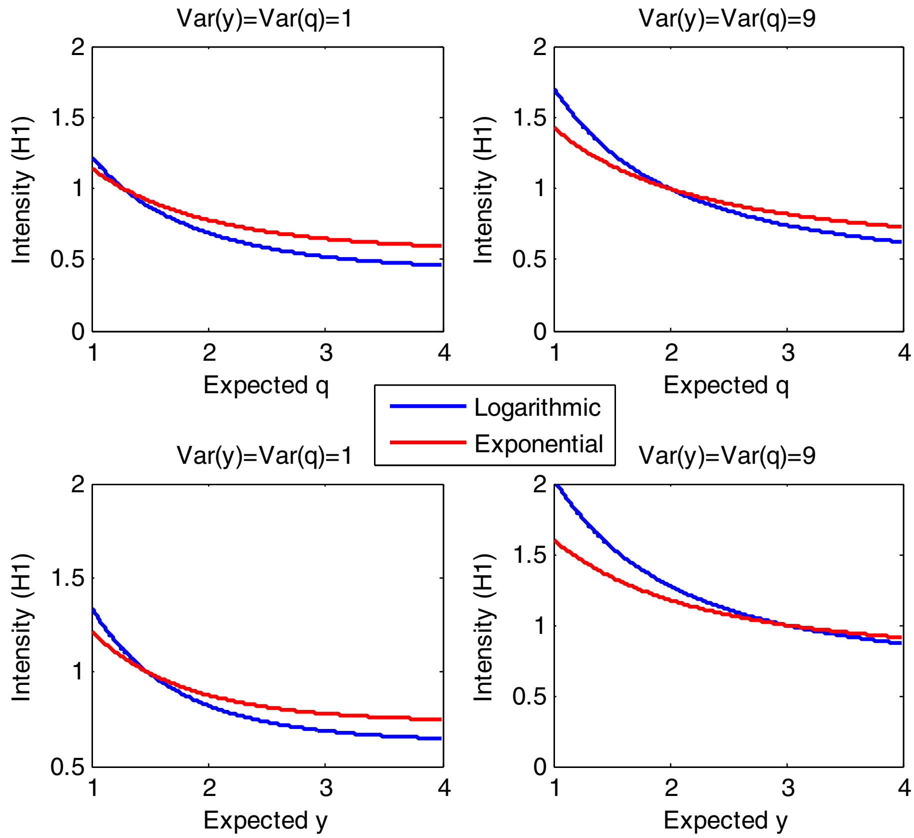

Fig. 3. Energy intensity of infrastructure investment as function of expected energy cost, and expected retrofit cost, respectively, in period 2, for different utility functions and variances, non-correlated costs.

Our simulations indicate that the resulting distortions, as a consequence of decision makers facing too low energy prices, can be very large; see a summary in Table 1 below.

Two key types of inefficiency are (i) too energy-intensive infrastructure investment; and (ii) inadequate retrofits of the infrastructure. To avoid such distortions, energy costs facing policy makers must meet two main requirements: anticipated future energy costs upon investing (the expected ex ante energy costs), and actually incurred ex post energy costs (in all cases embedding total environmental costs), both need to be "globally correct". Such prices would need to reflect costs as experienced and applied by a "global policy maker" who incorporates all possible global costs and benefits.

This is strictly speaking a tall order, not least for emerging economies with which we are here most concerned. Global efficiency, for both investment and operation of energy-demanding infrastructure, is exceedingly difficult to attain in practice. Failure to impose correct costs, and instead let relevant decision makers face the more partial costs (in many cases, dramatically lower), can then lead to highly excessive energy consumption and carbon emissions. A serious "red flag" must be raised for climate policy, in the short but even more the long run; and possible remedies contemplated.

Several types of market failure can be identified. We will here provide a brief overview, identifying five types of market failures, and their likely impacts.[30]

A. *Too low future energy costs when investing in infrastructure.*[31] This leads to excessive energy intensity as illustrated in Fig. 3.
B. *Too low energy costs both when investing in and operating the infrastructure*. As an add-on to point A, energy consumption at the operating stage is further distorted upward by this factor, as the later retrofit or closedown options are chosen too infrequently. The overall distortion is then greater than under A, as illustrated in Table 1.
C. *Incorrect expected future retrofit costs when investing in the infrastructure*. Anticipated retrofit costs could be either too high or too low. When future retrofit costs are too low when investing, energy intensity of infrastructure is set too high. Fig. 3 provides a clue. In log-linear or exponential utility cases, when the expected retrofit cost is 2 instead of a correct value of 3, chosen infrastructure is too energy-intensive, but only by about 10% or less. With too high anticipated retrofit costs, the distortion is opposite, but the effect is also then small. Under-assessing the future retrofit cost then has a moderate effect on the initial energy intensity.
D. *Realized retrofit costs are socially excessive*. This is a relevant concern when also future retrofit costs can be affected by policy such as technology investments; and these are under-provided. Consider then the response of both investments and retrofits to changes in *Ey*, cf. Fig. 2. Two factors affect energy use, in different directions. First, the higher than optimal expected future cost (implied by the higher retrofit cost) leads to too low energy intensity of the infrastructure. Secondly, retrofit is used too infrequently. The balance depends on cost uncertainty and on the utility function specification. From Fig. 4, energy consumption rises with retrofit cost, most when cost uncertainty is low. With greater variances, however, the probability of energy use changes much less, and the two factors more or less cancel out.

We will classify these 4 factors into two groups. The first (B and D) represents faulty climate or energy policies (including insufficient

[30] See also Strand (2011) for further discussion of these market failures.
[31] This could occur even when the decision maker would face the "true" energy/environmental cost. One such case is where the administrative procedure for making public investments involves incorporating future costs and benefits for a limited period (say, 20 years), while the investment lasts much longer (say, for 50 years or more).

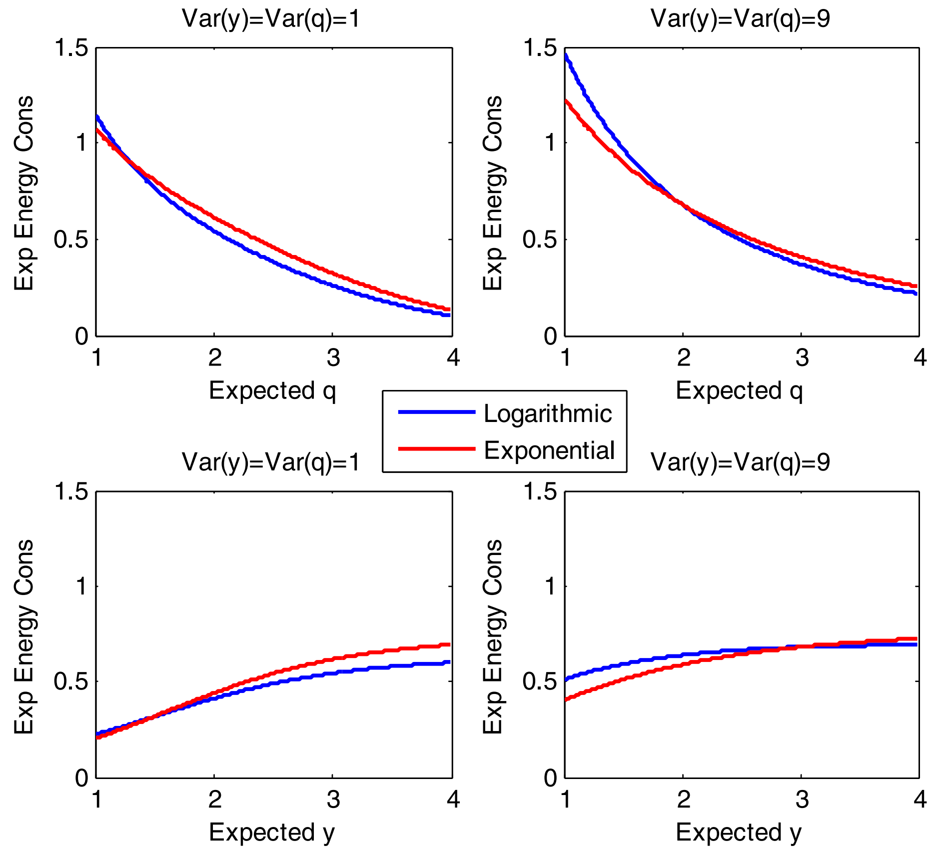

Fig. 4. Expected per-period energy consumption over the project's lifetime, as function of expected period 2 energy cost (retrofit cost) facing the decision maker, for different utility functions, given independent costs.

emission pricing and technology support). The second (A and C) relates to faulty future expectations.

All cases except D always imply excessive energy consumption over the infrastructure's lifetime. In A–B it occurs in two complementary ways: excessive energy intensity upon establishment; and too frequent "business as usual" operation in period 2. Under C, infrastructure energy intensity is too high, while operation is not affected. Factor D is different: energy intensity of the infrastructure is less than optimal; while retrofit is used too infrequently which increases energy consumption. Our simulations indicate that these two factors often approximately balance out or (for low variances) raise overall energy consumption.

A–B are useful for understanding the likely magnitudes of distortions caused by incorrect energy prices. Table 1 sums up some results from our simulations given uncorrelated energy and retrofit costs (focusing on log and exponential utility functions).[32] We present three sets of figures, one set representing case A below, and two set representing case B (with both a high and lower rate of phase-out of energy consumption upon a retrofit).

Case A "Policy error ex ante only". Numbers here represent approximate values for excessive energy consumption due to the investment decision only being wrong, due to too low expectations about future energy prices. Our simulations show that when the true expected energy cost is 3 (4), while the applied value is 2, energy consumption is excessive by roughly 20–35 (30–60) percent. We here show values only for the case of full energy phase-out given retrofit ($\tau = 1$); but figures here are very similar for our alternative case of only partial phase-out ($\tau = ½$).

Case B "Policy error both ex ante and ex post". Results given $\tau = 1$ here are found in Fig. 4. A too low energy cost faces policy makers both ex ante (in expectation at the investment stage), and ex post (actually at the operation stage); thus adversely affecting both infrastructure investment, and retrofit. The expected overall error can then be far greater. In our illustrations, energy consumption is now excessive by 65–100% or more (given full phase-out of energy consumption upon retrofit: $\tau = 1$), when $Eq = 3$ is correct and the policy maker faces $Eq = 2$ both ex ante and ex post. When $Eq = 4$ is correct (while policy makers face $Eq = 2$), the error can be even far higher. When τ is ½ only, energy consumption differs less (only half as much) in period 2, between normal energy use and retrofit. A general feature of all the simulations is that higher uncertainties about energy and retrofit costs lead to less overall efficiency loss in the form of too high lifetime energy consumption for the infrastructure.[33] The reason is the generally benign effect of greater uncertainty in this context, as it leads to more states with relatively high energy cost, with energy phased out through retrofits; thus reducing overall expected energy consumption. Note here that while we present only the cases of variances equalling either 1 or 9, results are "smooth" in variances in the sense that figures in the tables vary smoothly and continuously as variances change.

Our discussion is only illustrative and has limitations. First, we assume that ex ante distributions of energy and retrofit costs are log-

[32] These formulations imply long-run demand elasticities for energy that are either equal to (log case) or less than unity (exponential case) in absolute value; which we here view as practically realistic cases.

[33] The simulations on which the case of $\tau = 1/2$ are based are not included in the paper; they can be obtained from the authors upon request.

Table 1
Relative policy error in percent resulting from a) incorrect ex ante expected Eq (=2); and b) in addition incorrect actually incurred Eq (=2) ex post, for different correct values for Eq. Table figures derived from numbers in Figs. 3 and 4.

Policy error type	Utility function specification	"Low" variances			"High" variances		
		$Eq = 2.5$	$Eq = 3$	$Eq = 4$	$Eq = 2.5$	$Eq = 3$	$Eq = 4$
Ex ante only, $\tau = 1$	Logarithmic	18	32	50	18	35	61
	Exponential	12	21	31	12	22	37
Ex post + ex ante, $\tau = 1$	Logarithmic	42	109	430	37	84	213
	Exponential	34	91	363	30	66	168
Ex post + ex ante, $\tau = ½$	Logarithmic	30	71	240	28	60	136
	Exponential	23	56	197	21	44	108

normal and known. Secondly, we consider only two periods, "the present", and "the future". This allows for only one decision point (at the start of period 2) beyond the investment stage. These assumptions were guided by tractability concerns. Extensions to three or more periods should however be pursued. Costs of energy, emissions and retrofits as well as the utility of infrastructure all evolve continuously making the two-period framework less relevant. Several retrofit times, and separate time developments for energy and retrofit costs, are relevant extensions.[34]

In our model, scaling of the infrastructure does not affect the ex post retrofit decision. Also, retrofit costs are assumed to be proportional to energy consumption, and to the share of energy phased out through retrofit. Project size then does not matter e.g. for the retrofit decision. This could be generalized. The ratio of retrofit to energy costs might decrease in project size (unit retrofit costs would be reduced for larger projects). Larger ex ante projects would then be favored more as these would permit more cost avoidance later on (through more frequent retrofits). It is less clear how overall energy consumption over the project's lifetime would be affected; the project scale-up, and more frequent retrofits, would work in opposite directions.

Concerning utility function, the log and exponential utility function appear as reasonable in implying constant price elasticity of demand, unitary or less in absolute value. Both imply constant relative risk aversion, a special case; and generalizations should be investigated.

List of symbols used in text, and Appendix A

H energy intensity of established infrastructure
$U(H)$ public utility of operated infrastructure given H
K capital cost of infrastructure development (constant)
T length of period 2 (length of period 1 = 1)
q_i unit energy (including environmental) cost in period $i = 1,2$
y retrofit cost in period 2
$F(q,y)$ bivariate simultaneous distribution of q and y
P_j ex ante probability of selecting operation alternative j for the infrastructure in period 2 ($j = 1$: regular operation; $j = 2$: retrofit; $j = 3$: closedown)
$y^* = U(H) / H$ utility per energy unit from operated infrastructure
Q expected unit operation cost for infrastructure
$EW(i)$ net ex ante utility from infrastructure, for both periods ($i = 1$), or in period 2 ($i = 2$).
$CH(2)$ ex ante expected energy cost of infrastructure per time unit, given normal operation
$CR(2)$ ex ante expected retrofit cost of infrastructure per time unit, given retrofit
$ch(2) = CH(2) / H$
ex ante expected energy cost for infrastructure per time unit and per unit of H
$cr(2) = CR(2) / H$
ex ante expected retrofit cost for infrastructure per time unit and per unit of H
ρ coefficient of relative risk aversion in public utility function
α shift parameter for shift in energy cost (in Appendix A)
β shift parameter for shift in retrofit cost (in Appendix A)
R R&D cost of retrofit technology development

[34] Such extensions are studied in Framstad and Strand (2013), where energy and environmental costs are assumed to evolve continuously over time. An additional issue then arises, namely that continuous development of costs produces an "option value" of waiting which serves to further delay the retrofit decision; and this effect is larger with greater uncertainty.

Appendix A. Further analytical results

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2014.10.002.

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