Subsidizing the Adoption of Energy-Saving Technologies

Analyzing the Impact of Uncertainty, Learning and Maturation[1]

Henri L.F. de Groot[a], Peter Mulder[b] and Daan P. van Soest[c]

[a] Vrije Universiteit, Amsterdam, Dept. of Spatial Economics, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands; hgroot@feweb.vu.nl

[b] Vrije Universiteit, Amsterdam, Institute for Environmental Studies, De Boelelaan 1115, 1081 HV Amsterdam, The Netherlands; peter.mulder@ivm.vu.nl

[c] Tilburg University, Dept. of Economics, P.O. Box 90153, 5000 LE Tilburg, The Netherlands; d.p.vansoest@kub.nl

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OCFEB
Room H6-20
Erasmus University Rotterdam
P.O. Box 1738
3000 DR Rotterdam
The Netherlands
Telephone +31 10 408 2430
Telefax +31 10 408 9173
E-mail info@ocfeb.nl
Website www.ocfeb.nl

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Abstract

As part of the Kyoto Protocol, many countries have committed themselves to substantially reduce the emission of greenhouse gases within a politically imposed time constraint. Investment subsidies can be an important instrument to stimulate the adoption of energy-saving technologies to achieve emission reduction targets. This paper addresses the impact of adoption subsidies on the amount of energy savings, taking into account both the endogenous and uncertain nature of technological progress. Neglecting these two characteristics of technological progress tends to result in overestimation of the short-run effectiveness of investment subsidies, whereas the long-run effects are ambiguous.

1. Introduction

Mitigation of global climate change asks for significant reductions in the emission of greenhouse gases. Under the Kyoto Protocol governments of most industrialized countries have taken a first important step in that direction by committing themselves to substantially reduce their countries' emissions within a specific time horizon. Hence, important questions arise concerning *how* and *when* to stimulate the adoption of, for example, energy-saving technologies (Grubb 1997, OECD 1999). Answering these questions requires insight in processes of technological change. The main characteristic of technological change is its inherent uncertainty, both in terms of the arrival of new varieties of a technology and their performance, where the rate of technological progress may be driven by, among others, learning effects (see, for example, David 1975, Dosi 1988, Grübler et al. 1999, OECD/IEA 2000). With respect to technology adoption, two major stylized facts are (i) the (at least partly) irreversible nature of investments[2] which, in combination with uncertain technological change, gives an incentive to postpone investments to limit the likelihood of regret (see for example Dixit and Pindyck 1994, Farzin et al. 1998, Pindyck 1991), and (ii) heterogeneity among firms or industries which results in the typical S-shaped diffusion patterns that we observe in reality (for example, Davies 1979, Jaffe and Stavins 1994, Stoneman 2001). The challenge for government technology policies is to develop policies aimed at achieving the macroeconomic or generic goals imposed by emission reduction targets, while taking into account these microeconomic characteristics that determine adoption behavior of individual firms.

In this paper, we analyze the effectiveness of investment subsidies in achieving emission reductions taking into account the stylized facts of technological change and technology adoption. We analyze the impact of uncertain technological progress by explicitly taking into account the option value of postponing the adoption (that is, the opportunity cost of immediate investment). We find that standard NPV analyses result in an incorrect assessment of energy savings, both in the short and long term. The reason is that under the assumption of stochastic rates of technological progress, the energy savings that are not achieved in the short run due to the postponement of the adoption, may be (more than) compensated in the longer run due to the adoption of a superior technology. This implies that granting subsidies that tend to speed up adoption may have an adverse impact on long-run energy savings. We analyze the sensitivity of these results for the nature of technological progress by allowing for different assumptions with respect to learning- or spillover effects, the success of innovation, the speed of quality improvement, the discount rate and the existence of (physical) upper bounds of a technology's energy-saving potential.

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2 Investments are said to be irreversible if not all costs associated with the technology adoption can be recouped. Two important sources of irreversibility are the installation costs, and the fact that the resale value of the machinery generally falls short of the purchase price.

The results are interesting from a policy point of view because of the politically imposed time constraints for emission reductions. Traditional investment theories (for example, Stoneman and David 1984) would suggest the presence of a 'double dividend' associated with subsidizing the adoption of energy-saving technologies that are subject to learning effects. Not only do subsidies induce (immediate) adoption to meet politically imposed targets, they also induce further technological progress since technology adoption induces the 'take off' of learning effects. In this paper we illustrate with a simple model that once uncertainty is recognized as an important investment decision parameter, a trade-off emerges between early adoption of relatively inferior technologies on the one hand and late adoption of relatively superior technologies on the other hand. These results translate directly into a trade-off between short- and long-run emission reduction targets.

There are several related articles on investment under uncertainty, in which learning plays an important role. However, our paper differs from that literature as we focus on the uncertainty of technological progress rather than, for example, output price uncertainty (e.g., Majd and Pindyck 1989) or investment cost uncertainty (Purvis et al. 1995), and specifically acknowledge industry heterogeneity (compare with Alvarez and Amman 1999). Similar to Balcer and Lippman (1984), technology adoption in our model occurs if the technology lag exceeds a certain threshold. Apart from learning, we do not consider other types of firm interactions (compare with Choi 1994 who incorporates network externalities) and we also ignore explicit non-convexities in environmental damages that necessitate adoption as do Dosi and Moretto (1997).

The set-up of this paper is as follows. In section 2 we develop a simple model that captures the essence of investment under technological uncertainty. In section 3, we derive optimal adoption behavior with and without ignoring the option value of postponement. We analyze the consequences of uncertainty for optimal investment behavior in terms of cumulative energy savings. Section 4 assesses the effects of subsidy schemes on the diffusion of technologies. We analyze the sensitivity of the model in terms of cumulative energy savings by allowing for different assumptions with respect to the nature of technological progress. Section 5 concludes.

2. The model

We model a simple economy with $\overline{N}$ firms that can potentially benefit from the adoption of a specific technology in terms of reducing the amount of energy used. Over time, better vintages (indexed i) of that technology become available (with identical purchase price K).[3] To model irreversibility, we simply assume that firms can invest only once (see Farzin et al. 1998 for a more general model allowing for multiple investments). This is clearly an extreme case of an irreversible investment, but the qualitative results of the model spill over to other cases where investments are at best partially reversible (for example, when there are scrap markets for obsolete technologies), or when firms are allowed to invest more than once.

Vintage i can provide a maximum amount of per-period energy savings (measured in monetary terms) equal to R_i. We assume that firms (indexed $n = 1,..., \overline{N}$) are able to only reap a fraction (between zero and one) of the maximum potential energy savings, and that that fraction is firm-specific (i.e., $0 < q_n \leq 1$). In addition, we assume that firms can be ranked according to that parameter $q_n(n)$ with $\partial q_n / \partial n < 0$. In other words, all else equal, firm number 1 $(\overline{N})$ is most (least) likely to adopt the technology as its per-period monetary savings from the adoption of vintage i are equal to R_i (close to zero). The technology has an infinite life time and its performance, once adopted, does not change over time. Therefore, there is no uncertainty with respect to a new vintage's performance as soon as it is adopted, and hence the discounted value of the instantaneous profit stream from adopting vintage i for firm n can be defined as:

(1) $$V_n(R_i) = \int_{t=0}^{\infty} q_n R_i e^{-rt} dt = \frac{q_n R_i}{r},$$

where r is the (exogenous) discount rate.

Following Farzin et al. (1998) we assume that in each short period dt, there is a certain probability that a new improved vintage of the technology is discovered. Assuming a jump process, let the likelihood of a discovery in that very short period be denoted by $l_t dt$, and the actual size of the jump by u_t. Then technological improvement can be modeled as follows:

(2) $$dR_t = \begin{cases} u_t \text{ with probability } l_t dt \\ \text{O with probability } 1 - l_t dt. \end{cases}$$

To model endogenous technological progress through (external) learning-by-doing, we assume that the likelihood l_t of a new improved variety being discovered consists of an exogenous part (l_0) and a part that is an increasing function of the number of firms that have already adopted the technology (N_t):

[3] For simplicity, we assume that all new varieties of the technology require the same gross investment expenditures (K). If we assume that there is a scrap market for old technologies, K should be interpreted as the *net* adoption cost, that is, the costs of adopting the new technology minus the scrap value of the old one. The arrival of new technologies may cause the price of older technologies to decrease. This effect is ignored.

(3) $l_t = l(N_t, l_0)$,

with $\partial l / \partial N > 0$ and $\partial^2 l / \partial N^2 < 0$. This formulation captures the idea that the probability of the arrival of an improved version of the technology increases with the number of firms that is using it, representing a learning effect that is external to each individual adopter.[4] In other words, only those firms that have not yet adopted the new technology can reap the returns of improvements of technological performance: early adopters generate a positive externality to all other firms that are considering to purchase the technology (Kapur 1995). The underlying mechanism may be via the producer being informed through feedback from early adopters. Essentially, this reinforces the irreversible nature of adoption decisions and emphasizes the existence of lock-in effects. Furthermore, we assume that external learning-by-doing occurs at a decreasing rate due to the increased probability of duplication.

In addition to uncertainty associated with the timing of the emergence of new, improved vintages, we assume that the improvement itself is also *ex ante* uncertain. We formalize this by assuming uncertainty with respect to the size of the jump in energy efficiency. Furthermore, we assume that there is a maximum feasible efficiency for the technology (denoted by $\overline{R}$), and that the actual improvement of the technology in terms of new vintages is a decreasing function of the quality the technology already attained. In other words, we assume that a technology matures over time:

(4) $\overline{u} = u(R_t, \overline{R})$, with $\partial u / \partial R < 0$,

where $\overline{u}_t$ represents the maximum possible increase in the quality of the technology at time *t*. Given the range of possible jumps $< 0, \overline{u}_t]$, we assume for the time being that the realized technological improvement is uniformly distributed over the interval, and hence the associated density function can be defined as follows:

(5) $$f(u_t) = \begin{cases} \dfrac{1}{\overline{u}_t} & \text{for } 0 < u_t \le \overline{u}_t, \\ 0 & \text{otherwise.} \end{cases}$$

The firm's decision process can now be summarized as follows. In each period, until the investment is actually made, the firm has to decide whether it is going to invest or postpone the decision to invest to the next period. When exercising the option to adopt, the firm gets the pay-off $V_n(R_i)$ (that is, the present value of the profit stream as defined in equation 1) and pays the net adoption cost which equals the investment cost (K)

4 We thus ignore learning-by-using, which is the effect that adopters themselves gain experience with the use of the particular technology and hence realize a quality improvement and/or a cost reduction at the plant level (Rosenberg 1976).

minus the amount of subsidies received (S). Using (1), firm n's net present value of the decision to adopt vintage i, $\Omega_n(R_i)$, is given by:

(6) $$\Omega_n(R_i) = V_n(R_i) - (K - S) = \frac{q_n R_i}{r} - (K - S).$$

This value is often referred to as the 'termination value' of the option to adopt. If the investment is perfectly reversible, firms will invest whenever the termination value is positive (and hence the simple NPV rule applies). If investments are, however, not perfectly (and costlessly) reversible, having adopted a particular vintage can give rise to regret in future periods if new vintages arrive that outperform the purchased version. Therefore, the firm has to take into account the option to postpone the investment decision to future periods. The value of postponing the investment for a very short period dt is the difference between the termination value (as given by (6)) and the (discounted) value of the investment option as evaluated in that next period, which includes the expected capital gain in the form of the arrival of a new improved version of the technology. This latter value is usually referred to as the 'continuation value', which for the n^{th} firm can be written as follows:

(7) $$F_n(R) = \frac{1}{1 + rdt} E[F_n(R + dR)].$$

The difference between (7) and (6) is the option value of postponing the investment. In each period, the firm compares the termination value of the option to adopt in (6) with the continuation value given by (7). The opportunity costs of postponing adoption at time t are foregone profits associated with the fact that the best available technology at that time is not implemented. They increase over time because of ongoing technological progress, and hence the termination value will dominate the continuation value at some future point in time. Hence, for each firm there exists a critical technological quality or savings potential, denoted R_n^*, at which the firm is indifferent between investing and postponing. Adoption occurs as soon as the actual savings exceed that critical value.

To illustrate the basic mechanisms of the model, we turn in the next section to a simplified version of the model that highlights the importance of accounting for technological uncertainty. The implications of the learning-by-doing effects and the technological maturation are postponed to Section 4.

3. The impact of uncertainty on technology adoption

In order to illustrate the effect of taking into account the impact of stochasticity with respect to the rate of technological progress on adoption behavior, we simplify the model described in the previous section by assuming the rate of technological progress to be exogenous (i.e., there is no learning by doing), and by assuming that there is no physical limit with respect to the energy-saving benefits (i.e., there is no maturation). Technically, we specify equations (3) and (4) as $l_t = l_0$ and $\bar{u}_t = \bar{u}$, respectively. Hence, the process of technological progress (2) can be written as:

(2’) $$\mathrm{d}R = \begin{cases} u \; with \; probability \; l_0 dt \\ 0 \; with \; probability \; 1 - l_0 dt, \end{cases}$$

and the associated density function (5) as

(5’) $$f(u) = \begin{cases} \frac{1}{\overline{u}} & \text{for } 0 \le u \le \overline{u}, \\ 0 & \text{otherwise.} \end{cases}$$

Equation (5’) implies that the expected technological jump equals $\overline{u}/2$. For analytical tractability, we explicitly specify the fraction of the benefits of adoption that can be captured by firm *n* as:

(8) $$q_n = \frac{1}{2} - 4\left(\frac{2n - \overline{N}}{2\overline{N}}\right)^3.$$

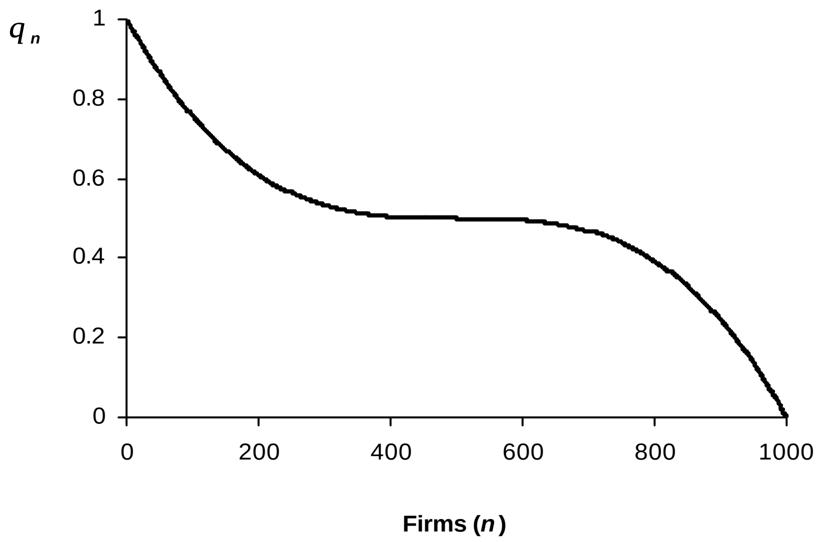
This specification of the benefit parameter q_n implies a non-uniform distribution of benefits from adoption among firms. The distribution is chosen such that the majority of the firms is located around the middle of the distribution space. These firms are characterized by an ‘average’ benefit from adoption. A minority of the firms is located at both ends of the distribution space. These firms either face ‘large’ or ‘small’ benefits from adoption. Figure 1 illustrates this: firms with a low index (*n*) benefit relatively much from adoption (and vice versa), while the majority of firms is clustered around the 'average' benefit from adoption.

To solve the model, we follow Farzin et al. (1998) and determine the critical quality of the technology (R_n^*) by equating the continuation and the termination value (equations 7 and 6, respectively); see Appendix A for technical details. This critical quality of the technology at which firm *n* will exercise its option to adopt equals:

(9) $$R_n^* = \frac{r(K - S)}{q_n} + \frac{1}{2}\frac{l\overline{u}}{r}.$$

This expression reveals that the critical technology level in the presence of uncertainty is equal to the critical technology level in the (theoretical) case that firms simply apply the standard Net Present Value rule (the first term on the RHS of equation 9),[5] *plus* a factor that is associated with uncertainty (the second term on the RHS). Technologies that are profitable from a NPV-perspective are thus not necessarily profitable when taking into account uncertainty. Evidently, the higher the expected capital gains (as a result of either a higher likelihood of technological progress $\bar{l}$, or because of larger expected improvements $\bar{u}/2$), the better the critical performance of the technology should be in order to trigger adoption.

Figure 1. Benefits of adoption for firm n (n=1, …, $\bar{N}$ =1000)



In the absence of learning effects, we can derive an analytical solution for the number of firms that has adopted at a particular point in time as a function of the quality of the technology at that time (R_t). When firms are assumed to apply the NPV-rule (see footnote 5), the number of firms that has adopted at time t can be determined by combining equation (8) and R_n^{NPV}. This yields:

$$(10) \qquad N_t^{NPV} = \frac{\bar{N}}{2} + \bar{N}\sqrt[3]{0.25\left(0.5 - \frac{r(K-S)}{R_t}\right)}.$$

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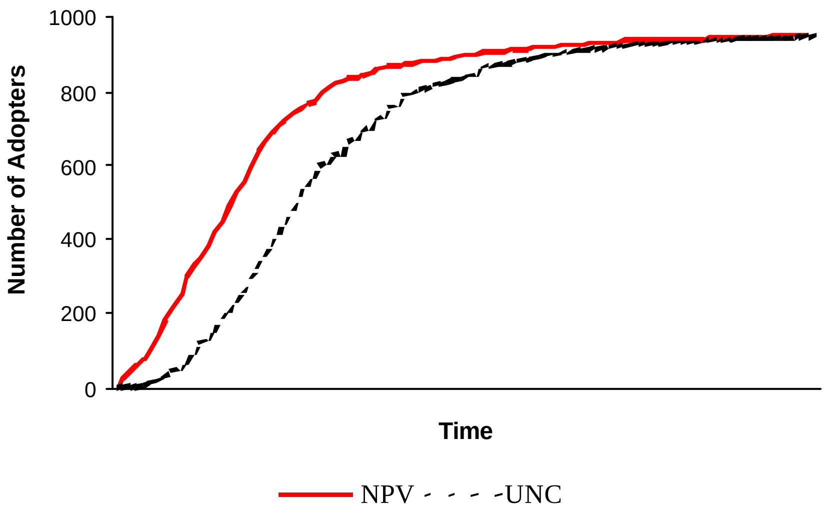
5 In a world without irreversibility, the appropriate decision criterion is the standard NPV rule, which says that investment should occur as soon as the (expected) net present value of adoption is positive. This holds if $\Omega_n(R_i)$ (equation 6) is larger than or equal to zero. The NPV criterion thus equals $R_n^{NPV} = r(K-S)/q_n$.

When investments are irreversible and firms take uncertainty into account, the number of adopters at time t can be found by combining equations (8) and (9):

$$N_t^{UNC} = \frac{\overline{N}}{2} + \overline{N}\sqrt[3]{0.25\left(0.5 - \frac{r(K-S)}{R_t - 0.5\overline{l}\,\overline{u}/r}\right)}. \qquad (11)$$

For illustrational purposes, we have taken a set of parameter values and conducted a Monte Carlo simulation with 1000 runs based on random draws from the distributions of the uncertain parameters u and l.[6] Figure 2 depicts the diffusion path of the technology, averaged over the 1000 simulation runs. It illustrates that adoption lags behind when firms take into account uncertainty about technological progress in their investment decisions.

Figure 2. Diffusion paths of the technology in the case of investment under uncertainty (UNC) and investment under the standard Net Present Value rule (NPV).



The consequences of these different diffusion patterns that reflect differences in adoption behavior for aggregate energy savings are illustrated in Figures 3a-c. The Figures depict the per-period energy savings (measured in monetary terms) that are achieved under the two investment rules for three different levels of technological

[6] The following parameter values were used: $\overline{u} = 0.03$, $\overline{l} = 0.3$, $R_0 = 0.1$, $\overline{N} = 1000$, $K = 1$, $S = 0.3$ and $r = 0.1$. We refer to these values as the baseline scenario.

sophistication. The upward-sloping curves depict the critical savings level (on the vertical axis) that triggers the investment for each firm type *n* (ranked on the horizontal axis according to decreasing net benefit from adoption). As is clear from equation (9), R_n^* is an increasing function of *n* (as q_n is decreasing in *n*), and the critical value taking into account uncertainty strictly exceeds the critical value based on the NPV criterion alone (the difference being $l\bar{u}/2r$). Therefore, as technology progresses (*R* increases along the vertical axis), one by one firms will adopt, depending on the fraction of the benefits they can reap.

Figure 3. Per-period energy savings for different investment rules. (a) Infant Technology, adoption only under NPV rule, (b) Technology has progressed, different levels of adoption under NPV and uncertainty rule and (c) Mature technology, all firms have adopted.

Figure 3a

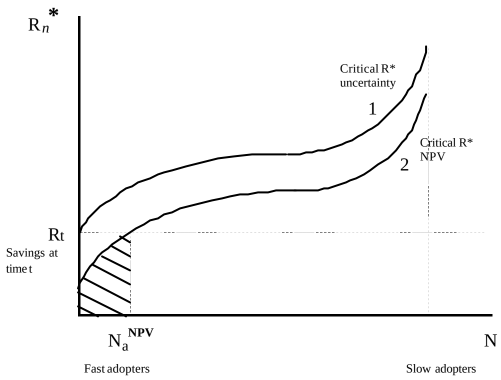


Figure 3b

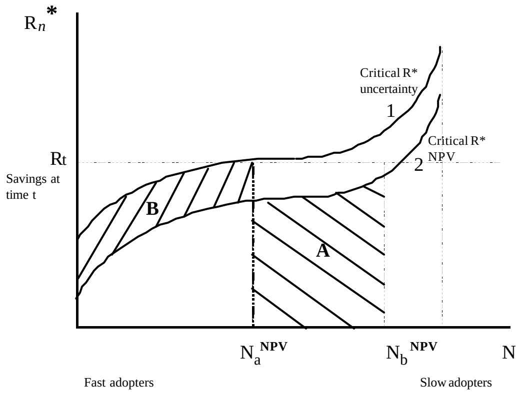
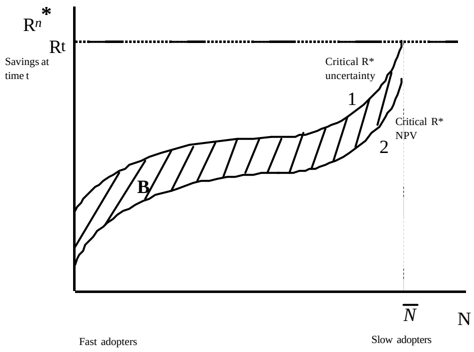


Figure 3c



In Figure 3a, the technology is still in its infancy; the amount of energy saved by the technology (R_t) is fairly low. The level of technological quality is not sufficient to trigger investment by adopters that take uncertainty into account, and their total savings (at one period in time) are thus zero in this instance. The number of firms that invest when they behave according to the NPV rule is positive and equals N_a^{NPV}. The per-period savings are then equal to the shaded area under curve 2. In Figure 3b, the technology has improved somewhat further. In case firms take into account uncertainty, the number of adopters equals N_b^{UNC}, whereas the number of adopters when firms behave according to a NPV rule is N_b^{NPV}. The difference in savings between the two 'regimes' can be calculated by subtracting surface A from surface B in Figure 3b. The net result denotes the additional savings when firms invest according to a NPV rule *as compared to* investment under uncertainty. At initial stages of technological progress (where energy savings are fairly low), this difference is positive. However, when the technology further improves, the difference becomes negative. The extreme of this final stage is depicted in Figure 3c, in which the technology has progressed to the extent that all firms have found it profitable to adopt the technology under consideration, independent of the adoption criterion used. In that case, the total savings in the regime where firms invest taking into account uncertainty unambiguously exceed the savings in the regime where firms invest according to an NPV-rule. This is caused by the fact that although the former type of firms that takes into account uncertainty adopts at a later point in time, they also adopt relatively better technologies.

The fact that adoption lags behind when firms take into account uncertainty about technological progress in their investment decisions, is thus not necessarily bad from an energy-saving point of view. In the longer run, total energy savings will increase due to the adoption of improved technologies. In other words, neglecting the effects of uncertainty on the adoption behavior of firms results in an overestimation of short-run energy savings while long-run energy savings tend to be underestimated.

4. The effectiveness of subsidies

So far, we have ignored the role of learning effects and the possibility of technological maturation. In this section, we relax these conditions and analyze the impact of adoption subsidies on (i) the timing of adoption and (ii) aggregate energy savings over time while taking into account learning and maturation. For tractability, we numerically analyze these effects by comparing the results for a low and a high subsidy level.

In order to be able to perform a numerical analysis, we need to specify the probability of the arrival of a new vintage and the size of the jump as described in equations (3) and (4). The likelihood of a technological improvement (l_t) is specified as:

(3') $$l_t = l_0 + aN_t^{\,b} \ .$$

This formulation captures the idea that the probability of a technological improvement increases with the number of firms using that technology. This represents the learning effect. We assume that learning occurs at a decreasing rate due to the increased probability of duplication (β<1). The maximum size of the improvement of the technology is specified as:

(4') $$\bar{u}_t = \bar{R} - gR_t \ .$$

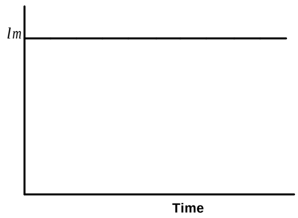
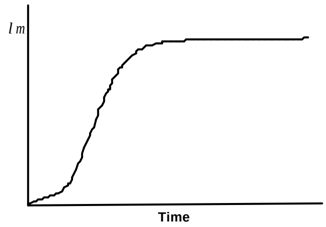
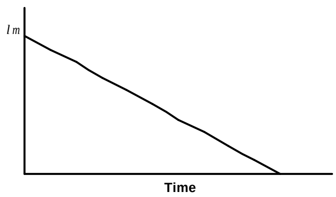
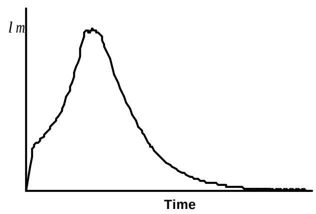
The technology has thus matured when $R_t = \bar{R}/g$. At that level, uncertainty regarding technological progress is completely absent.

Totally differentiating the number of adopters at each point in time (N_t) as defined in equation (11) with respect to the subsidies, we find that subsidies unambiguously speed up the diffusion process. The effect of subsidies on the level of aggregate energy savings is, however, ambiguous. Although subsidies speed up adoption and thus increase short-run energy savings, accumulated energy savings can be negatively affected since earlier adoption also implies adoption of relatively inferior technologies. Since we assume that firms invest only once, high subsidies may thus contribute to the occurrence of a lock-in that is not optimal from a policy perspective. Putting the argument the other way around: a low subsidy level leads, ceteris paribus, to a relatively slow diffusion of energy-saving technologies, but therefore also to the adoption of relatively better technologies. As a result, accumulated energy savings can be positively affected by low subsidies in the longer run since low subsidies can avoid a lock-in into inferior technologies.

To illustrate this, we conducted again a series of Monte Carlo simulations with 1000 runs based on random draws from the distributions of the parameters u and λ. We analyzed aggregate energy savings over time for two different subsidy levels: a low and a high one. In order to analyze the robustness of the results for specific parameter values, we conducted an extensive sensitivity analysis with respect to a (the degree of learning), r (the discount rate), g (the speed of technology maturation), l_0 (the exogenous arrival of new technologies; innovation success) and $\overline{R}$ (the level of maturation).

Depending on the assumptions regarding technological maturation and learning, we can distinguish four versions of the model. Each version is characterized by a specific pattern of expected technological improvement. The four possibilities are depicted in Table 1.[7]

Table 1. Expected technology improvement under four different assumptions with respect to the parameter values

	Exogenous technical change $\alpha = 0$	Endogenous technical change $\alpha > 0$
Non-maturation $\gamma = 0$	 A	B 
Maturation $\gamma > 0$	C 	D 

Quadrant A reflects the simple version of the model in which maturation and learning are neglected. One can think here of a small open economy in which innovations take place abroad, and are thus exogenous to the domestic country, whereas domestically no knowledge spill-overs occur. In this case the *expected* technological improvement is constant over time since both l and u are exogenous and constant. This is the case that was discussed in section 3. In quadrant B learning is introduced, while technological quality is still unbounded. This implies that u_t is constant, while l_t is a positive function

[7] We used the baseline scenario (see footnote 6) and put $\alpha = 0.03$, $\beta = 0.75$ and $\gamma = 0.03$.

of the number of adopters (see equation 3'). The technology is expected to improve at an ever faster rate as long as the number of adopters increases, but as soon as the model converges to the steady state, expected technological improvement becomes constant. The steady state is characterized by a situation in which all firms have adopted the technology ($N_t = \overline{N}$). Quadrant C depicts the pattern of technological improvement in the absence of learning, but with bounded technological improvement. Now, l_t is constant while u_t is a decreasing function of the quality of the technology (R_t) already attained (see equation 4'). A steady state will be reached with a constant number of adopters that is potentially smaller than $\overline{N}$, a constant technological quality, and no uncertainty regarding technological progress. Finally, the hump-shaped pattern in Quadrant D results from the combination of learning and maturation. An increase in the number of adopters results in an increasing probability l_t of a technology improvement. On the other hand, the resulting increase in the quality of the technology implies a decline in the remaining potential for further improvement. For reasonable parameter values, the second effect starts to dominate the first effect after a while, leading to the hump-shaped curve. A steady state will be reached that is qualitatively similar to the steady state described in the former case (Quadrant C).

We will now discuss the effects of subsidies on aggregate energy savings for the different cases that can be distinguished. Extensive sensitivity analysis for different parameter values has shown two possible outcomes of the model:

1. A high subsidy leads to a relatively *high* level of aggregate energy savings in both the short and the long run. In this case, the effect of the higher number of adopters caused by the higher subsidy – which we further refer to as the Scale Effect – dominates the low average quality of the adopted technologies associated with higher subsidies (further denoted as the Quality Effect). This case is illustrated in Figure 4;
2. A high subsidy leads to a relatively *high* level of aggregate energy savings in the short run, but to a relatively *low* level in the long run, since the slow adoption under a low subsidy regime is compensated by the adoption of relatively better technologies in the long run. So, in this case, the Scale and Quality Effects compete with each other, which results in a trade-off between the short- and long run (see Figure 5).

Figure 4 The Scale Effect

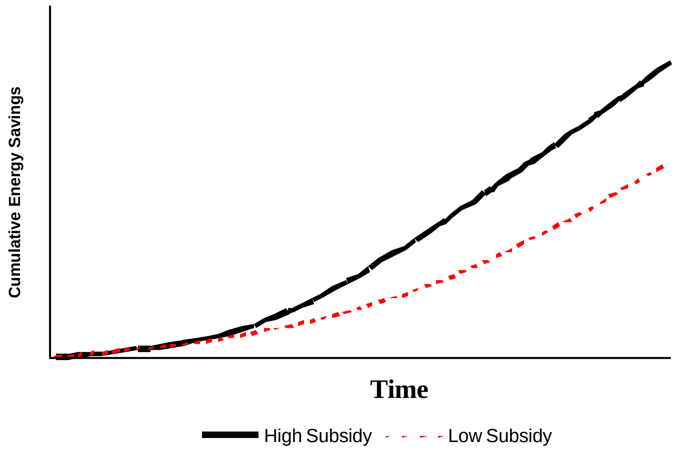
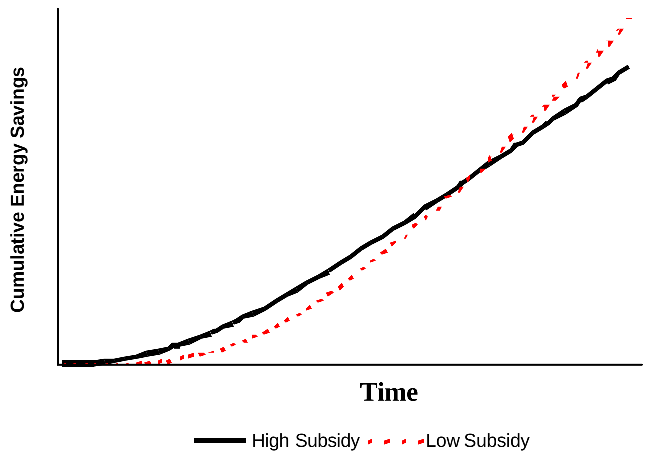
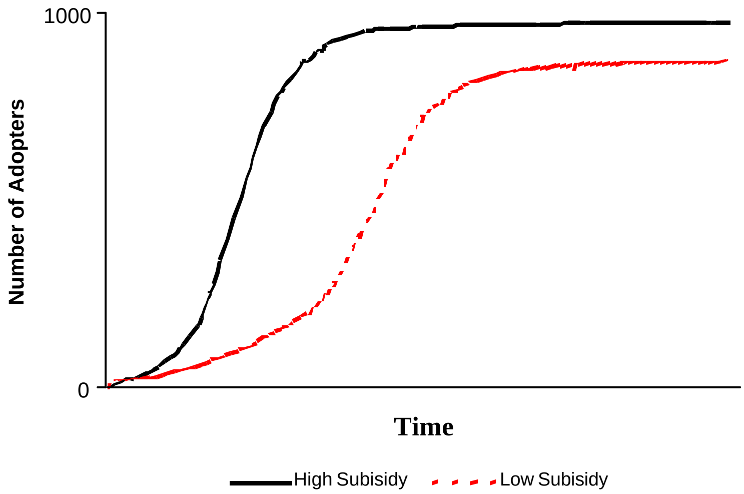


Figure 5. Trade-off between short- and long-run energy savings due to the opposed impact of the Scale and Quality Effects



The Scale Effect can only dominate in the long run if the technology matures over time. In the absence of maturation, all firms adopt the technology in the long run since the unbounded technological improvement assures that in the end even for the last firm – which has lowest benefit from adoption (see Figure 1) – the quality of the technology exceeds its critical level as defined in equation (9). When we allow for technological improvement to be bounded from above, at the time of maturation of the technology a stationary situation can arise in which not all firms have adopted the energy-saving technology (see Figure 6).

Figure 6. Number of adopters if technology matures.



The reason for this is that for a number of firms – those with a low benefit from adoption – the quality of the technology does not exceed the critical quality they face. A high subsidy scheme then results in relatively more firms adopting the energy-saving technology, since subsidies decrease the critical technology level (see equation 9). This Scale Effect can outweigh the effect associated with the adoption of relatively inferior technologies. The obvious condition for the latter to occur is that in the steady state the number of adopters under a high subsidy regime is sufficiently larger than the number of adopters under a low subsidy regime.

The series of Monte Carlo simulations we performed proved that this condition is met if we have a relatively slow diffusion process in the absence of subsidies. This is intuitively clear as slow diffusion reduces the chance that the Quality Effect starts to dominate. Diffusion is relatively slow if we have, ceteris paribus, a low learning rate (a), a high speed of exogenous arrival of new technologies (l_0), a high level of exogenous maturation (u_0), a high discount rate (r) or a fast speed of maturation (g). To see this, recall that equation (9) implies that an increase in expected technology improvement ($l\bar{u}$) or discount rate (r) will raise the critical technology level. This slows down adoption since the quality of the technology should be higher to trigger adoption. Intuitively, when large technological improvements are to be expected, firms postpone adoption. The same arguments hold for a high value of g : large jumps in technological improvement lead to a delay in adoption since better technologies can be expected within short time. A low learning rate implies that late adopters reap only limited benefits from early adopters' experience, as a result of which technological improvement is relatively slow. In sum, if parameter values are chosen such that diffusion is relatively slow in itself, then subsidies can play an important role in stimulating adoption and the resulting increase in the number of adopters can be sufficiently large to compensate for the relatively inferior technologies adopted.

If parameter values are chosen such that diffusion is relatively fast in absence of subsidies, the number of additional adopters due to a higher subsidy is limited and is not necessarily sufficient to outweigh the negative effect of adopting relatively inferior technologies. This leads to the dominance of the Quality Effect: increasing subsidies do have a beneficial effect on energy savings in the short run, but a negative effect in the long run due to the lock-in in technologies of a relatively inferior quality. We summarize these results in Table 2.

Table 2. Effect of subsidies on aggregate energy savings under four different assumptions

	Exogenous technical change $\alpha = 0$	Endogenous technical change $\alpha > 0$
Non-maturation $\gamma = 0$	*Quality Effect* A	B *Quality Effect*
Maturation $\gamma > 0$	C *Scale Effect* / *Quality Effect*	D *Scale Effect* / *Quality Effect*

In sum, investment subsidies are most effective if they stimulate aggregate energy savings while avoiding a lock-in in inferior technologies. In the context of our simple model, this criterion is most likely to be fulfilled if the diffusion process is slow in the absence of subsidies. In this situation, subsidies significantly increase the number of adopters and thereby aggregate energy savings, while a lock-in in inferior technologies is likely to be avoided. The reasons for a slow rate of adoption can be various: a low degree of knowledge spill-overs, a high discount rate, or the expectation of significant technological improvements in the (near) future.

5. Conclusions

Governments of many industrialized countries have committed themselves to achieving a certain level of greenhouse gas emission reduction within a certain short period of time. There is a plethora of available energy-saving technologies, ranging from new technologies where efficiency improvements are still possible (and subject to learning effects) to more mature technologies where the level of efficiency is more or less fixed. Subsidizing technology adoption induces investments because of increased profitability. However, the state of the technologies is not fixed: generally, their performance improves over time while the speed and extent of the improvements is uncertain.

To analyze the effects of uncertainty, the nature of technological progress and subsidies on adoption behavior in both the short and the long run, we developed a model integrating insights on technology adoption and investment behavior under uncertainty. A first result that we derived is that neglecting the effects of uncertainty on investment behavior results in an overestimation of short-run savings and an underestimation of long-run savings. Subsidies were shown to raise the speed at which firms adopt. This unambiguously fosters energy savings in the short run. In the longer run, however, account has to be taken of the quality of the technologies that are being adopted. The delayed response of firms receiving a low subsidy results in – on average – the adoption of better technologies. In the long-run, this quality effect may dominate the short-run effect of increased adoption of technologies in terms of the level of aggregate energy savings. In other words, increasing investment subsidies for energy-saving technologies can be counterproductive from a policy perspective as they may favor a lock-in into relatively inferior technologies.

These results are shown to depend on the nature of technological progress. We derived that in the presence of endogenous technological change, a high subsidy scheme may yield relatively high accumulated energy savings despite the fact that on average relatively inferior technologies are adopted. The reason lies in the (external) learning effect. Firms that have adopted the technology generate knowledge on how to improve the technology and these returns to learning accrue to firms that have not yet adopted the technology. As a result, the technology improves over time and ultimately matures. At the time of maturation of the technology a stationary situation arises in which not all firms have adopted the technology. A high subsidy scheme stimulates adoption in both the short and long run resulting in a relatively high number of firms that has adopted the technology, also when it has matured. It is shown that this 'Scale Effect' can outweigh the effect associated with the adoption of relatively inferior technologies in terms of accumulated energy savings. In conclusion, the politically imposed time constraints for realizing greenhouse gas emission reductions have induced policy makers to increase investment subsidies to stimulate the adoption of energy-saving technologies. The answer to the question whether this is a beneficial strategy in terms of accumulated energy savings depends crucially on the endogenous nature of technological progress and the degree of uncertainty.

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Appendix A: Solution of the model

To solve the model, we follow Farzin et al. (1998) and calculate the continuation value (7). The expected increase in the value of the option to adopt is a function of the exogenous rate of technological progress ($\bar{l}$) and the maximum jump size ($\bar{u}$). These parameters are exogenous to individual firms. If a new vintage of the technology becomes available, the question is whether it will trigger adoption. Clearly, the probability of adoption depends on both the critical value of energy savings that triggers adoption (R_n^*, which needs to be determined) and the current state of the technology in terms of energy savings, R. The improvement will trigger adoption if the jump in the quality of the technology is sufficiently large $\left(R_n^* - R < u \leq \bar{u}\right)$, whereas no adoption will take place if the jump in quality is relatively small $\left(0 \leq u \leq R_n^* - R\right)$. The probabilities of these cases to occur can be determined using equations (2') and (5'). This yields:

(A1) $$E\left[F_n(R+dR)\right] - F_n(R) = l\,dt\left\{\int_{u=0}^{R_n^*-R} \frac{1}{\bar{u}} F_n(R+u)du + \int_{u=R_n^*-R}^{\bar{u}} \frac{1}{\bar{u}}\left(\Omega_n(R+u)\right)du - F_n(R)\right\}.$$

The first term between brackets on the right-hand side (RHS) of (A1) reflects the expected value of continuation if the jump in the quality of technology is relatively small. If this jump (which occurs with likelihood $l dt$) is relatively small, the technology parameter will not exceed the critical value R_n^* after the jump, the investment option is kept alive and the decision to invest is postponed. The second term between brackets on the RHS reflects the expected termination value: if the improvement in the technology is relatively large, the option to invest is executed. Combining equations (A1) and (7) yields the value of the option to adopt as a function of the quality of the technology under consideration:

(A2) $$F_n(R) = \frac{l}{r+l}\left[\int_{u=0}^{R_n^*-R} \frac{1}{\bar{u}} F_n(R+u)du + \int_{u=R_n^*-R}^{\bar{u}} \frac{1}{\bar{u}}\left(\Omega_n(R+u)\right)du\right].$$

By definition, at $R=R_n^*$, investing is optimal after the next jump. Substituting $R=R_n^*$ into equation (A2) and using (6), we find:

(A3) $$F_n\left(R_n^*\right) = \frac{l}{r+l}\left[\int_{u=0}^{\bar{u}} \frac{1}{\bar{u}}\left(V_n\left(R_n^*+u\right) - (K-S)\right)du\right] = \frac{l}{(r+l)}\left[\frac{q_n}{r}\left(R_n^* + \frac{1}{2}\bar{u}\right) - (K-S)\right].$$

In the optimum it must hold that at the critical technology level, the value of the adoption project for the n^{th} firm is equal to its termination value:

(A4) $$F_n(R_n^*) = \Omega_n(R_n^*).$$

Combining equations (A3) and (6), we derive equation (9) in the main text.