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The political economy of technology support:

Making decisions about CCS and low carbon energy technologies

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Abstract

This article reviews the political economy of government choice around technology support for the development and deployment of low carbon emission energy technologies such as CCS. It is concerned with how governments should allocate limited economic resources across abatement alternatives. In particular, it explores two inter-related questions: first, should government support focus on a narrow range of options, or instead be distributed across many potential alternatives?; and second, what criteria should be considered when deciding which specific technologies to support? It presents a simple economic model with experience curves for CCS and renewable energy technologies to explore the lowest cost alternatives for meeting an emission abatement objective. It then goes on to explore a variety of economic and political factors that need to be considered when government decisions about technology support are taken.

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1. Introduction

Reducing greenhouse gas emissions sufficiently and fast enough to limit global warming to 2 – 2.5^{o}C over this century is a tough challenge that at the international level is likely to require a portfolio of technology options including carbon capture and storage (CCS), renewable energy, nuclear power, and improved energy efficiency. There is significant uncertainty with regard to how fast and how much each of these technologies can contribute to closing the vast gap between business-as-usual emissions and the required low-emission path, and how much government support this would entail (Stern, 2007; Sandén and Azar, 2005). Part of this complexity is limited knowledge about the rate of technological progress and learning-by-doing effects across the technology alternatives. Additional uncertainties relate to the nature of future climate policy regimes and associated emission allowance prices. Thus a number of challenges confront a government making decisions on how to distribute support across a portfolio of climate mitigation technologies.

This article reviews the political economy of government choice around technology support for the development and deployment of low carbon emission energy technologies such as CCS. It is concerned with how governments should allocate limited economic resources across abatement alternatives. In particular, it explores two inter-related questions: first, should government support focus on a narrow range of options, or instead be distributed across many potential alternatives?; and second, what criteria should be considered when deciding which specific technologies to support?

The argument is divided into four sections: the first provides an overview of the issue of technology support and CCS; the second presents a simple model that facilitates the exploration of linkages among a number of economic factors related to low carbon investment strategies; the third broadens the analysis to include other issues that influence government choice; and the final section draws together the economic and political dimensions, presenting the conclusions and some modest recommendations for policy makers.

2. Carbon Capture and Storage and the political economy of technology support

It is now widely accepted that substantial government support -- above and beyond favorable framework conditions created by the imposition of a price on carbon emissions -- is required to encourage the development and deployment of low carbon emission technologies (Stern, 2007; OECD and IEA, 2008). A strict climate policy regime including a gradually increasing CO_2 price (through a carbon tax or cap and trade system) can encourage a growing market for clean energy technologies. But there is a substantial challenge to reduce costs and encourage the uptake of climate-friendly technologies in a timely fashion. Investments in innovation -- for example, the establishment of large scale CCS demonstration plants -- can be both costly and risky, and this suggests an important role for government (Stern, 2007; OECD and IEA, 2008; Sandén and Azar, 2005). In many developed countries governments have already established subsidy regimes (including R&D support, feed in tariffs, and infrastructure support) to accelerate the emergence and uptake of clean energy technologies.

From an economic perspective, there are several reasons why government support for climate-friendly technologies makes sense. The first is related to positive spillover effects. The idea is that private investments in climate-friendly technologies will be too low from society's perspective, since individual investors do not consider the benefits from technology improvements reaped by others (Smolny, 2000). The second reason is due to uncertainty and risk attitude. Private investors tend to be risk averse, whereas a government strategy can be risk neutral due to the size and scale of government operations (Arrow and Lind, 1970; Holt and Laury, 2002). Given significant uncertainty linked to investments in climate-friendly technologies the difference in risk attitude may imply that private investments in such technologies are too small as seen from the societal perspective. Moreover, the higher discount rate typically employed by the private sector (implying that private investors more strongly prefer immediate to delayed returns) may depress investment below the optimum societal level (Hussen, 2004).

Political considerations also suggest that government action (including regulatory injunctions and/or financial support) above and beyond carbon pricing is necessary. In the first place, a variety of political factors (including feedback from voters and businesses) may keep the carbon price below the level required to induce rapid innovation (for example, through maintenance of a low tax rate or issuance of too many emissions allowances). Moreover, institutional 'lock-in' of established technologies (resulting from co-adaptation of dominant technical regimes with regulatory structures, education and research establishments, and other economic sectors) may pose additional barriers to change (Geels, 2005; Carrillo-Hermosilla, 2006).

Yet if governments are to provide such support for emerging technologies they face a series of vexing questions about how this should be carried out in the context of the particular conditions confronting their jurisdictions, and the uncertainty of future technological potentials. There are in particular four key issues that relate to: (a) the *concentration* or dispersion of investments; (b) the *selection* of particular technologies to support; (c) the *level* of support (overall and for each technology); and (d) the *policy instruments* appropriate to deliver this support. This article concentrates on the first two of these questions.[3]

With respect to the concentration or dispersion of investments the issue turns on whether a tightly focused or a widely diversified strategy is most likely to deliver satisfactory results. On the one hand, focusing support allows a concentration of effort, the development of economies of scale, and the maximization of the learning potential in chosen technologies. On the other hand, as Stern (2007) observes, the uncertainty of the returns from investment in any given technology, and the need to secure emissions reductions from many sources if cuts are to be achieved at the required scale, suggests that a diversified portfolio of mitigation options is wise.

With respect to the designation of specific technologies for support, governments are presumably interested in backing options that have *the highest likelihood* of delivering *the largest emissions reductions* at the *lowest cost*. But this already suggests possible tensions among the anticipated scale of reductions, the costs of developing and deploying any particular

[3] For a discussion of the forth issue, the relative merits of different support mechanisms, see von Stechow et al. (2010).

mitigation technology, and the chance that these ambitions will actually be realized. Risk hedging is important in a situation where the future value of any technology depends on a series of uncertain factors -- including the stringency of the carbon constraint at any point in time, the potential for technological improvement and cost reductions (learning potential), and the advance of competing technologies. Choices must be made in the context of particular national circumstances (resource endowments, existing energy infrastructure and competence, concerns over energy security, and so on). Moreover governments typically pursue multiple objectives. For example, the goals of preserving existing economic activities (energy intensive industries, fossil fuel extraction, and so on) and/or of developing new industries that can complete on the world stage also come into play. There may be complex trade-offs among these objectives: for example, if the intent is to maximize reductions of global greenhouse gas emissions, then technology spillovers to other countries should be encouraged (for example, through streamlined mechanisms for technology transfer). However, if the objective is to develop technology to capture future markets, it may make sense to limit access and keep out free riders. And of course, governments must be concerned that whatever technologies they do choose to support will ultimately be accepted by politicians, industry, and the public at large.

At this point it is worth noting that this discussion assumes *political choices* among technological options – decisions to provide more or less support to this but not to that specific energy/mitigation technology option – are virtually unavoidable (Meadowcroft, 2009). In recent decades there has been criticism of governments' (in)capacity to pick technological 'winners'. Examples of government technological 'missteps' are legion: the Anglo/French decision to finance the supersonic passenger aircraft Concord is often cited in this context: because it was not Concord but the Boeing 747, a product of corporate R&D, that dominated air travel in the final third of the twentieth century (Nelson, 1982; Willman and Smith, 2009). So the suggestion is that states should establish policy frameworks that proscribe functional ends (in this case low carbon emissions), but let companies and markets sort out which technologies to deploy. Carbon pricing operates in this way, discouraging carbon emissions without selecting which technologies are to be used to produce cleaner energy.

The problem (as we argued earlier) is that carbon pricing is not enough; and it is not always possible to design 'technology neutral' supports. Since resources are scarce, choices must be made. And since the potential benefits, costs and risks of different technologies will impact on public welfare, states are bound to make choices to support some mitigation/energy options over others. Of course, the problem is not that governments are especially bad at selecting technology winners (for companies often make mistakes, although they may be less likely than states to survive to endure continuing criticism), but rather that anticipating future technological trajectories is inherently difficult. Who, for example, would like to predict what the personal vehicle sector will look like fourty years from now when today biofuels, electric cars, hydrogen vehicles, and various combinations of hybrids are tussling for advantage (Vergragt and Brown, 2007; Hillman and Sandén, 2008)? Yet despite the uncertainties, choices to grant or withhold public support must be made. And since governments have to take these decisions, and are already taking them, it is worth exploring the criteria on which they are based.

Turning now to the specific case of carbon capture and storage, this involves a suite of technologies concerned with the capture of CO_2, its transport through pipelines or by ship, and its long term storage in suitable geological formations. There are a number of capture technologies, at different stages of maturity, which are often divided into pre-combustion, oxyfuel, and post-combustion processes. Post-combustion technologies, such as amine absorption of CO_2, are most mature. Alternative energy technologies that might displace sources emitting CO_2 are also at different levels of maturity. For example, on-shore wind is a well-established technology that has passed through decades of dissemination and experience, whereas off-shore floating wind turbines are at an early development stage. The technological and cost challenges of CCS are most acute with capture, while the political challenges are greatest on the storage side: consider local opposition to storage plans at Vattenfall's Schwarze Pumpe project in Spremberg, northern Germany (Godoy, 2009), and to Shell's plans to store CO_2 in depleted gas fields under the town of Barendrecht, near Rotterdam (U.S. News & World Report, 2009).

At present there is a large gap between the total cost per ton of CO_2 handled by CCS and the revenue available to operators for capturing and storing CO_2 (for example, from the price of emissions allowances in the EU ETS). For CCS to be attractive, this gap has to be closed: both through a higher allowance price induced by a stricter climate policy, and from technological advances lowering CCS cost, particularly the CO_2 capture cost, which represents the lion's share of the CCS chain cost (IPCC, 2005). Hence the emphasis placed by the International Energy

Agency, the EU and many OECD governments on funding twenty large scale international demonstration projects which can prove the technology at scale and initiate the first phase of learning-by-doing which should ultimately allow a significant drop in the cost of CCS (OECD and IEA, 2008; World Bank, 2010). In fact, continuing further financial support (for ongoing R&D, additional demonstration plants, the construction of infrastructure such a pipelines, and so on) may be required, depending on the results of this initial round of demonstrations, the evolution of the carbon price, and so on.

The remainder of this article considers further the interplay among political and economic dimensions involved in government decisions over support for CCS and other climate-friendly energy technologies. Public authorities face a complex balancing act in trying to maximize the achievement of societal goals, manage an array of uncertainties, and pay appropriate attention to national circumstances. Given the complexity of these issues we frame our cross disciplinary analysis by looking first at some core economic considerations, then noting a series of additional political issues, and finally integrating economic and political factors. The emphasis of this discussion is on making explicit and transparent the issues and linkages that need to be considered. And in this respect the analysis draws on, but also makes a distinct contribution to, the literature on the design of government policies to support emerging low carbon emission technologies.

Central to the economic discussion in the following section is the concept of ‘learning rates’: the notion that as experience with an emergent technology accumulates costs come down

(OECD and IEA, 2000). In some cases costs for new technologies first rise (as the initial optimism of proponents is tempered by experience and unexpected difficulties must be overcome), and then fall (as experience grows and economies of scale kick-in) (Rubin et al., 2007). Learning rates are potentially of great significance when considering technological futures since they influence the relative cost advantages enjoyed by different energy/mitigation options.

Learning rates can also be seen as one possible driver of ’path dependency’. An economic interpretation links path dependency to increasing returns, which can be due to economies of scale, adaptive expectations, network economies, or learning economies (Unruh, 2000). As a general example of path dependency, more investments in technology A than in B over time makes it more and more difficult to switch to B as the prioritized technology, even if B eventually should turn out to be the more desirable technology. Such effects are also referred to as ‘lock-in’. This development could be initiated by technology A being treated more favorably than B in terms of the regulatory system and/or direct government support. A classical example of technological lock-in is the QWERTY keyboard standard that was introduced to slow down typists and make jamming of mechanical keys less likely, whereas studies have claimed that QWERTY is not the ergonomically optimal design, particularly given present computer applications (McDonald and Schrattenholzer, 2002). The initial choice of technology can be influenced by vested interests in industries with political power (Sandén and Azar, 2005). Path dependency can be economic (costly to switch to another technology), technological, organizational, industrial, societal, and institutional (Unruh, 2002). Path dependency can be weakened if increasing returns are bounded or if learning effects are exhausted after some capacity has been established (Arthur, 1989). An initially preferred technology may over time become even more attractive because uncertainty with regard to what it can deliver is more reduced than for competing technologies (Sandén and Azar, 2005).

Some analysts have suggested that large scale deployment of CCS may enhance societal 'lock in' to fossil fuel dependent energy systems. Vergragt et al. (2010) compare fossil-fuel based CCS (FECCS) with bio-energy based CCS (BECCS). They find that research, interest and investments related to FECCS so far have dominated BECCS, but that BECCS under certain conditions could be feasible. An emphasis on BECCS could largely avoid the risk of fossil fuel path dependency and related lock-in effects.

At the end of the day, however, path dependency cannot be avoided when making important decisions on for example energy systems and infrastructure. The important issue is to have the best possible knowledge basis when making such decisions, particularly with regard to alternatives, long-term consequences, implied risks, and possibilities for robust and flexible strategies.

3. Learning curves and a simple economic model for low carbon technology support

We now turn to a simple economic model that can provide useful insights about a technology support strategy intended to minimize the total cost of meeting a given emission reduction target. In this framework we integrate a number of important considerations: the initial cost, potential scope, and learning rates of different technologies as well as learning rate uncertainty, and discounting. We have developed this model to explore important economic factors that determine costs and benefits of investments in emerging mitigation/energy technologies. One type of uncertainty is included explicitly in the model: low, medium, and high learning rates for CCS. Of course, the model can only illustrate interactions and the relative importance of various factors; it cannot suggest an 'optimum' overall investment strategy. But is does provide a reference point for evaluating 'common sense' beliefs about government technology policies and the assumptions on which these hinge. Despite its simplicity, the model is useful in making clear the processes that are at work. Indeed, while a more complex model might have captured a greater range of variables and dimensions of uncertainty, the results would have been more difficult to interpret and the interaction of factors less transparent.

To provide a foundation for this modeling exercise we first review cost estimates for CCS and renewable energy sources from the literature, as well as estimates of learning rates for existing technologies, CCS-equipped power plants, and renewable energy.

3.1. CCS and renewable energy cost estimates

To underpin the analysis of experience curves for CCS and renewable energy sources we need to check out the current technology status in terms of the costs per tonne of CO_2 avoided and per kWh of electricity produced. Table 1 presents some recent cost estimates. These cost estimates should be taken as illustrative only, since cost depends on technology and location. Furthermore, these cost estimates are based on current technology status, which may change significantly over time, and such changes may occur at very different rates for the different technologies.

[Insert Table 1 about here.]

Most of the cost estimates relate to renewable energy, and are expressed in US cents per kWh of electricity produced. The CCS cost is expressed as USD per tonne of CO_2 avoided, and as the cost per kWh of electricity generated by a coal- or gas-fired power station equipped with CCS. The table shows that most renewable energy sources are in a cost range of 5 - 12 US cents per kWh, but with some emergent technologies at a significantly higher cost. Coal- and gas-fired power stations equipped with CCS are estimated to be able to produce electricity at a total cost of 6 – 11 US cents per kWh, of which the base cost of the coal- and gas-fired power production is 4 – 7 US cent per kWh (Mims, 2009; OPT, 2007). According to the cited cost data, wind power (except the highest cost variants), biomass and geothermal energy are less expensive than coal- and gas-fired power production with CCS. Currently the least expensive CCS variant has about double the cost per kWh as compared to the least expensive variants of renewable energy.

3.2. Learning rates

There are many difficulties and uncertainties involved in estimating learning rates. Learning rates may differ with technology category and variants within a category, but they may also vary according to geography and other circumstances; and they may not be stable (Sagar and van der Zwaan, 2006). Estimated rates are based on weighting different forms of learning, and the significance of these forms can shift over time. Furthermore, learning rates may be overestimated since they are only calculated for surviving technologies (Sagar and van der Zwaan, 2006). And one must take care because an estimated rate may not be applicable to related technologies. Rubin et al. (2007) show that learning rates in some cases can be negative during early stages of commercialization.

With regard to interpretation of learning curves it is a challenge to identify the various factors that may have contributed to a reduced unit production cost during a period. Nordhaus (2008) argues that learning rates can easily be overestimated since it is difficult to discriminate between learning and exogenous technological change, and that this can lead to incorrect estimates of total marginal output cost and making technologies with high learning rates too attractive. Long-term cost decline is related to factors such as R&D, improved technology design, progress in related technologies, system optimization, age of production units, lifetime (shorter turnover makes technology upgrades easier), material changes, standardization of products, economies of scale, reduced input prices, market size, market structure and prices, and government regulations (McDonald and Schrattenholzer, 2002; Rubin et al., 2007).

Table 2 shows estimated learning rates for existing energy technologies, CCS and renewable technologies taken from the literature. Rubin et al. (2007) differentiate between learning related to capital cost, and to operation and maintenance (O&M) cost, for some existing technologies. Estimates for existing technologies and renewable energy are based on historical case studies, whereas numbers for CCS are projected (Rubin et al., 2007). Note that estimated learning rates may not be fully comparable due to different technologies being at different stages of development and to different assumptions across the studies cited.

[Insert Table 2 about here.]

The estimated learning rates vary significantly, between different existing technologies, even between capital based and O&M based estimates for the same technology, and to a smaller extent among CCS technologies, and among different renewable energy technologies. Estimates also vary significantly across the three main technology categories. The variation in estimates for each renewable energy technology is relatively smaller across different studies.

From these learning rate estimates it is difficult to have strong beliefs about whether the average learning for CCS will be higher or lower than that for renewable energy. It seems, however, that current estimates place learning rates for some of the renewable energy technologies somewhat higher than those for CCS.

3.3. A model with experience curves

Let us generate some illustrative experience curves and projections for coal-fired (or gas-fired) electricity production with CCS (hereafter simply CCS) and a competing climate-friendly technology. On such *experience curves* the cost per capital unit (e.g. measured as USD/MW) is plotted as a function of accumulated production capacity, see eq. (1).

(1) $C = A * K^{-a}$

where C is the unit cost, A is a constant equal to the unit cost of the first unit of installed capacity, K is total (cumulative) installed capacity, and a is the learning constant or elasticity, assumed to be positive.

To underpin this discussion of experience curves we have reviewed estimated and observed learning rates for existing technologies, recent CCS cost estimates, and estimated learning rates for some renewable energy technologies (see Table 2). Studies of a number of technologies have shown that the cost per unit is reduced in the region of 5% to 30% if production capacity is doubled (Table 2). The *progress ratio, P,* of an experience curve is defined as the cost reduction from doubling production capacity, see eq. (2). Thus the cost range cited above leads to progress ratios between 95% and 70%.

(2) $P = [A * (2K)^{-a}]/[A * K^{-a}] = 2^{-a}$

Finally, the *learning rate*, LR, measured in per cent is defined as 100% minus the percentage progress ratio:

(3) $LR = (100 – P)$

Now, let us consider a situation where a government has a budget available for spending on developing either CCS technology or a representative renewable energy technology, REW, or some mix of the two technologies. The government's objective is to minimize total financial support as the cost per capital unit is reduced to such a level that the technology is competitive -- meaning that the cost per ton of CO_2 mitigated reaches society's value of mitigated emissions (here understood to be fully captured in the emission allowance price). Furthermore, the cost of the two technologies follows well-defined experience curves, where the learning constant (a) and/or the initial cost level (A) may differ.

Figure 1 depicts the experience curves of the two technologies. Cost per unit produced by each technology is measured along the vertical axis. Production capacity is measured along the horizontal axis, where coal-fired power with CCS is measured from left to right, whereas REW is measured from right to left. Through this representation total capacity invested-in is defined as the length of the horizontal axis, which is constant, and every point along this axis represents a mix of the two alternatives CCS and REW. In the case shown in Figure 1 the CCS learning rate is set at 7%, whereas the REW learning rate is at 10%, which is reflected in the experience curve for REW falling faster than the curve for CCS. Thus the cost of producing one unit energy falls faster for REW than for CCS when production capacity is expanded. In this illustrative example the initial cost of CCS is assumed to be 10% lower than the initial cost of REW. Referring to the cost estimates of CCS and renewable energy sources in Table 1, this implies that we are comparing CCS to less mature renewable energy technologies, where the unit production costs are relatively high. Thus we interpret CCS as an immature technology that is to be contrasted with renewable energy technologies that are similarly at an early stage of their learning curves.

[Insert Figure 1 about here.]

Let us now consider the costs involved for a government investing in one of the alternatives CCS and REW, or a mix of these. We assume that the government is concerned with two cost types, the investment cost and the mitigation cost. For simplicity all investments are done by the government, and we define mitigation cost as a per unit cost at each investment (capacity) level times increase in capacity. The given total capacity, and related investments, is a function of the mitigation target. Further we assume that the government wants to minimize the sum of investment cost and mitigation cost. The investment steps are scaled to 1 each, and the cost of each investment step is assumed equal for CCS and REW. Since total investment cost (i.e. for REW plus CCS) is given and constant, it can be disregarded when the government makes its decision. Then we arrive at a simplified expression for the total mitigation cost being the sum of the unit cost at each capacity level from 1 onwards until the chosen capacity is reached, and over the two alternatives, see equation (4), where total mitigation cost is denoted total cost. The objective of the government is to minimize total cost through allocating its investments across CCS and REW (for the given total capacity and investment cost).

(4) $\text{Total cost} = \text{Cost}_{CCS} + \text{Cost}_{REW} = \sum_{i=1 \text{ to } x} C_{CCS,i} + \sum_{j=1 \text{ to } y} C_{REW,j}$

where $C_{CCS,i}$ is the unit cost for CCS at capacity level i, $C_{REW,j}$ is unit cost for REW at capacity level j, and total capacity equals (x + y).

Figure 2 illustrates some general findings in such a setting. In the figure cumulative capital (capacity) is measured along the horizontal axis and total (mitigation) cost in CCS and REW is measured along the vertical axis. Note that cumulative capacity for CCS is measured from left to right, whereas cumulative capacity for REW is measured from right to left. The total capacity required is equal to the length of the horizontal axis, where each point along this axis represents a combination of CCS and REW capacity that equals total required capacity. The upper curve shows total cost for different combinations of CCS and REW, where the lowest point represents total cost minimum. *The curve shows that a corner solution, where all investments are in CCS or in REW, generally represents lowest total cost*. The learning rate is the single most important factor deciding which alternative has lowest cost, in the figure shown as the end-points of the total cost curve. The initial cost of each alternative is also of importance. The case shown in the figure features CCS learning at 7% and REW learning at 10%, which is within the conservative range in Table 2. The initial cost of CCS is assumed to be 10% lower than the initial cost of REW, which is within the wide ranges shown in Table 1. The figure also depicts a variant where net present value is calculated based on a discount rate at 5% (TotCNPV), shown in the middle of the three curves at the lower end of the figure.

Since the learning rate is important we have included uncertainty in the model as two additional learning rates for CCS. In figure 2 this is shown as two more CCS learning scenarios, one low learning at 2% (TotCNPV_LowCCS), and one high learning at 15% (TotCNPV_HighCCS), which can be compared to the middle case at 7% learning. The three lower curves in the figure show that the higher the CCS learning rate, the lower the total cost for a given CCS capacity. Depending on the CCS learning rate, total cost for only investing in CCS (the right end of each curve) is lower, the same, or higher than the total cost in case of only investing in REW (the left end of the curves).

[Insert Figure 2 about here.]

The general findings from this illustrative model are that:

- In general it is optimal to choose the technology with the highest learning rate, or lowest initial cost if learning rates are equal.
- If the initial cost difference is large enough between CCS and REW (e.g. lowest for CCS) and in the opposite direction of learning rates, this will induce preference for CCS.
- If the learning rate for one technology approaches zero after some capacity is reached, this means a relative disadvantage to the technology, other things being equal. If the learning rate for one technology increases compared to the other technology after some capacity is reached, this will have the opposite effect.
- A capacity constraint on a technology (that is binding) leads to a higher total cost. If the capacity constraint is on the fastest learning technology, investments will be done in both technologies if this leads to the lowest possible total cost, or to investment only in the alternative with slowest learning if this leads to lowest total cost.
- Adding discounting and basing support on net present value (NPV) is a relative advantage for the technology with lowest learning rate. If the two technologies were equal in total cost due to higher initial cost for the technology with highest learning, introducing discounting will lead to preference for the technology with lowest learning rate, diminishing the importance of the difference in learning rates.

- Introducing uncertainty regarding the learning rate of CCS, e.g in terms of the three learning cases as depicted in Figure 2, means that the government only prefers CCS if the expected learning rate is higher than the certain rate for REW, given that government is risk neutral. Thus the probability of high CCS learning compared to probabilities of low and medium learning, combined with the differences in these three learning rates, and compared to REW learning, decide which technology has the highest expected learning rate, and thus deserves government support.

The main result from this model analysis is therefore that the least costly solution is for government to support only one technology. The technology with the highest learning rate is the best choice, unless there is a sufficiently large initial cost difference in the opposite direction. If the highest learning technology cannot deliver sufficient mitigation alone, or if for some reason this technology's learning rate should turn negative after some threshold is reached (e.g. dis-economies of scale), then there would also be some place for the alternative technology.

There is, however, substantial uncertainty with regard to learning rates both for CCS and many renewable energy technologies. This uncertainty may influence a government's choice in two ways. First, a government can hedge against this uncertainty through supporting both technologies, given that their risk profiles are different. Second, if a government should be risk averse, and risk profiles of the two technologies differ in a specific direction, this may sway its choice away from the technology with highest to lowest expected learning. In such a case the highest expected learning technology must have a sufficiently high probability of low or even negative outcomes for the learning rate compared to the other technology. Even if this technology has a relative high probability of low learning, this is balanced with the relative high probability of high learning, making expected learning slightly higher than for the other technology. In such a case the risk premium required by the risk adverse government to choose the technology with the highest probability of low learning would be sufficient to dominate the difference in expected learning.

4. Political and other considerations

The previous section explored the issue of how a government should allocate limited investment resources among emerging technologies in order to minimize the total cost of meeting a specified mitigation target. We presented a simple economic model that traced linkages among a series of important economic factors including initial costs, potential scope, learning rates, learning rate uncertainty and discounting. It indicated that when learning effects are strong, costs can be minimized by concentrating investment rather than by pursuing a diversified portfolio. On the other hand, uncertainty – especially about the real learning rates for the different technologies – makes it hard to pick exactly which technology is the one to focus on. Moreover, in order to meet the mitigation target and in time, two or more technologies may be needed. In this section we would like to contextualize these model results by considering additional economic and political issues that more closely resemble the situation governments actually face when they come to make difficult decisions about technology support.

The first thing to say is that while cost minimization is an important societal value – because public money that is saved can be deployed to other ends – it is far from being the only consideration in policy design. Indeed, economists often complain that it hardly ever prevails in the real-world of politics! Other options than the lowest cost might be preferred to provide additional assurance that policy goals will be met. Some goals may be so important that ‘redundancy’ (over-investment) is built in. Thus energy security may be considered so critical that it is worth paying higher energy prices to secure it. The promotion of equity or the perception of equity among different social groups or regions may also encourage deviation from cost minimizing strategies. Thus a less efficient investment strategy may be applied to ensure everyone has ‘a slice of the pie’ (think of the distribution of Airbus manufacturing facilities). The simultaneous pursuit of many goals may mean that lowest cost strategies for particular goals must be sacrificed. Often the lowest cost option is perceived to threaten powerful interests or accepted ways of doing things and therefore turns out to be politically infeasible. Political bargains may be needed to allow any policy movement. So cost minimization does not (and should not) automatically trump other considerations.

In selecting mitigation approaches governments must consider a range of issues. In the short term options are limited, and technologies must be chosen from those already available, with existing costs and benefits. Over time, additional technology options become available, but some older options may become less appealing as the relative costs and benefits of alternatives change. As we have discussed, future options are not independent of short term investments, because of the learning and other path dependent factors, in addition to changes in stock and quality of capital equipment due to investments in general.

The scale of the emissions reductions required to address climate change (not marginal reductions, but ultimately the virtual elimination of greenhouse gas releases from energy use) means that climate mitigation strategies cannot be considered as a separate realm of policy choice, but rather must be seen as an integral part of choices about meeting societal energy needs. In other words, decisions about mitigation and energy supply are entangled (Meadowcroft and Langhelle, 2009). For example, CCS makes sense in a carbon constrained world that is still relying on fossil fuels. And (if we set aside the application of CCS to other industrial processes or to biomass) the scale of potential CO_2 reductions secured through CCS is related to the scale of fossil fuel usage.

Assuming that governments are serious about dramatically reducing greenhouse gas emissions, important considerations influencing their political choices about technology in the energy and greenhouse gas mitigation field include (Meadowcroft and Langhelle, 2009):

1. The character of the existing energy system, infrastructure investments and expertise; as well as the existing scientific/technical/industrial/financial capacity that might be mobilized for alternative technologies.

2. The remaining domestic fossil fuel resources and potential rents (for fossil reserves may remain undeveloped if climate policy is stringent and CCS is not implemented); other resource endowments of potential energy/mitigation significance (hydro, wind, solar, biomass, and so on).

3. The significance of fossil fuel imports and the regions from which imports arise (worries about energy security).

4. The economic development potential of various energy options (potential for domestic industrial growth, new export markets, creating jobs, etc., in various technological pathways).
5. Regional distributional issues (fossil fuels and other energy options may be concentrated in certain geographic regions/sub national political units, and regional politics may come into play).
6. The economic and political strength of existing energy incumbents, of energy intensive industries, and of the proponents of various options.
7. International linkages: energy choices of neighbors, international interdependency, competition policy, energy exports, and so on.
8. Perception of relative environmental burdens of large scale deployment of different low carbon technological options (risks to safety or climate from CCS leakage and associated problems from fossil fuel extraction and combustion; waste, accident and proliferation with nuclear power; land use pressures from biomass; etc).
9. Public receptivity to different energy technologies and mitigation options.

Although these issues may be experienced as established ‘facts’ about the energy system and about mitigation potentials that condition which sorts of technological choices make sense, it is important to appreciate the extent to which they are not just historically given, but are *partly constructed through political argument* (Meadowcroft, 2009). Understandings of energy security rely on identifications of potential threats; and are influenced by political events and political arguments. Public perceptions of new technologies are not fixed in advance, but formed through interactions among proponents and opponents, and modified by experience.

The economic (and indeed the technological) prospects for new technologies are ‘hyped’ by advocates (Geels, 2005). And the strength of existing path dependencies are affirmed and challenged by societal actors.

The importance of some of these factors can be appreciated in relation to the different technological choices being made by governments with respect to CCS Research, Development and Demonstration (RD&D). In Canada, for example, CCS attracts a particularly high proportion of government support. The country has significant fossil fuel resources, including the carbon intensive oil sands. But regional distributional issues have been critical as provinces control natural resources, and the only way the country as a whole can contemplate emissions reductions is by adopting an approach that would allow continued expansion of fossil fuel exports (Jaccard and Sharp, 2009). Germany is interested in developing CCS to allow the continued flexibility of coal fired power generation. But renewables (wind, biomass and solar) have expanded rapidly in the past decade, with a governmental champion in the environment ministry, a growing industrial constituency and strong public support. So CCS appears more as one of a portfolio of emerging technologies government supports (Praetorius and von Stechow, 2009). Norway is the country where CCS absorbs the highest proportion of government research expenditure, and here too it serves as ‘political glue’ (Tjernshaugen, 2008; Tjernshaugen and Langhelle, 2009) allowing Norway to pursue oil and gas extraction, and to contemplate adding gas fired power stations to its all-hydro electricity system, while maintaining claims to a vigorous climate policy.

Although many countries have carried out strategic reviews of energy and climate policy and established priorities for research expenditure (for example, the UK Low Carbon Transition Plan, Department of Energy and Climate Change, 2009), most decisions about investment and research priorities are made incrementally, with funds allocated to new programs on a piecemeal basis as political constituencies that back particular options gain acceptance for their ideas. Existing interests typically dominate decision processes, and the capacity for producer lobbies to win support for favored options cannot be underestimated. Consider, for example, the subsidy programs and tariff protections granted to US corn-based ethanol, which are defended on energy security and rural development grounds but which provide marginal climate benefits at enormous cost (IISD, 2006).

The critical nature of energy choices for overall social welfare (economic prosperity, security and environmental performance) mean that governments should take account of a variety of factors when deciding how to invest in novel technologies. In Table 3 we present a general ‘check-list’ of such factors and considerations. It includes issues we consider to be important, but is not to be taken as a complete list of relevant factors. This list should be applicable for governments in industrialized countries that have introduced climate policies and are interested in CCS as a potentially important emission mitigation technology.

[Insert Table 3 about here.]

5. Conclusions and policy advice

This article has discussed the difficulty governments face when allocating scarce resources across a range of RD&D opportunities in order to reduce GHG emissions and secure other objectives. At first sight the results of the economic analysis (based on the model that compared the cost-effectiveness of supporting one *or* several promising technologies) and of the political discussion (that explored the wide range of considerations governments must balance in making technology investment decisions) seem to pull in different directions. The model suggested that costs can be minimized by concentrating investment along the most promising avenues: one, or perhaps a few, emerging technologies. While the political assessment, with its range of pertinent factors (including those listed in Table 3), seemed to suggest that cost minimization is not king, and that supporting a variety of options may best satisfy a range of different concerns.

Yet the contradiction is more apparent than real. In the first place, the *economic* results are not unambiguous. If one had accurate cost information, and knew in advance what the learning rates and learning potentials would ultimately turn out to be for various technologies, picking the 'winner' and concentrating investment would be comparatively straightforward. But in the real world there are substantial uncertainties about costs, learning rates and learning potentials. So there is a trade-off between diversifying risk across different technologies (but then risking acquiring only a little learning, and a little cost reduction on each one), and minimizing total expenditure (by focusing on only the most promising option, maximizing learning, and the potential cost reductions). So the prevailing uncertainties push the economic analysis towards an expanded portfolio of supported technology options: because in the event that the one chosen technology ultimately fails to deliver the anticipated improvements (cost reductions, energy production and mitigation volumes and efficiencies), costs would be much higher -- if the unsuccessful technology was deployed, or if another technology had to be belatedly developed or imported. Moreover, the fact that one technology alone cannot bear the full burden of the required mitigation effort again points towards diversification.

On the other hand, the operation of a complex range of *political* considerations does not necessarily imply an extremely diversified technology support portfolio. After all, these political considerations may largely pull in the same direction. For example, one or two large scale technologies, with substantial roots in the existing industrial system, perhaps with an important regional base, would be an appealing political focus for investment. And such technologies would be likely to enjoy substantial public acceptance; have significant industrial sponsors; and so on. Thus in a country with a large fossil export sector (such as Norway or Australia) and related support industries, CCS exerts an almost irresistible pull on political authorities. France's substantial nuclear infrastructure attracts a further RD&D effort in next generation reactor design; and the public is already accustomed to this technological trajectory. These factors play out clearly in Canada where there are major differences to the energy supply in different regions. In oil rich Alberta CCS is absorbing the overwhelming bulk of climate mitigation budgets (literally billions of dollars); but in Quebec which gets nearly all its electricity from hydropower, and exports electricity to the Northeastern US, hydro, wind and transmission are research priorities; while in Manitoba (a prairie province) the research priority is biofuels. In each case the resource base, local industrial expertise and pressure groups, and regional political priorities are aligned on a few basic axes.

In fact both economic and political analysis point toward what might be described as a 'lumpy' investment strategy: lumping investment towards a relatively modest set of priorities – neither concentrating it on just one option, nor spreading it out evenly across all alternatives. Such a strategy allows for a *relative concentration* of resources, allowing faster learning rates, economies of scale and accumulating a 'critical mass' in technologies identified as strategic priorities. But it also spreads risks, provides insurance against one or more technologies failing to pan out, and avoids putting 'all the eggs in one basket'.

Still several caveats must be made about such a strategy. First, size matters. The larger the jurisdiction, the more government can afford to spread its efforts: and while advantages of concentration still prevail, it is possible to achieve a critical mass (or world standard) in many more areas. Smaller jurisdictions cannot hope to compete across the board, and here careful choice of technologies to support is even more important. Of course, specialization in smaller jurisdictions that are federally-linked (or that achieve some technology-sharing arrangements) can collectively cover a broader range of options (for example, EU member states, or Canadian provinces), providing residual collective benefits if some options fail to pan out.

Second, large scale energy technologies are not really one technology but rather systems of inter-related technologies. CCS involves combustion and capture technologies, transport, and injection and geological storage technologies. Moreover, different feed-stocks (natural gas, coal, oil sands, and industrial applications) will use different technologies. Solar involves PVC and thermal; distributed and centralized generation. Windmills are on shore and off shore; they may be integrated into the urban environment; they require modeling, control systems, and maintenance; and then there are related storage and transmission needs. So this means there are not just dozens but hundreds of technological niches in which firms and countries can specialize. So even a small country like the Netherlands, which has no large scale domestic automotive assembly industry, can identify electric vehicles as a key energy/emission-reduction technology option and a priority for energy transition funding – because there are particular niches (e.g. control systems) where Dutch firms can compete to master an important piece of an emerging technological system. What is critical here, then, is playing to existing strengths; identifying strategic resources and trends; and leveraging future success. And again a 'lumpy' strategy fits the bill – appreciating the points where a concentrated allocation of resources may bear fruit.

Third, such a 'lumpy' strategy means that some technology areas will *not* receive significant government support. And it may be that these areas eventually turn out to be important, while some of the targeted areas turn out to be failures. In that case successes developed elsewhere may have to be imported to meet energy and emission reduction needs (clean energy imports, clean technology imports). But of course there is nothing necessarily wrong with that: indeed, in some cases, in the long run, it may be cheaper to allow others to bear the financial burdens of attempting to develop large scale technology platforms; to wait until it is clearer who the winners will be; to skip the first and second generation pilot phases with all their expensive 'learning'; and then to buy-in the technology once the new system has stabilized, and costs have significantly declined.

When making decisions about support for energy/mitigation options decision processes should be framed in appropriate terms. In this respect two elements stand out. First, is the goal of achieving making a transition to a carbon-emission free energy system in developed countries within half a century. Here the scale of the required emission reductions, the timeframe over which they are to be realized, and the idea of a '*transition'* from state to another circumscribes the technology search process. So visions of how this transition might unfold over time, and the role that specific technologies could play in the process, provide a context for choices about government supporting for particular technologies. Technological projects should not be financed just because they represent the next logical step in an ongoing sequence, but because the represent a potential link in the movement towards a carbon emission free energy future. So envisaging alternative transition pathways and assessing the versatility and robustness of technologies across alternative energy futures is important. Second, energy decisions can be set in the perspective of 'sustainable energy policy': where energy is in service of sustainable development, and economic, social and environmental dimensions are integrated in decision processes. This can provide a framework for drawing together different dimensions of choice, and different societal stakeholders, to build a coherent program for technology support (see Table 3).

In summary, we arrive at the following policy suggestions for targeted government support for climate-friendly technologies:

- Government should support a focused portfolio of emerging technologies, as a compromise between economic and political factors pulling in the direction of many technologies and factors such as learning effects pulling in the direction of one or a very few technologies.
- In designating priorities governments must consider many issues, but particular attention should be paid to a) building on existing strengths and capacities (natural resources, science and technological capacity, existing infrastructure, innovation and industrial clusters, etc); b) carefully monitoring emerging opportunities (foresight; scanning); and c) exploring transition pathways (scenarios, planning, back casting, transition forums, see Kemp, Rotmans and Loorbach, 2007, and Kern and Smith, 2008).
- Priorities should be considered at different 'levels': with major strategic technologies receiving a large proportion of funding, but selected niches being supported within secondary priorities. Regional specialization may also be useful to combine concentration of investment and spread of opportunities/risk (a 'lumpy' investment strategy).
- The many uncertainties involved in technology support decisions suggest developments should be monitored continuously and decisions reviewed periodically. Programs should have 'sunset clauses', so that support cannot be continued indefinitely and the public interest case for backing particular technologies must be regularly revisited.

- International collaboration or at least co-ordination makes sense given the large and uncertain investments needed to combat human-made global warming, to hedge against risks, and to exploit different national competencies and comparative technological advantages (Stern, 2007).

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Energy technology	**Cost; USD/tonne CO_2 avoided**	**Cost; US cents/kWh**
Coal power with CCS	60 – 75 [1)]	7 – 9 [1)] 8 - 11 [5)] 7 – 11 [6)]
Gas power with CCS	60 – 110 [1)]	6 – 9 [1)] 7 - 9 [5)] 7 – 10 [6)]
Wind power		4 – 6 [2)] 8 - 12 [3)] 8 – 16 [6)]
Solar photovoltaics		30 [4)] 14 – 15 [5)] 24 – 34 [6)]
Biomass		6 – 7 [1)] 7 – 12 (biomass) [2)] 0.4 – 0.8 (biogas) [2)] 5 [3)] 14 – 20 [6)]
Geothermal		4 [5)]
Ocean power		15 [6)]

Table 1. Current cost estimates of CCS and major renewable energy sources. USD/tonne of CO_2 mitigated and US cents/kWh. According to OECD and IEA (2008) the additional cost for CCS is 3 US cents/tonne CO_2 for gas fired power plants and 3 - 4 US cents/kWh for coal fired power plants. This additional CCS cost is added to the production cost of coal and gas fired power plants cited in Mims (2009) and OPT (2007). Sources: [1)] OECD and IEA (2008); [2)] Oulton (2009); [3)] KLIF (2010); [4)] Solarbuzz (2010); [5)] Mims (2009); [6)] OPT (2007).

Technology	Rubin et al. (2007)	McDonald and Schrattenholzer (2002)	McDonald and Schrattenholzer (2001)	OECD and IEA (2000)
Existing technologies				
PC boilers				
Capital cost	5			
O&M cost	18			
Hydrogen production	27			
Flue gas desulfurization				
Capital cost	11			
O&M cost	22			
GTCC				
Capital cost	10		4	
O&M cost	6		26	
Power plants with CCS				
NGCC plant	15.5			4
PC plant	14.4			
IGCC plant	17.6			
Oxyfuel plant	9.7			
Renewable energy				
Wind turbines, DK		8		
Wind power, EU		18		18
Electricity from biomass		15		15
Solar PV modules, World		20	18	
Solar PV system, EU		35	35	35
Ethanol, Brazil		20	22	

Table 2. Estimates of learning rates for existing technologies, CCS-equipped power plants, and renewable energy. Learning rate is defined as percentage reduction in cost per unit produced for each doubling of production capacity.

GTCC – Gas turbine combined cycle.

NGCC – Natural gas combined cycle.

PC – Pulverized coal.

IGCC – Integrated gasification combined cycle.

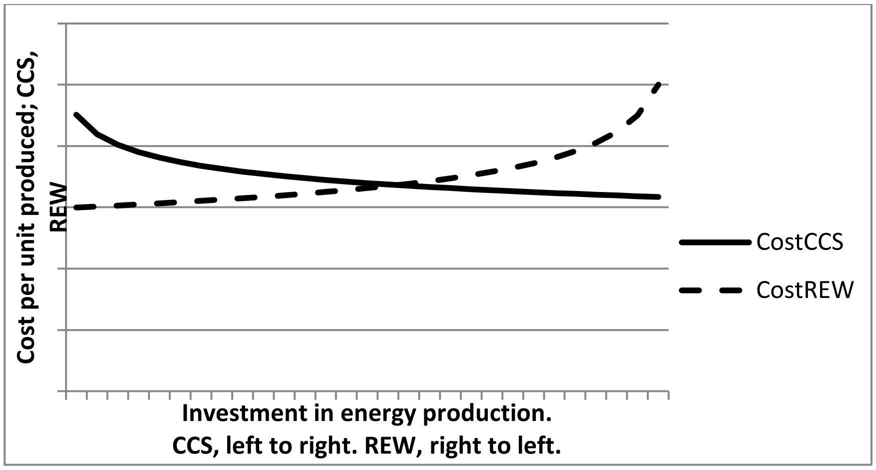

Figure 1. Experience curves for CCS (from left to right) and REW (from right to left).

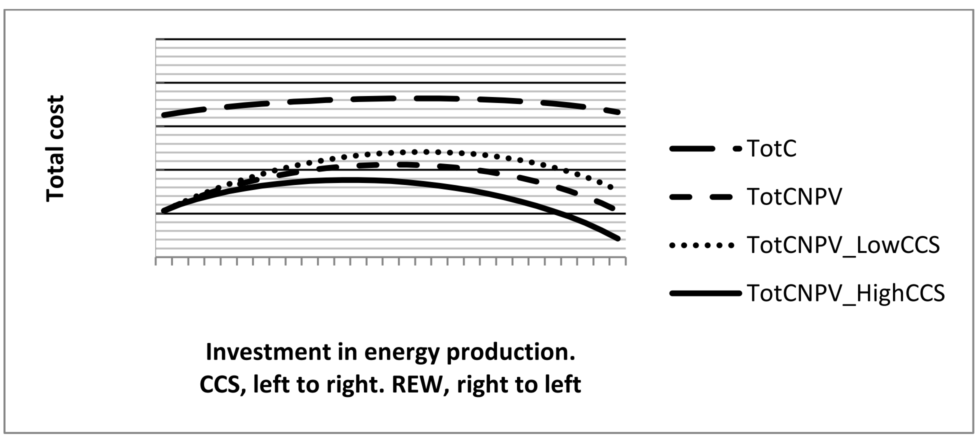

Figure 2. An illustration of economic attractiveness of investments in CCS compared to a renewable energy technology (REW) when moving along experience curves. Total accumulated cost for CCS and REW is shown along the vertical axis. REW has a learning rate at 10%. There are three learning rate cases for CCS, a low at 2%, a medium at 7% (TotCNPV), and a high at 15%. The initial cost of CCS is 10% lower than that of REW. In the upper curve (TotC) total cost is not discounted. For the three other cases net present value (NPV) discounted at 5% is shown.

Important factors	Key questions	Considerations
Core potential		
Energy provision potential	How much energy can this provide?	An option that meets a large share of energy needs is generally desirable. Technologies that come in large units have large capital costs but fit centralized generation grids well.
Emission mitigation potential	How much emission reduction could this technology deliver?	Dependent on characteristics and scale of deployment. Higher lifecycle reductions and larger scale of application are preferable.
Timing	On what time scale would it become commercially deployable?	The sooner the better. But the potential for really big gains even on a long time horizon can be attractive.
Costs		
Present cost	What is the current cost of the technology?	Must be seen in relation to current capacity investment (experience curve stage).
Learning rate	How fast can costs come down?	Higher learning rates are desirable. But rates are uncertain.
Learning potential	How far might costs eventually come down?	Higher learning potential is desirable but uncertain.
Co-benefits and concerns		
Development potential	To what extent can it generate economic benefits: jobs, markets, profits, taxes?	Investments are expected to generate economic benefits as well as energy/mitigation
Energy security	Does it enhance energy security?	Relates to import dependence, diversity of supply and robustness of infrastructure.
Regional implications	Is it significant for regional energy, mitigation or development interests?	Regional interests need to be accommodated.
Environmental perspective	What are the associated environmental benefits/costs and opportunities/risks?	Fossil fuel CCS, nuclear, hydro and new renewables have different cost/benefit profiles
Foreign markets and international competitiveness	What is the potential to develop export markets? How appealing would the technology be to other countries?	Technologies that appeal to other countries with growing energy and mitigation needs may represent important future markets..
Compatibility	To what extent is this option compatible with other favored technologies?	Some energy/GHG mitigation options do not ‘fit’ well with others.
Pillars of support		
Technical/industrial/resource foundations	Does it draw on existing strengths or potentials: resources, industries, innovation clusters?	The importance of exploiting existing knowledge/resource bases and relying on comparative advantages.
Co-funding of RD&D	To what extent will private interests and firms and/or international partners contribute to funding RD&D?	Collaborative engagement can reduce development costs, spread risk and cover more technological options.
Public receptivity	To what extent is the public supportive/resistant to the technology?	Awareness of public and stakeholder groups; communications; familiarity, accidents
System perspectives		
Transition to carbon emission free energy system within half century	How does the technology fit with transition pathways to a carbon emission free energy system?	The roles the technology might play; how its potential is distributed over time; potential interactions with other technologies; long term visions; ‘backcasting’.
Sustainable energy policy	How can it appear from the vantage of sustainable energy policy?	The provision of energy for sustainable development; economic/social and environmental dimensions; holistic assessment

Table 3. The political economy of government technological support: a check list of factors to be considered when allocating government support for low carbon emission energy technologies.