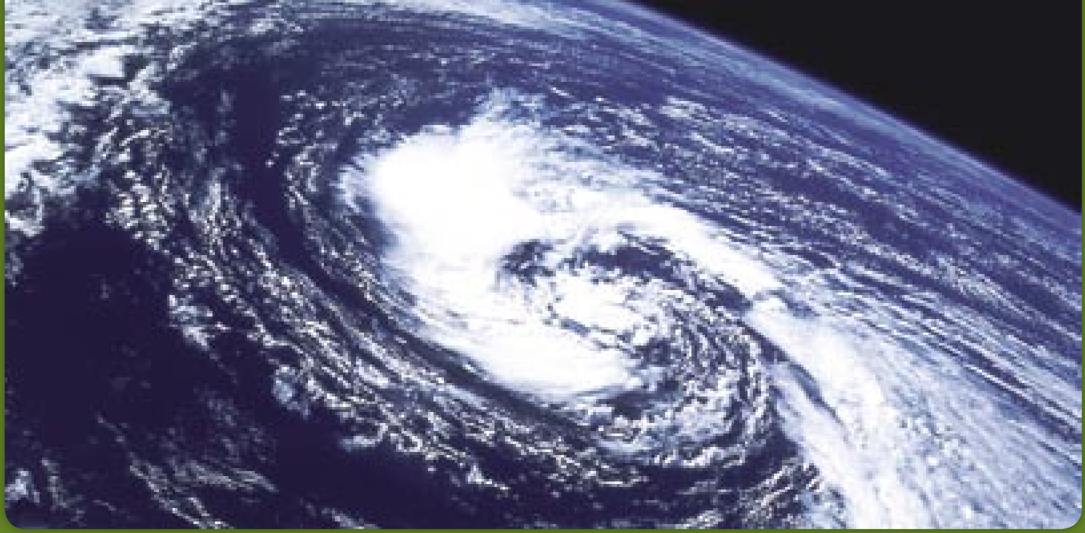

Scaling Up:

Global Technology Deployment to Stabilize Emissions

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Summary Points

- *Climate change is not just an environmental challenge. It is becoming a defining fact of economic development.*
- *A major obstacle to addressing the climate challenge is the daunting scale of potential solutions. In essence, reducing emissions to safe levels means transforming the way we produce and use energy, whether in power, transport, or heating and cooling, as well as many important industrial processes.*
- *A number of options exist for reducing emissions by managing energy demand and employing low-carbon energy supplies that can make major contributions to clean economic growth. Yet three areas need to coalesce into a coherent vision in order to achieve adequate levels of emissions reductions:*
  - *The **technologies** involved, including the physical and capacity-related constraints to deploying them.*
  - *The **investment** required: who will provide it, the mechanisms they will use, and its cost.*
  - *The **policies** that will offer the most effective incentives to providers of both technology and capital to implement lower-emission solutions.*
- *A paper by two Princeton researchers provided a mental framework to discuss these solutions by breaking the required emission reductions down into manageable (though still large) "wedges," each provided by a different technology or set of technologies. Owing to its solution-oriented framework, the wedges approach has captured the imagination of those eager to tackle climate change.*
- *This paper presents an overview, using the wedges framework, on how technology, investment and policy interact. It is intended to engage actors in the policy and investment communities as the key enablers of clean technology deployment worldwide.*

Introduction

Climate change is not just an environmental issue. It is fast becoming one of the defining facts of economic development in the 21st century. It will shape investment, technology deployment and human development around the world, and no sector will be more profoundly affected than energy. Thriving in the huge and fast-changing energy market will mean understanding the risks and opportunities presented by the public policy choices made in reducing emissions and the infrastructure that is required to implement these choices.

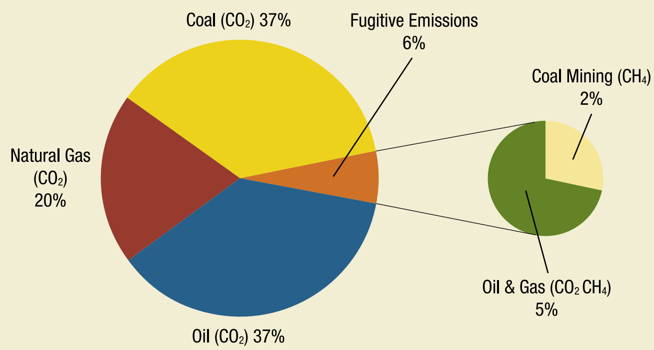
While our understanding of the global climate system is not perfect and uncertainties in certain variables still exist, the basic science of climate change is no longer in doubt. Perhaps the most striking example of the scientific consensus on climate change is summed up in the recently released report of the Scientific Working Group of the Intergovernmental Panel on Climate Change (IPCC) which has “very high confidence” that the observed warming trend around the globe is attributable to the net effect of human activities since 1750.[1] In IPCC terms, this means there is at least a 90% probability that global warming is human induced – and the IPCC offers no other scenario that could account for the magnitude of change.

The great majority of this impact is due to the use of fossil fuels, which is large and rapidly increasing. The International Energy Agency (IEA) has projected that fossil fuels will account for 83% of the overall increase in energy demand between 2004 and 2030.[2] In the IEA’s base scenario oil remains the largest single fuel in the global energy mix in 2030 (though since coal is more carbon intensive, it is just as important as oil in terms of emissions). Coal demand increases the most in absolute terms primarily led by consumption growth in China and India (see Figure 1). If greenhouse gases (GHGs) are to be reduced significantly, either current users of fossil energy will have to shift to low-carbon sources or will have to adopt technologies that capture and sequester carbon dioxide (CO_2), the dominant GHG. Further, low-carbon transportation fuels must be produced. Making these changes calls for the large-scale deployment of existing technologies as well as investments in the development of new technologies.[3]

There is no single “silver bullet” solution that can provide low-emission energy for our expanding economies. However, a number of options exist for reducing emissions by managing energy demand and employing low-carbon energy supplies and technologies that can make major contributions to clean economic growth. The question is not what technology or sector to target, but rather what suite of policy tools should be enacted that stimulate the advancement of low-carbon technologies and how these technologies should be financed.

No technological solution to climate change will materialize without sufficient levels of investment capital. This capital must support not only the development of new, promising technologies, but also the large-scale deployment of existing technologies, along with the related infrastructure needed to support them.

Figure 1: **Global GHG Emissions**



Source: World Resources Institute, Climate Analysis Indicators Tool, 2002.

The Scale of the Challenge

Massive technology shifts are needed in just about the most difficult place imaginable. Energy, the world's largest, most pervasive and in many ways least innovative economic sector, is at the heart of the challenge. The IEA projects that some $20 trillion of new energy investment will be needed in the next 25 years, much of it in developing countries.[4] Smart investment in energy efficiency can reduce the capital required but even these sums do not include the additional effort required to bring electricity to those that still lack it, a quarter of the world's population.

Investment in energy is often driven by policy priorities other than climate change. Countries need to provide energy across all sectors of the economy at a price that does not hamper economic development (see Box 1). In addition, there is a growing concern in many countries over the security of their energy supplies. Oil almost exclusively fuels transportation, and many countries depend on finite supplies of unknown scale. The search for alternatives to these supplies will remain an important factor in shaping policy. Finally, there are a range of other environmental and social issues attached to energy provision, including air and water pollution, siting problems and technology-specific problems such as radioactive waste.

Box 1: The challenges of developing country markets

The global nature of the challenge means that investments will be needed in all major economies. This means that investors in clean technology will be faced with a wide array of regulatory regimes, cultural environments and market demands. China and India in particular are likely to loom large in technology deployment strategies. At the moment these countries are reluctant to engage explicitly in climate policy, arguing that their low average per capita emissions and relative poverty make it neither practical nor ethical to commit to cuts. On the other hand, each has a burgeoning middle class with consumption and emission patterns that more closely resemble those of the industrialized world. Providing the poorest with energy services is a huge development prerogative but has little bearing on greenhouse gas emissions, as energy demand from those populations will remain very low for decades.

If GHGs are not an immediate concern in countries such as India and China, energy issues are. A rush for investment, energy security concerns and the staggering cost of pollution in terms of human life all make clean, efficient technologies highly desirable in the developing world, as elsewhere. Both Indian and Chinese energy markets are dominated by domestic capital resources, but both tend to strongly favor high-end technology. There is considerable scope to engage both private sector and government players in the promotion of clean technology markets. Just as for most technologies, this will no longer be a question of isolated countries but of global markets serving national demands.

The daunting scale of the problem, the interaction of so many policy priorities and the range of technologies and markets involved, have made it difficult to frame an overall solution to the climate challenge. In this report we discuss one promising approach to this framing, known as the "climate wedges". We consider the key factors in making these "wedges" reality, in particular focusing on three factors:

- What are the emergent **technologies** that will deliver these wedges in practice?
- What are the requirements to deploy **investment capital** efficiently to mobilize these technologies?
- How can an understanding of these dynamics guide the **policy** choices we make, and what do those policy choices mean for the providers of technology and capital?

Introducing the Wedges

The scale of the climate problem is so daunting that many policy makers and analysts are inclined to think that no reasonable solution exists. The search for a single "silver bullet" technology, such as nuclear power or some form of solar energy, that could plausibly supply global energy demand without carbon emissions has failed to produce a convincing prospect. This leads some to a gloomy conclusion: that until our researchers strike silver in the form of a totally new technology, we have no way to confront climate change at a meaningful scale.

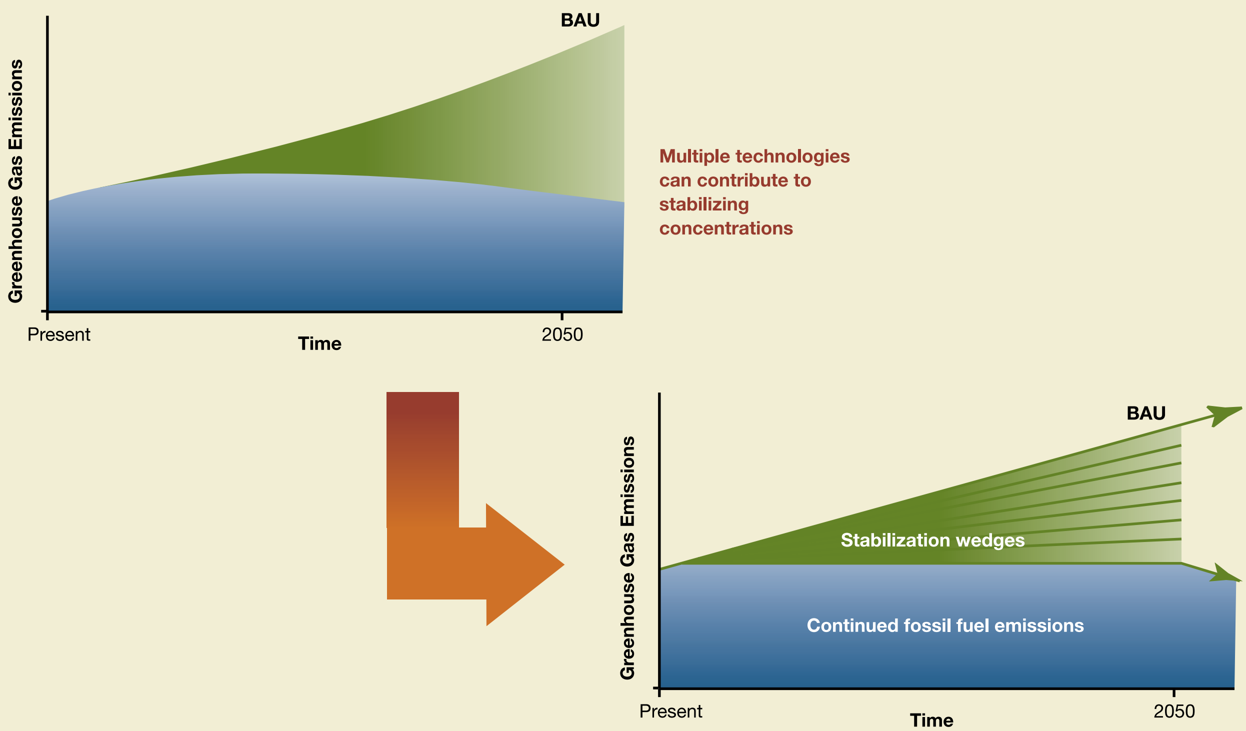
The evidence, however, offers a sunnier alternative. A 2004 paper by two Princeton researchers, Stephen Pacala and Robert Socolow, demonstrated graphically how a suite of existing technological options could be used to reduce GHG levels to a level that is sufficient to avoid the dangerous effects of climate change.[5] The paper illustrates this point by breaking the required emission reductions down into manageable (though still large) "wedges," each provided by a different technology or set of technologies (see Table 1 on page 5).

As Figure 2 illustrates, the concept is based on the comparison of a business as usual (BAU) projection of GHG emissions into the future with the desired trajectory of stable global emissions through the year 2050. The triangle-shaped gap between the two lines can be divided into smaller portions, each of which represents a technology option. The paper presented 15 such options, each with the potential to reduce emissions in 2050 by one gigaton of carbon per year and argued that implementing only 7 of these would be sufficient to avoid the worst effects of climate change.[6]

This visual illustration conveys a simple, powerful idea: that, despite the scale of the problem, we have the potential to solve it if we can deploy today's technologies at sufficient scale. The concept's resonance is such that now barely a discussion of climate technology fails to mention the wedge concept. It is "the iPod of climate policy analysis… an understandable, attractive package that people can fill with their own content."[7]

The wedges vision is by no means the only way to approach the climate problem, nor should it be seen as independent from other ways of framing emission abatement options. As with all simplifications it serves an important purpose in enabling us to break the problem down into mentally approachable pieces. This simplification means setting aside at least two factors. First,

Figure 2: **The Wedges Concept**



Source: Pacala and Socolow, Science, 2004. Note: Each "wedge" in this figure represents 1 gigaton of carbon per year; seven wedges are needed if emissions are to be brought back to current levels by 2050 globally – and because of the likely increase in demand, additional efforts would be needed post-2050 to stabilize concentrations. Pacala and Socolow identify options for 15 wedges in their analysis.

while it is technically possible to realize each of the wedges, an optimal climate response will certainly not feature equal one-gigaton contributions from each technology. Some may be absent entirely, and others may make smaller contributions at a given cost. Second, a range of diverse options for reducing emissions are known, and more will no doubt be found, that do not qualify for "wedge" status. In particular, policies that apply a uniform cost of carbon will not only propel the implementation of wedge technologies, but will provide an incentive for all kinds of efficiencies. Some of these will be technological, such as more rapid adoption of efficient lighting, house insulation, more efficient motors, and countless more, which are not accounted for in the wedge framework. Others may be behavioral: if the cost of energy rises, people may choose smaller homes or live closer to work. The wedges approach is not intended to capture these kinds of changes, which are studied in the climate literature.

The wedges approach offers a way to confront the problem of taking technologies to scale. A deployment of wedge technologies as described by Pacala and Socolow raises questions that are vitally important for both policy makers and private sector actors. How are such wedges to be realized in national policy? What are the needs in terms of technology, capital, market actors, and regulatory environment? How do we move from today's market and legislative conditions to those appropriate to the enormous task of realizing a wedge? How can we manage the synergies and potential conflicts between wedges? What

Table 1: **Pacala's and Socolow's Climate Stabilization Wedges**

Option	Effort by 2054 for one wedge, relative to 14 GtC/year BAU
	Energy Efficiency and Conservation
Economy-wide carbon intensity reduction (emissions/$GDP)	Increase reduction by additional 0.15% per year (e.g., increase U.S. goal of 1.96% reduction per year to 2.11% per year)
1. Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg
2. Reduced use of vehicles	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5,000 miles per year
3. Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2054
4. Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)
	Fuel Switch
5. Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (four times the current production of gas-based power)
	CO_2 Capture and Storage (CCS)
6. Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW coal in 1999)
7. Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)
8. Capture CO_2 at coal-to-synfuels plant Geologic storage	Introduce CCS at synfuels plants producing 30 million barrels a day from coal (200 times Sasol), if half of feedstock carbon is available for capture Create 3500 Sleipners
	Nuclear Fission
9. Nuclear power for coal power	Add 700 GW (twice current capacity)
	Renewable Electricity and Fuels
10. Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) "occupying" $30x10^6$ ha, on land or offshore
11. PV power for coal power	Add 2,000 GW-peak PV (700 times the current capacity) on $2x10^6$ ha
12. Wind H_2 in fuel-cell car for gasoline in hybrid car	Add 4 million 1-MW-peak windmills (100 times the current capacity)
13. Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of $250x10^6$ ha (one-sixth of world cropland)
	Forests and Agricultural Soils
14. Reduced deforestation, plus reforestation, afforestation, and new plantations	Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)
15. Conservation tillage	Apply to all cropland (10 times the current usage)

Source: Pacala and Socolow, Science, 2004.

constraints do we encounter from technical or public policy perspectives as, for instance, wind turbines come to dominate the landscape, as the types of energy sources supplying electricity to the grid proliferate, or as we try to build consistent international standards for more efficient vehicles?

When we look at the international level, the list of questions gets longer. How can the wedges concept fit within the development plans of developing countries? What is the balance between in-country policy and international mechanisms in bringing these wedges to market? How can the governance and decision making structures within developing countries lead to smarter and cleaner investment choices? How can rich countries work with poorer ones such as India and China to bring wedge technologies to market? What do policy makers and capital markets need to know to enable them to deploy clean technologies at the stupendous rate needed?

We need a solution framework that captures the complexity of implementation of each wedge technology (at a scale that matters) and, just as importantly, the complexity of implementing several wedges that require different regulatory structures as well as capital and deployment requirements.

Smart Wedges and Threat Wedges

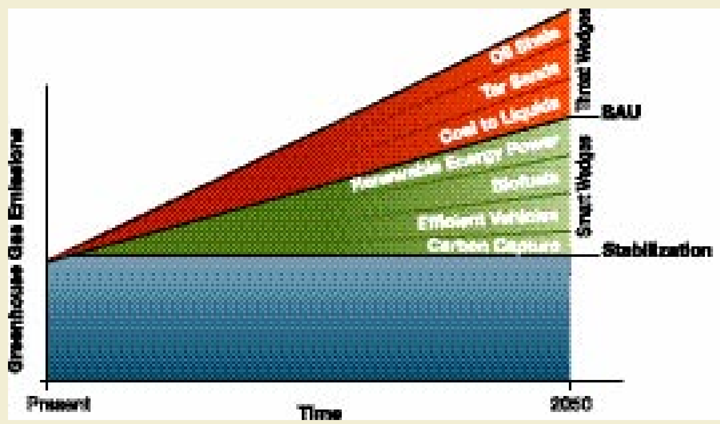
The Pacala and Socolow wedges vision focused on what can be done to help the climate by reducing emissions below BAU. However, the range of policy and technology choices available that are not included in BAU assumptions includes a number of options that could raise emissions significantly. These are likely to be driven particularly by energy security concerns and/or consistently high oil prices, and include:

- Production of synthetic liquid fuels from coal (known as coal-to-liquids, or CTL),
- Extraction of heavy oils from so called "tar sands," and
- Production of oil from crushed rocks called "oil shale."

Considering oil security issues in isolation, these options offer some advantages: although high-cost, they depend on fuels that are available in abundance in countries such as the United States and Canada. However, from a climate perspective they represent a serious threat. Employing CTL would nearly double the emissions of petroleum-based fuels, and both tar-sands and oil-shale require vast amounts of energy and water to process.[8] Extensive application of one or more of these technologies could have fatal effects on efforts to limit climate change.

In this report we term these "threat wedges" to contrast with the "smart wedges" of the Pacala and Socolow vision. Figure 3 shows how these expand the range of technology considerations that we need to confront, and the risk that some policy and investment choices could actually cause emissions to rise dramatically above business as usual, negating the beneficial effects of the clean technology smart wedges.

Figure 3: **Beyond the Wedges**



Source: World Resources Institute. Note that the wedges are schematic, indicative, and not drawn to a specific scale.

Making the Wedges Reality

In order to make wise choices, many entailing the resolution of highly technical questions, across such a range of sectors, political and private sector decision makers require accessible and accurate information. Providing this information demands a major undertaking in research and engagement with decision makers. This paper does not attempt to identify which wedges are the most promising in practice; rather it proposes a blueprint to structure this information, and thus to empower decision makers to implement smart wedges in the real world. The key ingredients of such a blueprint are:

- *Technology* - The scope, scale and availability of the technologies in question, as well as the risks and other impacts associated with them.
- *Investment* - How domestic and international investors respond to the incentives created by policy. In turn, how the combination of policy and commercial opportunity affects capital flows from the private sector and development assistance.
- *Policy* - Agreements, trade conditions and other factors that affect international deployment of the technology. The successful realization of any wedge depends on understanding decision-making processes in the country or region in which it is to be implemented.

Each of these informs the others: for instance, policy may accelerate investment in new technologies, and technological constraints should inform policy design.

The wedges vision brings climate policy into the realm of the imaginable, but hardly makes it easy. Implementing any one of the smart wedges is a massive challenge. Meeting enough of them to avoid the most dangerous climate change requires the mobilization of resources on a scale perhaps unprecedented in peacetime.

Technology

The wedges vision is about deploying broadly-defined but well-known technologies on a huge scale. The urgency of the climate problem is such that the wedges will need to be implemented using technologies that are either in commercial use today or that are visible on the horizon. Profoundly new technologies are unlikely to make a meaningful impact over the timescales we are considering. For instance, it is possible that future development will allow controlled nuclear fusion to be used as a commercial source of power, but the timescales over which that might happen make it essentially irrelevant for our purposes.

Even discounting such long-term bets, the range of wedge technologies considered by Pacala and Socolow includes some that are already deployed at scale (for instance, natural gas to replace coal power) and others that are at a relatively early stage of development (such as hydrogen capture from coal with carbon capture and storage) or operate currently within niche markets rather than at scale (such as solar photovoltaics).

A successful development of the wedges therefore will mean enhancing all stages of the technology development process, from research and development (R&D) through demonstration and commercial deployment. Each of these stages requires private sector innovation and well-designed policy to make the each wedge attainable.

Research, development and demonstration

Federal funding in the U.S. for energy research has been steadily falling since 1980. Federal funding for energy R&D has hovered between roughly $1 billion and $4 billion for the past twenty years, compared to recent expenditures reaching nearly $30 billion for medical science.[9] Nor is this a uniquely American phenomenon. A recent survey of eleven of the biggest energy R&D funders[10] demonstrated that energy R&D spending worldwide has indeed stagnated.[11] Private sector spending on energy R&D has also fallen.[12]

Wherever possible, R&D is most effective when funded by the private sector in response to clear price signals for future technology markets. Government R&D spending is sometimes vulnerable to capture by vested interests, or confined to technologies where companies do not see a likely commercial opportunity, and thus do not mind losing complete control over the results of the research. However, private sector funding alone is unlikely to be wholly adequate to driving a clean technology transformation. Well-designed government R&D efforts can bring a longer time horizon and investigate more risky options with the potential to generate breakthrough technologies. There is a potential role for government involvement where the lessons learned from R&D will apply beyond the private sector carrying out the research, and for research with long time horizons. Certainly in producing the technologies for deeper emission cuts in the second half of this century government research will be important. Even in some nearer-term wedges R&D may yet produce unforeseen technology breakthroughs (see Box 2).

Box 2: Disruptive technologies

In some markets there is a large potential for new and disruptive technologies. A prime example is solar photovoltaics (PV). Today, solar cells are manufactured from silicon in ultra-clean factories, an expensive and energy-intensive process. As long as silicon panels remain the mainstay of the solar electricity market, these are valuable investments. However, should much cheaper alternatives make it into the marketplace they could turn into expensive liabilities. Entrepreneurs at such companies as Nanosolar and Konarka are working on dramatically different technologies that can be produced at much lower cost.[13] Considerable questions remain over the longevity and performance of such technologies, but should these be resolved, they could have serious implications for the economics of existing PV.

Some wedges are likely to see relatively little disruptive technology. Switching from coal to natural gas for instance involves very mature technologies. These will likely see progressive improvements in efficiency, but brand new technologies are unlikely to make existing investments obsolete.

In the case of some wedges the issue is not so much technological development or demonstration but rather the early move to deployment needed to offset investor risk for first movers. Here the government may have some role, such as it is seeking to do in the case of CCS. The FutureGen project[14] is one example of government and private sector partnership in producing demonstration projects, but the IEA argues that at least ten such demonstrations will be necessary, costing from $500 million to $1 billion each.[15] On the other hand, the private sector may already be moving ahead of such government initiatives. BP is developing two new large-scale CCS projects at Peterhead in Scotland and at Carson in Southern California with (respectively) Scottish and Southern Energy and Edison Mission Energy (see Box 3).[16]

Box 3: Industry development of CCS

BP is developing a power project designed to generate electricity and to reduce greenhouse gas emissions by capturing CO_2. The Carson project brings together a number of technologies already operating around the world. A gasification unit will transform petroleum coke feedstock into hydrogen and carbon dioxide. The hydrogen gas will be used to fuel a power station capable of providing the California power grid with 500 MW of low-carbon electricity. At the same time, the CO_2 will be captured and transported by pipeline to California oil fields where it will be used for enhanced oil recovery and geologically stored.

Operational experience of CCS goes back over a decade. The Norwegian company Statoil separates CO_2 from the natural gas extracted from the Sleipner field and injects it into a deep aquifer lying about 1km below the sea bed. This project is commercial, undertaken in response to a Norwegian carbon tax equivalent to around US$50 per ton of CO_2. To date some 10 million tons of CO_2 have been injected, and monitoring suggests that the aquifer will store this gas reliably.

Supply chain bottlenecks

All the wedges require a series of technologies to work in concert. Fossil fuel plants that capture and compress CO_2, for instance, only have value if the infrastructure to transport that CO_2, sequester it and monitor and manage the sequestration site is already in place. The term "infrastructure" here means not only the physical capital stock, but the right human capacity and skill sets and the necessary regulatory and other frameworks.

In the case of some wedges this is a major challenge. For instance, two of the wedges rely on the use of hydrogen as a transport fuel. As Pacala and Socolow acknowledge, this implies a considerable infrastructure, some parts of which are yet to emerge from the laboratory. Handling and transporting a low-density fuel such as hydrogen is highly complex and energy-intensive. Storing hydrogen onboard a vehicle at acceptable cost, both in financial and energy terms, is likely to require new technology. Hydrogen requires a great deal of energy to compress, and in liquid form its evaporation raises safety concerns. While promising alternatives have been proposed, including metal hydrides and carbon nanotubes, their successful application is not yet assured. In the absence of a workable solution for hydrogen storage in vehicles, production of hydrogen aimed at the transport sector is naturally moot.

For some wedges, the constraints may not be technological, but social/political and physical, such as a limit to the number of pipeline networks that can be laid. Take wedges that scale the use of natural gas, increase the use of biofuels, or capture and sequester CO_2: each of these wedge technologies will require a pipeline support infrastructure to transport the gas, biofuels, or CO_2. If all these wedges are deployed together, would it be possible to site all the pipelines in the relevant markets? For that matter, what would these multiple policy pushes in the market mean for the companies expecting to deploy the pipelines? (see Box 4)

Box 4: Pipes that transport CO_2

Kinder Morgan is a leading transporter and marketer of CO_2 in the United States. This segment of their business is responsible for approximately one-fourth of operating income for the company, delivering more than 400 million cubic feet per day through 1,100 miles of pipelines to its oilfield customers for enhanced oil recovery (EOR).

Understanding these constraints often requires a larger vision of the trends in infrastructure deployment. For instance, under a distributed model of electricity generation, which is advocated by many, grids are flexible enough to absorb generation from a very large number and variety of generation sources.[17] This model may offer greater scope for allowing innovative technologies to emerge than the existing and exclusively centralized model in which grids are based around a small number of very large generation sources from which transmission and distribution networks extend.

A technology may also be dependent on a particular natural resource. One obvious example of this is wind energy. Recent research estimated the global wind power potential at 72 TW, technically sufficient to supply all the world's energy needs.[18] However, significant practical and technical barriers to harvesting this potential exist. Since the power output of a wind turbine, for example, varies with the cube of wind speed, the financial viability of wind power investments will depend critically on the quality of the sites designated.

Raw material constraints are also a factor for some wedges. Current PV technology is overwhelmingly based on crystalline silicon from the semiconductor industry. As PV manufacturing has rapidly expanded, the availability of this material has become a major constraint on growth. The development of additional supplies of crystalline silicon and/or the use of alternative materials will be necessary.

More importantly, wedges that rely on supplies of natural gas face significant questions of availability, cost and security. In some major markets, such as North America, adequate supplies will depend on a substantial new infrastructure for international transport of gas, including liquefied natural gas (LNG) terminals. As gas markets become increasingly global, supply-side threats have emerged, such as the idea of forming a "gas OPEC", and growing unease stemming from the reliability of some natural gas suppliers in existing markets, such as Western Europe.[19] Finally, even the physical state of natural gas reserves globally has been called into question, especially as impartial, third party-verified data are hard to obtain.[20]

Human capital

Deploying and managing large-scale energy infrastructure requires widespread expertise in a huge range of fields—expertise which can take many years to accumulate. A classic example of a sector suffering from lack of human capital at present is nuclear power. In North America there are fewer than 40 universities offering advanced degrees in nuclear engineering, and in recent decades graduate nuclear engineers have been a rare breed. The 345 graduate and undergraduate degrees awarded in the field of nuclear engineering in 2001 represent a 75% decrease from the 1977 peak.[21] Nuclear power education is making a comeback, but it will take years for the programs that were cut over the past 30 years to be sufficiently re-established and restaffed and to turn out appropriately qualified graduates in sufficient numbers.

Experts in CCS are similarly worried about the supply of reservoir geologists, who will be in great demand for identifying and managing carbon storage sites at a time when rising oil prices and expanding exploration efforts are already tightening the market for this expertise.

A related issue is that distributed technologies such as small-scale renewable energy plants will depend on extensive sales, installation, maintenance and billing networks that also represent a substantial new investment.

Public acceptance

All large-scale energy infrastructure projects have major potential impacts, both local and global, that can arouse public opposition. For investors in wedge technologies a deep understanding of these public issues can be the difference between success and failure.

The best example of this challenge is nuclear power. While it faces other constraints, particularly high capital costs, public opposition more than any other factor has ground new construction to a near-halt in OECD countries.[22] Issues of safety, radioactive waste disposal and nuclear weapons proliferation remain unresolved and contribute to the difficulties which help undermine the economics of new nuclear reactor builds.

Several other wedge technologies face potential resistance. As described above, implementing a large switch from coal to natural gas will, in many regions, mean building a large number of LNG terminals. But fears of attracting terrorist attacks make local populations generally hostile to such combustible installations.[23] CCS is a relatively novel technology that can involve either transporting or sequestering waste gases in populated areas. An accident in early deployment, or opposition by strong civil society groups, could conceivably make CCS as hard to implement as radioactive waste disposal.[24] Wind energy is often subject to strong local resistance; in many cases spontaneous community objections to impacts on the landscape emerge, in others, opposition is orchestrated by larger groups.

Adverse impacts of wedge technologies

Energy at the scale that humanity demands can never be delivered without major impacts of one kind or another. Each of the wedge technologies has severe downsides, which may appear more or less tolerable for various countries or affected groups. Nuclear power leads to risks of weapons proliferation and waste disposal; most forms of renewable energy entail major land use issues; biofuels are already impacting food prices. Even efficiency measures have effects that some will find harmful. If more efficient vehicles are smaller or have less power, some countries will prove less enthusiastic than others in promoting them. How technology choices reflect or adapt to social preferences in particular markets will have an important effect on their successful deployment.

Investment

There are clearly significant and intricate relationships between the regulatory and technological aspects to a wedges framework for solving climate change. In order for a wedge, or more importantly a portfolio of wedges, to be realized in the marketplace, significant amounts of investment capital need to be mobilized at a global scale. Given the evolving and interwoven nature of the policies that are stimulating demand for low-carbon solutions, as well as the pace of technological advancement, investment flows need to transcend traditional boundaries of public and private finance in order to match the challenge.

There are significant barriers to capital formation around low-carbon technologies. Technology risk, inflexible energy pricing structures, regulatory uncertainty, and other obstacles keep borrowing costs for renewable energy projects relatively high. When these projects are planned in developing economies, higher levels of sovereign risk and economic uncertainty, as well as higher transaction costs add to the cost of capital.

In addition to having higher transaction costs, most investors are unfamiliar with many low-carbon technologies and therefore perceive them as risky, which leads to higher cost of capital. With revenue streams essentially fixed in most energy projects, higher borrowing costs mean these projects could have greater challenges meeting debt service requirements and therefore have difficulty securing debt financing. High financing costs are especially significant since these projects generally require higher initial investments than fossil fuel plants, even though they typically have lower operating costs. This is exacerbated by the fact that many of the deals being considered are often too small to generate sufficient interest. For instance, to date the wind market has mostly been financed by specialist lenders that do not have access to sufficient capital for this technology to be deployed at scale. It is increasingly attracting ever larger investors though, which may indicate that the technology is becoming more widely understood.

Companies seeking to commercialize new technologies also face barriers to capital formation. Regulatory uncertainty, technological proof of concept, and lack of critical mass of intellectual capital and market demand for low-carbon products and services all conspire to keep investment flows to low-carbon technologies small when compared to the scale that is required.

Investment decisions are based on calculated risk. However, in addition to the aspects of technological and regulatory risk outlined above, a further exploration of the dynamics that can influence investment flows into low-carbon technologies unveils another set of inter-related components that are important to mobilize capital.

Investing in development versus investing in deployment

The discussion around investing in low-carbon technologies often centers on investment in technology development. This is clearly a result of recent interest in low-carbon technologies from the venture capital (VC) community. According to the Cleantech Venture Network, a group that tracks capital flows to clean technology companies, clean technology investments totaled roughly $2.9 billion for 2006, representing an 80% increase over 2005 and a 140% increase over 2004 (see Figure 4). The group also reports that in the fourth quarter of 2006 investment in the space ranked fourth in size as an industry segment, behind software, biotech and medical devices and equipment. VC interest has been driven in part by more ready exit strategies in the form of IPOs. London's Alternative Investment Market (AIM) has witnessed over 26 clean energy IPOs or secondary offerings since late 2004.[25]

However, interest from the VC community is not necessarily a leading indicator of deployment at scale. Private risk capital spurs development of technological prototypes that form the basis for continued development and investment–if investors believe the product has commercial potential. It can take years, if not decades, for these prototypical technologies to be commercialized at a sufficient scale. Because the risk-return profile differs between wedges, private risk capital is only likely to be of interest for some technologies, which may or may not be the most effective in reducing emissions. In the case of wedges based on wholly established technologies such as coal to gas switching, VC investors are unlikely to be involved.

In the context of a wedge framework, the development aspect of technology investment will always be a key dimension. However financing technology *deployment* is more significant for a wedge to be realized in the marketplace. Many technologies are ready for large scale and rapid deployment and therefore require different financing needs from different players in the market. Even within one technology wedge investment requirements can vary. For instance, investors in solar technologies can focus on a utility scale, which requires significant project financing and debt, or place capital into advanced photovoltaics on a consumer scale and pursue a more traditional risk capital strategy.

The large-scale deployment of key low-carbon technologies will likely be funded through financing vehicles such as: corporate debt financing or through existing capital on the balance sheet (e.g. Toyota spent an estimated $1 billion to market the Prius), through structured finance products in the energy sector (e.g. wind energy), or in through creative export financing in technology transfer agreements. Banks are setting up clean technology groups that are targeting investments from internal capital or focused on underwriting and structured finance. The bond market, which can provide longer term and lower cost financing than traditional loan facilities, is increasingly interested in financing wind farms. Moreover, there is evidence that banks are innovating in structured finance in the wind market by bundling assets from several projects to collateralize bonds sold to the market. The Italian bank UniCredit's HVB Group, for example, sold upwards of US$600 million in bonds last year to finance 39 wind projects in France and Germany.[26]

The international dimension - distribution of investment needs in different sectors and countries

There is an international dimension of capital flows to low-carbon technologies. Investing in key emerging economies such as Brazil, Russia, India and China, the so-called BRIC countries, requires navigating complexities specific to each country. This includes understanding the network of investment players that can support large-scale deployment of technology. For instance, utility scale project finance in China involves a different set of players than venture backed financing of a PV company based in Silicon Valley.

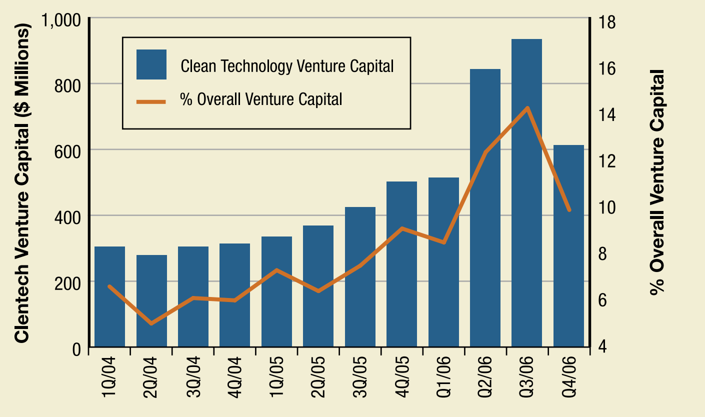
Understanding the distribution of financing is important because different countries draw on very different sources of capital. In China, for instance, the vast majority of capital deployed in the energy sector is domestic, and less constrained by ROI requirements than in more liberalized markets. According to the *World Energy Outlook* the largest investment requirements in the power sector, some $3 trillion, will occur in China by 2030 (see Figure 5).[27]

While the majority of capital invested in BRIC countries is from domestic sources, the sovereign risk characteristics of these countries can differ significantly, which can influence the types of international lenders willing to invest in these markets. Investor risk tolerances, combined with the capacity of a country to absorb and deploy technologies, and the local policies and measures influence which technologies will influence investment capital in the BRIC countries.

Financial innovation is required

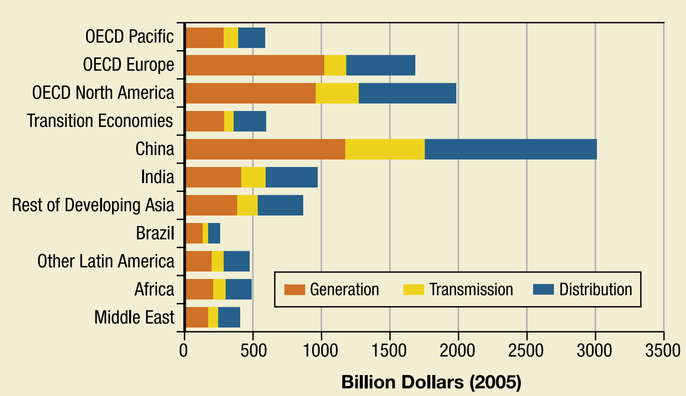
While some of the complexities of investment risk are likely to subside in the coming years, they will not disappear entirely. Therefore, while it is true that greater policy certainty will drive more investment flows into wedge technologies, total regulatory certainty is not feasible. In fact it might not even be possible given the inherent nonlinearities of the climate problem. The regulatory structures driving a number of low-carbon technologies forward are highly complex, interdependent and likely to evolve over time. Continuous and systematic audits of the changing regulatory environment and technological value chain

Figure 4: **North American Venture Capital Flows into Clean Technology Companies**



Source: Cleantech Venture Network

Figure 5: **Cumulative Power Sector Investment by Region, 2005-2030**



Source: IEA, World Energy Outlook, 2006.

are needed to mobilize capital. Financial innovation is a required part of the broader design of policies and institutional structures framed for wedge implementation.

Just as there is no technological silver bullet, there is no single investment structure that would fit the requirements of this diverse market. Because different segments of the financial community can support different levels of risk, a range of custom-designed instruments will be required to finance low-carbon technology deployment. This must occur from private pools of capital, as public resources will prove insufficient to meet the financing requirements of low-carbon technologies. But, these segments cannot act in isolation of each other. There needs to be cooperation between players in public and private finance.

Policy

Investment on the scale required to implement the climate wedges can only be achieved with an adequate policy framework. Climate change is a classic "tragedy of the commons," in which private actors lack adequate incentives to invest in reducing emissions because the benefits will accrue to all, including free riders. Accordingly, public policy will be critical in enabling providers of technology and capital to establish working markets.

At the same time, investors and technology providers will have to work in the absence of clear policy, at least in some parts of the world. Climate change is so pervasive that its policy drivers will inevitably overlap with those in other policy spheres, such as energy security, agriculture and development. Understanding how these policies will emerge and interact is vital to successful wedge technology deployment.

Loud, long and legal

To be effective, a policy framework must provide incentives to invest in cleaner technologies—whether positive incentives such as subsidies or mandates, or negative ones such as taxing or capping pollution. It must reduce investor risk by providing clear, reliable signals over timescales that allow adequate returns on investment.

In the slightly awkward formulation used by a number of industry groups, policies need to be "loud, long and legal". Alliteration aside, this gets at three important characteristics:

- The policies need to be clear and unambiguous. This argues for simplicity in policy design where possible, and for a minimum of bureaucratic detail. In a broader sense, it also means that the political leadership behind the policies needs to be clear and credible, to create confidence that policy direction will be maintained. It also implies that the policy commands public confidence and cooperation, which has implications for the communication and consultation processes involved in both forming and implementing policy.
- Policy signals need to apply over a timescale that counts. Too short, and they do not provide enough confidence among investors that they can plan for adequate returns. Given the kinds of infrastructure that matter for climate change—power plants, roads, buildings, etc.—the appropriate time periods can be long. There is a limit to the length however: political cycles and technology changes mean that targets over multi-decadal timescales will always be viewed with some uncertainty.
- Policies only give clear signals if they are credible, which generally means legal and enforceable. Voluntary measures are unlikely to be significant drivers of the wedges in themselves, because so many of the technology responses, at least in their early stages, entail additional costs. The scope of companies to adopt more costly options while their competitors are not obliged to do so is inevitably limited.

Technology-specific or technology-neutral

Policies for promoting cleaner energy can be roughly divided into two types. The first type applies incentives explicitly to particular technologies. This could include the use of mandates - U.S. biofuels policy for instance has a mandated quota for renewable fuel, with part of that mandate ring-fenced for ethanol derived from cellulose. This category also includes specific support for research, development or demonstration of a particular technology. Subsidies such as the tax credits given to solar in some parts of North America and Europe are an example. Some policies are specific not to just one technology but to a narrow group of them, such as renewable portfolio standards, which support a range of renewable energy technologies for power generation.

The second type of policy applies a blanket incentive to which many technologies could respond, and is neutral on which of these technologies wins the day. Carbon taxes fix a specific price for carbon emissions and thus provide an incentive to reduce emissions where the marginal cost of doing so is lower than the tax. Emission trading is a similar approach but fixes the total amount of emissions permitted and allows the price to be set by the market. Emissions trading is favored in some countries, partly because taxes are politically unattractive and partly because they offer a new market in allocating incentives to invest in reducing emissions. Conversely, the higher institutional capacities needed and the higher transaction costs mean that emission trading will not be a more attractive option than taxes in all cases. In fact, many European countries operate both carbon taxes (or related measures such as energy taxes) together with emission trading.

As a general matter, technology-neutral policy design is strongly preferred from economic and environmental perspectives. After all, the role of government is to set social and political boundaries, leaving the market to innovate. Governments have, on the whole, a mixed record of picking technological winners, and a policy designed around a prescribed technology is less amenable to innovation.

However, the role of technology-specific policies is likely to remain important for two reasons:

- Price signals may emerge gradually, and take time to command investor confidence. For some wedges there may be a role for government support to bring new technologies to the point where carbon prices set by policy are sufficient to let the market take over.
- Some technologies serve other public goods or political constituencies, and in such cases policy makers may wish to single them out. A good example of this is biofuels, which are attractive as a means of increasing farmer revenue.

Interaction with other policies

Even as understanding increases of the importance of tackling climate change, it is unlikely to trump other important policy issues. Climate policy as a driver will coexist with other policy sets, some of which will reinforce the incentives for wedge technologies and some of which will conflict with them.

Energy security is high on the political agenda, pushed by both fuel prices and geopolitical concerns. For technologies such as renewable energy and efficiency improvements the policy responses to energy security concerns complement the "smart" climate wedges. However, energy security is also the main driver behind the "threat" wedges that could divert major effort in technology and capital into making the climate problem worse.

Agriculture policy has dominated biofuels policy, particularly in the United States and Europe, and will continue to have an important role. From an energy perspective this means that suboptimal methods for producing biofuels, in particular the use of starch-based crops, will continue to attract public support disproportionate to their actual energy benefits.

Trade issues are of great importance, given the international scale of wedge deployment. Countries apply tariffs to trade in technologies and services that can impede investment. Related issues such as intellectual property protection and the liberalization of domestic energy markets are also critical and will be shaped by political considerations wider than even the wedges vision.

Policy types

For each wedge a range of possible policy approaches can provide the incentives needed to move technology into the market. Which is chosen will depend only in part on the wedge technologies in question. More important will be the political conditions of each country, the other social or political benefits the policy is expected to achieve, and the legacy of existing policy frameworks. Investors need to be prepared not only for different policy approaches to a given technology in different countries, but also for multiple overlapping policy signals within a particular market.

Box 5: European Union Emissions Trading Scheme

In January 2005, the European Commission launched the European Union Emissions Trading Scheme (EU-ETS) to help achieve its Kyoto Protocol commitments. The EU-ETS is a cap and trade system which covers CO_2 emissions from some 12,000 installations in 27 countries and 6 major industrial sectors. These regulated installations, which entail specific size thresholds, include: large emitters in power and heat generation, oil refineries, coke ovens, metal ore and steel instillations, cement kilns, glass manufacturing, ceramics manufacturing, and pulp and paper mills. Proposals are currently being examined to include CO_2 emissions from aviation and non-CO_2 gases in industry applications. In addition, it allows access to the Kyoto project mechanisms: Joint Implementation and the Clean Development Mechanism. These allow projects in developed and developing countries that can cover six GHGs and all emitting sectors. The EU system has taken a huge step towards a reliable price signal for carbon. Recent surveys show that large numbers of EU companies are already responding to this price signal in their investment decisions.[28] A brief price collapse for the year 2007 has not spooked the market, and prices from 2008 onwards continue to be robust.[29] The EU is actively engaged with other governments at national and state levels to allow linking of emergent trading systems with the EU-ETS. There are good reasons to suspect therefore that the EU-ETS or something like it will feature strongly in an emergent international system.

Many different policy approaches *could* be taken to advance selected wedges. Any or all of these might be applied in different jurisdictions, though some of them may be far from optimal.

Cap and Trade systems cover one or more sectors with an absolute emissions limit, allowing participating companies to trade emission allowances to find the lowest-cost options for reducing emissions (see Box 5). *Taxes* enforce payment of a specific tariff for a unit of emissions, providing a known incentive to find abatement options. *Subsidies* are applied to technologies or practices that reduce emissions. A *technology standard* mandates a specific technology, while a *performance standard* sets a legal minimum for emissions from a given technology or sector.

These policy approaches are not mutually exclusive, and many may coexist at the same time. It is important to understand the diversity of policies: this is not a question of transition, but a permanent feature of policy. In addition, policy design does not start from scratch. Where existing policies such as vehicle efficiency standards, renewable energy portfolio standards or biofuels subsidies exist there will be a strong preference for incrementally improving those policies over designing fundamentally new ones, unless there is a strong consensus that existing policies have failed.

Investors in any wedge technology should expect to encounter any or all of these policies in the countries in which they operate. For instance, the sale of efficient vehicles at present is affected in the U.S. by performance standards (CAFE) and technology support (e.g., HOV lane rights for hybrid vehicles), in Europe by voluntary agreements (ACEA), fuel taxes (all member states) and congestion charging (London), in China by performance standards, in India by mandates (compressed natural gas for public vehicles in Delhi) and so on. While some wedges (particularly those in the power sector) will be more likely than others to get a straightforward price signal through a cap-and-trade system, many such proposals currently in the U.S. Congress also cover transport fuels. Variety of policy tools is not a transitory condition, but the likely permanent state of any market.

Table 2 gives an illustrative (but far from exhaustive) idea of what various types of policy approaches may look like for selected wedges across the power and transport sectors.

Conclusions

Climate change will be a dominant force in economic development and patterns of energy use in the coming decades. A long-term solution to global climate change rests on shifts in technology deployment and use, especially for power generation and transport. Given the urgent nature and enormous scale of the problem, the solution will require immediate implementation on a huge scale of technologies that are already either at or near commercialization. Additionally, all the wedges, to some degree, require a series of technologies to work in concert.

No technological solution to climate change will materialize without sufficient levels of investment capital mobilized both for the development of new, promising technologies as well as for the large scale deployment of existing technologies along with the related infrastructure needed to support these technologies. Yet, in order for sufficient levels of capital to form around low-carbon technologies, the investor community will need to inform and support the policies necessary to stimulate demand. Understanding how these policies will emerge and interact is vital to successful wedge technology deployment.

Uncertain or poorly-designed climate policy presents major risks for companies in the energy sector. Conversely, a well-designed climate policy framework will create huge opportunities for innovative companies to flourish as new markets are created and demand shifts to more efficient, more advanced and higher-value-added products and services.

Table 2: **Illustrative Policy Option for Selected Wedges**

	Policy Choice	Cap and Trade (C&T)
Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg	Applied upstream. Impact similar to tax on fuel, and depends on price (see next column)
Efficient base load coal plants	Produce 2X today's coal power output at 60% instead of 40% efficiency (compare with 32% today)	Applicable policy; would allow sector to determine timing of retrofit, shut-down, new builds. Not likely to narrowly target base load efficiency gains from coal unless policy was tailored with caps applied by plant generating type
Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas (compared with 1060 GW of coal in 1999) Note: may also be undertaken at industrial facilities, including aluminum, steel, etc	Depends on cap sufficiently stringent to set price at around \$30/ tCO_2.[30] Provide incentives by double counting (issuing 2X allowances to any CCS facility) or through inclusion in offset program
Geologic storage	Create 3500 Sleipners	Provide separate allowances to holders of storage sites as well as to capture sites
Wind power for coal power	Add 2m 1-MW peak windmills (50X current capacity); would occupy $30x10^6$ ha. land or offshore area	Provide allowances for wind (essentially double counting benefits – as fossil would already be disadvantaged by having carbon price)
Biomass fuel for fossil fuel	Add 100X current US or Brazilian ethanol production (use of $250x10^6$ ha. or 1/6 of world cropland)	Provide allowances to (1) producers of biofuels, (2) vehicle manufacturers who produce biofuel- using vehicles allowing participation in C&T system. (Could also allow participation through offset projects at any point in biofuels production/end-use cycle)

Source: World Resources Institute

The capital exists, and the technologies exist; what is required is a regulatory framework that allows financial intermediaries to earn a sufficient return on investment. Investment flows in the context of a wedges framework will require financial innovation. If harnessed correctly, investments can yield significant emissions reductions. However, financial innovation does not only mean creating new investment products or financial structures; it requires increased coordination and engagement between all actors in the financial value chain. This includes engaging with stock exchanges, multilateral development banks and export credit agencies, foreign sources of private equity capital, commercial banks, investment banks, pension funds and other players in the capital markets.

To confront the climate challenge and inform policy design, financial and political communities must depart from the standard incremental vision of building markets. We need to overcome the obstacles to deploying low-carbon technologies and smarter infrastructure on a large scale. The wedges model provides a useful framework for tackling this set of challenges.

Tax/Subsidy	Technology Standard	Performance Standard	Notes:
Easily applied via vehicle surcharge or subsidy. Can be developed for specific technology application (e.g., hybrid vehicle) as well as overall efficiency ratings (e.g., vehicle class)	Could be applied to engine technology (hybrid, diesel) or other performance standards in vehicle (transmission, tires, etc). Much technology is proprietary	Fuel efficiency standards (e.g., CAFE)	Reduced vehicle size/power
Could apply tax exclusively to coal-fired base load, with variable rates depending on efficiency. May be element of subsidy to support new technology penetration	Examples: IGCC, fuel cell technology, BAT, hybrid options. May require subsidies to bring untested technologies to market. Could use variable/ratcheting standard for new builds to adjust penetration rates and control costs	Set performance standard 155 gC/kWh (equivalent to a 60% efficiency); compare 232 gC/kWh for 40% efficiency	Retirement is 50+ years, although retrofits may occur earlier
Subsidize CCS plants at 1 – 3¢/kWh (approximate cost differential for CCS technology vs non-CCS plants)	Require new plants to be capture-ready by specific date. Require plants to capture a certain percentage of CO_2 by specific date Mandate IGCC (instead of pulverized coal or fluidized bed combustion technologies)	Set emissions standard at level that can only be met by fossil fuel with capture (e.g., less than anticipated natural gas at 60% efficiency)	Capture alone is not adequate – will need policies also to promote storage
Provided tax write-off for any non-EOR facility (assuming EOR is self financing and already occurs) Tax emissions from flaring at oil/gas wells to induce EOR. Subsidize (allow accelerated depreciation of) construction of pipelines to transport CO_2 from capture to disposal sites	Set storage standards for safety and long term disposal		Other policy options: Government to assume liability for any leaks from storage Declaration of eminent domain for any subsurface reservoir with potential for storage – allowing disposal without NIMBY concerns
Subsidize production/maintenance costs though increase in Production Tax Credit or feed-in tariff Subsidize power storage (e.g., compressed air, pumped water, hydrogen production through electrolysis) Subsidize transmission line construction	Federal Renewable Portfolio Standard with wind as specific share of total (allowing it to be tradable will ensure that locations with limited wind capacity can still support national focus)	Wind turbine efficiency standard (increasing turbine efficiency could lower levelized costs, increasing competitiveness)	Other policy options: Address offshore issues related to liability
Shift agricultural subsidies to biofuels production Increase and extend ethanol subsidies Eliminate import tariffs for production of ethanol (promoting lower cost imports and stimulating larger market use)	Establish Renewable Fuels Standard nationally (note that more than one dozen states have biofuels standards or biodiesel standards already) Require any fuel to be blended (e.g., require 10-20% blended ethanol) Set standards to ensure consistent fuel quality	Set vehicle/engine performance standards for biofuels vehicles	Potential conflicts: Genetically modified organisms Land use, food, water Competition for biomass for electricity/heat generation

Notes

[1] Intergovernmental Panel on Climate Change. "Climate Change 2007: The Physical Science Basis." *Intergovernmental Panel on Climate Change*. 2007.

[2] International Energy Agency. *World Energy Outlook 2006*. Paris: OECD/IEA. 2006.

[3] In this report we use the term "technology" broadly, to include shifts in infrastructure patterns and types of available services as well as purely technical solutions. The adoption of some technologies, such as mass transit systems, implies significant behavioral change, and this is reflected in some of the Pacala-Socolow wedges, for instance reductions in vehicle mileage. Since all these wedges involve deployment of capital to shape a new solution to an energy problem, they all involve common issues.

[4] International Energy Agency. *World Energy Outlook 2006*. Paris: OECD/IEA. 2006.

[5] Pacala, Stephen and Robert Socolow. "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies." *Science* 305. 2004: 968-972.

[6] Some of the wedges are at least partially mutually exclusive. For instance, one wedge is based on doubling vehicle efficiency, while another is based on reducing mileage per vehicle for *inefficient* vehicles. Implementing both would clearly be a good idea, but would reduce emissions by a total of 1.5 gigatons, not 2.

[7] David Hawkins, National Resources Defense Council. Quoted in Energy & Environment News. Available at http://www.eenews.net/special_reports/climate_repair/

[8] Brandt, Adam and Alexander Farrell. "Scraping the Bottom of the Barrel: Greenhouse Gas Emission Consequences of a Transition to Low-Quality and Synthetic Petroleum Resources." *Climatic Change*. (Forthcoming 2007).

[9] International Energy Agency. "Energy R&D Database." 2006. Available at http://www.iea.org/RDD/ReportFolders/ReportFolders.aspx.

[10] Canada, Denmark, France, Germany, Italy, Japan, the Netherlands, Spain, Sweden, the UK, and the US.

[11] Runci, Paul. "Energy R&D Investment Patterns in IEA Countries: An Update." Pacific Northwest National Laboratory/Joint Global Change Research Institute Technical Paper PNWD-3581. 2005.

[12] Kammen, Dan and Gregory Nemet. "Reversing the Incredible Shrinking Energy R&D Budget." *Issues in Science and Technology*. Fall 2005: 84-88.

[13] Nanosolar (http://www.nanosolar.com/) is a leader in using the printing method that makes it possible to simply roll-print solar cells that require only 1/100th as thick an absorber as a silicon-wafer cell. Konarka's (http://www.konarka.com) photo-reactive materials can be printed or coated inexpensively onto flexible substrates using roll-to-roll manufacturing, similar to how newspaper is printed on large rolls of paper.

[14] FutureGen Alliance, http://www.futuregenalliance.org/.

[15] International Energy Agency. *Energy Technology Perspectives: Scenarios and Strategies to 2050*. Paris: OECD/IEA. 2006: 199.

[16] See http://www.bp.com/sectiongenericarticle.do?categoryId=9007871&contentId=7014998.

[17] See, for instance, Amory B. Lovins, E. Kyle Datta, Thomas Feiler, Karl R. Rábago, Joel N. Swisher P.E., André Lehmann, and Ken Wicker. *Small Is Profitable: The Hidden Economic Benefits of Making Electrical Resources the Right Size*. Rocky Mountain Institute. 2002.

[18] Archer, Cristina and Mark Jacobson, "Evaluation of Global Wind Power." *Journal of Geophysical Research* 110, no. D12110. 2005: 19.

[19] Russian President Vladimir Putin was the first to propose the idea of a gas OPEC. At a meeting with Turkmen President Saparmurat Niyazov in 2002, Putin suggested that Central Asian countries join Russia in what he called a "Eurasian gas alliance". His perspective alliance members were not interested at the time. In 2006, however, Iranian President Mahmoud Ahmadinejad proposed that Iran and Russia begin cooperation "in fixing gas prices". While many Russian officials and businessmen reject the idea and any talk of a cartel as the product of a "sick imagination", when Putin visited Saudi Arabia, Jordan, and Qatar in February 2007, the leaders pledged to expand cooperation to better manage the worldwide supply of natural gas, and a meeting of major gas producers and exporters is planned for April 2007 in Qatar to discuss the concept.

[20] Simmons, Matthew R. "Is the World Supply of Oil and Gas Peaking?" Presentation at International Petroleum Week, London. February 13, 2007.

[21] Kean, Sam. "Universities Prepare for Nuclear Reaction." *The Chronicle of Higher Education* 53. 2006: A10.

[22] In 2006 there were 443 operational nuclear reactors worldwide but only two under construction in OECD countries (one each in Japan and Finland). See International Energy Agency. *Energy Technology Perspectives: Scenarios and Strategies to 2050*. Paris: OECD/IEA. 2006: 233

[23] There have been three LNG-related accidents at LNG facilities: In 1944 at an LNG plant in Cleveland, an LNG storage tank failed, spilling LNG into a sewer. The ensuing explosion killed 128 people. In February 1973, an industrial accident (unrelated to the presence of LNG) occurred at a plant on Staten Island. And in 1979 an explosion at the Cove Point, MD terminal killed one plant employee and causing $3 million in damages. While the industry points to this relatively clean safety record to inspire confidence, the public remains unconvinced. In countering proposed LNG facilities, opponents often reference counterterrorism expert Richard Clarke who wrote about the dangers of LNG facilities in his book *Against All Enemies*, claiming that pre-9/11, al-Qaida operatives had boarded LNG tankers in Algeria and used them to gain entry into Boston Harbor, and that on 9/11 tankers in Boston Harbor were top target concerns for federal officials (the FBI denies these assertions). Another resource for opponents, James Fay of MIT, writes about the dangers of LNG, modeling the damage fires would do to our nation's harbors in the event of an explosion – attack or accident.

Terrorism is not the only objection local populations have to LNG facilities. Economic and environmental concerns about shipping canals and sensitive coastal areas are other barriers LNG facility planners have to overcome.

[24] Disch, Andrea and Jeff Logan. *Carbon Capture and Sequestration Policy Brief on Public Acceptability* (working title). Washington, D.C.: World Resources Institute (Forthcoming 2007).

WRI has an important project to design regulations and guidelines to ensure public confidence in the effectiveness and safety of CCS.

[25] Liebreich, Michael. "AIMing Too High?" *Environmental Finance* 7, no.6. 2006: 24.

[26] Martinot, Eric. "Renewables Global Status Report: 2006 Update." Renewable Energy Policy Network for the 21st Century. 2006.

[27] International Energy Agency. *World Energy Outlook 2006*. Paris: OECD/IEA. 2006.

[28] Per-Otto Wold, Point Carbon CEO. Testimony to the Senate Committee on Energy and Natural Resources. March 26, 2007. Washington, D.C.

[29] As of March 29 2007, EU Allowances for December 2008 are trading at €17.34 (US$ 23.14), as reported by Point Carbon (www.pointcarbon.com).

[30] Massachusetts Institute of Technology. *The Future of Coal*. 2007.

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