GLOBAL ECONOMY & DEVELOPMENT
WORKING PAPER 39 | MARCH 2010

Global Economy and Development at BROOKINGS

DECARBONISATION STRATEGIES

HOW MUCH, HOW, WHERE AND WHO PAYS FOR $\Delta \leq 2^{\circ}C$?

Urjit R. Patel

Global Economy and Development
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Acknowledgments:

This paper was written for the conference presidential address delivered on January 23 2010 at the 40th Annual Meeting of the Gujarat Economic Association in Kim (Surat District), India. I am thankful to the Gujarat Economic Association for inviting me to give this lecture. I would like to dedicate today's paper to the memory of my grandfather, P. K. Patel, who spent much of his life not far from here, in Udvada. The time that I spent in India during part of my childhood was also there. Hence, I am doubly grateful to be here today among friends. I should thank Claire Casey, Shivkumar Venkataraman and Ashish Puntambekar for useful conversations and help. The views expressed here are personal and should not be attributed to the author's affiliated institutions.

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DECARBONISATION STRATEGIES

HOW MUCH, HOW, WHERE AND WHO PAYS FOR △ ≤ 2°C?

Urjit R. Patel

INTRODUCTION

At a panel discussion at the London School of Economics (LSE) in early October, I said in my concluding remarks that while I was not optimistic about the likelihood of a *robust* global climate deal at Copenhagen, "there seemed to be a *strong* consensus in world capitals for a *weak* agreement." Well, I was more or less right. We ended up with something rather ineffectual: a less than unanimous declaratory announcement (of feeble aims), although they call it an accord; and, in any case, it is neither a treaty nor even a binding commitment underpinned in law. In fact, domestic politics and the recession have probably put paid to hopes for a precise emissions quota-focused treaty in the near term. At any rate, a legally binding multilateral document is hardly sufficient: emission outcomes even under the formally binding Kyoto Protocol with a built-in enforcement mechanism are widely perceived to have been inadequate.

An address of this sort has the advantage that it is not entirely out of place to share expansive thoughts, which is, of course, another way of saying that I can take some liberty or that this is a work in progress and therefore bits of the paper are, "cognitively speaking", unsettled. Nonetheless, I shall be forgiven since I was a guest.

Regardless of what has transpired in Copenhagen, the sheer scope and longevity of the challenge of climate change will be impacted by and impinge on four factors:

1. Coordination among nations: Without further engagement, the amount of global abatement realized, due to the free rider problem, will almost certainly be undersupplied relative to the magnitude of the global "public bad" threat (if the scientists are right, and the balance of probabilities warrant action commensurate with the "precautionary principle").

2. Technology transformations: Highly capital intensive ones, in part because of more demanding "*target & regulate*" national policies.

3. Instruments for pricing carbon: These may change, for instance, from cap and trade (CAT) to a carbon emission tax (CET). Also, there are likely to be multiple prices; as it is, there is a spread between EU-issued tradable allowances and Clean Development Mechanism (CDM)-generated offset permits; and, if CETs are imposed, then (international) harmonization will inevitably be a long drawn affair.

4. Institutions and capacities, both domestic and multilateral: New ones *may* have to be created and existing ones will have to be strengthened for funding, facilitating transfers, monitoring, implementing, etc.

The paper has been motivated primarily to outline and delve into *what is entailed*—along key dimensions—in bringing about emissions reduction for climate stabilization. In some way, this tack, *inter alia*, may help to implicitly explain why it has been so difficult to agree on sharing responsibilities and confront other challenges. The plan of the paper is as follows. In the next section, I briefly review the desired quantum and possible timeline for global carbon abatement for minimizing the likelihood of irreversible climate change. The subsequent two sections explore promising approaches in the transport and power sectors that are likely to be at the crux for halving energy-related emissions by 2050. Also in these sections, the indispensable technologies are described and the obstacles in the way of routine commercialization are explained. I analyze the "well-to-wheel" strategy for curtailing use of liquid hydrocarbon fuels and associated discharge in the transport sector in the context of rising incomes driving increasing aspiration for personal transport in the coming decades. The role of decarbonizing the electricity sector is underscored, and the chasm that has to be crossed in reaching emission targets in this area is critically drawn to attention. Next, I evaluate the relative merits of worldwide carbon policy mechanisms that are crucial for incentivizing a low-carbon outcome. Specifically, we look at how best to dynamically price emissions through markets-based instruments. A case is made for establishing explicit rules rather than unfettered discretion for policy makers. In the absence of other credible instruments for helping developing countries with costs of mitigation, suggestions are made for widening the scope of the CDM, as also strengthening its integrity. Following on, the subsequent section assesses the scope for financial help for developing countries from the rich nations towards mitigation. The final section has conclusions.

HOW MUCH AND HOW FAST?

The industrialized countries did agree in 1997 to quantitative emission targets for the Kyoto Protocol's first budget period, 2008-12. Most of the Kyoto signers are likely to miss their 2008–2012 targets—those who meet them will do so mainly on account of the present recession—and of course the U.S. never even ratified.[1] Notwithstanding this failure, at multilateral venues such as the United Nations Framework Convention on Climate Change (UNFCCC) and the G8 meeting in Hokkaido in July 2008 world leaders agreed on a broad long-term goal of cutting total global emissions in half by 2050.

According to the consensus among climate science practitioners, a business-as-usual (BAU) path would raise carbon concentration to 1,000 ppm CO_2e by 2050, possibly instigating a global temperature rise of about 6°C. On the face of it, commitments leading up to the circus in Copenhagen were not immodest compared to the BAU. The pathway embedded in these offers (Chart 1) are, *prima facie*, broadly not inconsistent with a 2050 concentration of 550 ppm, but this is incompatible with keeping climate change consequences within safe limits ($\triangle \geq 3$°C by the end of the century if the science is correct).

If the objective is to limit to 25 percent the probability that temperature elevates, above the pre-industrial level, in excess of 2°C (or, a 40-60 percent chance of restricting the increase in global average temperature to < 2°C),[2] then the cumulative balance of the world carbon budget for 2010-49 is estimated to be 687 billion tons CO_2. (During 2000-09, 313 billion tons of the 2000-50 carbon budget of 1 trillion tons CO_2 was used up.)

At the July 2009 G8 meeting in L'Aquila, Italy, leaders of 17 major economies agreed to an environmental goal of limiting the temperature increase to 2°C, which roughly corresponds to a long-term greenhouse gas (GHG) concentration level of 450 parts per million (ppm) of carbon dioxide equivalent (CO_2e), or approximately 380 ppm CO_2 only. For the purpose of this paper, we deploy a target concentration of 450 ppm since thinking by several credible stakeholders, including the UNFCCC, has coalesced around this number (Project Catalyst 2009; Stern 2008; International Energy Agency 2009). Furthermore, businesses (and their financiers) in sectors as varied as autos, renewables, energy storage, power utilities, hydrocarbon exploration and production, and others seem to have internalized, at least in their public pronouncements, aims that are congruent with this target.

The 450 trajectory is an overshoot pathway, i.e., the concentration of GHGs peaks at 510 ppm CO_2e in 2035, remains flat for around a decade and then finally declines to 450 ppm CO_2e (World Energy Outlook 2009).[3] To limit the temperature rise outlined above, energy-related CO_2 emissions would have to peak just before 2020 at 30.9 Gt and decline steadily thereafter, reaching 26.4 Gt in 2030 and under 15 Gt in 2050 (Table 1).

The concomitant pace of the decline in energy-related CO_2 emissions is about 1.5 percent/year in the 2020-2030 decade, but the annual pace of reduction has to double to around 3 percent during 2030-2050.

At the heart of the transformative targets for a low-carbon outcome is the energy sector:

- It accounts for over four-fifths of total CO_2 emissions and just under two-thirds of the world's GHG emissions.[4]
- Going forward, in the coming decades, the average rate of growth in emissions from energy is expected

Chart 1: Pre-Copenhagen assurances by major economies

Country/region	Pledges of emissions reduction
World (IPCC)	25-40 percent below 1990 by 2020 (target).
EU	20 percent below 1990 by 2020, then progress to 50 percent below by 2050.
U.S.	17 percent below 2005 level by 2020 (translates to 3-4 percent below 1990 level). 30 percent below by 2025, 42 percent by 2035, and 83 percent below by 2050.
U.K.	34 percent by 2020.
Japan	25 percent by 2020.
Norway	40 percent by 2020.
China	Cut carbon emissions/GDP by 40-45 percent below 2005 level by 2020. In other words, it has committed to just about (or even a little less than) its business-as-usual (BAU) trajectory over the next decade.
India	20 percent cut in emissions intensity by 2020. The offer is within India's BAU projections.

Source: Media reports.

Table 1: Global business-as-usual (and 450 ppm scenario) emissions in giga tons

	1990	2005	2007	2020	2030	2050
Energy related	20.9	27.0	28.8	34.5 (30.7)	40.2 (26.4)	51(14.5)
All greenhouse gases	NA	42.4	45.0	50.7 (43.7)	56.5 (37.1)	68.4 (21.0)

Note: figures in bracket in the last three columns are for the 450 ppm scenario.
Source: WEO 2009.

to be 1.5 percent/year, much faster than the average growth rate of 0.3 percent/year of other GHGs.[5]

All major sectors will see growth in energy-related CO_2 emissions over the next two decades with power generation and aviation being the fastest-growing sectors, although the latter is from a relatively small base in absolute terms. The power sector accounts for over half the increase in emissions between 2007 and 2030 (column ii in Table 2 below), with a 60 percent increase from coal-fired generation.

The investment and effort that would need to be incurred and expended between 2007 and 2030 has the transitional goal of *cutting* aggregate emissions by about 8 percent instead of an *increase* in global emissions of almost 40 percent in the do-nothing (or baseline or reference) scenario (see "Net" figures in Table 2).

A breakdown of the additional worldwide investment of US$ 10.5 trillion during 2010-2030 is quite revealing with the share of developing countries, including

Table 2: Change in emissions between 2007 and 2030 in (i) 450 ppm scenario and (ii) BAU

Sector	(i) Change in Gt	(ii) Change in Gt
Electricity	-3.4	+5.9
Industry	-0.3	+1.4
Transport	+1.0	+2.7
Buildings	≈0	+0.3
Other	+0.3	+1.1
Net	-2.4	+11.4

Source: Compiled from WEO 2009.

Table 3: Cost of achieving 450 ppm CO_2-e by 2050

	Gt/ year	Gt/ year	Gt/ year	Gt/ year	Gt/ year	Gt/ year	Cum. invest-ment (US$ bn)	Cum. invest-ment (US$ bn)	o/w cum. inv. in low-carbon power genera-tion[a.] (US$ bn)	Incr. inv. (as % of GDP)	Incr. inv. (as % of GDP)
	1990	2007	2020 (ref)	2020 (450 ppm)	2030 (ref)	2030 (450 ppm)	2010-20	2020-30	2010-30	2020	2030
World	20.9	28.8	34.5	30.7	40.2	26.4	2,400	8,100	6,600	0.5	1.1
China	2.2	6.1	9.6	8.4	11.6	7.1	400	1,700	1,500	0.8	1.5
US	4.8	5.7	5.5	4.7	5.5	3.2	520	1,500	1,100	0.5	1.0
EU	4.0	3.9	3.6	3.1	3.5	2.3	500	1,100	1,300	0.3	0.6
Russia	2.2	1.6	1.7	1.6	1.9	1.3	18	180	220	0.3	1.0
India	0.6	1.3	2.2	1.9	3.4	2.2	100	500	550	0.9	1.4
OCs	3.5	5.0	6.7	6.1	9.1	6.4	400	1,500	1,450	0.6	1.2

Source: WEO 2009.
Notes: Gt: billions of tons; emissions are energy-related; ref.: reference/BAU; [a.] Renewables (incl. hydro, wind), nuclear and CCS; OCs: Other (developing) countries, including India, but excluding China, Brazil, South Africa and the Middle East.

India, but excluding China, at US$ 1.9 trillion; the large costs are on account of the long life of the capital assets used in power generation (energy sector *lock-in*) and the even longer durability of CO_2 in the atmosphere.[6] In terms of share to GDP, incremental costs are projected to rise from 0.5 percent in 2020 to 1.1 percent in 2030 (Table 3).

More than three-fourths of the total additional investment for the $\triangle \leq 2°C$ target is "postponed" to the intermediate future (that is, for the third decade rather than the second decade of this century) for five reasons:

- Political expediency in advanced countries, in part, due to the recession has induced *eco fatigue* and skepticism about the urgency of the requisite action.
- Developing countries are unlikely to commit to non-trivial emission cuts before 2020.
- The rate of natural replacement of capital stock on account of obsolescence is higher after 2020; for instance, the bulk of the 350 GW capacity of U.S. coal-fired power generation will come for replacement post-2020.
- Time needed to develop low carbon emitting technologies:
    - Carbon capture and sequestration (CCS) needs another 10 years or so to be developed on a large scale; establishing safety of CO_2 injected underground is a must for instituting confidence.
    - Electric vehicles will take about 10 years to permeate major markets—Europe, U.S. and Japan—and to build up the requisite scale so that the share of passenger light duty vehicles (PLDVs) with conventional internal combustion engines (ICE) could be as low as 40 percent by 2030.
- Lead time in planning nuclear power plants is notoriously long, up to 10 years, for obvious reasons such as NIMBY,[7] identifying secure locations etc., and then a further 4-5 years to build them.
    - Even modest ambitions of nuclear capacity enhancement will face constraints on component supply[8] and production capability of the uranium mining industry.

A "WELL-TO-WHEEL" STRATEGY?

Overview

The largest investment for abatement, US$ 4.75 trillion, is in transport and the bulk of the outlay, US$ 3.4 trillion, is for buying more efficient light-duty vehicles, in particular hybrid and (plug-in) electric cars (WEO 2009). Unabated annual carbon emissions from passenger vehicles are projected to increase by more than one-half by 2030, reaching 4.7 Gt CO_2e. Underlying this growth is a virtual doubling in the number of vehicles from 730 million at present to more than 1.3 billion over the next two decades. The objective is to decrease emissions of PLDVs from the current global average of 210 gCO_2/km to 80-110 gCO_2/km by 2030 (Table 4); this will be a highly capital-intensive endeavor, not least due to cost of sophisticated auto batteries, which are essential for hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and full electric vehicles (EVs).

Higher market shares for low or zero emitting cars are necessary for reaching climate policy targets, but they will be insufficient if the change is not accompanied by the decarbonization of the power sector, a "well-to-wheel" pathway if you will. After transport, an extra US$ 1.75 trillion will be needed for generating power to make greater use of renewables, such as hydro and wind, etc., nuclear, and to incorporate CCS in thermal plants. The average carbon intensity of electricity generated is targeted to decline by more than half, from about 540 gCO_2/kWh at present to about 240 gCO_2/kWh by 2030 (Table 4).

The decarbonizing trend is expected to accelerate after 2020, as the CO_2 price increases sufficiently to displace the majority of coal plants not fitted with CCS. In summary, the primary drivers for the low-carbon outcome are:

- Curb vehicle emissions by switching fuels.
- Decarbonize electricity generation.

The fuel-switch trade-off [9]

Only 15-20 percent of the energy contained in gasoline is used to propel the vehicle; the rest is lost primarily as waste heat. In contrast, electric motors are able to convert 86-90 percent of available energy into motive power. At the consumer level, the choice between gasoline and electric driving rests on the arbitrage opportunity of the additional higher upfront cost, essentially of the battery, and the associated saving in fuel expenditure over the life of the car.[10] For instance, the average small car (C-Segment vehicle such as the Ford Focus, Honda Civic or Toyota Corolla) in the U.S. achieves 28.5 miles per gallon (mpg) in mixed city and highway driving. At the current relatively low gas price in the U.S. (US$ 2.55 per gallon), the cost of gasoline/mile comes to about 9 cents. Elsewhere, say Germany, France, Switzerland, or the U.K., where gasoline costs are approximately US$ 6.00-8.00 per gallon, the fuel cost works out to 21-28 cents/mile. For comparison, if the global average price of electricity is taken to be approximately 10 cents/kWh, then a similarly sized vehicle would achieve 4 miles/kWh, implying an *e-driving* cost of 2.5 cents/mile or 1.56 cents/km. If we assume that electricity is supplied from a (conventional) pulverized coal power station, then the resultant emissions work out to 125 g/km of driving.

The proximate dimension in the typical consumer's trade-off "calculus" is the cost of a battery (high capital outlay versus low operating expense). With regard to auto energy storage costs, economies of scale are important. The battery cost/kWh declines with size of the battery pack; in other words, per kWh, a smaller pack is more expensive than a larger one. An HEV is equipped with the equivalent of 1-2 kWh of batteries, a

Table 4: Global "well-to-wheel" CO_2 emission targets

	Electricity gCO_2/kWh (actual and target)	Electricity gCO_2/kWh (BAU)	Auto emissions gCO_2/km (actual and target)	CO_2 price (US$/ton) (projection)
1971	> 600	--	409	NA
1981	--	--	337	NA
1991	510	--	229	NA
(2001—U.S. avg. est.)	(604)	--	(200)	NA
Present average (2007)	540	--	176-210/270	10-15
2015 (EU in bracket)	--	--	163 (130 in 2013)	≈ 22 in 2012; 15[c]
2020 (EU in bracket)	420	495	130 (95)	45[a]; 50[b]; 80[c]
2025	360	--	--	≈ 84[c]
2030	237-240	478	80-110/130	84[a]; 110[b]; 130[c]
2050	--	--	--	400[c]

NA: Not applicable. BAU: business-as-usual.
Note: For CO_2 price: [a] refers to CERA 2009; [b] refers to WEO 2009; [c] refers to Jacoby et al. 2008.
Compiled from: Deutsche Bank 2009; Energy Information Administration 2009; WEO 2009.

PHEV with 8-16 kWh, and an EV with a 100-mile range would require a 25kWh battery. The median price for the lithium ion "energy" battery packs used in EVs and some PHEVs is currently around US$ 650/kWh and the median price for "power" batteries used in HEVs is priced at US$ 900-1,000/kWh.[11] With innovations currently under development combined with a ramp-up in volume, some sector observers don't rule out a 25 percent reduction from this level by 2015; it has been reported that a few battery vendors are already quoting prices of about US$ 500/kwh for energy batteries.

Table 5 presents plausible scenarios regarding payback periods for EV-plus (PHEV/HEV/EV) vehicles. On a total cost of ownership basis, the payback period in the U.S., with a graded government subsidy that is a fraction of the present one—US$ 7,500 for PHEVs and EVs—is simulated to be three years or thereabouts (scenarios 1, 2 and 3).[12] A gas price of US$ 4/gallon—consistent with a base case outlook of petroleum prices over the next decade—reduces the payback time to less than two and a half years for EV cars (scenario 5). (In sharp contrast, at a European petrol price of say US$ 7/gallon, the payback is one and half years for an HEV and three years for an EV without any subsidy.)

By 2020, industry optimistically anticipates a substantial reduction in prices for energy batteries, to approximately US$ 325/kWh, lower than the assumption in Table 5 for all scenarios. The storage industry, to its credit, is not sanguine (even if their financiers are) about hurdles that still have to be crossed for meeting technical and commercial objectives (see Box 1).

The bulk of the expenditure will be borne by consumers for buying EV-plus vehicles. To the extent that gov-

Table 5: Payback/sensitivity analysis for the U.S. EV-plus market with a gasoline price of US$ 3/gallon, some government incentives, and 2020 battery cost projections

	HEV vs. ICE	PHEV-40* vs. ICE	EV vs. ICE
Battery US$/kWh	500	425	375
kWh	2	13	25
Battery total cost (US$)	1,000	5,525	9,375
Balance of system costs	1,500	1,000	NA in full EVs.
ICE increase (US$)	(1,000)	(1,000)	(1,000)
Govt. subsidy (US$)	--	3,000	5,000
Net additional costs (US$)	1,500	2,525	3,375
Annual fuel savings (in US$ @ US$3/gallon)	445	659	989
(1) Payback in years: base case	3.4	3.8	3.4
(2) Payback if gas price is 10 percent higher	3.1	3.3	3.0
(3) Payback if battery cost is 10 percent lower	3.1	3.0	2.5
(4) Payback if subsidy is 10 percent higher	3.4	3.4	2.9
(5) Payback if gas price rises to US$ 4/gallon (or, through an apposite gasoline tax)	2.5	2.6	2.3

**Note: PHEV-40 refers to a plug-in hybrid with a 40mile range; NA: not applicable.*

Box 1: Auto bettery "tests"

Against the desirable goals established by the U.S. Advanced Battery Consortium (USABC), Sloan Automotive Laboratory at MIT and the Electric Power Research Institute (EPRI) regarding five categories, viz., power, energy, life, safety and cost, the battery challenge for even a 20-40 mile range all-electric vehicle is immense. Battery development is constrained by inherent trade-offs among these attributes (Axsen, Burke and Kurani 2008). Compared to extant HEVs, batteries for PHEVs and EVs are required to store more energy and release this energy over a longer period. The cost target of US$ 500 (let alone US$ 200-300)/kWh is the most obvious one, as research endeavors to simultaneously optimize power, energy, longevity and safety. Li-Ion batteries hold promise for achieving higher power and energy density goals, due to lightweight material, potential for high voltage, and anticipated lower costs relative to NiMH. Although Li-Ion batteries can be made from cheaper materials, they face drawbacks in longevity and safety due to uncontrolled thermal discharge, which still needs to be solved; presently, NiMH is superior to Li-Ion on safety grounds. It is felt that in the medium term, NiMH batteries are commercially viable as a "bridge" technology; the largest selling HEV, Toyota *Prius*, runs on a NiMH battery. Furthermore, multiple design paths underscore the complexity and uncertainty of selecting a single "technological" winner, which will, at some point, be essential to catalyse potential economies of scale.

It is noteworthy that in 1995 the lithium cobalt oxide cells used in laptops were sold for US$ 2/Wh, and today they are selling for 24-28 cents/Wh (US$ 240-280/kWh), including cost of electronics, cooling/heating components, fasteners, etc. (Deutsche Bank 2009). Battery makers think it is not inconceivable that overall cost of an EV battery could be brought down to US$ 400/kWh. The proximate question for the efficacy of the $\triangle \leq$ 2°C objective is when?

ernments may provide direct and indirect subsidies to consumers, they will also bear some of the cost. The burden on the exchequer depends on the government target for EV-plus penetration, and there are diverse projections for the latter. Table 6 provides a snapshot of forecasts from three sources; of course, these are *endogenous* to both subsidy and evolution in the trade-off economics enunciated above. It is noteworthy that industry's expectation of the ramp up (< 20 percent), by 2020 in the share of EV-plus vehicles is considerably more circumspect than that envisioned by some policy makers (48 percent).

A disruptive business model with technological breakthroughs and conducive risk sharing

Decoupling the battery from the vehicle is the key for a more rapid penetration of electric vehicles.

A business model in the making, through unbundling, will simplify the fuel (gasoline—electricity) arbitrage for the consumer.

Service companies, on behalf of the consumer, could invest in capital (the battery), lock in energy costs through long-term power purchase agreements with electric utilities, and mediate the arbitrage to the consumer by billing for a service. In effect, service providers will sell "miles" to the consumer every time the EV-plus vehicle plugs-in to a charging device. A comparison of this business model is often made with that of a mobile phone network provider; the latter invests in communications infrastructure to provide highly subsidized, or free, phones in exchange for 2-3 years worth of "minutes" bought upfront. In the *e-mile* business, "vendors" would sell a multi-year contract for "miles" and in exchange, the service provider would supply the vehicle with a battery, install a charging device at the owner's home, and also endeavour to install a *network* of conveniently-located recharging "stations" (during initial years, "fuel cost" risk of *e-miles* is borne by the service provider). The pre-paid *e-mile* model allows the service provider to benefit from taking a depreciation charge on batteries that are installed, which a non-corporate individual battery owner cannot and enjoy discounts from placing bulk orders; on the other hand, expenditure for investment in associated infrastructure will have to be borne by the service provider.

Target and regulate

Governments are playing an active role by assuming (some) risks that they are best placed and equipped to manage, as also address market failures such as the public good nature of research and development. Major economies are pursuing a three-pronged approach to manage vehicle emissions.

1. Using regulatory powers to mandate the development of advanced technologies by auto makers through enactment of stringent fuel economy/emission standards.

Europe and Japan have proposed automotive CO_2 emission standards for 2020 that are unlikely to be achieved without significant penetration of zero emission vehicles (ZEVs). The Japanese government has projected a 40 percent penetration for EV-plus vehicles by 2020, and newly proposed targets could boost the target further to > 50 percent. The U.S. has tightened and accelerated national fuel economy standards through 2016, changed regulations to disproportionately benefit electric cars—for example, plug-in cars are counted twice in weighted average fuel economy calculations—and it has effectively given California the mantle for regulating the fuel

Table 6: Auto shares (in percent)

	2007[a.]	2010[b.]	2015[c.]	2020[d.]	2030[e.]
Internal combustion engine (ICE) (DB/WEO/CS)	99/99	97.8	92.9/NP	80.4/52/88.4	42/85.2
Total EV-plus	1/1	2.2	7.1/3.8	19.6/48/11.6	58/14.8
HEV	0.6/NP	2.0	4.8/2.4	8.8/32/4.9	29/5.6
PHEV	--	0.1	1.3/0.7	6.2/12/2.25	21/2.8
EV	--	0.1	1.0/0.7	4.6/4/4.4	7/5.4
Memo: # of number of EV-plus cars (in '000s)	≈1,000	1,346	5,626	17,287	--

NP: Not projected; [a.] DB and WEO; [b.] DB; [c.] DB and CS; [d.] DB, WEO, CS; [e.] WEO and CS.
Compiled from: DB 2009; WEO 2009; CS 2009.

economy. (The newly proposed standards by the U.S. Environmental Protection Agency and the National Highway Traffic Safety Administration are expected to have a significant impact in reducing GHGs by improving fuel economy standards. The new standards are "foot-print" based, meaning vehicles of different sizes would have different hurdles to meet under the proposed measures; this would translate into a target mpg equivalent of 35.5 against the current average of about 25 mpg.) The California Air Resources Board (CARB) believes that achieving their "Pavley 2" standards would require 30 percent EV-plus penetration by 2017-2018 and 50 percent by 2025. In May 2009, the Chinese government released new fuel economy standards that target a fleet wide average of 42.2 mpg by 2015. China currently has a fuel economy average of 36.8, owing to a fleet mix that is heavily weighted toward cars with small engines.

2 Catalyze the development of superior technologies through low-cost loans and grants to automakers and component suppliers for research, development and demonstration (RD&D).

Lately, there has been a significant fillip in financial support for manufacturers of advanced technology vehicles, batteries, components and associated infrastructure. It is estimated that governments worldwide have already pledged to spend US$ 15 billion in this area over the next 5 years. EV projects accounted for a large proportion of the U.S. Department of Energy's US$ 27.4 billion Advanced Technology Vehicle (ATV) loan and grant programs. France has moved even more aggressively with plans for spending €1.5bn on infrastructure towards a target of 4.4 million vehicle recharge points by 2020; the French government is also providing loans to transform existing auto plants into EV factories.

3. Incentivize purchase of low and/or zero emission vehicles to engender learning-by-doing and propel economies of scale.

Government subsidies for EV-plus purchases have increased dramatically. Notable fiscally-inspired initiatives include credits of up to € 5,000 in France and RMB 60,000 (about US$ 8,800) for public use vehicles in China. Denmark, Israel, Japan, Spain and others also offer substantial financial incentives for these products. The U.S. government has a goal of 1 million PHEVs/EVs by 2016. The 2009 stimulus bill allocated US$ 2 billion to a graded PHEV tax credit, which is essentially a subsidy for vehicles propelled by a battery of 4kWh or more.[13] In addition, each U.S. OEM will enjoy a 100 percent tax credit for their first 200,000 PHEVs/EVs with further, albeit declining, incentives for four subsequent quarters.

Deploying data in Table 5 (baseline scenario) and Table 6, an implied weighted average subsidy/car of ≈ $ 2,100 and assuming that the additional number of EV-plus cars over the next decade is such that their share reaches about 20 percent in 2020,[14] an illustrative projection for a subsidy outgo of US$ 36 billion in 2020 can be made, which does not seem like a particularly onerous fiscal drain from a global perspective.

"FUTURE OF FUELS" (LOW-CARBON POWER GENERATION)

The world is dependent on hydrocarbon-generated electricity because coal has major attributes: (i) it is the lowest-cost fuel source for base load electricity generation; and (ii) coal endowments are widely distributed around the world. Hence, it supports the national energy security objectives of a number of large economies, including India. Coal is the growing fuel globally and therefore it is the major challenge for any effective climate change policy. Put simply, unless coal is (a) replaced as a fuel or (b) it can be burnt in a less harmful way, there will be limited progress in abating emissions.[15] In Joshi and Patel 2009, I have already argued that any credible climate change policy has to have the coal problem at its core. Since we analyzed (b) above, I will mostly explore (a) for most of the rest of this section.

Two inter-related trends are forecast or desired for a low-carbon future. By 2030 the share of renewables (including hydro) in electricity would have to more than double to slightly less than 40 percent; nuclear would have to increase to about a fifth and 5 percent may come from CCS-enabled hydrocarbon for halving emissions from the global average of 540 gCO_2/kWh to ≈ 240 gCO_2/kWh by 2030 (see Table 7). This represents a major change from BAU where fossil fuels still account for about two-thirds of generation; compared to the BAU, coal-based generation bears the brunt with capacity cut by one-half. Within renewables, the envisaged trend towards hydro imputed for a country like India is striking; a (more than) quadrupling of capacity to enhance production from 124 TWh to 537 TWh by 2030,[16] which, *prima facie*, looks to be difficult given the allergy against big dams in the country on environmental and rehabilitation grounds. On the other hand, a major enhancement of nuclear capacity may be feasible, but it is from a paltry base.

Supply costs are the key

For the decarbonizing strategy, the critical presumption (leap of faith) is that renewables production will become generally more efficient over time and fossil fuels more expensive, thereby enhancing the relative competitiveness of the former. Compared to the recent push towards commercializing EV-plus PLDVs, governments for quite sometime have been encouraging the drive towards economies of scale in wind and solar through a variety of target and regulate instruments. The list includes, for instance, regulations through, *inter alia*, aggressive renewables portfolio standards, RPS, in as many as 28 U.S. states, most notably California[17], and assured high feed-in tariffs—Germany & Spain have had feed-in laws since the early 1990s, and India has introduced assured tariffs of Rs. 12/kWh for solar PV grid interactive projects. In addition, there are production tax credits, as in the U.S. for wind, subsidized financing (especially for R&D), priority access to the grid, and implicit support in the form of avoided taxes, when taxes are paid on other energies that can be replaced by renewables.

Belatedly, funding CCS demonstration projects is gathering pace, which is about time given the centrality of base load hydrocarbon (coal and natural gas) generated electricity in the absence of cost-effective alternatives. The delay in funding CCS-enabled electricity generation projects is inexplicable, almost mysterious (Joshi and Patel 2009), especially when you consider that there are 23,000 fossil fuel-fired power stations in the world. Among strategic mistakes, the frequent postponement in funding CCS on both sides of the Atlantic may turn out to be the most costly for missing the $\triangle \leq 2°C$ target. I am not belittling the technical and safety challenges of commercializing CCS. Rather, multiple demonstration projects in different locations (geologic formations) are required to establish the basic efficacy, or not,[18] of the technology and provide

Table 7: Share of electricity output by fuel (source) in the 450 ppm scenario (in percent)

	World (2007)	India (2007)	World (2020)	India (2020)	World (2030)	India (2030)
Hydrocarbons:	68.3	80.6	60.2	73.8	44.7	54.7
o/w Coal	41.7	67.8	37.0	60.0	24.2	38.5
Natural Gas	20.9	4.5	20.8	11.6	19.0	14.9
Oil	5.7	78	2.4	2.2	1.5	1.3
Nuclear	13.8	2.1	14.8	4.5	18.3	10.8
Hydro ("nouveau" renewable)	15.6	15.6	16.2	14.7	18.9	22.4
Conventional renewables:	2.6	2.8	8.8	6.5	18.1	11.8
o/w Wind	0.9	1.5	5.1	5.0	9.3	6.3
Other	1.7	0.3	3.7	1.5	8.8	5.7

Compiled from WEO 2009.

a sound empirical basis for conducive frameworks. This is important since, not entirely without merit, CCS is perceived in some circles as a misbegotten Frankenstein technology. It entails using more energy and then storing the larger quantity of CO_2, hoping that it will stay trapped underground forever.

Technology breakthroughs for reducing the per unit (life-cycle) cost of renewables and carbon pricing are the two pivots for the "cross over" in marginal costs (Table 8). Of course, one should be cautious when making comparisons. Needless to say, there is inherent imprecision in projecting future levelized costs; these are often little more than guesstimates for some emerging technologies (see Figure A1 in the Appendix for an example). The essential uncertainty can be appreciated in the published range of even *current* levelized costs for generating electricity from renewables (see first and second effective columns of Table 8); and ditto for forecasts of CO_2 prices (see the last column of Table 4).

The extent to which the world has to traverse in terms of making renewables economical even when carbon from fossil fuel use is priced can be appreciated when one examines estimates of implicit and explicit subsidy costs/ton of emissions avoided with accepted levels of marginal damage cost of CO_2 (see Table 9).

Except for wind and biomass in the U.S., the economics against renewables in other countries seems pretty daunting; it is especially sobering when one considers that the price of EU allowances under the second phase of the ETS has plunged to €10-15 levels, even less on occasions in recent times. It gets worse when a full cost approach encompassing, *inter alia*, additional investment in new transmission lines from remote locations and enhanced grid management is incorporated when making comparisons; the renewables industry usually defines its cost base as narrowly as possible and highlights a wider cost base for competitive (conventional) sources.

Table 8: Long-run (levelized) cost of power generation (in US$/MWh)

	Current	2020 excl. CO_2 price	2020 incl. CO_2 price of $50/ton[a]	2030 incl. CO_2 price of $110/ton[a.]	Life-cycle CO_2 emissions/kWh (range in grams)[c.]
Coal	57-74	53-66	98	137	790-1182
Natural Gas CCGT	58-73	80-84	97	118	389-511
IGCC with CCS	65-131 w/o CCS	100	105	98	‹ 100
Nuclear	49-99	57-109	≈ 77	≈ 75	6-26
Wind onshore (avg. for wind)	44-128	33-75	(≈ 85)	(≈ 80)	5.5-37
Wind offshore	142-232	--	--	--	5.5-37
Solar PV	109-276	66-100[b]	For solar, close	--	50-95
Solar PV (Thin Film)	79	58	to previous	--	‹ 20
Solar CST	120-250	190-264	column.	--	--

Note: [a.] The projected price of CO_2 varies considerably even between informed and credible sources. A lower price for emissions makes renewables less viable. [b.] ‹ US$ 150/MWh in much of the OECD by 2012, and in some cases ‹ US$100/MWh (PHOTON). [c.] For hydro: 3-18 g/kWh.
Sources: Bharadwaj 2007; Electricity Policy Research Institute; Energy Information Administration 2009; Garten Rothkopf 2009c; OECD 2006; Patel 2008a; Petroleum Intelligence Weekly 2009; WEO 2009.

Table 9: Average cost of CO_2 displaced when fossil fuels are replaced with renewables (in €/ton)

	Solar PV	Wind	Hydro	Biomass	Biofuels	Geo-thermic
Germany	1200	167	118	195	--	163
France	328	154	155	86	--	--
U.K.[a.]	117	117	117	117	--	117
Italy	200	200	200	200	--	200
U.S.	--	49	--	39	315	--

Note: [a.] Composite average for all renewables.
Source: Strand 2007.

Towards accelerated change: opportunities and constraints

Running costs of renewables capital assets are relatively low in terms of O&M, and there is virtually no direct fuel cost. Therefore, high per unit levelized costs of generation are predominantly due to large upfront capital expenditure in relation to the effective operating capacity of assets; in other words, the efficiency (effective PLF, if you will) of renewables is low compared to equipment costs. There have been important developments, especially in wind where turbines with larger capacities are helping to drive down costs towards grid parity. In 2000, the average wind turbine had a capacity of 860 kW. Today, there are 6 MW turbines available and 10 MW turbines are in the pipeline (Boyle 2008). Progress in enhancing efficiencies in solar has been more modest, although it is the fastest growing renewable source with installed capacity of 15 GW.[19] Nanoscale engineering will play a critical role in creating ultra-low cost (organic) and ultra-high efficiency (quantum dot) solar PV materials, and a breakthrough in this area would dramatically accelerate their development, but this is unlikely before 2020 (Garten Rothkopf 2009a).

A broader risk-based approach in conjunction with a commercial (cost-driven) perspective is helpful for a more thorough evaluation of different future sources and options. Most policy, and even hands-on, discussion on the scope for renewables, conveniently, ignores the challenge of intermittency on account of variations in wind speed, location and solar insulation over a single day and through the year due to changing seasons. Even hydro in the tropics is intermittent; for instance, during the dry season PLF is much lower than otherwise. It is instructive that an otherwise comprehensive report (WEO 2009) put out by an authoritative source does not have a single reference to this subject.

Intermittency by definition undermines renewables in the absence of cost-effective storage solutions or the requisite back up generating capacity as base-load providers of electricity and as substitute for conventional grid-based supply (Bharadwaj 2007; Patel 2008b; Heal 2009; Rattie 2009).[20] Estimated levelized cost of electricity from renewables, cited in this paper (and practically everywhere else), rarely include an imputed cost for the inconvenience or unreliability due to intermittency, which makes the grid-parity economics for renewables even less attractive. Presently in this area in important markets such as California, effort is being expended on distributed electricity generation through small home-based solutions underpinned by smart grids, with PHEVs integral to storage, emergency supply and grid stability. In other words, it is deploying a household as energy "*Prosumer*" (EPRI 2007a; Patel 2008b).[21] This strategy is designed to secure storage at the opposite (i.e., consumer) end compared to grid-level high density storage which is at the supplier end.

Among low-carbon alternatives, it would seem that presently only nuclear is a like-to-like substitute for coal- and natural gas-fired thermal generation in terms of all-year base load reliability at a competitive full cost per unit of electricity generated (see Box 2 for another advantage of nuclear). However, it has been pointed out that the nuclear power industry does benefit from government-sponsored hidden exemptions from costs that other businesses face, prominent among these includes limited liability clauses for catastrophic accidents, loan guarantees, and support for decommissioning old plants (Energy Fair Group 2009).

Scope for a "bridge fuel"

An important viewpoint is that natural gas may emerge as a relatively clean *bridge fuel* to facilitate the transition between reducing dependence on coal-based power generation and the emergence of renewables as a competitive class of electricity resource. There are compelling arguments for this. New natural gas discoveries in a variety of geographies are now not uncommon, so energy security considerations of major economies are preserved. It is not inconceivable that both U.S. and India are at the threshold of becoming gas abundant countries (Garten Rothkopf 2009b; Kelkar 2009); ample unconventional shale gas reserves and new technologies to exploit them are becoming almost ubiquitous. While gas generated electricity is costlier compared to coal, the economics are manageable once carbon pricing is brought into the picture. Emissions per unit of kWh from gas-fired power stations is only about half that from coal. As an illustration, at a gas price of US$ 5.5/MMBTU and a price of US$ 54.4/ton for CO_2, switching of fuel is economical. Moreover, in power short countries like India, natural gas-based generation is already broadly competitive in the electricity portfolio.

Box 2. Land intensity of renewable generation

Just taking physical factors into account, if a country's energy consumption per unit of land is the same as the world average, 0.1 W/m^2, then the power densities/m^2 of renewables—0.5 (biofuels), 2.5 (wind farms), 5 (solar parks), or 20 (CST in deserts)—are all larger (hydro is 11 W/m^2 of lake surface area). That means such countries could match today's power consumption if they covered, for example, 20 percent of their land with energy crops; or 4 percent with wind farms; or 2 percent with solar parks; or 0.5 percent with desert CST stations (assuming they have desert). Therefore, for average countries, it is technically possible to live on renewables. However, countries are not average and most are likely to have growing power consumption due to trend population and income increase. Countries, whose power consumption per unit area is larger than 0.1 W/m^2 such as those where most people in the developed world live, should expect renewable facilities to occupy a significant, intrusive fraction of their land if they ever want to live on their *own* renewables. Countries with power consumption per unit area of more than 1W/m^2, like the U.K., Germany, Japan, the Netherlands, Belgium and South Korea would have to industrialize much of their countryside to live on their own renewables. Alternatively, their options are to radically reduce consumption, buy additional renewable power from other less densely populated countries, or use nuclear power. The power per area of nuclear power facilities, in contrast, is about 1,000 W/m^2—much higher than that of renewables. When it comes to land requirement, nuclear power stations and uranium mines are relatively small and unobtrusive.

The average per capita energy consumption on earth is 56 kWh/day, and in Europe it is more than double at 120 kWh/day. What sort of building project is required to deliver that much energy? For illustration, imagine getting one-third of that energy from wind, one-third from desert solar power and one-third from nuclear power. To obtain 20 kWh/day from wind, one person would require roughly 330 m^2 of wind farm—or, to put it another way, s/he would need to share a 2 MW turbine with 600 friends. To get the same power from deserts would require roughly 50 m^2 of concentrating solar power station—the same area as a typical U.K. house. 20 kWh/day of nuclear power would require roughly a 1 millionth share of a modern nuclear power station. If a country with the size and population of the U.K.—61 million people—adopted that mix, the land area occupied by wind farms would be nearly 10 percent of the country, or roughly the size of Wales. The area occupied by desert solar power stations—in the case of the U.K., they would have to be connected by long-distance power lines—would be five times the size of London. The 50 nuclear power stations required would occupy considerably less area, about 50 square kilometers.

Source: MacKay 2009.

How plentiful will gas supplies turn out to be will ultimately determine the scope for wholesale replacement of gas for coal in thermal generation, and then due to the longevity of capital assets in energy, whether a 450 ppm by 2050 scenario is feasible if the switch to gas is substantial. It is possible that the next "leap" from gas to renewables is undermined because of the large investment in gas fired power stations and the associated infrastructure, including pipelines and LNG facilities that would have taken place in the interim. The deployment of natural gas as a bridge fuel, while helpful, is likely to push back climate stabilization goals.

THE POLITICAL ECONOMY OF MACRO INTERVENTION

In this section, we critically examine and assess the architecture that is either being (partially) implemented or is under consideration in important developed economies for correcting the carbon externality. From first principles and common sense any intervention should have the following characteristics if durable political and intellectual support is desired:

- Efficient: so as to minimize the overall cost of mitigation.
  - Transaction costs should be low/minimum compared to the alternatives.
- Equitable: perceived to be fair by economic agents who are directly affected.
- Relative stability is ensured by design/construction.
- It should not develop a reputation of being a con.
  - It should be relatively easy to grasp; voters should be able to discern the mapping between instrument and objective(s).
  - In other words, simple + transparent = honest!

Cap and Trade (+ con) vs. Carbon Emission Tax

Conceptually, there are three instruments to internalize the social (i.e., global) marginal cost of emissions: a carbon emission tax (CET), a cap and trade (CAT) emission allowances system (trading market for permits and carbon offsets), and a set of command-and-control regulation, including sector restraints and incentives. Economists have been partial to the first two since they are market based. Although, upon reflection, it is obvious that considerable progress on environment issues in most countries has actually been due to the last instrument, viz., a panoply of emission standards for vehicles, content of petroleum-based refined products, phasing out/banning of HFCs, energy-related building standards, and subsidies to promote renewables.[22]

The incentive to save carbon-emitting energy and to innovate would be the same under CET and CAT if the former is imposed at a level that induces the volume of emissions equal to the cap on permits under CAT (*regardless of initial allocations*); this is true within and across countries. There are two considerations that drive a wedge between this "equivalence." The first pertains to uncertainty, for example about the costs of abatement. If costs change, CET keeps the price of carbon unchanged but leaves the quantity of abatement undetermined; conversely, CAT fixes the quantity but allows the price to be undefined. It may be thought that CAT is preferable in the climate-change context since a quantity mistake would be especially dangerous. However, this consideration is not essential since the tax rate could be changed periodically (see the REACT hybrid tax proposal in Metcalf 2009). The second aspect is that transaction and administrative costs as well as corruption are likely to be higher under CAT than under CET. On balance, CET would probably be preferable to CAT if efficiency were the sole objective. The argument in favor of CAT hinges on the "practical" degree of freedom regarding an initial allocation of allowances without sacrificing efficiency that the CAT facilitates between sectors and across countries. Transfers would take place automatically—and under the radar of public glare/voter angst—as part and parcel of the working of the carbon trading market. With CET, a uniform international tax would have to be agreed upon, and equity can only be achieved by explicit (visible) transfers, which, it is argued, would be politically impossible to deliver. This is especially the case for government-to-government flows when we consider that foreign aid has never reached even half the U.N. target of 0.7 per cent of rich countries' GDP (Joshi and Patel 2009).

All too hastily (easily?), members of our profession who are influential in this area have accepted that once equity is brought into the picture, CAT scores over CET.[23] Of course, there are some honorable exceptions such as Buiter 2009, Metcalf 2009 and Wittneben 2009 among others. While voters in developed countries may not have been keen to transfer resources to developing countries for the latter's "economic wellbeing," transfers in the context of climate change mitigation is (directly) for resolving a global "public bad" that they are impacted by. In other words, "the point of concurrence between the parochial and the general interest seems clear."[24] After all, climate change has been brought to the top of the international policy agenda almost entirely by citizens of developed countries. Education of the public backed by persuasive arguments, of which there are many, on the merits of CET has not been attempted with much conviction by politicians and economists—the fight has been given up before it started! Furthermore, official transfers need not take place government-to-government; suitably enhanced intermediaries like the World Bank, ADB, AfDB, IADB and the U.N. can fulfill this task as indeed they already are through their grant disbursement functions, which are financed by developed country governments from domestic tax revenues.

The shaky intellectual scaffolding of CAT could undermine its political durability

Influential stakeholders—in particular, but not limited to, those representing the "Treasury" or "City of London/Wall Street" view—who have strongly endorsed the CAT seem to have either made assumptions (or swept under the carpet practical aspects) that have the potential to undermine the emerging architecture where it is already functioning such as Europe and/or where it is envisaged in the U.S., courtesy the Waxman-Markey (H.R. 2454). The doubtful intellectual foundations on the basis of which CAT has been anointed as superior against the alternative are the very seeds for potentially undermining its durability (see Chart 2 for a detailed comparative dashboard for CAT versus CET).[25]

- The subterfuge of hidden transfers, especially cross-border, under CAT will not last. For example, all it will take is a rise in regulated electricity utility bills for citizens to figure out that free emissions permits could have been allocated to their domestic generators in the U.S. Midwest where there is a concentration of coal-fired power stations instead of an entity in another country, say, in South Asia. Introduction of CAT in the U.S. would by 2030 raise average real retail electricity prices by 29 percent compared to a baseline without federal GHG legislation and 42 percent compared to 2008 prices.
- Transaction costs of CAT have been grossly underestimated and virtually ignored, once market infrastructure and the concomitant regulation and institutions for permit trading/settlement/banking are explicitly taken into account.
- In mature economies where the composition of sectors/industry is relatively stable, allocations are easier to make than in developing countries where the industry structure is more dynamic and less settled; there is a distinct possibility that allocations can turn out to be entry barriers (license-permit *raj*) for new firms (Patel 2007).
- Counting "offsets" in one place (developing countries) toward emission curbs in another (developed country) won't fool many for long. The "non-cutting" forest component—international and domestic—in H.R. 2454 is incredible!

Chart 2: Taxonomic dashboard for cap & trade vs. carbon tax

Attributes/Shortcomings	Cap & trade	Tax
Efficient	✓	✓
Certainty over time-bound quantum of emissions reduced.	✓	Taxes can be changed, say, every five years to steer emission reduction volume.
Cost of running the system.	High (new institutions have to be established).	Low (countries have time-honored processes for collecting taxes).
(Short-term) volatility in price signal (by design).	✓ (therefore requires risk-mitigation instruments)	×
Stability (clear price signal).	×	✓
Time consistency/ commitment.	×	×
Flexibility.	✓	✓
Transparent in terms of incidence (incl. incorporation of offset mechanisms like forestry).	×	✓
Transparent allocations in issuing country.	× (✓ if permits are auctioned)	NA
Transparent in international allocations (permits or tax revenue) to developing countries from advanced countries (governments/private sector?).	×	✓
Scope for rent seeking/lobbying.	High (much room for speculation). Clear danger of falling prey to *excessive financialization*.	Low (although lobbying for tax exemptions for individual sectors is possible)
Seamless transfer of financing from developed to poor countries through initial allocation of permits.	✓ (?) (as long as the deception lasts!)	× (some say, no way Jose!)

The highly discretionary flexibility in allocation of permits that CAT allows will undermine domestic public and political acceptance of CAT in the developed countries as unseemly lobbying gets underway to get free permits (rent seeking). It is not essential that CET across countries have to be uniform at the outset. The argument for instantaneous harmonization is a "practical" red herring; as it is, the price of carbon is often considerably different between sources—Carbon Emission Rights (CERs)[26] and European Union-Emissions Trading System (EU-ETS)—so the contention that (moderately) different taxes between countries will not work as credible price signals is, *per se* and *prima facie*, not tenable.

In this context, the issue of carbon leakage, while not unimportant may have been overplayed by politicians, but the economics profession, to its credit, has not been prone to exaggeration.[27] While the service sector in developed countries is unlikely to be affected, costs in a relatively narrow set of the manufacturing space, viz., petrochemical production, cement, iron and steel mills, lime products and aluminum in the U.S. and elsewhere will be adversely affected (Fischer and Morgenstern 2009; Ho et al. 2008). Estimates modeled by CICERO 2007 and cited in WEO 2008 indicate that carbon leakage would be under 3 percent for the Kyoto regime as a whole and concludes that if these figures are accurate, "the problem is not critical with respect to environmental effectiveness—or competitiveness effects."[28] After all, domestic energy price, which will, *inter alia* be determined by a CET, is only one determinant of international competitiveness for a tradable product, and energy prices anyway differ considerably between countries due to geographical proximity to primary sources and domestic taxes (see Appendix Table A1). Energy intensity is hardly the most important, let alone the sole driver, of comparative advantage—the argument that industry will relocate wholesale merely on the basis of differential carbon taxes is not quite convincing. Moreover, one obvious way in which carbon leakage can be mitigated is if economies that don't impose CET commit to the (minimal) acceptance of BAU emission targets, which practically every country that matters is agreeable to.

The uncritical acceptance of the EU-ETS

Have (potentially) very large rents bought silence?

"The EU-ETS came about as a combination of the growing enthusiasm for market mechanisms, the recognition that there needed to be a carbon price, and the strong lobbying by polluters for a permits scheme rather than a tax. EU attempts to go down the carbon tax route in the early 1990s had failed to get off the ground, and the U.K.-only ETS experiment provided an example to draw upon" (Helm 2009).

As enunciated at the beginning of this section, economists have not adequately highlighted the data/empirics of the one functioning CAT, namely the EU-ETS, against an acceptable outcome metric that any markets-based intervention must be assessed against. Even on the "first level" dimension of credible price discovery, the performance of the EU-ETS has been dismal. Some uncertainty in permit prices may be inevitable, but serious almost inexplicable price volatility has been experienced. The EU-ETS has not even succeeded in delivering a short-term settled price, let alone long-term stable signals considered essential for incentivizing investment and consumer choice; furthermore, in recent times for prolonged periods (e.g., early-mid 2009) the price was much lower than what was envisaged and certainly less than even conservative estimates of the social marginal cost of a ton of emissions.

In the EU-ETS and the proposed U.S. system, allocations are likely to be dominated by ad hoc allocations rather than auctions where the government gets the revenue.[29] The inherent uncertainties in the permits system regarding supply, prices and policy changes have the potential to spawn a financial hedging industry centered in London and New York by the same folks who recently brought the international financial system to its knees. Permits can originate a financial asset class (including associated derivatives) whose aggregate size can be huge. H.R. 2454 caps on U.S. GHG emissions has the potential to create a trading market for allowances and carbon offsets estimated at US$ 4 trillion in value (CERA 2009). It is noteworthy that the legal and advisory professions have also come out in favor of CAT on both sides of the Atlantic; these lines of work are known to exploit and prosper from intrinsic complexity and the concomitant opaqueness, latitude for "playing" between different jurisdictions, and scope for arbitrage between different markets and instruments, viz., permits and offsets, and spot and futures.

Institutional aspects of CAT

It is essential that the relaxation of caps is rule based.

Every cap-and-trade proposal under serious consideration has some form of relief mechanism.[30] For example, "a safety valve" approach, which allows firms to purchase an unlimited number of permits from the government at a set price and thus sets a ceiling on the price of permits. Of course, if the market price for permits is below the safety valve price, then firms will simply purchase permits in the open market. Safety valve provisions protect against upside price risk at the cost of "relaxing" the emissions cap; the strategic allowance reserve proposal in H.R. 2454 is an example. In other words, permits may be legally moved over time—*inter-temporal borrowing and repayment*—to address near-term large price spikes.

Even in cap-and-trade approaches with no explicit "relief" mechanism, government/legislature serves as the ultimate safety valve anyway; if prices rise too high because of a shortfall in permits, the cap can be relaxed, or, even suspended (akin to a central bank ultimately having recourse to printing money). This initiates political risk for permit holders, which means a higher requisite risk premium for holders.

Constructing specific rules, versus discretion, for exceeding a cap, even temporarily, may be necessary to lessen risk of protracted deterioration of overall goals. Deviation is unlikely to be costless due to feedback effects on the environment. Explicit and implicit costs of temporary deviations from (optimal) path need to be taken into account and compared with the obvious benefit of higher economic growth and lower unemployment due to lower energy prices. Some of the tools that economists are familiar with in the context of optimal monetary policy determination may provide useful pointers.[31] Specifically, the "tool kit" for evaluating *trade-offs* that corresponds to balancing inflation and output gap objectives could be helpful in this regard. The capacity of nature, for example, the oceans, to ingest CO_2 is endogenous, i.e., even temporary delays in meeting emissions reduction (or, even worse, exceeding targets) may undercut nature's capacity for absorbing CO_2 ("self healing").[32] According to Stern 2008, "The nature of the stock-flow system, whereby it is not only the concentrations of GHG emissions that have accumulated that cause the damages, but also the annual flow of emissions that relates to economic activity, gives rise to the urgency of action… The costs of meeting a given temperature or stabilization target will tend to rise for every month that policy action is delayed." Another cost is that even a temporary change in the supply of permits can disrupt the economics of renewable sources (can induce *hysteresis*); this is analogous to a sharp appreciation of the exchange rate on account of a temporary surge in capital flows undermining competitiveness, even causing dislocation, in tradable sectors of an economy.

The point is that there are consequences. For instance, in a given five-year period for which an emissions budget is specified to push cuts towards the end of the period or conversely "borrow" emissions from the future at the beginning of the five-year period. To ensure that the timetable for preserving caps on emission allowances is adhered to, establishing explicit rules based on economic and scientific considerations will be required.

Suggestion for reforming the offsets mechanism

The Clean Development Mechanism (CDM) is presently the only market instrument in the Kyoto Protocol where developing countries participate—China and India are by far the largest beneficiaries of the CDM. Moreover, the CDM has been a modest success in terms of financing mitigation in developing countries whereby CERs, issued to developing country sponsors who can show that their projects will emit less than the stipulated baseline, can be bought by EU emitters so that the latter can emit beyond their allocation. The Waxman-Markey bill will also allow for carbon offsets purchased domestically and internationally; in fact, the bill allows polluters to buy up to 2 billion tons/year in offsets over and above the total allowance provided by permits under the CAT; the 2 billion ton annual offset, astonishingly, exceeds *all* the emission reductions in the U.S. envisaged between now and 2040.

The main criticism of the offsets mechanism is that it relies on a counter factual baseline for determining the additional abatement for which tradable CERs are issued. By assumption, it has to be accepted that emissions reduction would not have come about if the carbon offset scheme did not exist.[33] Prevalence of additionality concerns can be partially addressed, not least to ensure continuing political support in developed countries. First, activities that are more obviously amenable to cheating such as not cutting down trees should be excluded. Secondly, as I have argued elsewhere (Joshi and Patel 2009), a programmatic approach will help immensely. For instance, developing countries will not be able to afford installation and running of CCS-enabled coal and natural gas power plants (the increase in per unit cost of generation is two-thirds to double). When CCS is ready for large scale deployment by, say, 2020, a CCS-specific facility for using the technology extensively in developing countries is an option. A relatively uncomplicated course would be to expand the scope of the CDM, call it C-CDM, to incorporate sequestration of power-related CO_2 as an offset that can be traded into a carbon trading system. Of course, the permanent storage of CO_2 will need to be demonstrated and guaranteed to ensure that credits are justified on a scientific basis.[34] Additionality of abatement through a C-CDM will be genuine unlike doubts over whether some segments of the present portfolio of projects or even entire sectors that are eligible for credits actually supplement emissions reduction.[35] Broadening the span of the CDM would enhance the financial flows to developing countries[36], and since thermal power plants entail large and more or less similar investments, the overhead cost related to establishing offsets—which has been found to be onerous for small projects—will turn out to be lower per unit of emissions since a relatively easy cookie-cutter approach will be feasible.

HELPING DEVELOPING COUNTRIES

According to the Pew Center on Global Climate Change, the U.S. contributed 30 percent of the cumulative CO_2 emissions after 1850; the EU-25 together 27 percent (Germany 7 percent, the U.K. 6 percent, France 3 percent, and 2 percent each for Poland and Italy); Russia 8 percent; China 7 percent; Japan 4 percent; and Ukraine, Canada and India 2 percent each. In other words, about 70 percent of the emissions are accounted for by the U.S., EU, Russia, Japan and Canada alone.

The implied shares of the mitigation burden—for the low-carbon objective—in WEO 2009 indicate that rich countries expect developing countries to bear disproportionate responsibility for carbon-mitigation plans, going forward (see Table 10). Note: It would help to broaden the International Energy Agency's credibility beyond that of an OECD-centric think tank/spokesperson if it was upfront about the normative implications of its scenarios.

Investment in climate mitigation, especially for curbing energy-related emissions, will not come cheap. It is acknowledged that earlier calculations were an underestimate and that once policy costs are taken into account, 2 percent of GDP—double the previous estimate—may be more realistic (Stern 2009a). (*The Economist*, December 5, 2009, even now carries a figure of "as little as 1 percent of output.")

As early as 2020, as a ratio to GDP, investment by China and India is required to be higher than the U.S. and EU (see last two columns of Table 3).[37] It has been argued that developing countries' have a "comparative advantage" in embracing a low-carbon growth path since much of the energy-related capital stock that will be potentially required has yet to be built so scrapping of existing assets has a limited role, unlike in developed countries where further new increase in capacity at the margin will be limited so emission reduction entails "active obsolescence." Therefore, from a global welfare (resource) perspective, it may be cheaper to mitigate in developing countries. But the geographical and sectoral distribution of abatement expenditure and investment does not equate to how those actions should or will be funded.

UNFCCC parties have agreed that developed countries must provide financial support to developing ones, although the determination of support is up in the air. The key operative term in burden sharing discussions is "additionality" to underscore that finance provided to help developing countries deal with climate change is wholly on top of the aid sums they currently receive from developed countries. The fear is that, without this guarantee, developed countries will fulfill negotiated obligations by simply diverting their aid flows and the money that once went to schools and public health will be switched, for instance, to CCS-enabled power stations.

Not surprisingly, compensatory financing wish lists have come from the usual suspects. Here is the timeline for notable demands and resultant "offers":

- China called for developed countries to spend 1 percent of their GDP to help poorer nations cut GHG emissions. The funding—amounting to more than US$ 300 billion (€ 237 billion, £ 195 billion) based on the economies of the G7—would be spent largely on transfer of green technologies such as renewable energy to poorer countries (October 2008).
- India decided to raise the issue of effective technology transfer and funds amounting to about US$ 80 billion for developing economies for meeting their adaptation and mitigation costs (November 2008).

Table 10: Burden sharing in emission cuts (against BAU) for △ ≤ 2°C (in percent)

	2020	2030	Present share
China	31.6	32.6	21.2
U.S.	21.0	16.7	19.8
EU	13.2	8.7	13.5
Russia	2.6	4.3	5.6
India	7.9	8.7	4.5
Developing countries incl. India	15.8	19.6	17.4

Source: Compilation based on WEO 2009.

  - o The above "demand" by China and India was made prior to a UNFCCC meeting in Poznan in late 2008.

- By the time the UNFCCC meetings reached Bangkok, amnesia had taken hold. So, in mid-2009, the U.K. Prime Minister Brown talked about US$ 100 billion per year, but no one reacted to him. (He did this on the day Michael Jackson died; consequently, the developed world, and its press, had far more important news to mull over and digest.) In the run up to Copenhagen, the EU made a vague commitment of about half of Brown's suggestion.

- Stern calculated the implied "annual carbon flows" to developing countries for climate stabilization at "US$ 20-75 billion by 2020 and up to US$ 100 billion by 2030" (Stern 2008).

- Stern recently suggested US$ 50 billion per year by 2015 rising to US$ 100 billion by 2020 (Stern 2009b).

- The International Energy Agency, under the 450 ppm scenario, estimates that US$ 197 billion of additional investment is made in non-OECD countries in 2020 and the rich countries (OECD-plus) might contribute anywhere between US$ 13-151 billion, in *addition* to supporting technology transfer and adaptation (November 2009).

- An EU offer of € 7.2 billion for both mitigation and adaptation over three years for the poorest developing countries was made as part of the Copenhagen give-and-take (December 2009).

- The final Copenhagen document has an appeal to developed countries to provide US$ 100 billion by 2020, but without specifying how and who pays what to whom, it is frankly vacuous.

A less than promising trend and vague phrasing on the subject of financing by developed countries should be discernible from the above snapshot.

Except for the Chinese figure, all the numbers are small compared to what careful and unbiased academic work suggests. Jacoby *et al*. (2008) conducted one such simulation. If the G8 proposed goal of a 50 percent reduction in GHGs relative to 2000 levels by 2050 is pursued in conjunction with a global CAT and the proviso that developing countries are fully compensated for mitigation costs, but not adaptation,[38] through apposite allocation of internationally tradable emission permits, then the implied net financial transfers to developing countries are large: in 2020 over US$ 400 billion/year (of which India's share is US$ 50 billion), rising, by 2050, to over US$ 3.3 trillion (India's share is US$ 180 billion).[39] The analogous welfare cost for developed countries measured as loss in national consumption, is about 2 percent in 2020, increasing to around 10 percent in 2050.

Most large developed economies can credibly—in the literal time consistent sense—say that they don't have money. They are running humongous deficits as far as the eye can see to subsidize their financial sectors; not surprisingly, this task is now touted as a global "public" good, much like mitigating climate change. If their contingent liabilities and debt are added up, they may need help in the foreseeable future when the tab is due for repayment. So the bottom line is that developing countries cannot expect the requisite help either from "hot air" allocation under the CAT or direct transfers if eventually sanity prevails and CETs are imposed.

CONCLUSIONS

First, the reorientation towards a low-carbon future commensurate with climate stabilization is large and hence will be expensive, probably double of initial estimates; the transport and power sectors are fundamental for reducing energy-related emissions.

Second, achieving systemic CO_2 emission reductions require deployment of a broad set of both new (under development) and proven technologies, none of which will singly induce the majority of potential curtailment. In other words, there is no "silver bullet," and a portfolio of options will be deployed for a low-carbon outcome. As a consequence, if one or more of the technology options analyzed in the paper are stubbornly commercially unviable or prove to be unsafe, then aggressive levels of technology performance and deployment would be necessary in the remaining technology areas. But perfect substitutability between options is, of course, not guaranteed.

Third, while governments may bear some initial risks and even provide subsidy, the financial burden for reducing transport-related emissions through diffusion of electric vehicles will essentially be borne by consumers. The subsidy to EV-plus car buyers towards a 20 percent market share by 2020 is, *prima facie*, modest, with a back-of-the-envelope calculation of US$ 36 billion in 2020.

Fourth, replacement of hydrocarbon-based electricity will be difficult even a decade down the line. While there is little technological and cost uncertainty with regard to hydro and nuclear, there are safety, roll-out capacity and environmental hurdles which are not wholly appreciated. With regard to wind and solar, intermittency basically makes them inadequate for base load generation. In addition, the comprehensive, all inclusive, cost of reliable generation, transmission and supply from these sources makes their economics, even prospectively, much inferior when compared to other fuels.

Fifth, if one had the temerity to make judgment on the timing and efficacy of "well-to-wheel" developments and targets, which are critical for the 450 ppm outcome, then it is more likely that auto electricity storage may become viable for widespread adoption before hydrocarbon-free electricity generation goals are realized.

Sixth, relatively cleaner natural gas may turn out to be the bridge between base load coal generation and carbon-free sources, but this will require postponing targets for gCO_2/kWh.

Seventh, the "public bad" nature of the carbon externality requires global coordination in some form, otherwise mitigation will be undersupplied. An explicit international arrangement may not be required or even possible, but the pace of technological change is *endogenous* to the price of/tax on carbon dioxide. Therefore, it is essential to have dynamic long-term (global and national) signals congruent with correcting the externality.

Eighth, as far as instruments are concerned, green industrial policy in the form of national regulate and target and fiscal strategies have been deployed in both transport and power sectors with some success. The private sector, on which considerable faith is being placed for establishing the sustained commercial efficacy of technologies, would be incentivized by a secularly increasing price of CO_2.

Ninth, regarding a global markets-based architecture, the "strikes" against CAT may move the pendulum towards CET with associated harmonization and transfer-related issues brought to the fore. A potential allowances trading market in the U.S. alone of US$ 4 trillion has fashioned a powerful lobby of the financial, legal and advisory professions. Economists have their work cut out to push them back. Ironically, the failure at Copenhagen has given us a time window to do just that.

Tenth, challenges related to imparting formal rules—based on economic and scientific trade-offs—for effective implementation of the timetable on carbon targets, and making the CDM credible will entail experimentation with respect to tools and institutional design.

Eleventh, external financing for developing countries will be disappointing as the richer nations are fiscally mired in securing the future of the international financial sector. Funding, if and when it comes about, needs to be formulaic, dynamic and ring-fenced to impart predictability; in other words, there should be minimal discretion. It is also unclear presently whether the US$ 100 billion by 2020 "placed on the table" for the benefit of developing countries is *additional* to current ODA.

Long-term public buy-in is essential. The primary driver of strategies to sustain the likelihood of keeping $\triangle \leq 2°C$ is the desire of richer citizens of this planet to pay for it, which depends on whether they find the associated price of CO_2 needed to transform production and consumptions decisions affordable or prohibitively high. In this context, while the cost of mitigation has been reduced to sound bites for uncomplicated "digestion" by voters, the arguments for atmospheric and environmental sustainability for *everyone* on the planet have been (to my ears) less forceful. There is an underlying callousness that while millions may be affected by larger temperature change (if the science is correct), they are likely to be in the "tropical periphery."

Finally, as for political risks, there is a distinct possibility that the U.S. electoral cycle—mid-term elections after a bruising fight over health care reforms—may conspire against any climate-related legislation, CAT-centric or otherwise, in 2010. Furthermore, talk of trade sanctions in the climate context by developed countries, particularly the U.S. and France, will most likely only ratchet up the belligerence quotient. The harmful consequences of this do not require any elaboration to an audience of economists.

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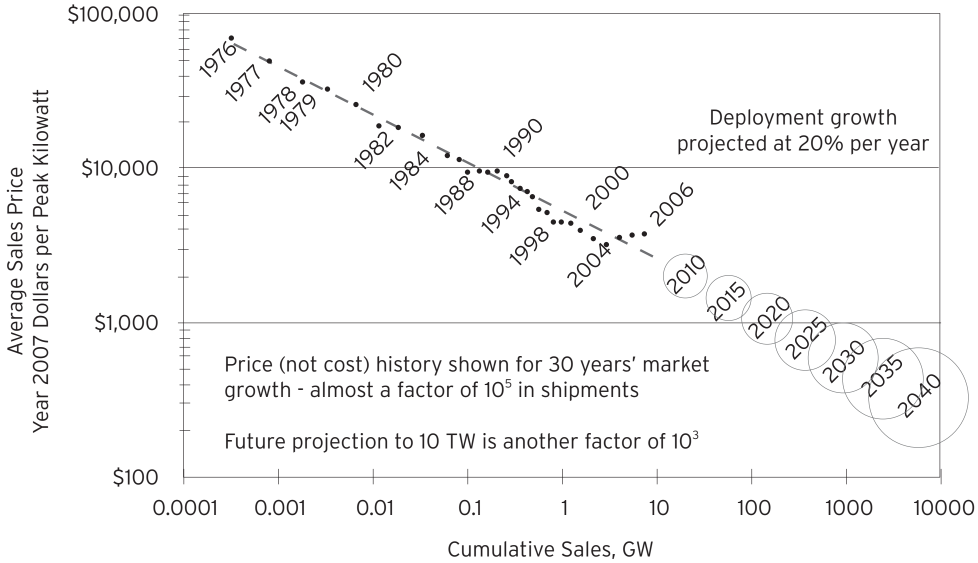
APPENDIX

Appendix Table A1: Energy taxes in important countries

Country	Gasoline taxes	Other notable taxes on energy consumption and production
U.S.	US cents 47.3/gallon	2-6 percent tax on natural gas (NG) for households, industry and electricity generation; severance taxes (as percentage of value of production) that vary from state to state; 2-6 percent sales tax on electricity.
Germany	€ 1.0297/liter	10 percent production tax by value on natural gas. NG for industrial consumption is exempt from VAT but is charged an excise tax of €25.21/10^7kCal; households pay VAT, excise and an eco tax aggregating €115.35/10^7kCal. Household consumers of coal pay VAT of 19 percent. Electricity: manufacturers with an annual consumption of > 50 MWh pay an eco tax of € 0.0123/kWh; households pay VAT and eco tax of 0.0512/kWh.
U.K.	£ 0.4652-0.5419/ liter depending on grade and octane.	Industrial coal is taxed at £12.42/ton, and household consumers of coal pay 5 percent VAT. NG production is subject to a Petroleum Revenue Tax of 50 percent on net income, Ring-Fence Corporation tax of 30 percent on profits, and a Supplementary Charge of an additional tax of 20 percent on "ring-fenced" NG activities. A climate change levy (specific rate/nominal unit of energy) on industrial consumption of petroleum gas or other hydrocarbon in a liquid state at £0.0096/ kg, gas supplied by a utility at £0.0015/kWh, and electricity supplied at £0.0043/kWh. Household consumers of electricity pay 5 percent VAT.
France	€ 0.640-0.811/liter	Annual production of NG larger than 300,000 m^3 is liable for royalty payments of 5 percent. VAT on industrial NG consumption of 25.1 percent. There is an additional consumption tax on NG (but with many exemptions) of €13.84/10^7kCal. Household consumers pay €87.46/10^7kCal on NG and €44.99/10^7kCal on coal. Industrial consumers of electricity are exempt from VAT but average combined municipal and department taxes are levied at 11 percent, and households pay a VAT of 25.1 percent in addition to municipal and department taxes (average at 11 percent).

Figure A1: PV Power-module global average sales price



Source: EPRI 2007b.

ENDNOTES

1. Revised estimates suggest that post-downturn business-as-usual (BAU) emissions in 2020 might be closer to 58 Gt than original estimates of 61 Gt; the primary reasons cited include a 1.5 Gt curtailment due to the economic recession and a 1.5 Gt reduction due to revised numbers for emissions from deforestation and anthropogenic peat emissions (Project Catalyst [2009]).
2. The world is already committed to a 1.3°C rise. 2°C is considered the tipping point for irreversible natural calamities. Also, the 2°C is a global average surface temperature, so it "hides" considerable geographical variability. For example, Africa may suffer a 3-3.5°C increase, anyway. An average 4°C rise implies a 5.5°C rise overland and 6°C over the poles.
3. Global GHG emissions peak in 2020 at 44 Gt of CO_2-e and decline to 21 Gt in 2050 (i.e., half of 2005 levels); in other words, the pathway entails implementation of strategies for slowing, stopping and eventually cutting of annual CO2 emissions.
4. In 2020, the share of energy-related CO_2 in all GHGs is projected at over 70 percent.
5. CO_2 and other greenhouse gases have their source in both energy-related and non energy-related activities.
6. The influential Stern Report estimated the cost of mitigation to be around 1 percent of GDP (Stern 2007). It has been cogently argued by Helm 2008 that this is an underestimate. Note also that the Stern Report does not allow for the important possibility that the shadow price of capital may be greater than unity.
7. Not in my backyard.
8. For example, presently Japan Steel Works is the only company manufacturing very large forgings for reactor pressure vessels.
9. Sub-sections b, c and d draw on DB 2009 and CS 2009.
10. In the US in 1900, 28 percent of the vehicles manufactured were electric drive. However, by the 1920s, electric cars were no longer commercially viable (Anderson 2009).
11. Electricity in HEVs is used only for acceleration; hence, "power" is the key requirement for the battery.
12. It is assumed that annually 15,000 miles are driven; mpg for an ICE car is 33 and for an HEV it is 49; a PHEV is driven 1/3 in gas mode and 2/3 in electric mode; and cost/e-mile is 2.5c.
13. US$ 2,500 for any 4kWh vehicle, plus US$ 417 for each additional 1kWh up to a maximum credit of US$ 7,500 for a car with a battery of 16 kWh or more.
14. Without subsidy, industry estimates of EV-plus penetration rates are in the range of 5-10 percent by 2020.
15. For a low-carbon future, emissions from power generation have to be cut by almost three-quarters by 2050, which implies that after 2030 *no* fossil fuel-based plant is built without CCS.
16. It is instructive that the hydro capacity for 2031-32 projected in Government of India 2006 also seems to be high at > 150 GW (with an assumed PLF of 30 percent), compared to the current capacity of 27 GW.
17. The U.S. Department of Energy has impressive objectives: 10 percent of electricity should come from renewables by 2012 and 25 percent by 2025. US states have targets ranging 15-20 percent by 2020 and 2030 mandated by state-level RPS.
18. Some have called CCS a dangerous delusion!
19. For 25 years the cost of solar panels declined, sliding to US$ 3.15/W_p by 2004. Then global demand soared, and spot price of polysilicon, normally less than US$ 200/kg, jumped to more than US$ 450/kg, which pushed the price of solar panels to US$ 5/W_p. However, polysilicon manufacturers are reportedly bringing into production new capacities

(more than 50 companies have entered the market in the last two years); in addition, the global crisis and a severe slowdown in some key markets has taken its toll on demand, therefore spot prices of polysilicon have plunged and the price of solar panels has sunk to US$ 3/W_p with more declines predicted.

20. The world has about 120 GW of pumped hydro storage, but this serves a different purpose, viz., manage the daily load in dense urban markets. Up until relatively recently, electricity storage was dominated by grid-level (public utility-inspired) applications. Hence, the focus was on large sodium sulphide (NaS) and lead-acid battery solutions to flatten base load factor requirements (peak shaving), replace spinning reserve, and moderate ramp rates (NaS requires 3,200 sq ft of storage area/MW). AES Corp., one of the largest emerging market utility companies with capacity of 44 GW has installed a 12 MW advanced Li-ion battery in Chile, which will pay back in three years.
21. Household is both producer and consumer of energy in a distributed context.
22. The importance of some of these in the transport and power sectors has already been described in earlier sections.
23. Stern 2007 and Stavins 2009, among others.
24. Quote is from Bacevich 2008.
25. See Wittneben 2009 for a thoughtful and cogent metric for assessing CAT and CET.
26. CERs held in India are at present reportedly worth € 5.
27. Carbon leakage comes about when there is a price differential in actual or shadow prices on GHG emissions *between* countries. In the case of the Kyoto Protocol, the price differential is brought about by abatement policies in Annex B countries that will create a significant and positive price on emissions, while the price on emissions in non-Annex B countries will be low or zero if no climate policies whatsoever are implemented.
28. Estimates of "leakage" rates—damage in terms of tons of increased emissions from developing countries for every ton abated in developed countries—vary from 5-20 percent (Frankel 2007).
29. Emitters lobby hard for permits so that they can be beneficiaries of grandfathering.
30. See IMF 2008.
31. While Helm *et al*. 2003 draw an analogy between carbon tax policy and monetary policy, they concentrate their discussion on establishing credibility through independent institutions. Our purpose here has been to emphasize the importance of explicating (modelling) the intrinsic trade-offs in a CAT context and recommend institution of clear rules for (even temporary) relaxation of caps, rather then leaving it solely to the discretion of the policy implementer regardless of whether the latter is the legislature or an independent body.
32. The world's oceans are the main sinks for CO_2, and their continual warming may reduce plankton which is the main mechanism by which oceans absorb CO_2 from the atmosphere. As it is, 90 percent of the extra warming so far caused by greenhouse warming of the atmosphere has ended up in the oceans (Pearce 2009).
33. Recently, more careful scrutiny seems to have been introduced. The U.N. committee overseeing the international credit trade refused to approve 10 Chinese wind farms (*Business Week* December 21, 2009).
34. Others have gone even further. Teng et al. 2008 argue that to further incentivize carbon-efficient electricity generation, there is a case for inclusion in an expanded CDM of emissions "saved" by installing natural gas combined cycle (NGCC) power capacity *without* CCS, since CO2 emissions from gas-based plants are around half of those from coal, which is the alternative fuel.

35. Measurement, reporting and verification (MRV) would be relatively straightforward.

36. Power generation with CCS is "big ticket" (500 MW and beyond), hence transaction costs are bearable (normalized by size of project); it is an archetypical concentrated rather than dispersed emission source. Currently, from validation to registration, the CDM regulatory process on average takes about 300 days, and the associated transaction costs can easily reach half a million dollars.

37. Earlier, I had mentioned that the share in additional investment for mitigating emissions (separate from adaptation) of developing countries, including India but excluding China is estimated at US$ 1.9 trillion.

38. That is, execute the UNCCC mandate to protect developing countries from "the impact of the implementation of response measures". The "impact" to be avoided is defined in terms of "loss in national consumption" (Jacoby *et al.* 2008).

39. The associated trajectory of the price per ton of CO_2e is US$ 50 in 2015, US$ 80 in 2020, US$ 130 in 2030 and about US$ 400 in 2050. Emissions decline linearly after 2015.

The views expressed in this working paper do not necessarily reflect the official position of Brookings, its board or the advisory council members.

ISSN: 1939-9383

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