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Climate Change and the Economics of Targeted Mitigation in Sectors with Long-Lived Capital Stock

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Abstract

Mitigation investments in long-lived capital stock (LLKS) differ from other types of mitigation investments in that, once established, LLKS can lock-in a stream of emissions for extended periods of time. Moreover, historical examples from industrial countries suggest that investments in LLKS projects or networks tend to be lumpy, and tend to generate significant indirect and induced emissions besides direct emissions. Looking forward, urbanization and rapid economic growth suggest that similar decisions about LLKS are being or will soon be made in many developing countries.

In their current form, carbon markets do not provide correct incentives for mitigation investments in LLKS because the constraint on carbon extends only to 2012, and does not extend to many developing countries. Targeted mitigation programs in regions and sectors in which LLKS is being built at rapid rate are thus necessary to avoid getting locked into highly carbon-intensive LLKS.

Even if the carbon markets were extended (geographically, sectorally, and over time), public intervention would still be required, for three main reasons. First, to ensure that indirect and induced emissions associated with LLKS are taken into account in investor's financial cost-benefit analysis. Second, to facilitate project or network financing to bridge the gap between carbon revenues that accrue over time as the project/network unfolds and the capital needed upfront to finance lumpy investments. Third, to internalize other non-carbon externalities (e.g., local pollution) and/or to lift barriers (e.g., lack of capacity to handle new technologies) that penalize the low-carbon alternatives relative to the high-carbon ones.

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Climate change and the economics of targeted mitigation in sectors with long-lived capital stock

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Climate change and the economics of targeted mitigation in sectors with long-lived capital stock

Introduction

1. Two approaches to mitigation currently coexist. In the first, namely ***carbon markets***, carbon finance tends to flow, as one would expect, towards the regions and sectors where mitigation costs are lowest. This is illustrated, for example, by the dominant share of HFC23 destruction projects in the Clean Development Mechanism[2] until 2006, and by the dominant share of non-CO_2 mitigation projects and of end-use industrial energy efficiency projects in 2007 (Capoor and Ambrosi, 2008).[3] In the second, the international community recognizes the need to develop larger-scale ***targeted mitigation programs*** in regions and sectors in which long-lived capital stock is being built at rapid rate to avoid getting locked into highly carbon-intensive capital stock (e.g., the energy sectors in China or India). This is illustrated, for example, by the new World Bank Climate Investment Funds, which explicitly target large-scale pilot and scaling-up investments in sectors with long-lived capital stock, such as transportation, building or power generation.
2. **The objective of the paper is to clarify the economic rationale(s) for the two-tier approach**, particularly the need for the second approach, i.e., mitigation programs targeted to long-lived capital stock, even though the focus of international negotiations post-Kyoto is on expanding the first approach, i.e., the role of carbon markets to more countries and to another commitment period. The argument is presented in three sections:
    - In the first section, we note that long-lived capital stock investment and related emissions have special characteristics that differentiate them from other types of investment. Decisions made by rational agents (based on local technological options and budget constraints) can lock-in energy/emission paths for long periods—as much as a century or more. Casting a backward glance, we show—using a number of historical examples from industrial countries—that, because of the *lumpiness* of investments, the full capacity of long-lived capital stock (in the form of networks or systems, and not just projects) is often installed in a relatively short period of time, even though associated greenhouse gases (GHG) emissions and mitigation costs (high or low) have long-lasting implications. This highlights the importance of limited *windows of opportunity* to shift from high-carbon to low-carbon long-lived capital stock where appropriate alternatives are or can be made available.

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[2] The Clean Development Mechanism (CDM) is a instrument under the Kyoto Protocol by which private or public entities in countries with emissions targets under the Protocol (the so-called Annex B countries, i.e., developed countries and economies in transition in Eastern Europe) can participate in the financing of projects that reduce greenhouse gases emissions in a non-Annex B country (basically, developing countries) and get emission credits in return. For more on the CDM, see Lecocq and Ambrosi (2007).

[3] The unit costs of mitigating emissions of greenhouse gases other than carbon dioxide (CO_2), such as methane (CH_4) or nitrous oxide (N_2O), tend to be lower than the unit costs of mitigating CO_2 because these molecules are more potent greenhouse gases than CO_2, and are valued accordingly under the Kyoto rules. For example, avoiding the emissions of one metric ton of N_2O is equivalent to avoiding the emissions of 310 metric tons of CO_2, and thus valued 310 times as much. Among non-CO_2 gases, the unit costs of reducing HFC23 emissions are particularly low because HFC23 is 11,700 times as potent as CO_2 under the Kyoto metric, and because the technologies necessary to burn this gas are cheap. Hence the popularity of HFC23 emissions destruction projects in the CDM.

- In the second section, we cast a forward glance, and draw analogies to show—using a number of current examples from developing countries—that with urbanization and rapid economic growth important choices about the carbon intensity of future long-lived capital stock are being made today (or will be made in the near future), and that avoiding similar lock-ins in highly carbon-intensive pathways is important for global climate mitigation.

- In the third section, we show that short 'commitment periods' for carbon markets such as in the Kyoto Protocol do not provide private or public agents with a price signal that correctly reflects the special characteristics of long-lived capital stock, notably (i) the long horizon of the direct emission streams of projects and networks, and (ii) the stream of emissions indirectly resulting from or induced by investment decisions regarding long-lived capital stock. In addition, neither the necessary price incentives arising from the regulatory intent of carbon markets, nor the financing available from such markets are likely to be sufficient to overcome financial and non-financial barriers associated with low carbon technologies for long lived capital.

3. The importance of capital turnover for mitigation costs is not a new observation. In fact, capital turnover has been a central issue in the debate on the optimal timing of climate policies (see e.g., IPCC, 1996, chapter 9, and IPCC, 2001, chapter 8).[4] On the one hand, avoiding premature retirement of capital or costly retrofitting has been one of the arguments in favor of delayed mitigation action (e.g., Wigley et al., 1996).[5] On the other hand, the inertia of the socio-economic system (of which capital stock duration is a component) and the inertia of the climatic system can make it very costly to reduce GHG concentrations rapidly should the ultimate damages of climate change prove to be high. It has thus been argued that when inertia, uncertainty about damages and increasing information are correctly taken into account, the optimal abatement path includes *more* mitigation in early periods than it would were increased information not accounted for and uncertainty treated via certainty equivalents (Ha-Duong et al., 1996, Ha-Duong, 1998).[6] Going from one-sector to two-sector models (i.e., with long-lived capital stock distinguished from short-lived capital stock) leads to the same conclusion, in particular that one should abate quickly in the most rigid sector because it is where rapid efforts, if needed, will be the most costly down the road (Lecocq et al., 1998).

4. The analysis in the current paper is different from, and a complement to, this literature. First, it intends to clarify the concept of 'inertia'—typically modeled in a very crude way in the above mentioned literature—by disentangling, with the help of some examples, the different channels through which long-lived capital stock may lock-in emissions paths over the long run. Second, and more importantly, it addresses a *how to,* and not a *when* question. By discussing the specificities of investments in long-lived capital stock, it explores the extent to which the presence of capital stock with a long life affects the choice of instruments to implement mitigation objectives; and it provides some insights on how and where governments might set up incentives for early action.

[4] A debate particularly intense in the years leading to the signature of the Kyoto Protocol, and being revived now as post-Kyoto targets are being negotiated.

[5] Another key argument is that technological innovations will drive down the unit cost of carbon mitigating technologies over time (partly because innovations, or even breakthroughs, will make carbon mitigating technologies more efficient and effective—in terms of energy conversion—over time).

[6] This is a quasi-option value argument (Arrow and Fisher, 1974, Henry, 1974, Hanemann, 1989)

Section 1. Choices about long-lived capital stock are usually made in short periods of time, but have long-lasting implications for GHG emissions

5. **Capital stock is not homogenous**. In fact, long-lived capital stock is a composite of capital stocks with different lifespans which can be disaggregated into the subgroups as follows:[7]

    - Group 1 is capital stock with a lifetime of 5-15 years, which includes most types of consumer durables (excluding short-lived consumer durables, such as personal computers with 3-year life horizon, but including fridges, cars, etc. with 10+ year life horizons). Investment decisions for group 1 capital stock are very decentralized (at the level of households or individual units within firms), and the costs of energy services plays a central role in the choice of equipment.

    - Group 2 is capital stock with a 15 to 40-year time horizon, such as factories and power plants. Decisions for group 2 capital stock are made for the most part by higher-level entities, such as firms' headquarters or highest levels of governments. Except for power generation capital per se, energy costs play a limited role in investment decisions relative to other considerations such as e.g., strategic/competition criteria.

    - Group 3 is infrastructure, with a 40 to 75+-year time horizon, such as road and rail networks, power distribution networks, etc.[8] As we will see below, such networks are typically built-out in one to two decades and their size remains stable for decades with only minor extensions. As in the case of group 2, group 3 decisions are mostly centralized, and energy costs play a limited role. The initial projects in each network increase the benefits of subsequent projects in the network.

    - Group 4 is land use and urban form (land conversion and urban density) which can persist beyond a century or more. This level is governed both by group 2 and 3 infrastructure decisions, and by policies that directly or indirectly influence urban forms and land-use (e.g., tax policies, etc.). The conversion of land to urban uses is generally unidirectional and irreversible. Early density patterns persist for decades or longer (see also paragraph 44).

6. **This note focuses on investments in capital stock with life duration in excess of 15 years**—i.e., on capital stock in groups 2, 3 and 4 above—**which have potentially significant and long-lasting implications for greenhouse gases (GHG) emissions**. In fact, the share of emissions directly influenced by long-lived capital stock in total GHG emissions is significant: **roughly on the order of 41% of total World GHG emissions** in 2000 (50% when land-use change is excluded). This number is computed as follows. On the energy supply side, the emissions from *electricity and heat generation* represent one quarter of total World GHG emissions. These emissions are a function of the type of fuel used by the long-lived capital stock (group 2 in the typology above), and would be different with a different type of capital stock. On the energy demand side, direct emissions from the *transportation*

[7] This division is based on the threefold categorization in Jaccard (1997) and Jaccard and Rivers (2007)—i.e., Group 1, Group 2+3, and Group 4. Here Jaccard's second group has been split into two to distinguish factories and power plants (our Group 2) from infrastructure networks (our Group 3).
[8] We have moved buildings from Jaccard's category 2 (our 3) to his category 3 (our 4), in light of Jaccard and Rivers (2007) analysis suggesting their lifespan exceeds a century.

sector represent more than one tenth of total World GHG emissions. These emissions are generated by relatively short-lived end-use equipment (group 1 above), but the demand for transportation, and thus for energy, derives to a large extent from the complementary transportation infrastructure that is in place, and from urban forms induced by it (groups 3 and 4 above). Similarly, direct emissions from the *residential sector* (which include energy directly consumed by the residential sector for heating, cooking or heating—e.g., coal, biomass, or gas—but excludes the emissions related to electricity or heat consumed by the residential sector and produced off-site) account for more than one twentieth of total World GHG emissions and originate from end-use equipment, but are driven in part by the energy efficiency of buildings and thus by long-lived capital stock (group 3).[9]

7. A second key feature of long-lived capital—particularly the infrastructure component—is the ***lumpiness of capacity installation—***both at a plant or project level, as well as, at a network / system level. At the level of an individual plant or project, it is well known that capacity installation (entailing high upfront costs) will peak in a fraction of the time period the plant or project will be functioning (plant life) before tapering off, even though output (in the form of services generated by the capacity) and hence emissions associated with those services may follow a smoother expansion path. It is the capacity installation process that locks-in the subsequent emissions expansion path because once capacity is installed, high switching costs[10] determine the emissions path over the full life of the installation.[11]

8. More interestingly, the same dynamics is often encountered at network level (national scale) which we show in this paper through examples with readily available public data. Aggregate investments in networks of long-lived capital stock also tend to be concentrated in time (i.e., are 'lumpy'). In other words, the capacity of these networks is put in place in relatively short periods of time. Lumpiness might be related to, inter alia, economies of scale in technology provision (as in the French nuclear case, where the program was cost-effective for manufacturers only if a large enough number of plants were built, box 1), distributional considerations (as in the case of the U.S. Interstate Highway, where federal resources might have been more difficult to appropriate if the program had only targeted a few segments in a few States, box 2), or historic and demographic shocks (as in the post-war housing reconstruction in Europe, coupled with rapid population growth, see box 3). However, not all investments in long-lived capital stock are lumpy at the national level (e.g., the French high-speed train example in box 4 below). With readily available data we have not been able to determine whether capacity expansion at the global level is lumpy or not. Our presumption is that it is less so than at the national level.

9. Third, besides having potentially long-lasting implications for GHG emissions, and besides the lumpiness of investment, **systems built around long-lived capital stock also tend to**

[9] According to the World Resources Institute (2009), 2000 World GHG emissions are 33.2 $GtCO_2e$ (excluding emissions from land-use change), of which the electricity & heat sector accounts for 10.3 $GtCO_2e$ (31.0%) and the transportation sector for 4.8 $GtCO_2e$ (14.6%). Fossil-fuel emissions from the residential sector (excluding consumption of energy from the electricity & heat sector) is estimated at 1.9 $GtCO_2e$ (5.6%) (IEA, 2002). The shares of energy production, transportation, and residential use fall to 25.2%, 11.9%, and 4.6% respectively when emissions from land-use change are accounted for.

[10] In the form of expensive retrofitting or premature retirement.

[11] Or at least until low-carbon alternatives to the complementary end-use technologies associated with the long-lived infrastructure—e.g., cars for road infrastructure—are introduced, see paragraph 26.

generate *externalities*, thus making it even more difficult to shift away at future points in time. For example, investing in gas pipelines will make gas more competitive relative to other fuels, thereby increasing demand and providing additional incentives for utilities, firms, and households to invest in gas-fired heat and power generation capacity, thereby further increasing demand, and generating further development in gas exploitation, extensions of the gas network, and further reducing the relative price of gas—while at the same time limiting resources available for investment in other types of energy, such as renewables. Cumulative mechanisms such as *increasing returns to scale* (e.g., in the development of a dedicated network branching off the main pipeline artery), *induced technological change* (e.g., in the design of gas-fired appliances), *learning by doing* (e.g., creation of a specialized workforce), or *agglomeration economies* (e.g., dependency on or clustering around the cheapest source of fuel) might then make it more difficult to switch away from gas in the future.

10. The difficulty is that the entity that finances an individual project within a program or network of long-lived capital stock does not necessarily include in its profitability/financial cost-benefit analysis the effects of that particular project on the remainder of the program/network via the above-mentioned externalities. Similarly, an entity that finances a complete program or network of long-lived capital stock does not necessarily include in its financial analysis the effects of that program/network on the remainder of the economy via the above-mentioned externalities. Yet in both cases, the induced effects may have positive or negative consequences socially. Where positive, such induced effects may justify, from society's point of view, the implementation of the long-lived system, even if the net present value is lower than other, shorter-lived options. But when negative, such induced effects may create systems that outlive their usefulness by making it more difficult for *other* projects in the future to adopt different technologies, thus creating *path dependency or lock-ins*.[12]

11. Though widely used in the economic and innovation literature, the term 'lock-in' does not have a unique definition, and it is used in various (if closely related) ways. In the presence of 'switching costs', decisions made at one point in time can partially or totally lock-in decision-makers' subsequent choices—making it very costly to reverse *ex post* choices that were not necessarily economically distinguishable *ex ante* (Farrell and Klemperer, 2007). One famous example is the competition between technology standards, for example between the AZERTY and the QWERTY keyboards, or between the VHS and BETAMAX video standards.[13] In the economic geography literature, positive feedback such as agglomeration economies can also lock-in the growth / expansion path of locations / regions once initial choices are made (Fujita et al., 1999). **Here we use the term 'lock-in' in an analogous way to designate cases in which (i) the life duration of capital stock and the aforementioned *cumulative mechanisms* generate a long-term stream of emissions, and (ii) *high switching costs*, discourage later adoption of alternate paths with lower emissions**.[14]

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[12] See also paragraph 74 and beyond.

[13] Though the concept of increasing returns has a long tradition in economic history, the implications of increasing returns and other cumulative mechanisms have been systematically explored only over the past three decades or so, notably around issues of monopolistic competition (Dixit and Stiglitz, 1977), international trade (Krugman, 1979), economic geography (Fujita et al., 1999), economic growth (Romer, 1990), or adoption of technologies (Arthur, 1983).

[14] In standard cost-benefit analysis "sunk costs" (i.e., costs associated with past investments) are treated as irrelevant to new investment decisions. This may seem to be at odds with the notion of lock-in discussed in this paper, which suggests that extensions or subsequent steps *are affected* by initial investments or earlier steps. However, there is no

12. Positive feedback can generate 'virtuous' or 'vicious' cycles (World Bank, 2002). As such, **lock-ins are not good or bad *per se***. It depends on the objective pursued or consequences generated. **So is the potential for lock-in/path dependency a real problem vis-à-vis climate change?** This question has a two-fold response: an empirical one and a theoretical one. The empirical answer is that because the share of long-lived capital stock in total emissions is large (see paragraph 6), and because emissions path tends to be locked-in for long periods of time once capacity is installed, **inability to influence/re-orient the emissions from this portion of total capital stock to meet an emissions target by a given date will necessitate greater and possibly earlier effort on the remainder of the capital stock—** particularly if, with new information, the emissions reduction targets have to become deeper than currently anticipated.[15]

13. The review of stabilization scenarios conducted in the IPCC Fourth Assessment Report (Fisher et al., 2007, Table 3.5 and Figure 3.17) provides some basis for illustrative calculations. Table 1 shows how much emission reductions would be necessary in the sectors that do *not* involve long-lived capital stock for the World to be on a path (as per the IPCC) to meet a given concentration target by a given date, *provided no mitigation is undertaken in the sectors that involve long-lived capital stock* (here energy, transport, and housing).[16] These calculations suggest that a 450 CO_2-eq concentration target would not be achievable this way (because emission reductions would have to exceed 100% in the other sectors). Even meeting a 550 CO_2-eq stabilization target would require that nearly all emissions from the non-long-lived capital stock sectors be abated.

real contradiction between the two. Even though previous investments (sunk costs) are not accounted for in determining the cost-benefit ratio of the extension, the stream of future costs and benefits associated with the extension may be different *because* of the earlier investments. That is, future costs and benefits may be different in the presence of the earlier investments than they would have been in the absence of the earlier investments—as such, the streams of costs and benefits are *not independent.* For example, if the backbone of a ring road or of a highway network has been built, then building a new road to connect a suburb to that ring road or to that highway network (as opposed to building a rail track) becomes much cheaper than it would have been had that initial investment in the ring road or highway network not been made.

[15] The IEA World Energy Outlook makes a similar point that "any delay in implementing emissions-reduction policies will reduce the likelihood of the world achieving its climate-change goal. In the absence of incentives to invest in low-carbon technologies over the 2012-2020 period, the CO2 mitigation potential in the power sector in non-OECD countries would be reduced significantly, because less efficient solutions become locked in." (IEA, 2008, p.493)

[16] These calculations are based on the following conservative assumptions: (i) shares of electricity & heat, transportation and housing sectors in emissions as described in paragraph 6, remain constant over time in the business-as-usual scenario; (ii) capital stock in each sector is assumed to be evenly distributed across vintages, with average lifetime of 100, 70 and 40 years in the housing, transportation and electricity & heat sectors respectively; (iii) baseline emissions 50%, 80% and 100% higher than 2000 emissions in 2030, 2050 and 2100 respectively; (iv) emission reductions in 2030, 2050 and 2100 to meet given GHG atmospheric concentration target as per Fisher et al. (2007), Table 3.5 and Figure 3.17. Assuming that only half of the emissions from the electricity & heat, transportation and housing sectors depend on long-lived capital stock does not fundamentally alter the results.

Table 1. The required level of mitigation in non-long-lived-capital-stock-driven emissions to be on a stabilization path in 2030, assuming no mitigation at all in long-lived capital stock driven emissions

(in percent adjustment relative to the baseline)

Stabilization target (CO_2-eq)	2030	2050	2100
445-490	>100%	>100%	>100%
535-590	73%	90%	>100%
590-710	55%	44%	>100%

Source: Authors' calculation

14. The theoretical answer is a bit more complicated. Since the issue of increasing returns and path dependency started being discussed in the late 70s,[17] a large literature has emerged providing examples and debating the conditions under which path dependency is likely to be observed. In this literature it has been argued that while increasing returns or positive feedback (as is often observed in network externalities) can contribute to path dependency, it is not a necessary condition, and that any type of negative externality can create path dependency (Page 2006).[18] More importantly, the presence of path dependency does not necessarily mean that the path is economically inefficient. In a seminal work, Liebowitz and Margolis (1995) distinguish three different types of path dependency:

- Type 1: Past decisions affect future decisions. This suggests an intertemporal relationship[19]— i.e., the path is sensitive to initial conditions. This is relatively commonplace, and normal. This type of path dependency does not in itself suggest any inefficiency problem. There can be multiple equilibria, e.g., driving on the right hand or the left-hand of the road (Arthur, 1983), but no sub-optimality.

- Type 2: The chosen path proves to be inferior, but only *ex-post* (based on counterfactuals or a change in circumstances). Since the regret factor emerges with hindsight, it does not imply an inefficiency emerging from poor decisions, because it could not have been avoided ex ante with available knowledge at the time the initial decisions were made.

- Type 3: The chosen path can be demonstrated to be inferior and avoidable with information available at the time the initial decisions were made. Liebowitz and Margolis identify this last case as the one that does in fact imply *an economic efficiency cost to path dependency*, but then go on to argue that the necessary

[17] See footnote nb.13.

[18] Four related (but separate) causes have been associated with path dependence— increasing returns, self reinforcement, positive feedbacks, and lock-in. "Increasing returns means that the more a choice is made or an action is taken, the greater its benefits. Self reinforcement means that making a choice for taking inaction puts in place a set of forces or complementary institutions that encourage that choice to be sustained. With positive feedbacks, an action or choice creates positive externalities when that same choice is made by other people. Positive feedbacks create something like increasing returns, but mathematically, they differ. Increasing returns can be tought of as benefits that rise smoothly as more people make a particular choice […] Finally, lock-in means that one choice or action becomes better than any other one, because a sufficient number of people have already made that choice." (Page, 2006)

[19] That is, the pair or sequence of events are not independent of each other.

conditions aren't often met in practice, and most decisions are rational at the time they are taken. In other words, those arguing for inefficient path dependency need to demonstrate why, with the information available *at the time* that the chosen path is going to be suboptimal, that that path is nonetheless chosen over the superior alternative.

15. Foray (1997) argues that the last condition is much too stringent. To generate this strong form of inefficiency, he argues that "the system requires two classes of agents – some have the right information to make the correct choice but fail to take advantage of the implied profit opportunities, and agents who know nothing more than the payoff going to the next adopter." In reality, however, there is often real uncertainty regarding the consequences of future trajectories (that are resolved through experimentation and learning) at the time options are selected. In addition, the selection of options may be based on local and not on global optimization—in other words, the selection of options can be rational in terms of local experience but not in terms of global experience. In fact, time and budget constraints may favor a quick decision based on local experience, but not because it has been demonstrated to be superior. Thus, **choices do not have to be irrational at the time they are made to generate inefficiency from an economic perspective. High switching costs can then lead to the persistence of the selected option despite new information and options**.

16. With regard to climate change mitigation, some lock-ins, such as structuring of energy supply around coal or high carbon emission paths, are undesirable, while others, such as structuring the economy around renewables or low carbon emission paths, are more desirable. The same lock-in can in fact be both "good" and "bad" depending on the objective. For example, reliance on abundant resources of domestic coal might be *un*desirable from a carbon emissions perspectives, but be desirable with regard to energy security—which is why it is important to weigh trade-offs not just in the short run but over the life of the lock-in. In the following two boxes we give examples of a good and a bad lock-in. Box 1 illustrates the case of a 'good' lock-in from the perspective of carbon emissions, even though investment decisions were not based on that objective. Box 2 illustrates how prior commitments to long-lasting residential capital stock can generate a stream of carbon emissions and increase the costs of abatement in the future.

Box 1. An unintended positive lock-in: The case of the French nuclear power program

17. **One example of a "good" lock-in, from the climate change point of view, is the French nuclear program, even though climate change mitigation was not an objective at the time the program was passed.**[20] In 1974, after the first oil embargo, France embarked on a massive program to develop nuclear energy capacity in the name of energy independence. **The program** (consisting of the construction of a multitude of similar plants[21] based on a single standard technology) **was implemented in a very short period of time (lumpy investment)**. In fact, half of the total program capacity was online within a decade (i.e., by 1985), and nearly 80% by 1990.

18. Following the implementation of the program, the share of nuclear energy in total electricity generation jumped from 16.5% in 1979 to 65% in 1990, and reached its plateau of around 77% in 1995. Between 1979 and 2007, overall electricity production in France grew 2.4-fold, from 241 to 540 TWh, but nuclear power production grew 11-fold, from 40 to 440 TWh. As a result, the production of thermal electricity has been cut in half during this period. And as a consequence, overall CO_2 emissions from energy generation have been cut in half since the early 1970s. CO_2 emissions per KWh of electricity and heat generated in France are now 1/5th of that in other large OECD countries, such as Germany, the UK, or the U.S.[22]

19. From an industrial point of view, the cost-effectiveness of the program required that nuclear power plants be built faster than expected demand, leading to excess supply. As a result, electricity exports increased. In addition, the government pushed for the development of demand for electricity, notably water heating and electrical heating both directly via incentives and indirectly via uniform pricing of electricity across the country (including overseas departments), thereby *de facto* subsidizing electricity generated from the grid relative to other energy sources. Between 1975 and 1988, the share of electric heating in total domestic electricity demand increased from 26% to 44% (de Gouvello and Jannuzzi, 2002).

20. As of January 2009, about three quarters of the generation capacity was between 21 and 30 years old. This points to the need for **another round of lumpy new investment in power generation capacity to compensate for the retirement of the current nuclear capital stock** around 2020-2030 (depending on the effective average lifespan of nuclear reactors, currently estimated at around 40 to 45 years, even though extensions to 60 years are being discussed).

21. Looking forward, scenarios for electricity generation until 2050 (Charpin et al., 2000) suggest that for a given energy demand scenario,[23] cumulative CO_2 emissions from electricity generation 2000-2050 will double if the nuclear capital stock is not renewed in the 2020-2030 period relative to scenarios in which the nuclear capital stock is renewed. The difference is significant, on the order of magnitude of 3-5 years of (current) emissions of the country. Interestingly, extending the 30-year average design horizon by 15 years, through modification of existing plants, will save as much in avoided emissions as the difference between the with vs. without nuclear power scenarios.

[20] This historical example aims to illustrate how investments in networks of long-lived capital stock can lock in a country's emission path over a long period of time even though they unfold in a very short period of time. This example does not discuss or evaluate the overall merits of nuclear power generation, neither historically for France, nor in the future for France or for other countries.

[21] Subtype 2 of long-lived capital stock noted in the decomposition above.

[22] Data for Box 1 are from the French Ministry of Industry (http://www.industrie.gouv.fr/cgi-bin/industrie/frame23e.pl?bandeau=/energie/statisti/be_stats.htm&gauche=/energie/statisti/me_stats.htm&droite=/energie/statisti/se_stats6.htm)

[23] And assuming significant but limited penetration of alternative renewable energy sources.

22. In Box 2 we discuss an example of long-lived capital stock of type 4, which is strongly associated with the dynamics of urbanization. This dynamic can be graphed as a logistics curve starting with a low proportion of total population living in urban areas, gradually accelerating in response to rural to urban migration, and then decelerating, before stabilizing with a high proportion of total population living in urban areas. Construction of physical capital in response to this urbanization process creates a cumulatively larger stock of buildings (residential, schools, civic buildings, offices, etc). The later energy efficiency standards are adopted and implemented in this one-way process, the smaller the potential for growing out of inefficient energy use later, as evidenced in the example below.

Box 2. Poor energy efficiency in long lived buildings increase future costs of abatement: The case of the residential sector in France

23. **The building sector in France provides a good example of how investment decisions over a relatively short period of time can determine carbon emissions over long periods of time (up to 100 years)—especially when technical and economic costs of *retrofitting* or *premature retirement* are high.** In 2006 there were an estimated 25.7 million residential (habitation) units in France. The vintages of this residential building stock can be roughly divided into three groups of approximately equal size:
    - one third (30.6%) built prior to 1949,
    - one third built during the 25 year post-war reconstruction boom (1949-1975) prior to the adoption and enforcement of any regulation on building energy efficiency, and
    - one third built after 1975, under increasingly strict energy efficiency standards.

24. GHG emissions associated with the residential buildings include both direct on-site emissions from e.g., home boilers or fireplaces, and indirect, off-site emissions associated with the production of the power and heat consumed by (but not produced within) buildings. Direct emissions were 90 $MtCO_2$ in 2002, and indirect emissions can be estimated at *circa* 12 $MtCO_2$ (a small number due to the predominance of nuclear power generation, and thus the low emissions per kWh in the country). Overall, the residential building stock accounted for approximately 18.5% of France's GHG emissions in 2002 (by vintage, the youngest third accounts for approximately 25 percent, while the oldest two account for approximately 75 percent).[24]

25. Since the national share of the urban population has more or less stopped growing in France since the 1990s, the bulk of the housing stock in France is already built and the rate of annual additions is very small. Because the average life duration of habitation units in France is well over a century, further improvements in the efficiency standards for *new* building alone cannot prevent further growth in energy consumption and emissions from the residential building stock over the next half century (Traisnel, 2001). In fact, 60% of the expected residential building capital stock in 2050 has already been built. To reduce emissions in this sector, accelerated retrofitting of old buildings (via e.g., improved window and wall insulation) and/or accelerated replacement of capital stock are necessary to meet mid-century emission targets—even though both options will be costly, and are likely to be costlier than having adopted and implemented higher energy standards 25 years earlier than they were. This dilemma contrasts strongly with the 'short window of opportunity' to grow out of inefficient energy use described in the Chinese case (Box 6).[25]

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[24] Direct emissions from the residential sector are derived from IEA (2005). Indirect emissions are computed by multiplying the share of residential consumption in total final consumption of electricity by total emissions from the electricity & heat producing sector. Emissions by vintages are estimated based on data in Traisnel (2001) showing that post-1975 buildings are on average 40% more energy-efficient than pre-1975 ones.

[25] There is only limited scope for fuel-switching in domestic heating systems, as most coal-fired boilers have been already been eliminated, and as liquid fuels represent only 20% of total energy consumption in the residential sector

26. **It is important to note that the relationship between long-lived capital stock and emissions differs between capital stock associated with energy provision (supply side) and capital stock associated with energy use (demand side)**. **On the energy supply side, emissions are typically a direct function of the installed capital**. Thus, the flow of emissions associated with a particular stock of capital will generally last as long as the underlying investment.[26]

27. **On the energy demand side, on the other hand, the link between physical capital stock and emission flows is generally less rigid.** The relationship depends on the technology used to supply the energy needed to meet the service demand *induced* by the long-lived capital stock. In other words, demand side lock-ins can undermine the potential for energy conservation, but not the use of any particular type of energy—low carbon or otherwise. If energy were cheap (i.e., abundant relative to demand) and if harmful emissions were free (both locally and globally), then there would not be any need for energy conservation / energy efficiency (i.e., managing both final and intermediate demand). However, if energy is expensive because of scarcity (or because the technology to avoid harmful emissions increases the price), or if new technologies cannot generate energy without some harmful emissions, then reducing the demand for energy becomes a necessary complementary pillar of a low- or no-carbon energy strategy. In fact, according to the IEA (2006c), as much as two thirds of emissions targets to 2030 will have to come from reducing energy demand, rather than fuel switching in energy supply towards low carbon or zero carbon alternatives. Similarly, the IPCC (2007, p.13) notes that "it is often more cost-effective to invest in end-use energy efficiency improvement than in increasing energy supply to satisfy demand for energy services."

28. The purpose of the next illustration is to highlight how demand-side infrastructure (e.g. a highway network) can lock-in carbon emissions for the long-term (multi-decade), even though partial decoupling can be achieved by changing emissions standards of complementary physical capital (i.e., the fuel efficiency of the vehicle fleet).

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as of 2003 (source: Ministry of Industry, http://www.industrie.gouv.fr/cgi-bin/industrie/frame23e.pl?bandeau=/energie/statisti/be_stats.htm&gauche=/energie/statisti/me_stats.htm&droite=/energie/statisti/se_stats6.htm). Entire conversion of domestic boilers from fuel oil to gas would save an estimated maximum of 18 $MtCO_2e$. And in fact this alternative is not available in most rural areas.

[26] However, there are some cases where retrofit techniques (such as carbon capture and storage in the case of production of energy from coal) can limit the emissions path *ex post*. In these cases, the life duration of the emissions is not necessarily the same as the life duration of the underlying capital stock, even on the energy supply side. But this is not a common feature of the relationship between emissions and the installed capital stock on the supply side.

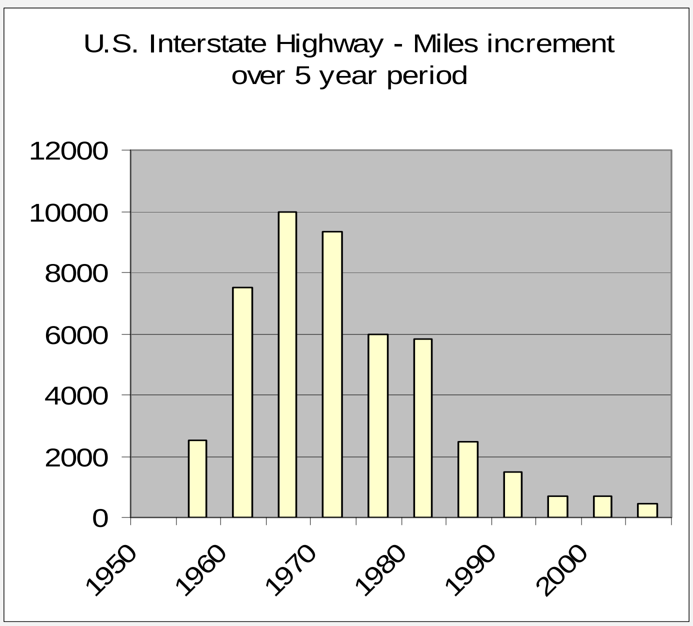
Box 3. The complementarity of road infrastructure and the road vehicle fleet in generating energy demand with its associated carbon emissions: The case of the US Interstate Highway System

29. **The Interstate Highway System in the United States provides an example of a major demand-side lock-in but with partial decoupling between capital stock and emissions.** This example also illustrates the concentration of investments in a short period and the shift in vehicle miles traveled and energy consumption that it entailed.

30. The U.S. Interstate Highway System program, enacted in 1956, created a 42,700 mile network of high quality highways linking major U.S. cities across the country. This massive undertaking was a lumpy investment in a structural (not marginal) change in transport patterns. The network was built in a relatively short period of time, with **two thirds of it completed in less than two decades** between 1965 and 1985 (Figure 1).

31. The interstate network represents only one percent of the total U.S. road network, but about one quarter of the total U.S. national highway system. The interstate network also accounts for nearly a quarter of total vehicle miles traveled (VMT) in the U.S. (24.4% in 2004), and nearly **half** of all heavy truck traffic associated with interstate and global commerce. The networks share of total traffic grew in proportion to the completion of the network: 10% of total VMT by 1966, 15% by 1971, and 20% by 1982. For all practical purposes the network was completed by 1990 and its share of traffic has remained more or less constant since then.

Figure 1. U.S. Interstate Highway System Mileage Increment over 5-year periods. 1950-2005.

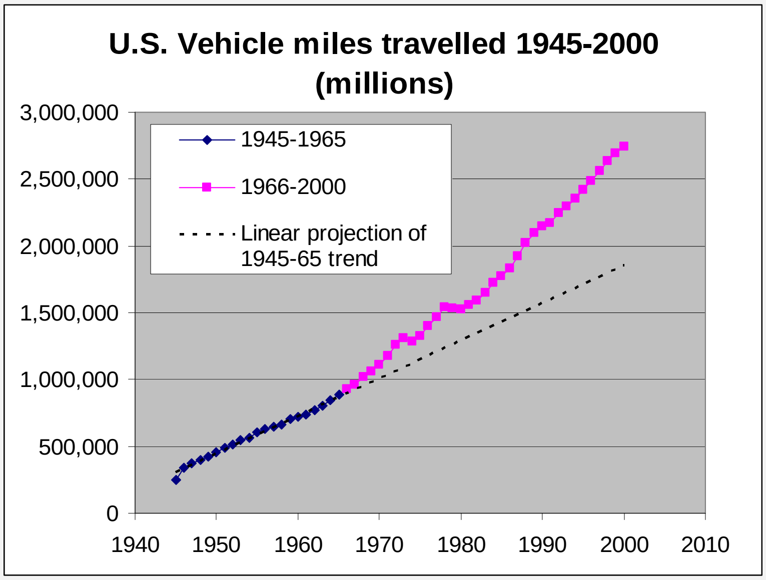


Source: Cox and Love (1996) for 1950 to 1965 data, and Weiss (2008) for 1970 to 2005 data

32. The rapid increase in the Interstate network's share of traffic can be explained in part by a shift in vehicles away from older roads. More significantly, by reducing transportation costs, the Interstate Highway System also made it possible for firms to both expand their reach and decentralize their production over several sites, and to eventually reduce warehousing by adopting the Japanese innovation in logistics of "just in time" delivery. We observe a doubling in the annual increment in vehicle miles traveled after the mid-1960s (Figure 2) which can be attributed to additional demand for transportation *induced* by the Interstate Highway System.[27]

[27] We also observe that GDP and total VMT increase at nearly the same rate over the 1955-1965 period, but that total VMT increase faster than GDP in the 1965-1973 period.

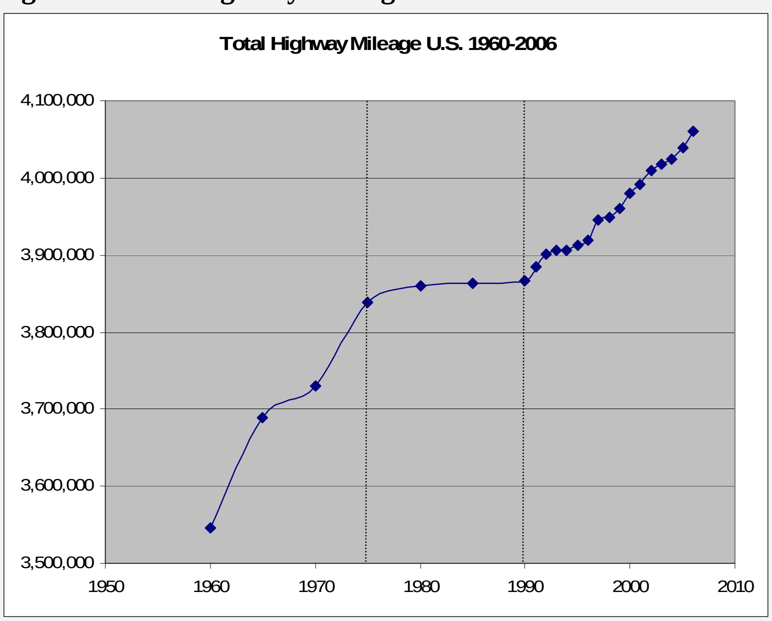
Figure 2. U.S. Vehicle miles traveled 1945-2000 (millions)



Source: U.S. Federal Highway Administration

33. The Interstate Highway System also made it cheaper to develop land farther away from city centers, thus playing a major role in an induced second "hump" in transport infrastructure investment and energy use associated with accelerated suburbanization post-1990 (Figure 3).[28]

Figure 3. Total Highway Mileage in the U.S. 1960-2006



Source: U.S. Bureau of Transportation Statistics[29]

34. The conjunction of long-lived physical infrastructure, modified logistics patterns and resulting systemic changes in the way businesses operate, and modified land-use in cities has led to a durable

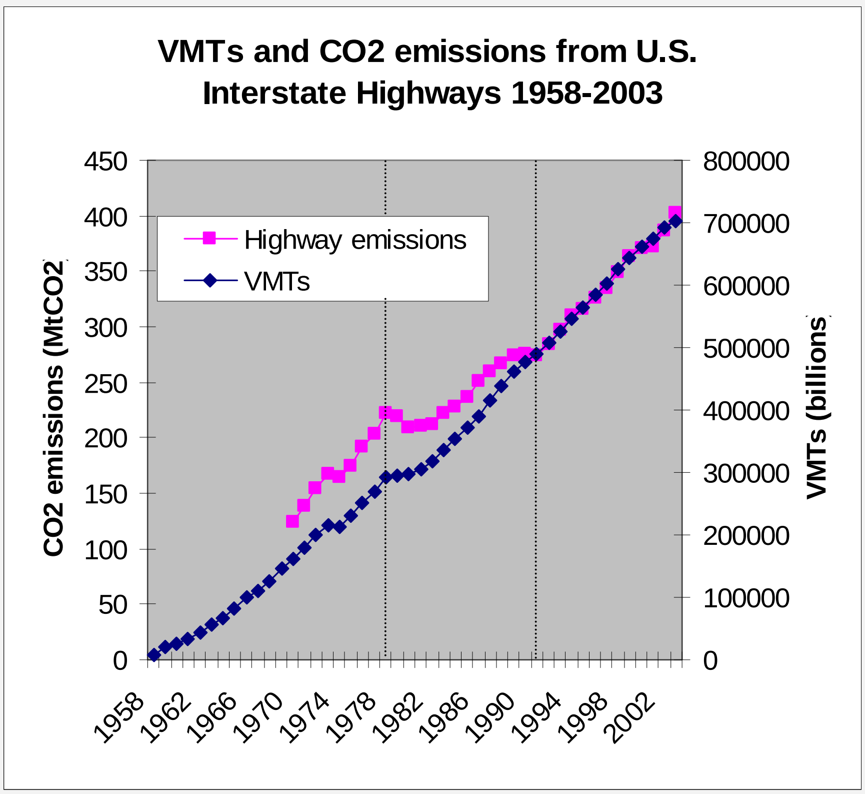
[28] In fact, the increase in urban highway mileage over the 1980 – 2006 period is higher than the increase in total highway mileage because the mileage of rural roads has been decreasing over the same period.
[29] A total of 43,000 miles of Bureau of Federal Land Management roads—excluded starting in 1998 from official U.S. BTS statistics—have been reintegrated in this graph to avoid break in time series.

increase in total VMT. It has also contributed to the decline of the national railway network and made it difficult when determining *marginal* extensions to meet growing transport demand to seriously contemplate the introduction or restoration of alternate rail and transit links given the absence of a larger supporting rail networks (as in Japan or Europe)—as opposed to adding more arterial roads. This has reinforced the grip of the road network on meeting transport needs and generating carbon emissions

35. CO_2 emissions associated with the Interstate Highway System are significant, about 7% of total U.S. emissions from fossil-fuel combustion.[30] These emissions initially increased faster than the growth of total VMT as the System developed. There was a temporary decoupling of emissions growth from total VMT when higher energy efficiency standards were adopted in the mid-1970s (Figure 4).

36. However, emissions have resumed growing in tandem with total VMT in the absence of further higher engine energy efficiency standards being adopted or enforced. Until more low-carbon or zero-carbon vehicle engines are deployed, these emissions induced by the physical infrastructure network are to a large degree locked-in.[31]

Figure 4. VMTs and estimated CO_2 emissions from Interstate Highway Traffic 1958-2003



Source: U.S. Bureau of Transportation Statistics, Lee Schipper (comm.pers.), authors' calculation

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[30] Total emissions from the Interstate Highway System have been estimated by taking one quarter of total emissions associated with road transportation in the U.S. (since the Interstate Highway System represents one fourth of total VMT). This is likely to be an understatement as trucks represent a disproportionate share of travels on Interstates, and emit more per VMT than cars.

[31] Though Box 3 focuses on CO_2 emissions, it should not be interpeted as downplaying the other externalities associated with transportation. In fact, transport projects/networks should be designed to solve transportation problems first. Conversely, solving the carbon externality may do nothing to solve these other externalities. For example, congestion may still be a problem with zero-carbon cars.

37. The U.S. Interstate Highway program was discussed for more than two decades before actually being built. It does not appear that any clear alternative transport investment plan was being discussed at the time. The options were to finance the new program, or to keep the existing transportation network.[32] From this one could conclude that there was no alternative and an investment in the interstate highway system was unavoidable. To some extent, that was true. However, roughly at the same time, high-speed train systems were designed in Japan and, a decade later, in France (as discussed in the following box). At least at the global level it is clear that alternative transportation technologies (with low carbon emissions) were known at the time the U.S. Interstate Highway System was established. But, the alternative was an imperfect one—it was costlier per unit mile of construction, it did not handle freight transport, and it was not a dense network linking all the cities. Nonetheless, it was far more efficient in terms of energy and emissions per passenger mile in the corridors in which it operated, and there was nothing in the technology that precluded design of a denser network.

Box 4. Low carbon emissions in transport is linked to how electricity is generated: The case of France's High-Speed Train Program

38. The French high-speed train program was initiated in the late 1960s by SNCF, the French public enterprise which had monopoly over both rail infrastructure and rail transportation. The objective was to limit train ridership erosion by competing more efficiently with cars and planes over major inter-city corridors, not specifically to save energy or to limit greenhouse gases emissions. The first high-speed train (TGV) prototype was natural-gas powered, but after the 1973 oil shock electrical engines were adopted. This shift was a conscious decision to limit the energy cost of running the future train. It is unclear whether it was made specifically to take advantage of the nuclear power generation program that was launched in 1974 (see box n°1). (Again, even though at the time reducing emissions was not a goal, the shift away from fossil fuel in the name of energy independence had the same effect.)[33]

39. The first high-speed railway between Paris and Lyon was commissioned in 1974 and became operational in 1981. Travel time between the two cities—400 km apart—was reduced from 4 to 2 hours, and travel time to cities further South along the same corridor was also reduced considerably. Ex-ante and ex-post traffic surveys show that the modal share of rail increased considerably relative to both roads and aviation in the corridors with high-speed rail. For example, the share of rail on the Paris - SE corridor jumped from 44% to 61% from 1981 to 1984, while the share of road diminished (from 46% to 30%) and the share of air also eroded slightly (from 10% to 8%) (OEST, 1986). The surveys also point to a long-lasting overall increase in travel demand induced by the opening of the new line along the corridor where the TGV is built (OEST, 1986, 1987). As new high-speed railways were built, similar effects have been observed for inter-city trips up to 800 km. For example, it is

[32] See the extensive discussion of the origins of the U.S. Highway System by Lee Mertz (http://www.fhwa.dot.gov/infrastructure/origin.htm).

[33] High speeds (i.e., over 220 km/h) can be achieved only on special railtracks with, inter alia, higher curvature radiuses than regular railtracks, larger mid-track intervals, adapted bridges and tunnels, etc. Since the speed of all trains on a given railtrack cannot exceed the speed of the slowest train, high-speed railtracks are TGVs-only (in addition, slower trains are not adapted to certain physical characteristics of high-speed railtracks such as steep ramps). TGVs, on the other hand, can run on regular railtrack (albeit at lower speed), thus making high-speed railtracks an extension of the existing railtway network, and not an entirely new network. (This is no longer the case when high speed is achieved through different technologies, such as magnetic levitation.) The higher design standards are similar to the Interstate highway systems which are very different from regular highways. To support high speeds 'on and off ramps' have to have higher curvature radii, traffic in different directions have to be separated from each other, entrances and exits from the traffic stream are spaced much further apart, etc.

estimated that air traffic from Paris to Marseille (750 km apart) was cut by a quarter due to modal shift to TGV from 2001 to 2003.

40. This shift is important because average CO_2 emissions per passenger.km are significantly lower for train trips, because of the low emissions intensity of the French electricity system:[34] 15 gCO_2/passenger.km against 111 for cars and 169 for planes (Raux et al., 2005). Overall, however, the share of rail in total passenger transportation has continued to decrease since 1981 (though rail ridership has increased) relative to road and to a lesser degree air (because the high-speed rail network is not as extensive as the corresponding road and air network, it is important only in selected corridors). Emissions have clearly been reduced relative to what would have happened had modal shares remained as they were pre-TGV along the corridors where TGV was built. However, the TGV program alone (at least as it stands now) has not been able to reverse overall trends in modal share evolution.

41. Unlike the Interstate Highway Program which was meant as a network from the start, the high-speed lines have been designed corridor by corridor. As such, the implementation of the program was not lumpy. The first line was approved in 1974, the second in 1981, and the third and fourth in 1988 and 1989 respectively (but this may be due to the particular geometry of the country in which all lines radiate out from Paris). However, the proposed extensions of the network (+ 2000 km, or doubling, by 2020) are expected to be lumpy investments. High speed train programs elsewhere in Europe are also being conceived as networks from the beginning rather than corridor by corridor extensions (notably in Spain, which plans to build over 7,000 km of high-speed railtracks criss-crossing the country).

42. Finally, it is important to note that the average cost of new high-speed railtracks in France is estimated to be around 1.5-2.0 b€/100 km, or about four times as high as the upfront costs of new 2x2 highways (0.4-0.8 b€/100 km). The difference in upfront cost is significant. The current market price of carbon may not be sufficient to compensate for the difference.[35] In other words, high-speed rail is not a complete substitute for interstate highways, but rather a complement in high-density corridors. The extra cost may not be justifiable on carbon grounds alone. But other related objectives, such as reducing local air pollution or congestion related to cars may provide additional rationale for railway development.

[34] Had France the same CO_2 emissions per kWh as the U.S., and everything else equal, rail emissions per passenger.km would be around 100 gCO_2.

[35] For example, a 1000 km addition to the national network would cost about 10 b€ more with high-speed rail than with highways. At a 10€/tCO_2 price of carbon, the high-speed train program would need to generate 1 btCO2e emissions savings to justify the extra-cost *solely on climate change ground*. Since the emissions difference is about 100 gCO_2 per passenger.km between rail and road, the rail program would need to shift at least 10,000 billion passenger.km from road to rail over its lifetime to produce 1 $btCO_2e$ of emissions savings. Yet total road traffic is currently 560 billion passenger.km in France against 80 for rail. So even if *half* the road traffic were somehow shifted to rail, it would take at least 40 years for sufficient emission reductions to be generated.

Section 2. There is ample evidence that important choices about the carbon intensity of future long-lived capital stock are being made today or will be made in the near future, particularly in developing countries; and that avoiding similar demand-side or supply-side lock-ins in highly carbon-intensive pathways is important for global climate mitigation

43. **Economic growth—spurred on by urbanization and globalization—is inducing rapid expansion of long-lived capital stock in developing countries**, similar to the development of long-lived capital stock in Western Europe or in Japan post-World War II.

44. **First**, **urbanization** (i.e., an increase in the share of urban population in total population) **will be accompanied by major decisions about urban forms** (category 4 of long-lived capital), which will influence the energy system. In fact, as noted by Jaccard and Rivers (2007), density configurations and land-use patterns affect the energy intensity of various end uses (e.g., ratios of external wall to floor space for space heating), the energy requirements for urban transportation (e.g., travel distances for shopping and commuting), and the character and prospects for alternative energy supply and delivery systems (solar access, combined heat and power, public transit, hydrogen refueling networks, etc.). This component of long-lived capital stock has been estimated to have a 120 year turnover rate based on Canadian data. We are not aware of any comparable estimates for developing countries (or even other industrial countries).

45. More than 80% of the people on Earth live in developing countries. The bulk live in countries that are predominantly rural. The sectoral shift from a primarily agricultural-based economy to one based on manufacturing and services will be accompanied by a shift in the spatial location of the population, i.e., urbanization. Approximately one third of developing countries population lived in cities in 1990, whereas two thirds of that population is expected to live in cities by 2050. In China alone, it is estimated that the share of urban residents in the total population will increase by 50% over the next 25 years, from 40% in 2005 to about 60% in 2030.[36] This will generate a lot of construction in a relatively short period as discussed in box 5, with potentially significant consequences for emissions.

[36] Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2007 Revision, http://esa.un.org/unup .

Box 5. An important demand-side lock-in for the future arising from the major expansion of the building stock: The case of China

46. Rapid urbanization and economic growth in China is generating a boom in construction—comparable to post-War reconstruction efforts in Western Europe. Yet space heating in buildings in China is inefficient: it consumes 50-100% more energy than in Western Europe or in North America. The Chinese Government has promulgated new energy efficiency standards for buildings, but the standards are often *not* enforced. Almost all of the new buildings being constructed are still based on old, highly energy-inefficient designs (World Bank, 2001).

47. Emission-wise, China's space heating alone consumes on the order of 130 million tons of standard coal equivalent per year, more coal than the unified Germany consumes for all purposes (in energy terms). Total direct (on-site) and indirect (off-site) emissions from residential buildings in China are on the order of 500 $MtCO_2$ per year in 2003, the equivalent of total annual GHG emissions from France.[37]

48. Enforcing standards in China for new buildings now can still have a significant impact on the rate at which total emissions grow in the near future. Half of China's urban residential and commercial building stock in 2015 will be constructed after the year 2000 (this contrasts with the fact noted above that 60% of the expected building stock in France in 2050 will be buildings already built before 2000). In other words, in China, unlike Europe and Japan where postwar reconstruction is over and costly retrofitting maybe necessary, there is still an opportunity to "grow out" of the enormous energy waste problem at relatively low cost.

49. Data remains scarce, but a rule of thumb estimate is that with existing technologies, Chinese buildings can be made more energy-efficient, saving over 50% on energy costs with increases in construction costs of some 10% (World Bank, 2001). Applied broadly, such a program would have national implications for energy dependency, and could reduce a large amount of GHG emissions—with global implications for climate change. However, energy expenditures savings alone may not be sufficient to compensate for increased upfront building cost.[38] Putting a price on carbon (via e.g., a market or a tax) would help, but it is unclear whether it would be sufficient to tilt the result of the financial cost-benefit analysis towards energy efficient buildings. In addition, it is recognized that the development of energy efficient buildings in China face many other barriers, related inter alia to information asymmetry or institutional design (Richerzhagen et al., 2008). Yet if, on the other hand, actions are ***not*** taken now, every year lost in developing more efficient buildings will ***lock-in*** some 700-800 million square meters of urban residential and commercial building floor area with inefficient energy use for future decades. This could generate more than two billion tCO_2e of additional carbon by 2030 relative to an efficient energy use scenario for residential and commercial buildings.[39]

[37] Direct emissions from the residential sector in 2003 are based on IEA (2003). Share of residential sector in electricity & heat generation are estimated using China 2003 energy balances (IEA, 2006a). *In addition*, the residential sector in China consumes 217 Mtep of biomass. We did not find data on the associated emissions, but if emissions/consumption ratios observed in the OECD are of any guide in the China context, the emissions from biomass use might be larger than the emissions from all other energy uses in residential buildings combined.
[38] In fact, indicative data provided in World Bank (2001) suggest that it may not be the case.
[39] This figure is estimated by assuming that an average of 750 Mm^2 of new building is built from 2004 to 2030, either at 2003 emissions per square meter (of about 0.016 tCO_2e/m^2), or at half that rate (if new buildings are more energy efficient).

50. **Second**, as a result of the **globalization** of the world's economy, many developing countries are under pressure to engage in international trade more actively, and to become more competitive. This is putting a premium on investing in category 3 type long-lived capital in the form of infrastructure (transportation, power, and telecom) networks, whether provided publicly or privately.

51. **China's transportation sector provides an example of investment in long-lived capital stock induced primarily by concerns about competitiveness and trade**. As of 2004, China had about 34,000 km of expressways, out of a total of 1.87 million km of roads. The first segments were opened in 1988, and the bulk of the 2004 network (90%) was opened in the previous nine years (1996-2004).[40] In 2004, the country approved the National Expressway Network Plan to connect all capitals of provinces and autonomous regions with Beijing and with each other, linking major cities and important counties. The new expressway network is explicitly designed to reduce transportation costs from the interior to the coast, and thus to foster domestic trade and economic development inland. The network is expected to add an additional 85,000 km to the current expressway network. The project is expected to be undertaken over a 30 year period, with the bulk of the investment made in the first two decades. This is another potentially important demand-side lock-in, akin to the example of the U.S. interstate highway system discussed earlier, which is likely to generate additional indirect (cf., box 4, Figure 2) and induced emissions (box 4, Figure 3).

52. The two examples above are both demand-side examples, but **major lumpy investments in supply-side long-lived capital stock are also expected**. In fact, the IEA (2003) estimates that 6 trillion U.S. dollars investment in energy supply is required in developing countries until 2030, two thirds of which would be for power generation alone. Box No.6 provides one example of major lumpy investments on the supply side that may generate lock-ins.

Box 6. A potential supply-side lock-in: The case of coal-fired power plants in China

53. **With rapid economic growth, electricity demand in China has skyrocketed over the past two decades.** New power plants are being built at rapid pace to keep up. Total power generation capacity in 2006 was 623 GW. This is twice the capacity of year 2000 and more than four times the capacity of year 1990. As coal is plentiful and cheap in China, it accounts for about 75% of power generation capacity. Because coal-fired power generation has higher GHG emissions per KWh than other power generation technologies and because *average* efficiency of coal-fired power plants in China (33%) is lower than in the U.S. (37%), Western Europe (39%) or Japan (42%) (Zhao and Gallagher, 2007), CO_2 emissions per KWh in China are about one third higher than in the U.S.,[41] and about twice as high as in Europe. With 1.8 $GtCO_2$ (2003)—of which coal accounts for 97%—**the power & heat generation sector represents about half of China's total CO_2 emissions**, and as much as the CO_2 emissions of Africa and the Middle East combined. Coal-fired power generation also has severe consequences for local air pollution.

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[40] Source: China Statistics 2005, available at http://www.allcountries.org/china_statistics/16_4_length_of_transportation_routes.html.

[41] China's current higher emissions per KWh must, nonetheless, be viewed in the context of its overall declining energy intensity over time. As a result of using more efficient technologies, combined with its faster GDP growth, energy intensity in China declined by an extraordinary 4.8 percent per annum in the 23 year period from 1980 to 2003—more than double the 2 percent per annum decline in the US. As a result, China's energy intensity dropped by half relative to the U.S. This significant pattern of change over more than two decades is the same whether one uses GDP at market prices or purchasing power parity prices (Shalizi, 2006).

54. **Looking forward, the IEA (2003) estimates that power generation capacity in China will have to more than triple between 2002 and 2030 to keep up with demand**. There is thus a priori a possibility for China to at least partly grow out of its current high-emissions power generation system, since some half to two-thirds of the emissions of the power sector in 2030 depend on the *additional* power generation capacity that will be installed between now and then. How this additional capacity is balanced between coal, gas, nuclear, hydro and other renewables will be a prime factor in determining those emissions. But the choice of technology within each primary fuel will also make a difference.

55. China is rapidly becoming a major player in non fossil-fuel energy.[42] Yet because coal resources are extremely abundant, and because the country is essentially devoid of natural gas, coal has so far remained the cornerstone of the new power generation and is likely to continue playing an important part in future capacity as well.[43] The choice of technology for coal-fired power generation will thus play an important role. China is installing some of the most sophisticated clean coal technology (supercritical, ultra supercritical, integrated gasification combined cycle, etc.). However, since energy demand is so large, many traditional dirty coal plants are also being built. Overall, until recently, the average emissions per unit of electricity generation of the *new* coal-fired power plants were higher in China than in the U.S.[44]

56. **Recent modeling of the evolution of China's power sector (Wang and Nakata, 2009) provides some economic insights on how the fuel mix, and resulting emissions, might evolve in the coming decades**. In their business-as-usual scenario, without any policy to internalize carbon or local pollution externalities, the share of coal in power generation remains as high in 2030 as it is today, and coal generation efficiency improves relatively little—thus resulting in a tripling of the CO_2 emissions of the power sector in 2030 relative to 2005. In an alternative scenario, introducing a carbon tax of $120/t$CO_2$ (about 6 times the current price on the carbon market) reduces electricity generation in 2030 by about 15% relative to the business-as-usual scenario; it reduces the share of coal in the power generation mix from about 75% to about 50%; and it facilitates the penetration of advanced clean coal technologies. In this scenario, CO_2 emissions in 2030 will be about one third lower than in the business-as-usual case. **According to Wang and Nakata's analysis, there is real potential to reduce China's emissions from the power sector by 2030 despite the cheapness and abundance of coal**—one-third of business-as-usual emissions in 2030, i.e., as much as today's (2005) emissions. The question is how easy it will be to shift course

57. **This study does not take into account the cumulative mechanisms that may make it more difficult to reduce the share of coal and/or increase the share of advanced clean coal within total coal-fired power generation**. Besides the sheer lifespan of coal-fired power plants, ***cumulative mechanisms*** such as *increasing returns to scale* (e.g., in the development of sector specific transportation networks), *induced technological change* (that may make future coal technologies cheaper rather than cleaner), *learning by doing* (e.g., on training of a specialized workforce), or *agglomeration economies* (encouraging clustering and dependency on cheapest source of fuel) can generate an **undesirable lock-in** to inefficient energy paths.

58. **In addition, investment in renewables and clean coal face important barriers**. Wang and Nakata include one of these barriers, namely the fact that local air pollution is not internalized. But taking into

[42] For example, China is already the largest producer of hydropower in the World (IEA, 2007), it is the second largest market for new wind capacity behind the U.S. (World Wind Energy Association, 2009), and it has embarked on a large-scale nuclear power generation program to increase generation capacity from 10 GW to about 70 GW in 2020 (Machenaud, 2009).

[43] In fact, the share of coal in total power generation capacity has remained very stable over the past two decades, which means that the *additional* capacity over the period has relied as much as coal as the initial capital stock.

[44] Estimated by comparing the ratios between the additional emissions from the combustion of coal in the electricity & heat sector between 1998 and 2003 (IEA, 2005) and the additional electricity production between 1998 and 2003 (IEA, 2006a, b) in the U.S. and in China. We do not have data for additional capacity installed post-2003.

account others may also alter the picture. For example, developing countries often don't have the necessary access to cutting edge technology to avoid the high GHG emissions associated with the normal development of coal. Where the problem is a financing and/or technology sharing or technology transfer one, one will need to design and adopt a targeted mitigation program (bilateral or multilateral) to link buyers and sellers of the relevant technologies.

59. Until then, the adoption of dirty coal technology in coal abundant developing countries meets not just Foray's observations about rational inefficiency, but even the more stringent criteria of economically inefficient path dependency enunciated by Liebowitz and Margolis. Dirty coal investments may generate lock-ins that are known to be sub-optimal ex ante from a global perspective—carbon generated anywhere on earth has the same negative global consequence. However, with strong budget constraints, and the lack of technology transfer agreements, a developing country's decision to adopt the inferior technology can be locally rational ex ante—even though it leads to inefficient long-term emissions paths.

60. Though both the demand-side and supply-side lock-in examples above are from China, they are not unique. India is another large rapidly growing developing country with abundant coal reserves to power cheap, but high carbon emissions electricity production. It has also initiated a major interstate highway / road transportation infrastructure program, and is experiencing a major expansion of its housing stock associated with urbanization. **Similar investments in long-lived capital stock with potentially large impact on GHG emissions can be observed or foreseen in many other developing countries as well**.

61. **The current energy inefficient and emissions intensive long-lived capital (e.g. infrastructure) expansion programs need not be treated as unavoidable**. In many cases, infrastructure networks providing similar services can be built using different technologies, some with high carbon intensity, and others with lower or even zero carbon intensity. For example, there exist coal-fired power plant technologies in China and elsewhere that are more efficient than those typically used in China (e.g., Zhao and Gallagher, 2007). Similarly, energy efficient buildings have been designed with better standards than existing ones (World Bank, 2001). Similarly, a more balanced road + rail networks can be an alternative to a road-dominated system. There are many reasons why low carbon alternatives are not currently pursued. These alternative investment opportunities may be more expensive than the currently used ones. They may not be secure strategically (e.g., alternative energy sources may be less reliable because they are located abroad), or they may not be directly available to local decision-makers because of barriers such as, the absence of technology transfer arrangements, adequate human capital capacity, etc. Addressing all of these different barriers ***will take time***, especially in developing countries with limited institutional capacity.

62. **However, as we have tried to note in this paper, the opportunities to shift from high- to low-carbon intensity long-lived capital stock, are *not evenly distributed over time*. In fact, the windows of opportunities may well be very narrow because these investments are *lumpy* and *concentrated* in time.**[45] Installation of capacity for long-lived capital follows a logistics curve. Changing an emissions path at the early stages will be a function of the availability of alternate networks with lower emissions and of the cost-effectiveness of shifting to those networks. For example, building urban infrastructure from scratch (or rebuilding it after a war)—or establishing a road or rail network—will result in a large lumpy

[45] Often these investments entail structural changes rather than marginal ones. Some will be based on centralized economy-wide decisions and others on decentralized project by project decisions.

capital investment in a short period of time. After that capacity expansion will decelerate (or cease once the network is completed). Thereafter the scope for shifting the emissions path through new investments will be low as new investments in that category of capital stock will be marginal at best (plus maintenance costs). Once one is well along the logistics curve switching costs make it difficult to shift to an alternative without incurring substantial costs of retrofitting or premature retirement of otherwise functional capital stock.

63. As discussed in Section 1, **emissions associated with long-lived capital stock are large and, if mitigation is not undertaken early in those sectors, even deep and early adjustments in the remaining (relatively short-lived) segments of capital stock may be insufficient to meet stringent concentration targets**. In addition, we have seen in Section 1 that **uncertainty about long-term emissions goals (or about climate change damages) tends to put an additional premium on acting early in sectors with long-lived capital stock.** Thus, if there is a peaking of infrastructure investment in the next 2-3 decades (as China, India, and some other developing countries **urbanize** and **rapidly build out their multiple infrastructure networks)**, there will be a premium on earlier action rather than later action on climate change in these countries because the impact on cumulative emissions will be higher.[46] If the necessary action is not undertaken, the ability to catch-up with target emission goals later via the fraction of capital stock that are short-lived will be weaker, and possibly insufficient. The next Section examines whether carbon markets alone can provide appropriate incentives to influence investments in long-lived capital stock.

[46] It is an irony that delaying imposition of carbon commitments on developing countries till their per capita income is higher (a very laudable objective) runs the risk of missing the windows of opportunity to influence the carbon efficiency of long-lived capital stock to be built in the next 2 to 3 decades as part of urbanization and globalization associated with the process of development. This is one reason why climate change negotiations cannot be separated from development objectives. In principle, CDM type programs can help, but their current scale is woefully inadequate. Hence, scaling up targeted mitigation programs will be critical.

Section 3. Carbon markets do not necessarily provide economic agents with correct signals to make the decisions vis-à-vis long-lived capital stock

64. The previous discussion has established the importance of the magnitude of long-lived capital stock, such as networks and urban forms, and of the lumpiness of investments in time. It has also demonstrated how such capital stock investments can lock-in the generation of a stream of carbon emissions that lasts a century or more in some cases.

65. On the basis of this information, the present section returns to the central question of the paper, i.e., whether a two-tier strategy—carbon market *plus* targeted mitigation towards sectors with long-lived capital stock—is economically justified or not. Specifically, we use a *reductio ad absurdum* type of reasoning, and ask **whether a one-tier, carbon-market-only strategy could be sufficient to provide proper incentives for investments in long-lived capital stock.** To provide proper incentives to investments in long-lived capital stock, this strategy would need to meet four conditions.

    - First, **the price of carbon generated by the market would need to** be a correct reflection of the shadow price of carbon. The relationship between market and shadow price of carbon has many dimensions, most of which are general and not specific to long-lived capital stock. For our purpose, the most important dimension is the compatibility of the time duration of the long-lived capital stock, and the time horizon of the carbon constraint.
    - Second, as discussed in the two previous sections, investments in long-lived capital stock projects or networks not only generate direct, long-lived, emissions, but also indirect and induced emissions, which can be significant. Erroneous decisions can be made if those are not taken into account. Thus, **the carbon-market-only strategy would need to provide a price signal relative to indirect and induced emissions**, and not just to direct emissions from projects/networks involving long-lived capital stock, **at the level of individual project or network developers**.
    - Third, carbon markets would have to provide **sufficient additional financing for lumpy investments**. This is particularly important since networks of long-lived capital stock tend to be established in short periods of time.
    - Finally, even if the previous three conditions are met, the carbon-market-only strategy would still need to occur in a context where **investments in low-emissions long-lived capital stock can compete on a level-playing field with investments in high-emissions long-lived capital stock** -- and this is not a trivial concern given the presence of many unpriced externalities and transaction costs that implicitly favor high emissions, long-lived capital stock.

66. In the remainder of this section, these four conditions are discussed in turn. Even though we will see that carbon markets *as they currently exist* do not meet the first condition, we nonetheless ask whether a revised carbon market that met condition No.1 would also meet condition No.2, etc. We thus build a set of increasingly hypothetical carbon markets, in which the limitations of the current design are progressively lifted. Yet we will see that in all cases—even with the most inclusive design—a two-tier strategy is economically justified and necessary.

67. Before we proceed, it is important to note that the carbon market (and hence the resulting price of carbon) is different from other markets. The carbon market attempts to perform a **regulatory function** by dealing with an *externality* via a market price rather than a tax. As such, **it is a *proxy market for an artificial commodity.*** The prices generated are not only a function of supply and demand in the carbon market, but also a function of policy decisions on the parameters defining the commodity and the market—which carbon emissions to include or not, for which periods, etc. Thus, the institutional design of the carbon market becomes central to the analysis.

68. Returning to our four conditions, we **first** ask **whether carbon markets (as *currently* designed) can accommodate the 'direct' long term emissions consequences of long-lived investments**.

69. **In the current Kyoto agreement, an artificial time limit is created by the first commitment period. As a result, carbon markets (including the CDM) price "avoided carbon emissions" until 2012 only**. There is no regulation constraining carbon beyond this point (and in fact, several countries have adopted non-binding mid-century targets). However, the 'futures' market for carbon emissions is not deep (i.e., there are few buyers for emission reductions beyond this point). Consequently, projects that save large quantities of carbon (or carbon equivalent) until 2012 are favored by the market over projects that save small quantities of carbon until 2012, regardless of what happens beyond 2012 (see Annex 1). **This skews investment decisions towards those that generate emission reductions before that limit**, i.e., towards emission reduction projects related to short-lived rather than long-lived investments.

70. One could argue that this artificial time limit / constraint is irrelevant in practice because investors in long-lived capital (say, utilities) anticipate that there will be a carbon constraint in the future, and thus choose their equipment accordingly. Such an argument, however, understates the relevance of the constraint. In fact, a given population of investors will have a wide range of expectations about future climate policies. Some will expect that the regulation will become tighter in the future, and will build this expectation into their investment decisions; while others will assume that the regulatory constraint will be relaxed, delayed, or will disappear (e.g., investors optimistic about future technology solutions to climate change). The observed price in the carbon market may thus be higher than what it would have been with just the deadline of 2012, because some investors may expect more stringent policies in the future, but lower than it would have been had there been a full regulatory framework in place for the period beyond 2012. There are also voluntary approaches to mitigation, some going beyond 2012, but since reducing global climate change is a global public good, this public good is likely to be undersupplied by voluntary actions alone (the standard "free rider" problem in collective action).

71. A related issue is that many countries are not subject to emissions targets under the Kyoto Protocol. It is true that the CDM (i.e., certified emission reductions) provides some incentive for mitigation in non-Annex B countries. However, the demand for CDM credits (by Annex B countries to meet their Kyoto targets) remains small relative to the number of potential mitigation projects. In addition, these credits are subject to the same 2012 time limit. Finally, because it is a *project*-based mechanism with high transaction costs, the CDM is ill-equipped to deal with investments in large-scale programs or networks. Consequently, despite the

CDM, most long-lived investments in non-Annex B countries do not face any form of constraint on carbon.

72. Even in Annex B countries there are, in fact, two different types of constraints. At the national level, all GHG-emitting sectors are accounted for in the Kyoto emissions cap. But the national constraint is not passed on the same way to all sectors. Some sectors, such as energy and industry, are typically included within domestic (or regional, in the case of the EU Emissions Trading Scheme) carbon markets. As a result, individual actors within those sectors (i.e., firms and, in some cases, households) receive emissions allowances that they can trade on a market, thus being directly confronted by a market price for their GHG emissions. But other sectors such as transport or construction are typically excluded from carbon markets. They are dealt with through other types of policies and measures, such as, inter alia, taxes, incentives, standards, etc. (For example, it would be very costly to give tradable emissions allowances to individual households for gasoline use, while it is relatively cheap to tax gasoline.) As a result, long-lived investments in these sectors face different incentives from long-lived investments in sectors covered by domestic carbon markets, with a different price (or a shadow price) of carbon.[47]

73. Ultimately, **one has to advocate longer-term emission reduction commitment periods** for those countries that already have commitments, and a broadening of the countries and sectors subject to mandatory restrictions where carbon markets are not currently operative. This problem seems to be recognized by the current negotiations for a post-Kyoto framework, which are likely to expand countries and sectors subject to carbon regulations. However, they are still likely to institute a new commitment period rather than an unlimited one. To that extent, the bias in transactions/projects against emissions streams associated with long-lived capital is likely to persist, but for a different time period. If the new commitment period is substantially less than 30 years, this would continue to create problems for infrastructure projects, in so far as typical cost-benefit calculation for *energy or infrastructure projects* go up to 30 years in the future. They generally do not go longer because of (i) the increasing uncertainty surrounding all parameters as the horizon is extended; (ii) the discount rate, which erodes the value of future streams of costs/benefits; and (iii) institutional limitations (difficulties in establishing contracts or making commitments for the very long run). Thus, a 30-year commitment period for carbon markets would probably be sufficient to provide a signal to **project** developers (private and public). But this would still not be sufficient for **network** developers. For the latter, an even longer period may be required (but may not be practical yet). **Until more activities are subject to carbon constraints, and carbon is priced for longer periods, 'targeted mitigation programs' to reduce emission streams associated with long-lived capital are justified**. In this case, 'targeted mitigation programs' may take the form of instruments that support low-carbon long-lived investments, such as public purchase of emission allowances beyond the carbon market horizon.

74. **Second**, we ask whether **carbon markets can accommodate (*in principle)* the 'indirect' and 'induced' emissions consequences of investments in long-lived systems**

[47] This difference arises because in practice there is no reason why the shadow price of carbon that derives from the domestic policies and measures imposed on the sectors not covered by domestic carbon markets should equal the price of carbon on formal carbon markets—even though this would be the most desirable outcome from a national welfare perspective.

75. As **noted in section 1, investments in most categories of long-lived capital stock differ from other types of mitigation investments in that they can generate externalities** that induce more investments in similar technology in the future, restrict the ability to shift to less carbon intensive options, **and thus influence mitigation costs down the road**. The intertemporal externality or positive feedback mechanisms involved have been enumerated before (cf. paragraph 8). They include inter alia economies of scale for technology producers or for upstream/downstream operations (e.g., in the fuel supply chain for fossil-fuel power plants) that reduce unit costs, learning by doing effects along the chain, or agglomeration economies. In addition, high switching costs may make it even more difficult to shift away from one technology once it has been adopted, thereby reinforcing the lock-in effect.

76. These externalities are particularly important in the first phase of investment programs,[48] because the **choice of technology in the initial projects can lock-in the commitment to that particular technology for the whole program**. This has important implications for the way the first projects in a program should be evaluated.

   - **If the initial projects are evaluated on a stand-alone basis, and not as part of a program**, the resulting decision might be erroneous. Suppose for example that the initial project of alternative A emits less carbon than the initial project of alternative B, but that *program* A emits more carbon than program B. Then, a cost-benefit analysis based only on the emissions of the initial projects of A and B—even with the 'right' price for carbon—would underestimate the merits of the superior alternative B (in terms of carbon emissions). In this case, **the pricing of carbon is insufficient to provide the right incentives** [49]—even though a carbon cap, in principle, applies to all emissions (direct, indirect and induced).

   - **If, on the other hand, the initial projects are evaluated within the context of the complete program**, then in principle **the problem identified above should not hold** – though in practice it may still be a problem for lack of knowledge, methodology or data re: indirect and induced effects. There are examples of such projects that are conceived and executed as part of an integrated program from the start, such as in the case of the U.S. Interstate Highway System, the Chinese highway system, or the French nuclear program.

77. In addition, a program or network can in turn **induce the development of a host of new extensions or end uses that are *not* formally part of the original program or network**. The induced emissions can be *private* (and the result of decentralized decision-making), even though the original program is *public* (and the result of centralized decision-making). Examples include, inter alia:

   - *Increase in the demand for goods or services* induced by the development of the program or network, but not included in the estimates conducted when the program or network is

[48] Here a 'program' can either be the aggregation of a multitude of similar projects (e.g., the construction of multiple nuclear power plants in France) or the construction of a full network (e.g., the U.S. Interstate Highway), etc.

[49] The decision is suboptimal from society's point of view because the decision-maker does not take into account the fact that his or her decision locks in other decisions (and thus other emissions) down the road. This is the case when there are multiple decision-makers (e.g., when several utilities compete in the power generation system), or when there is one decision-maker who reasons on a project-by-project basis only.

being developed (and thus not included in the original estimates of the potential 'range' of expected emissions associated with the implementation of the program or network).

- *'Indirect' creation of additional long-lived capital stock* to complete and extend the backbone network, leading to additional emissions. One example is the construction of arterial roads by individual States to feed into an Interstate Highway system (and not part of the original design); and the additional transportation demand they generate.[50]

- *Modifications in the development of other long-lived capital stock* made possible by the development of the network. For example, the change in land use associated with suburbanization in the U.S. was made possible, in part, by the Interstate Highway System. In turn, suburbanization generated increased commuting times, increased demand for transportation, and thus higher transport-related emissions (this was compounded by the decline in the share of traffic on public transit systems in U.S. cities because, in part, low density suburbanization made them less cost-effective)—these induced effects of suburbanization related to the transport sector are separate from the energy demand for e.g., heating and cooling, generated by lower density development associated with suburbanization.

- *Indirect macroeconomic effects on economic growth that generate emissions*. For example, it is estimated that by making trade easier, the U.S. Interstate Highway System has contributed to an increase in economic growth relative to what it would have been in the absence of the System (Cox and Love, 1996). As a result, total U.S. GHG emissions are likely to have been higher with the Interstate Highway System than they would have been in its absence.[51]

78. Induced emissions are external to the program and difficult to predict. But induced emissions cannot be ignored because they would not have been possible without the core program. **The historical examples provided in section 1 suggest that indirect and induced emissions can be significant, but empirical measures are scarce.** Laird et al. (2005) review empirical evidence of the combined network + induced effects on total economic benefits of transportation projects in Europe. They show that taking these externalities into account can effect total benefits positively *or* negatively (the latter, for example, when congestion effects are significant). The modeling studies they cite find in fact an increase in benefits on the order of +10% to 30% in most cases. They do not, however, provide figures on the resulting additional *emissions*. Indirect and induced effects might be very difficult to estimate when a new network is initially established (e.g., in the case of the U.S. Highway System, which was only the second of its kind in the World after the German highway system pre-World War II). But patterns emerging from the first example need to be taken into account when subsequent similar networks are established (e.g., a new highway system in China). This underlines the importance of backcasting studies using ex post data, and the learning from and sharing of experience from other countries or regions.

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[50] The observed increase in annual rate of growth of VMTs after the Interstate Highway System was built was the result of the combination of the two effects discussed previously (increased demand for transportation on the network + creation of complements to the network).

[51] This is a positive, and not a normative statement. We do not evaluate here whether or not the welfare gains associated with higher GDP in the U.S. have been greater than the value of the externality created by the higher GHG emissions.

79. **How should one deal with network and induced effects?** As long as the cap on emissions has both a sufficiently long time horizon and a sufficiently large sectoral and regional coverage, then all future direct, indirect and induced emissions caused by a given program or network will also fall under the cap.

   - If the program or network is financed by the public sector, **indirect and induced emissions can in principle be accounted for in the public sector's financial analysis**. However, indirect or induced emissions that occur in foreign countries would not be accounted for by the public sector.[52]

   - If, on the other hand, the program or network is financed by a private entity, the indirect or the induced emissions might occur beyond the purview of the private entity's boundaries, and thus not be material for the entity's financial analysis of the project. In this case, **some form of policy intervention is required to make sure that the public costs attached to the indirect and the induced emissions of the project are internalized.**

80. If indirect or induced emissions are underestimated, decisions to invest (whether from private or public agents) may be regretted ex post (a type 3 error in the typology of Liebowitz and Margolis). As a result—if, again, the cap on emissions has both a sufficiently long time horizon and a sufficiently large sectoral and regional coverage—**the issue is to make sure that indirect and induced effects are taken into account, and estimated appropriately ex ante**.[53] For example, carbon accounting rules for projects could be set up so that indirect and induced effects are taken into account, via some. "standard factors". There is, however, a need to improve methodologies for estimating these "standard factors" of indirect and induced effects based on past patterns of similar project in similar contexts (rather than making exact predictions for a given project in a specific context).

81. **Third, we ask whether carbon markets can provide sufficient additional financing for lumpy investments.**

82. **Long-lived infrastructure investments often require larger capital outlays upfront,[54] and have lower financial returns** due to the inability of the private sector to mobilize resources on the scale required by these investments, and, more fundamentally, to the inability of the private sector to restrict access and capture the returns from the project benefits that are in part public and extend over a longer period of time. This is a *classical problem* in **project financing**, and it provides a rationale for public intervention in infrastructure project financing—since private capital is not available for long enough periods at reasonable costs (the private sector generally requires much higher returns than generated by the project to

[52] Taking into account the emissions implications of public programs or networks also requires coordination among public agencies. This is because the agency responsible for the budgetary line related to the Kyoto (or post-Kyoto account), typically the Ministry of Finance, is likely to be different from the agency responsible for the financial analysis of long-lived programs or networks (e.g., Ministry of Interior or Energy).
[53] There is a need to improve methodologies for estimating indirect and induced effects based on past patterns of project and context types (rather than making exact predictions of a given project).
[54] Altering the design of such long-lived investments, and therefore of the associated stream of carbon, will be costly since the costs of many of these networks are extremely large.

justify the higher risk premiums associated with keeping capital locked up in a particular investment for very long periods.) [55]

83. For the subset of long-lived capital stock that is provided by private public partnerships or by private participation in infrastructure, or financed through **corporate finance** rather than project finance, for example in the case of utilities, the availability of a price of carbon beyond 2012 should increase the flow of private capital to low-carbon long-lived capital stock **because in those cases private investors are able to privately capture some of the rent generated by the carbon assets.**[56] However, carbon revenues (or lower carbon-related costs) occur in the future, as the project unfolds. Thus, the fact that the differential in carbon revenues between low-emitting and high-emitting long-lived capital stock projects can be accounted for in the financial analysis of the project **does not alleviate the need for project financing to transform long-term revenues into upfront capital**.[57] Because of the longer horizon and larger upfront costs, comparable **network financing** will be required to complement carbon finance in the case of networks. Early experience with carbon finance suggests that it is not easy to get financial institutions to enter this market and provide loans using carbon purchase agreements as collaterals (Lecocq and Ambrosi, 2007). This situation is likely to persist so long as low-carbon alternatives are deemed to be riskier because of a lack of a track record relative to traditional projects with established parameters[58].

84. For the (majority of) investments cases in which long-lived capital stock remains publicly provided, we have seen above that direct, indirect and induced emissions should have a material implication for the financial cost-benefit analysis (see paragraph 79). However, publicly-provided programs or networks suffer from the same disconnect between the time at which capital is needed (upfront) and the time at which carbon revenues materialize (over the project lifetime). **Project or network finance is thus also needed in the case of publicly-provided long-lived capital stock**. However, they may not necessarily tip the balance towards low-carbon options in public infrastructure if strategic, social, and other non-economic considerations, outweigh changes in economic returns determined by cost-benefit analysis. As a result, **it is with public projects that the price signal and financing resulting from the carbon market is likely to have the weakest effect, even though it would still be relevant**.

85. In addition, for both privately and publicly provided long-lived capital stock projects or networks, project or network finance requires some degree of certainty over the price of carbon in the medium and long-run—regardless of the volatility of the price of carbon in the short run. Whether carbon markets, even if extended over time, would provide such a signal is in fact an open question (see paragraph 97). A lot will depend on the ability of parties to

[55] Clearly there have been many cases historically of large infrastructure networks being provided by the private sector, and more recently there has been an expansion of private participation in infrastructure provision (public-private partnerships or PPPs and private participations in infrastructure or PPI). But the scale of what has been built via those arrangements is still dwarfed by the size of publicly provided infrastructure.

[56] To the extent, of course, that the national-level constraint on emissions has been correctly passed on to them via regional or domestic markets (see paragraph 72).

[57] Carbon revenues may not only increase the project or network's financial rate of return, but might also, with proper financial engineering, improve its ability to obtain upfront financing (Lecocq and Ambrosi, 2007).

[58] This problem might be compounded by the even more cautious lending by private financial institutions in the future to avoid a repeat of the current economic crisis.

commit credibly to some tightening of the constraint on carbon emissions over time (e.g., announcing ex ante that a carbon tax will increase over time at a fixed rate).

86. **Fourth,** even assuming that the pricing of carbon is correct and that the additional financing for low-carbon lumpy investments can be arranged for, **we ask whether we can be sure that investments in low-carbon technologies will be competing on a level playing field with investments in high-carbon technologies**.

87. **All projects, regardless of their size, face *barriers* that make their implementation difficult or even impossible despite positive net present value**. Examples include inter alia *policy/regulatory barriers* (e.g., landlords not having incentives to provide efficient insulation when tenants pay the energy bills), *financial barriers* (e.g., lack of access to international capital), *institutional barriers* (e.g., structure of governance that provide more weight to certain interest groups in the final decision), *capacity barriers* (e.g., lack of skilled workforce to operate new equipment), *international/diplomatic barriers* (e.g., lack of international cooperation with neighboring countries making investments that potentially pass the cost-benefit test difficult to implement),[59] etc. **A subset of barriers that are important for our purpose are externalities (other than carbon) that are not priced** (e.g., the local pollution from coal-fired power plants when they are not priced correctly).

88. **Some barriers are more likely to emerge in the case of long-lived capital stock projects**, for two main reasons. The first set of barriers that projects involving long-lived capital stock face relate to their size and duration, thus requiring the (i) larger resources and (ii) the coordination of a broader range of individuals and institutions, over an extended period of time. The second set of barriers relate to the fact that long-lived capital stock projects often produce club goods or public goods, the benefits of which cannot be easily captured.[60] For example, devising urban transport strategies that do not rely solely on the extension of one mode of transport (e.g roads) requires *institutions* that are able to balance competing interests for mobility vs. accessibility between modes / users with different needs and incomes—particularly those of poor people (World Bank, 2002). As a result, resolving burden-sharing and distributional and transfer issues become more difficult with long-lived capital stock projects.[61]

89. Even if other barriers exist and are important, why worry about them *as long as carbon is priced correctly*? If barriers are different in the high-emissions alternatives and in the low-emissions alternatives, then the choice is biased—resulting in either over-investment in the low-emissions alternatives (if barriers are higher for the high-emissions alternatives) or under-investment in the low-emissions alternatives (if barriers are higher for the low-

[59] For example, gas-fired power generation in India and China is very much dependent on their ability to credibly secure supply from neighboring countries, and, in the case of India, of credibly transferring the resource across neighboring countries.

[60] The balance along the public-private dimension varies by type of long-lived investments. The benefits of telecom networks or of individual power plants are easier to capture privately. But the benefits of power transmission lines or of transportation networks are less easily captured by the private sector (World Bank, 1994)—though the most cost-effective links can be privatized, i.e., "creaming".

[61] Note that the use of carbon finance itself may face barriers, as carbon finance is a new financial instrument which requires skills to be used. Otherwise, carbon may be treated only as a risk, and emissions allowances may be inefficiently used by their holders. The global knowledge and expertise about carbon finance has yet to be established. (In fact, it appears that newly established carbon desks in financial institutions have been disbanded with the economic crisis.)

emissions alternatives). Thus, **if barriers are not addressed, major biases in investments in long-lived capital stock may occur.** In particular, under-investment in low-emissions alternatives may lead to high emissions now and in the future (due to lock-ins).[62]

90. What can be done in practice, then? Recognizing the presence of barriers (possibly including non-carbon externalities) and recognizing the necessity to still act (i.e., implement low-emissions options) **requires that the barrier(s) be tackled directly**. This can be done via barrier removal, and via internalization of the non-carbon externalities. The design of these targeted mitigation programs will depend on the nature of the barrier and/or non-carbon externality to be removed. This suggests that the "targeted mitigation programs" that are the focus of our paper are **incorrectly named**. In fact, they should not be targeted at mitigation per se, but at other project/network development issues that constitute the barriers (e.g., capacity building, etc.) and /or at the non-carbon externalities (e.g., local pollution). **In other words, we are facing complex, multi-externality, multi-barriers problems that cannot be tackled by pricing just one of these externalities—hence the need for complementary 'targeted mitigation programs'**.

Conclusion

91. At present there are two approaches to mitigation, 'carbon markets' and 'targeted mitigation programs'. We ask whether there is any clear economic rational for this two-tier structure. Drawing on an analysis of the characteristics of investment in long-lived capital stock (lumpiness, network effects) and on real-world project financing realities (notably, observation of the role of market prices in public sector infrastructure decisions, as opposed to shadow prices), we identify the limitations of a carbon market only approach and from that determine the need for a combination of carbon market plus targeted mitigation policies.

92. In Section 1, we show through examples that there are categories of long-lived capital stock that have limited turnover in a century-long period. The bulk of the capacity of networks of long-lived capital stock (and not just individual projects) is installed in a relatively short period of time (lumpy investments). In addition, because of externalities such as economies of scale, learning by doing or agglomeration economies, the choice of technology in the first projects of programs or networks can lock-in the technology over the whole program or network. Similarly, investments in programs or networks of long-lived capital stock can induce the development of a host of new extensions or end uses that are not formally part of the original program or network. This has the following consequences. First, it locks-in the future flow of emissions over the long run (or at the very least, it increases the probability that this flow of emissions is realized). Second, failure to build-in a change in the trajectory of these networks early will require greater and earlier efforts on other components of the capital stock—which may not be sufficient to meet the more stringent mitigation targets, should they become necessary.

93. In Section 2, we provide examples to illustrate that under pressures of urbanization and globalization similar long-lived networks are being built right now in large rapidly growing developing countries and have the potential for locking-in emissions paths for a very long

[62] It is important to recall here that emissions related to long-lived capital stock are a significant part of total emissions (see paragraphs 6 and 12), and it may become very costly to just leave out long-lived capital stock from the global mitigation effort.

time (a century or more). We also observe that emissions paths associated with demand-side lock-ins are not as long-lived as their associated capital stock – this is unlike the long lived emissions path associated with energy supplying capital stock. However, until clean technologies can be scaled up to replace supply-side lock-ins, actions on the demand-side are necessary to constrain demand for energy in the interim.

94. In section 3, we show that *current* carbon markets do not provide adequate incentives to low-emissions investments in long-lived capital stock, as the cap on emissions extends only to 2012, and as many countries are excluded from the system. As a result, targeted mitigation programs in regions and sectors in which long-lived capital stock is being built at rapid rate is necessary to complement carbon markets and avoid getting locked into highly carbon intensive capital stock.

95. We also show that *even if the constraint on emissions were extended over time, sectors and regions*, a balanced approach combining carbon markets and 'targeted mitigation programs' (direct policy intervention towards mitigation) that involve long-lived capital stock would remain warranted. First, policy intervention is required to ensure that the emissions externalities (indirect and induced) attached to *publicly and privately produced* long-lived capital stock are taken into account and priced, above and beyond the direct emissions of the project. Second, project and network financing may be required to bridge upfront capital needs and effective emission reductions. Third, policy intervention may be required for both privately and publicly provided long-lived capital stock to fix non-market barriers and non-carbon externalities that prevent investments in long-lived low-emissions capital stock from competing on a level playing field with high emissions alternatives, even if the former pass the cost-efficiency test when the price of carbon is taken into account.

96. The conclusions above raise three questions. First, **can indirect and induced emissions related to a particular project be estimated ex ante?** To our knowledge, no comprehensive model exists that consistently predicts indirect and/or induced effects (or even part of induced effects, e.g., induced demand) in any sector, even in well-studied sectors such as transportation. But some models exist that capture part of these mechanisms, for well-defined situations (e.g., Laird et al., 2005). In addition, indirect and induced consequences are not always completely unpredictable either. History, economic and technical analysis and expertise may provide insights on those indirect and induced consequences. This is clearly a topic for further analysis.

97. A distinct, but related question is the following: **Can prices on the carbon market accurately reflect the supply/demand balance if the cap is extended over a long period of time?** The assumption that even if the cap is extended over several decades, project developers will find a carbon price (or a price path of carbon over time) that accurately reflects overall supply / demand over the whole period is implicit in the above discussion. Yet existing carbon markets display important price variability, translating for the most part uncertainty and shifting expectations about supply and demand. For example, investors in a three-year project with emissions subject to the European Emissions Trading Scheme would have factored in a price of carbon of at least 5-10 €/tCO_2 in early 2005, at the onset of the market. Six months later, they might have used a reference price of 15-20 €/tCO_2. Yet EU allowances ended up with a quasi zero value, as it was progressively discovered that the overall cap on emissions was actually above business-as-usual emissions. Though future carbon market may be institutionally different from current ones, uncertainty about the

resulting price is a central feature of cap-and-trade systems. This question is related to the first in that uncertainty about indirect and induced emissions makes it difficult to evaluate future emissions, and thus future demand for emission allowances. (In addition, future mitigation costs are uncertain because of technical change.)[63] In fact, a lot of the current debate on the carbon market revolves around putting a ceiling and a floor to the price of carbon (the so-called safety valve, Kopp et al., 1998).[64] Defining appropriate price ceilings and floors and the evolution of the price band is also an important topic for future research.

98. Finally, **how should 'targeted mitigation programs' be designed?** The paper underscores the diversity of rationale for developing 'targeted mitigation programs' to complement carbon markets, and the design of these programs will be very different depending on the challenge to be overcome. We have even noted that the name 'targeted mitigation programs' might be misleading since programs aimed at overcoming barriers that have nothing to do with climate change may be necessary in some cases. This reinforces the need for incorporating development objectives (through long-lived capital financing) into climate change negotiations (Shalizi and Lecocq, 2009).

[63] In fact, investors in long-lived capital stock project may collectively find themselves in a "lose-lose" situation where either they invest in low-emissions projects on the basis of high anticipated prices and end up with low prices, or invest in high-emissions projects on the basis of low anticipated prices, and end up with high ones.

[64] The debate between implementing a carbon tax (i.e., creating known future prices but unknown reductions in emissions quantities) vs. a cap and trade system (own reductions in emissions quantities, but unknown prices) was resolved in favor of the latter in the Kyoto Protocol, and seems to be poised to remain the centerpiece of the post-Kyoto arrangement.

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Annex 1. A carbon constraint extending to 2012 only may result in incorrect investment decisions from an economic perspective: A simple analytical illustration

Let A be a “clean” project that reduces emissions by an amount xA relative to its “dirty” baseline BA until 2012, and by quantity yA after 2012. We consider the choice between the clean project and its dirty alternative in a financial cost-benefit framework. Let NPVBA be the net present value of the dirty baseline, NPVA- the net present value of project A without taking carbon into account, and CA = NVPBA – NPVA- the abatement cost. We assume that CA > 0, i.e. that the clean project has a lower NPV than the dirty one when carbon is not accounted for.

Under the current Kyoto rules, only carbon until 2012 is valued. Let p be the price of carbon until 2012, and let NPVA the net present value of project A with carbon. Project A should be undertaken over the baseline, if and only if its NPV is positive (condition 1) and if its NPV is superior to the NPV of the baseline (condition 2).

$$NPVA = NPVA- + p\ xA > 0 \qquad (1)$$

$$NPVA – NPVBA = p\ xA – CA > 0 \qquad (2)$$

If carbon pre- and post-2012 were valued (or if the investor was conducting an *economic* cost-benefit analysis), conditions (1) and (2) would transform into (3) and (4) below, where p’ is the price of carbon beyond 2012. Everything else equal, valuing carbon beyond 2012 increases the NPV of the clean project, both in absolute terms (eq.3) and relative to the dirty alternative (eq.4).

$$NPVA = NPVA- + p\ xA + p'\ yA > 0 \qquad (3)$$

$$NPVA – NPVBA = p\ xA + p'\ yA – CA > 0 \qquad (4)$$

Now let B be a second project in a different location, that for the sake of argument only reduces emissions beyond 2012, but by a large amount (i.e., xB = 0 and yB >> 0). Even if NPVB > 0, project B will automatically fail condition (2) if carbon is priced until 2012 only – but it would be likely to meet condition (4) if carbon were priced beyond 2012.

Note that although we have described this framework in terms of valuing emission reductions (like, for example, in the CDM), it also applies to investment decisions where carbon emissions are taxed at level p. In this case, p xA is the amount saved by clean project over the dirty one in tax payments.

If projects A and B are somehow mutually exclusive (for example, if buyers seek only a limited amount of emission reductions), then pricing carbon over the first period might lead to channeling resources to the emission reductions activities that are in fact the costlier. Let CA/xA be the ‘apparent price of carbon’. A carbon buyer will select the project that has the lowest apparent price of carbon, even though this indicator does not correctly convey the ‘real’ costs of emissions over the project lifetime.