Stepping off the hydrocarbons regime: the challenge of technological transition for Latin America

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ABSTRACT

This paper approaches the diffusion of new process technologies as a problem of technology adoption and replacement. The diffusion of environmentally sound technologies (EST's) is viewed as a transition process from a technological regime based on hydrocarbons. From this we identify specific technological and economic barriers to technology replacement in Latin American economies. The first section elaborates on the concept of regime transition, where sunken costs and organizational inertia associated with embedded, large scale technologies generate important barriers to technology replacement and innovative absorption of technologies. These rigidities to change have a negative circular causation with the production of new technological capabilities, which adds to the more traditional drivers of technology adoption (prices, regulation, and investment and market rates). The second section examines key macroeconomic and technological factors gravitating over decommissioning, capital replacement timing and accumulation of technological capabilities. A heuristic framework is presented to characterize the interaction of capabilities and investment decision as drivers of technology selection under different economic environments. Two broad sets of factors determining macro-environments of selection are identified and characterized in the region.

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Introduction

Energy systems and energy intensive industries are among the largest sources of anthropogenic greenhouse gases (GHG)[1]. The multifaceted technological regime of hydrocarbons upon which these systems rely constitutes a generalized unsustainable metabolism in the planet. All medium and long term projections suggest that hydrocarbons will still be the dominant energy source for at least the first half of the 21st century. IEA World Energy Outlook 2002 projects that non-hydro renewables will only account for 4.4% of world primary energy by 2030 due to their minimal actual share, while hydro-power share will slightly diminish to 14%. The same report indicates that 90% of the increase in energy demand will be satisfied with fossil fuels, mainly natural gas. Under such a scenario, and despite the shift to a less emission-intensive fuel like gas, greenhouse gases (GHG) emission will continue to grow. Mitigation goals in the next decades can therefore only be met by enormous efforts in energy efficiency and GHG capture.

The limited availability of hydrocarbons, together with multiple and uncoordinated efficiency requirements in final use of energy, and regulative pressures from environmental concerns have established since at least the 1970's a visible yet very weak front of selective pressures for alternatives. Nevertheless, search efforts and innovation capabilities are very unequally distributed. While most R&D in energy alternatives is concentrated in the industrialized world, most of the increase in energy consumption and GHG emission will come from developing countries. The nations of the South will have to include the technological switching in their energy systems as a development condition, and even when the transition seems inevitable in the long run the process will be far from being automatic. The critical question then is how, and at what cost different societies will adapt and transform their economic and institutional resources to qualitatively change their technological base.

The outline of the paper is as follows. In the first section we examine the technological profile of Latin America, distinguishing its current fuel mix structure and recent trends. Next, we present some basic insights from the literature on the technology diffusion behind large scale energy transitions, and elaborate on the concept of technological regimes. We highlight the role of systemic inertia and sunken costs as sources of inertia in regime configurations.

The second section identifies systemic barriers to absorption of new technologies in energy systems and energy intensive industries in the Latin American region, focusing on key macroeconomic and technological factors gravitating over decommissioning, capital replacement timing and accumulation of technological capabilities.

I the third section a heuristic framework is presented to characterize the interaction of capabilities and investment decision as drivers of technology selection under different economic environments. End-of-pipe versus clean technologies are examined as alternative and complementary transition paths. Latin America's financial constraints and

[1] The list includes also transport systems, which are excluded from this analysis.

technological efforts are broadly characterized, before we conclude identifying key aspects in the regional development pattern critical for reversing unsustainable trends.

SECTION 1

ENERGY TRANSITIONS, TECHNOLOGICAL TRANSITIONS

The record of the global diffusion of energy technologies as a process of multiple substitution among primary energy sources has been documented extensively.[2] In these models (formally inspired in Fisher and Pry, 1971), technologies diffuse in a sigmoid way with more efficient technologies out-competing older ones. Several paradigmatic solutions co-exist in time and compete for use shares. This approach shows a flow of technological succession resembling a sort of "struggle" for dominance among primary energy sources: wood, coal, oil, gas, and nuclear, each one networked with complementary developments in other technologies and infrastructure (railroads, steam lines, steel making and electrification with coal; automotive transport and petrochemicals with oil). This models project natural gas as the dominant source of primary energy for at least the first half of the 21st century, a development that is an already visible trend in energy statistics. New versions of these modeling efforts have projected detailed regional patterns of primary sources substitution considering different scenarios of growth and technical change orientation[3]. The actual pattern of substitution at the regional and national levels, especially those of areas with different resource endowments, may look considerably different, but the general picture of energy sources substitution is a good reference of the sort of technological dynamics hidden behind.

In the following sections we examine a set of relevant determinants for energetic transition in Latin America. These determinants constitute the broad structural context of diffusion and technology transfer in energy systems and energy intensive industries in the region. It is of course a partial analysis since the linkage to the transport sector is excluded, in order to narrow the scope of the paper. After reviewing the current energy profile we will turn to the conceptual framework on technological of large technological systems.

Energy sources in Latin America: where do we stand?

With grossly 9% of the world's population, Latin America contributes with 3.6% of global GHG emissions, due to its low per capita energy consumption and its high shares of hydroelectric power in the world (IEA, 2003). But GHG emission and energy profiles are highly differentiated in the region. Brazil and Mexico are among the 15 countries with higher industrial emission of CO_2, while Central American countries are among the lowest rank. If we consider the use of hydrocarbons (both gas and oil), it seems clear that use patterns differ mainly due to the local availability of oil, and to the relative degree of industrialization. Excepting Argentina and a small subgroup of Caribbean countries, renewables hold shares of more than 10% of total primary energy in the region (Coviello and Montalvo, 2003). Paraguay and Costa Rica get 90% of their primary energy from

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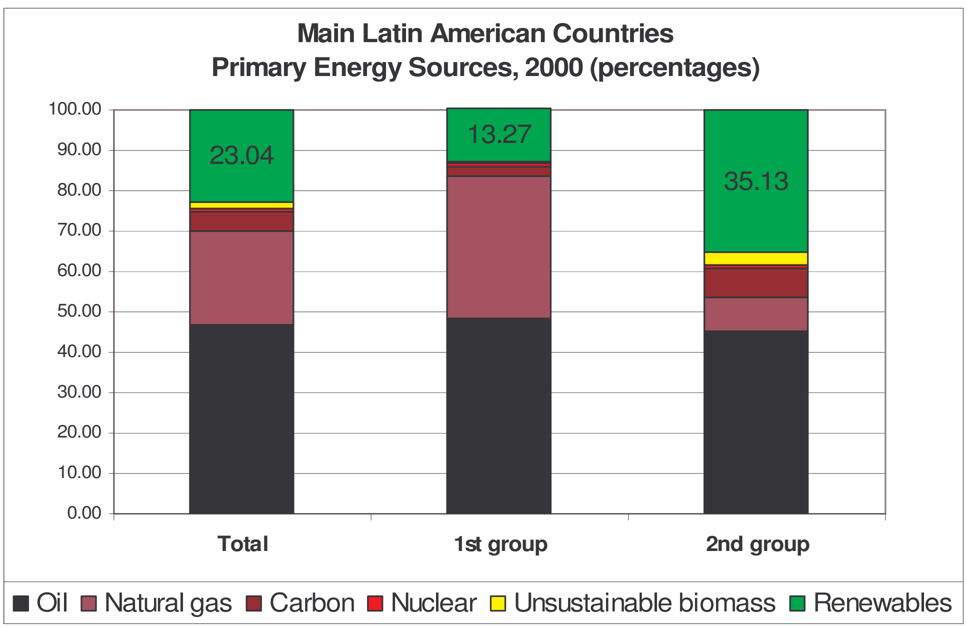
[2] See Marchetti and Nakićenović (1979), Grübler and Nakićenović (1988), Nakićenović, Grübler and A McDonald (1998). This view has also been incorporated in the design of energy transitions developed for the IPCC (see Mart, Nakićenović and Nakićenović, 2000). A comprehensive historical account can be found in Smil (1994).

[3] See IIASA-WEC (1995).

renewables, while hydrocarbons reach between 80 and 90% of total primary energy (TPE) in countries like Argentina, Ecuador, Mexico and Venezuela.

In comparison with the structure of TPE in the rest of the world, Latin America holds relatively low amounts of coal, and higher amounts of hydro-power. Additionally, in comparison with industrialized countries it is relatively more intensive in oil, and less intensive in nuclear energy and natural gas. While the first feature can be attributed to energy resource endowments, the second is clearly due to the pattern of differential diffusion of energy technologies. Graph 1 summarizes the two dominant patterns of energy shares in total primary energy (TPE), considering the 9 countries that comprise 95% of TPE in the region[4]. Renewable sources account for 23% of TPE, a very high level for world standards. Within renewables, 51% comes from hydropower and 48% from biomass, and 1% geothermal. Groups 1 and 2 barely differ in oil use, but they strongly contrast in the relative importance of gas versus renewables, given a much higher importance of biomass in group 2. From this superficial information, it can be asserted that countries in group 2 have better options to improve their TPE fuel profile, because a higher diversity of sources and wider room for substituting gas for oil. Group 1, on the contrary, looks much more locked into oil due to the exploitation of local resources.

GRAPH 1



Source: Own calculations based on Coviello and Montalvo, 2003.

Considering only oil shares in TPE, a slight "de-carbonization" trend can be appreciated (see graph 2). This has been remarked as a signal of global development in energy source substitution (Nakićenović, 1997). Nevertheless, in absolute terms there is no such a trend. Energy consumption in Latin America doubled between 1980 and 2002, growing annually

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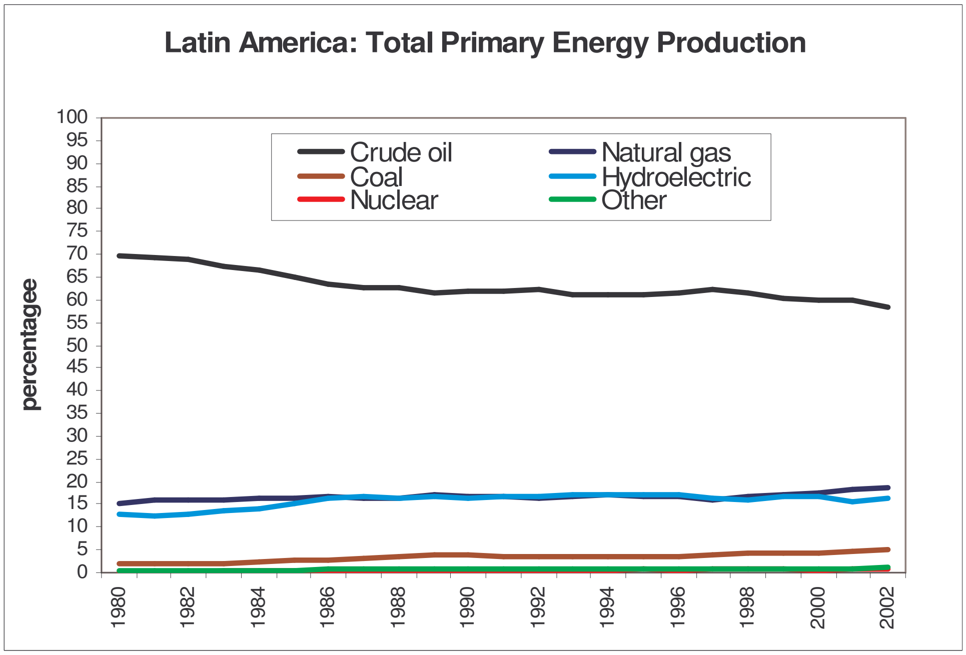
[4] Group 1 includes Argentina, Ecuador, Mexico and Venezuela; group 2 includes Brazil, Colombia, Cuba, Chile, Paraguay and Peru.

at a 3.1% rate. Oil share in TPE reduced in the period, but at a slower rate than it did in the rest of the world. Still, even when all other fuel types grew at faster rates, oil consumption increased at a healthy 2.3% each year from 1980 on. Moreover, if we break down the period, oil accelerated slightly in the 90's with respect to the previous decade. Economic growth and low energy prices re-aligned the existing consumption pattern. If we break the period down a little bit more (in 5-year subperiods), it is clear that in absolute terms oil accelerates again in the nineties, while all other fuels slow down.

GRAPH 2



Source: International Energy Annual 2002, Energy Information Administration.
Notes: TPE excludes biomass. "Other" refers to net geothermal, solar, wind, and wood and waste electric power generation.

Even when most developing countries are experiencing a reduction in the share of oil in their energy profiles, oil is the dominant energy source at the global level. Energy consumption will rise 59% between 2000 and 2020 (IEA, 2003). In Latin America, energy requirements are projected to grow almost 60% in the next two decades. Oil will continue to represent at least 40% of total energy until 2020. From 1973 to 2003, oil consumption grew at 1.6%, with reductions in many countries triggered by the oil crisis of 1973 and 1979; projections nevertheless account for absolute increases in oil consumption from 75 million barrels a day in 1999 to 120 million in 2020, growing at 2.3% each year. Developing countries will be consuming approximately the same amount of oil than developed countries by the third decade of the 21st century. Conventional oil production capacity, nevertheless, will have reached a limit of 100 million barrels a day; the gap of 20 million will have to be fulfilled by non-conventional oil and coal.

The process of substitution of gas (and hydro-power in the case of LA) for oil shows signs of a strong inertia that keeps the "old" fuel growing in absolute terms by spurts, while at the same time its smaller competitors accelerate and de-accelerate also irregularly. The trend in oil dominance in Latin America, despite a higher share of hydroelectric power in comparison to the rest of the world, is signaling a lag in the gas-based intermediate period of hydrocarbon substitution.

As we will discuss below, the region shows a scattered presence of clean sources (hydro, geothermal, solar, wind), and cleaner fuels (ethanol, sustainable biomass); but niche presence of alternative technologies is not “strategic” at all; i.e., it is not directed to systematically test, redesign and develop technology alternatives in order to increase their shares massively. Instead, niche presence is held by very thin technological and institutional pins, while economic forces constitute enormous barriers for introducing non-fossil technologies.

What are the forces behind energy transitions? What are the lessons we can learn from theories about the structure of technical change and the persistence of large technological systems?

Diffusion, adoption and substitution dynamics

The original problem addressed by the economic literature on technology diffusion was why it takes time, and the methodological focus centered on the micro-economic determinants of the rate of diffusion (Mansfield, 1961). Later models explained lags by relating the time distribution of adoptions to the distribution of differences among users, picturing full adoption as an equilibrium adjustment process. This type of models introduced structural criteria as an explanation of adoption delays (David, 1969), but shared with the Mansfield model the assumption of an unchanging technology.

As a reaction against this assumption, other studies introduced diffusion as part of a longer developing process of technologies, where a progressive flow of innovations results from a cumulative learning process through diffusion (Rosenberg, 1976, 1982; Dosi, 1982; Sahal, 1981). This approach acknowledged that innovations perform badly at the moment of their introduction, and very rarely remain unchanged during its diffusion. Sometimes, changes in design are pre-requisite to its adoption. Other changes accelerate its diffusion, and some others facilitate its adoption beyond their original domains. Moreover, diffusion of innovations never takes place in isolation; most of the time it consists in the substitution of a new technique for the old, and the character of one tends to affect the character of the other.[5] The central insight is that technologies change while diffusing, and that these changes feedback into the diffusion process.

The relationship between diffusion and innovation demands focusing attention to the contexts in which new technologies diffuse. Innovation takes place via learning, i. e. through cumulative investment in new skills and technical knowledge, generating new articulations between organizations, new institutions, and new rules. These investments root technologies into the routines of the organizations that use them, reshaping the latter and enabling routes for further advance. The feedback channels between diffusion and innovation, as well as between technologies and their knowledge bases, structure the nature and scope of technological change. This structure consists of trajectories of incremental change, following basic designs or guideposts (Sahal, 1985) and paradigms of techno-scientific design and heuristic principles (Dosi, 1982). Such avenues of gradual change are

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[5] Many times, competition from substitutes triggers intense improvements in old technologies, extending their lifetime, a development popularized as the “sail ship effect” by Rosenberg (1982).

eventually disrupted by the emergence of qualitatively new trajectories triggered by radical innovations and new paradigms. The long term pattern of technology evolution is then a mixture of continuity and change, cumulative synthesis and structural discontinuities.[6]

The dynamics of energy transitions suggested by Grübler, Nakićenović, et. al. (mentioned above) resembles these ideas of structured technological change in long waves of persistence and discontinuous change. Causes of persistence or "stasis" are key factors hindering the transformation of energy systems and diffusion within them.

Diffusion within large systems: technological regime transitions

Energy systems are large complexes of technologies. The dynamics of gradual change and disruption incorporate hundreds of changes in their components and networks. Diffusion within them can then be approached as a process of adaptation of a system, within which the introduction of new components (and the practices associated to them) is spreading. A systems' view focus its attention to the interrelatedness of specialized components of a system, a property that is crucial to understand change. This property implies simply that modification in one component demands changes in other components, triggering and adjustment process that is transmitted through a hierarchical network. To a certain degree, diffusion can therefore be considered as equivalent to structural change in a system. What, then, prevents systems to change and adapt? Or, to get closer to our issue, what gives energy producing and energy using technologies their observed persistence?

Large systems like infrastructures and energy systems have very strong internal and external technological and economic linkages. We state that sunken costs and organizational inertia associated with embedded, large scale technologies generate important barriers to technology replacement and innovative absorption of technologies.

Take for example the components of power systems. Power systems are constituted by related parts and dedicated components (in generation, transformation, control, and utilization functions) connected by transmission and distribution networks. This configuration is embedded on a large base of technological and scientific knowledge, standards, and operative rules. To follow a physical metaphor, a large system has mass (machines, devices, structures, physical artifacts where capital has been invested), velocity (rate of growth), and direction (goals): "The momentum arises also from the involvement of person's professional skills, business, government agencies, professional societies, educational institutions and other organizations that shape and are shaped by the technical core of the system" (Hughes, 1983:15).

A contemporary group of scholars has coined the term "technological regimes" to characterize rigidities in large systems. As defined by Kemp, Smith et al. (1994, p. 15) a technological regime encompasses "the overall complex of scientific knowledge, engineering practices, production process technologies, product characteristics, skills and procedures, institutions and infrastructures which make up the totality of technology." The behavior of agents is then structured by "the dominant practices, rules and shared assumptions that guide private action and public policy in a field" (Kemp and Rotmans, 2001). Socio-economic and technological factors drive and shape each other. Regimes are

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[6] Levinthal (1998) associates this view of change with the "punctuated equilibria" of evolutionary biology.

of course dynamic configurations where changes are fundamentally oriented towards optimizing the system along defined trajectories, but its embedded-ness in practices and routines, and the "momentum" gained by its "mass", together with vested interests and interlocked demand and supply, prevent the transformation of its technological base in a radical way.

System innovation involves then changes beyond the realm of simple components. Adapting to the irruption of radical innovations implies that the whole socio-economic configuration must then develop "new linkages, new knowledge, different rules and roles, a new 'logic of appropriateness', and sometimes new organizations" (Kemp and Rotmans, 2001).

The learning metaphor should not overstate socio-technical factors over economic rules, but rather the interfaces between them. Technology changes and incorporation of new knowledge realize only through new investments. Past investments and their influence on the structure of future capital flows reinforce socio-technical persistence and barriers to adoption in a dynamic way.

The past among us: old investments and sunken costs

When substitution and replacement are involved, capital turnover is a key leveler of technology diffusion. The productive life-time of plants and equipment is a barrier to introduction of new equipment, with disregard of price movements in inputs and products, and even when new technologies have proven more efficient in certain niches. The weight of sunken costs against replacement is bigger the higher the indivisibility of investments and the larger the unit of capital. When capital units are large, it is much easier to introduce additional (peripheral) investments than replace the whole unit, even when the latter additions have smaller impacts on efficiency and revenue. This is why investment in most capital-intensive systems involves a long-term commitment with present technologies, the technological design of which is to remain practically unchanged during the life span of the facility.

This is the core of the well known "vintage capital" argument (Salter, 1960), where technology adoption is subject to an adjustment process involving the cost-revenue distance from past investments to best technique. The crucial factor in this process is that capital costs (obsolescence, amortization and required profits) are relevant for investment decisions only *ex-ante*. Once gross investments are transformed into equipment, these capital costs become rents[7]. Various rules can alternatively govern equipment replacement and decommissioning criteria (for example: a) when unit variable costs of old equipment exceed total unit costs of current best practice; b) when unit variable costs exceed the price attained per unit of output).

Decommissioning criteria are then crucial standards for technological succession in energy intensive industries, and probably the central levelers in the transition to new energy sources.

[7] Salter recalls here that "the stock of existing capital goods is comparable to land, and forms the rationale for Marshall's dictum that the earnings of existing capital goods are quasi-rents". He also recalls the insistence of J. B. Clark that "such earnings are pure rents indistinguishable from those of land" (Salter, 1959, p. 61).

The lesson from dynamic models where technical change is incorporated in capital goods (Silverberg, 1984; Soete and Turner, 1984) is that the feedback between investment and profitability can create waves of investment biased to certain technological configurations. The share of preferred technologies in the total capital stock will follow replicator dynamics. If learning and innovation derives from use, technologies that benefit from investment flows are more explored and eventually become cheaper; in turn, profit rates of those technologies increases, making subsequent investments more attractive, and so on. From the perspective of latent new EST technologies, the argument works the other way around. As long as investment is kept off alternative technologies, the latter will remain untried and expensive and short term flows will restrict to existent technological configurations. This is why tapping the development potential of technological alternatives by redirecting investment flows into niches and explorative fields becomes crucial for increasing diversity and breaking the inertia of technologies "crystallized" in the capital stock.

Capital turnover and economic growth are closely linked. But in the case of a large technological regime, sunken costs constitute a formidable source of inertia and directed momentum. Capital replacement in energy intensive industries with slow growth and high excess capacity is unlikely without incentives and strong market regulation. Facing new regulations, the "gravity" of sunken costs may attract resources into end-of-pipe solutions and technological efforts into enlarging the life cycle of dominant technologies. But more importantly, sunken costs raise the performance and cost requirements of alternatives and delays application decisions downstream and upstream any interconnected system. Especially in the case of energy systems due to their high interconnectedness, sunken costs set "hurdles" of minimum profitability for substitute technologies, narrowing their domains of application, retarding the accumulation of experience and hindering their development and diffusion. Turnover of capital in heavy, long-life units gravitating one over the other can only come from strong growth and heavy investment rates, which become a requirement for technological development.

Tapping alternatives

Since dominant regimes have co-evolved with application domains, shaping each other to their own image, alternative configurations can only emerge developing in "strategic niches." Niches are local domains where new or non-standard technologies are used. These domains provide a development field where new options can be learned and further improvement be stimulated. Firms create niches for strategic reasons; a heterogeneous demand can also build niches for differentiated products; governments create and nurture niches systematically as part of their industrial and technology policies.

Candidates will only show its potential after a period of test, correction and improvement, once "bugs" have been cleaned up and interrelated systems' adjustments have cleared the way to more exploitative applications. No technology can be picked-up without uncertainty and it is not possible to assert *a priori* that an emerging candidate is the best among alternatives. Technologies that show increasing returns to adoption can easily "lock-in" sub-optimal solutions (David, 1985; Arthur, 1989). But in order to overcome rigidities and previous "lock-in," the choice menu must be broadened and development must be stimulated. Increasing diversity is crucial in order to achieve resilience. The stability of established technological regimes is relative. Following Berkout, Smith and Stirling (2003), it is “shifts in the relative strength of the selection pressures” which generates opportunities for change.

To assess a technological transition from a technological regime approach suggests focusing on four aspects: the goal or projected end state; the different phases through which that goal can be pursued; the barriers that characterize each phase (the cost of adoption, resistance of vested interests, and uncertainty about the best option); and the internal and external selection forces shaping the outcomes of the transition. Managing the transition implies then focusing on multidimensional levels influencing the process, in order to identify proper policy and institutional drivers oriented to system innovation in conditions of high uncertainty.[8]

A transition is the result of long-term developments in stocks, and short term developments in flows. Stepping off the hydrocarbons regime will demand to unlock energy carriers from fossil fuels, while at the same time reducing GHG emissions by capture and increasing energy efficiency. This challenge will come from developing new energy sources and sustaining its diversity, but also from technological learning and investment everywhere in the subsystems of conversion, grids, final consumption, and suppliers of equipment.

How prepared are Latin American economies and their technological systems to face this large scale demands of coordinated technological efforts?

SECTION 2

REGIONAL SELECTION ENVIRONMENTS

This section identifies systemic barriers to adoption of new technologies in energy systems and intensive industries in the Latin American region, focusing on key technological and macroeconomic factors that characterize their economic structures. Despite the pointed differences in fuel mix profiles among Latin American countries, the types of structural constraints to adoption and assimilation are very similar in the region.

Meso-level: local capabilities and distributed knowledge bases

Approaching technological diffusion as the assimilation of new varieties into pre-existing structures and organizations has immediate consequences for technology transfer to developing economies. The literature on technological capabilities (developed closely to the evolutionary views on technology mentioned above), stresses that costs of diffusion and imitation as well as of original innovation can be reduced once an autonomous capability has been established, contrary to the common sense idea of late-comers-advantage. Moreover, local technological capabilities determine the nature of what is transferred and the deepness of technology diffusion.

The probability of adoption of new technologies, just as the scope and deepness of absorption depends critically on the accumulated experience of firm’s in dealing with technological change. In turn, making incremental, adaptive, and innovative modifications to selected technologies depends on assets qualitatively distinct from those required to

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[8] “Transition management does not attempt to choice the best path but attempts to learn about various options and to modulate dynamics [of myopic agents] towards societal goals. An energy transition policy contains the current climate policy, but adds three things to it: a long-term vision, an impulse for system innovation, and a framework for aligning short-term goals and policies to long-term goals” (Kemp and Rotmans, 2001).

efficiently manage and operate production units (Bell and Pavitt, 1997). The absorptive capacity of economic organizations is determined by their ability to identify, assimilate and exploit external knowledge (Cohen and Levintal, 1989), which takes place in defined circuits of productive and technological linkages, framed by institutions and policies constituting industrial and national systems of innovation (see the contributions in Edquist, 1997).

Perez (1983) and Freeman and Perez (1988) have argued that the absorption of new technologies depends on a "proper" match between the techno-economic system and appropriate institutions (including legal frameworks, labor relations, and cultural attitudes). These institutions may only adapt with considerable delay and in a somewhat discontinuous manner. Of course, we can only guess what types of sociotechnical systems will "match" the emergence of new sources of energy. A "proper" match can only emerge after intense institutional adjustment base in trial-and-error, a flexible coordination directed to clear goals and wide social involvement.

In order to identify specific barriers and drivers for change technological regimes must be focused at a mesoeconomic level. We identify here the mesoeconomic level, in tune with Cimoli and Dosi (1995) with the level of networks of linkages between firms and other organizations, both within and outside their primary sectors of activity. Technical knowledge is unevenly distributed across such networks, and this immediate realm of interaction critically enhances or hinders a firm's opportunities to improve problem solving activities. The historical path followed by science and technology institutions, which shape this meso-economic realm in particular industries, explains at a very large extent the differences in technological development across countries. [9]

It is crucial here to distinguish between capabilities to "efficiently use and manage equipment", from capabilities to solve critical engineering problems and re-design the architecture of technologies and systems, and the latter form capabilities to change engineering paradigms and generate radical innovations. Transfer is never totally successful and sustainable when local learning is restricted to the knowledge of "how to use" a technology. Demands on the local sociotechnical environment does not stop there; even when incremental innovation is possible in laboratories and research centers, successful application into new domains requires additional financial, managerial (and sometimes marketing) skills (Amsden, 2001).

Energy technological regimes in Latin America developed in a pattern of fast growth based on import substitution. This development model pushed industrialization and urbanization in larger nations at very fast rates, pressing for a correspondent pace in capacity of energy supply without stimuli for qualitative diversification. Scale and income barriers of energy demand, together with difficulties of developing clusters of specialized equipment suppliers, set limits to technological diversification in energy systems which revealed after the oil crisis in the mid 1970's. Only Brazil was able to develop a significant capital goods

[9] As stressed by Katz (1997), Kim (1997) and Lall (1997), differences in the historical paths of industrial and S&T policies are crucial in explaining the diverging paths of technological learning between South East Asian and Latin American countries

industry[10]. Oil reserves in Argentina, Brazil, Ecuador, Mexico, and Venezuela biased heavily investment policies to exploitation rather than exploration (in the technological sense). The debt crisis, its following effects during the 1980's, and the structural adjustment programs instrumented afterwards acted as "massive selection mechanisms" on the national industrial technology base in all countries in the region (Katz, 1997). Privatization, foreign direct investment, and corporative restructuring have profoundly reshaped the industrial organization at different levels, but the accumulation of technological capabilities has tended to focus on already acquired competencies rather than to diversify them. Of course, these general trends have important exceptions, and many Latin American energy firms and their suppliers have developed networks across many technological areas, and specialized technological competencies.[11]

Approaching a technological transition simply as a problem of technology transfer from abroad (understandable in the early stages of development, but self-defeating for capability building) reduces the probability of up-grading technological regimes, but more importantly asphyxiates the creation of innovation niches. Specifically, the exclusion of active industrial and science and technology policies has only reinforced the Latin American syndrome of buying, rather than building, technological skills.

Since the 1950's many Latin American countries developed national research institutes to supply technology to their energy sectors. These institutions, have acted as catalizers of technology transfer and technology development, and have accumulated a significant degree of expertise in innovation and technology development capabilities. Nevertheless, these innovative efforts have very rarely acquired the critical mass to consolidate proper innovation systems. Even when inventions and patent registry has become routinized in many Latin American R&D institutes, there are serious barriers to absorb these capabilities at fast learning rates early at the energy production level (and at the production level, in the case of energy intensive industries). It is at this stage of the innovation process where local firms are surpassed by transnational companies, with century-long accumulated capabilities in development and market introduction. Sometimes, local industries end up importing substitutes of technologies they can replicate at the research level but cannot spin-off from the lab.[12] Of course, the insights gained through research help local industries to identify and adapt successfully new technologies through transfer, but the process at the national level does not open tracks for further advance and new applications.

Research capabilities may be weak (and financially constrained), but it is the absence of market development and manufacturing capabilities at early stages of introduction which critically hinders the feedback channel between knowledge generation and productive systems. Structurally, this systemic mismatch is reflected in the absence of local firms specialized in supplying the vast majority of capital-goods nurturing their energy and

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[10] Electricity and oil industries in Mexico import around 70% of capital equipment; the gross of local suppliers provide relatively simpler components and building infrastructure.

[11] A salient example is the Techint Group, based in Argentina, an industrial holding of large firms specialized in seamless steel pipes for the oil industry. This merge of Argentinean, Brazilian, Italian, Japanese, Mexican and Venezuelan leaders controls 30% of the world market.

[12] Aboites, Loria and Rosado (2004) show that, despite the innovation capabilities of PEMEX's R&D institute (the National Oil Institute, IMP) in catalytic processes, the transnational oil companies are the main suppliers.

energy-intensive technological regimes. As is the case with most technologies in Latin America and the rest of the developing world, transfer and diffusion of embodied technologies has not included the accumulation of a critical mass of technological capabilities directed to creative imitation and autonomous replication.[13]

The technological knowledge base surrounding dominant energy and energy-intensive technologies is broad (comprises very different engineering areas), deep (demands profound specialization), and science based (the boundaries between basic and applied research are blurry). As the technological regimes of energy production evolved at the global level, technological competence has spread to specialized suppliers of equipment, while at the same time, R&D demands for up-stream and downstream incumbents have increased.

Renewable, carbon-free energy technologies are "well known" to engineers and university researchers in Latin America. Plenty of organizations and associations promoting the diffusion of solar, wind, biomass, and hybrid technologies and components are to be found all around. The point, however, is that technological applications do not occur driven by systematic forces, but against them. Technical knowledge and opportunities are restricted to small circles and remain out of reach of other important stakeholders and decision makers, many times inside the same institutes and corporations. Moreover, institutional and regulation frameworks at many levels of government prevent this technological and engineering base of nurturing potential strategic niches (Huacuz, forthcoming).

While some sustainable alternatives like wind and industrial biomass seem to have relatively simpler knowledge bases (in comparison with oil, gas and petrochemical families of technologies), others do not. This may raise technological barriers to assimilate technologies when investment and scale obstacles are still easy to overcome. The knowledge base of new technologies tends to be broader and less codified at the moment of their introduction. As Pérez and Soete (1988) argue, this "learning" barrier tends to diminish with exploration and standardization of technologies, but by the time this happens investment thresholds have already rose up. Some scholars have argued that many emerging technologies (biotechnology, nanotechnologies, and) rely on broader and more complex knowledge and competence bases than its predecessors; this would be the case of the fuel cell compared to the internal combustion engine (Mytelka, 2003). Some views about future energy configuration also point at higher degrees of complexity, with more elaborated systems of energy conversion and delivery, and "leading to ever more sophisticated energy systems and higher-quality energy carriers" (IIASA-WEC, 1995). Since technology is a strategic asset, this will probably require more sophisticated forms of generating, appropriating and controlling technology. Both aspects could build bottlenecks

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[13] Creative imitation is a threshold concept when assessing technology transfer into underdeveloped economies (see Kim and Nelson, 2000: Introduction). Creative imitation (this is, imitation with a plus of originality at some level of the technology) is important in three ways; first, for realizing the necessary design adaptations to make technology appropriate to the local environment (both in technical and economic senses); second, as the outcome of a deep learning process, that contributes to the accumulation of technological capabilities and competitiveness (dynamic efficiency), finally, both appropriateness and learning are needed to guarantee the economic viability of technological up-grading in the long run.

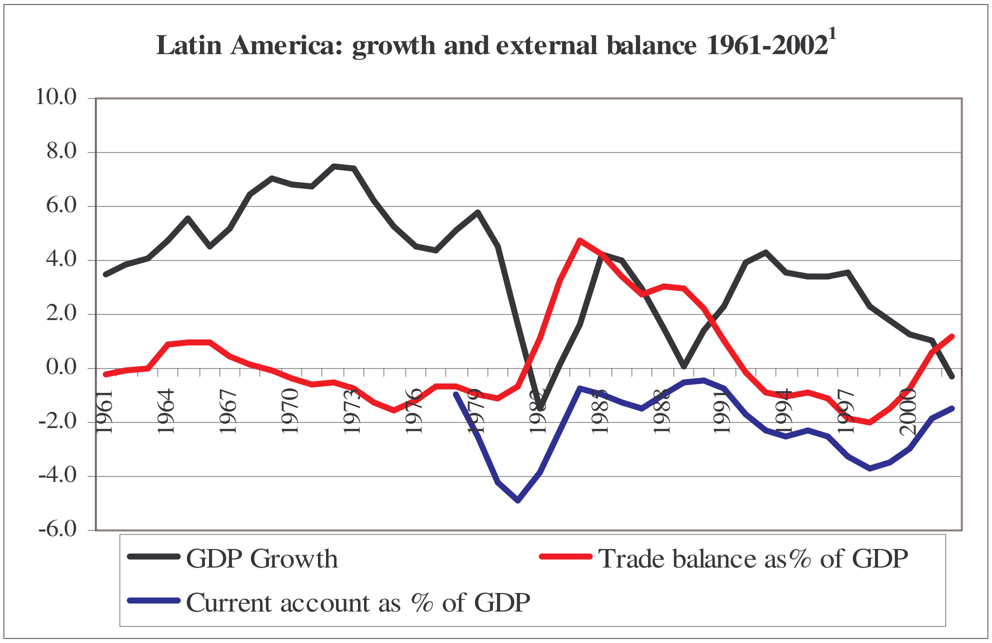
to early assimilation, leading Latin American economies to repeat the pattern of late, passive technology absorption.

Macro-structural barriers

The macroeconomic landscape behind technological transition from hydrocarbons looks quite complicated for Latin American economies. The construction of large energy systems in the region, from the 1950's until the late 1970's, occurred in conditions of sustained GDP growth, low inflation rates, stability in exchange rates and positive financial transfers from the outside. The crisis in the Bretton-Woods system of trade and exchange rates, together with the excessive accumulation of foreign debt brought to an end the inward oriented industrialization patterns developed in the region. But economic reforms after the "lost decade" have failed in assuring growth, stability, and structural change based in technology upgrading.

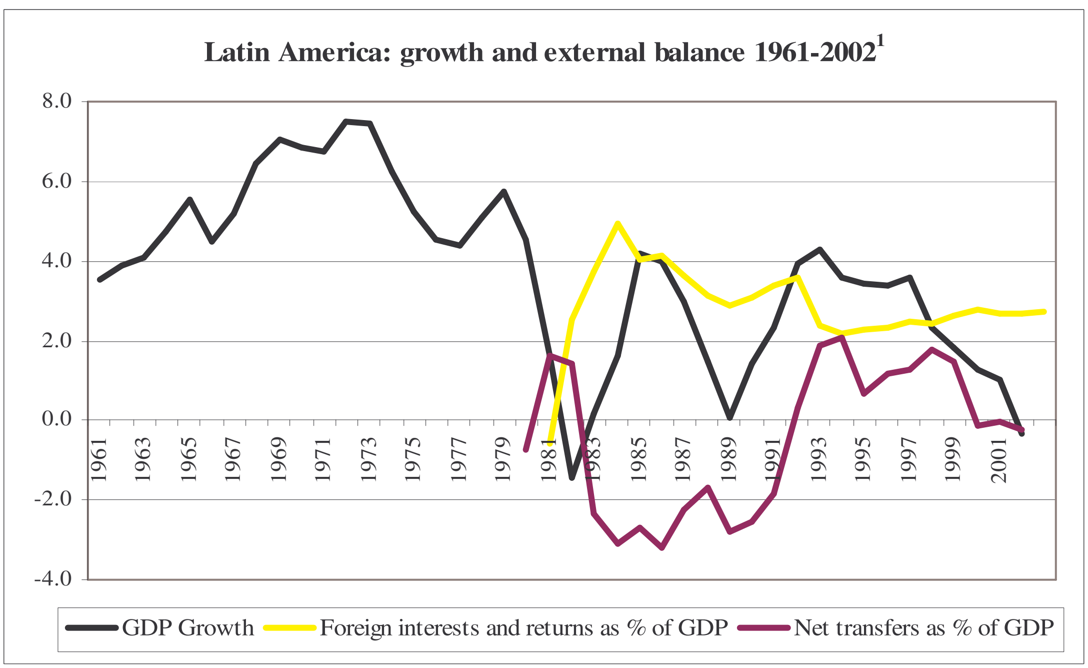
Since the topic is broad (and surely controversial), we would focus here on three features of the macroeconomic profile shared to a similar degree by all Latin American economies. First, since the late 1980's macro stability has relied upon the systematic contraction of the domestic market and high interest rates in order to keep down inflation and exchange rates, neutralizing anti-cyclical policy instruments. Second, adjustment in public finances has relied mainly on cutting down public expenditure without increasing public income; this, next to the persistence of foreign debt obligations, has curtail the ability of the government to "steer" the economy through times of adjustment and transition. Third, globalization and liberalization of the financial systems in the region have installed fragile scenarios characterized by high volatility in capital markets, exchange rates and interest rates. Even though exports have increased as a share of output, trade deficits continue to be structurally embedded into economic growth (see Graph 3). Despite the aims of "structural adjustment," the trade profile of the region reveals it is trapped in a low technology, resource-intensive path, unable to capture and secure dynamic efficiency gains. External debt services constitute a permanent tax to growth (see Graph 4). Capital flows in the form of FDI, have not recovered after the short boom during the 1990's, and the region is entering a trend of negative net capital transfers.

GRAPH 3



Notes: [1] Three year moving averages. Includes Argentina, Brazil, Chile, Colombia, Ecuador, Mexico, Paraguay, Peru and Venezuela. Source: World Bank National Accounts Database; International Monetary Fund, Balance of Payments Statistics.

GRAPH 4



Notes: [1] Three year moving averages. Includes Argentina, Brazil, Chile, Colombia, Ecuador, Mexico, Paraguay, Peru and Venezuela. Source: World Bank National Accounts Database; International Monetary Fund, Balance of Payments Statistics.

Volatility, high interest rates, slow growth and technological lags in the industrial base form a syndrome of systemic risk that hinders diffusion and innovation:

- retarding productive investment and capital turnover
- biasing productive investment to short term goals and "working capital"
- delaying projects aimed at meeting environmental regulation
- biasing environmentally-innovative projects to EOP and to incremental improvements in energy efficiency
- reducing the probability of carrying projects that involve CTs
- reducing the probability of engaging in intramural R&D and reducing investment in broad technological capabilities

Macro structural factors gravitate heavily upon the cost of capital, influencing significantly scrapping-decommissioning criteria and the rate of capital turnover. Energy infrastructure investments are big, "lumpy," and risky. Many times they involve coordination among complementary investment projects. *Ceteris paribus*, a lower cost of capital equipment enhances the likelihood of an industry modernizing its plants with new equipment. At the same time, it increases the likelihood of making anticipated plant-scrapping decisions. On the contrary, high costs of capital induce decision makers to postpone major investment decisions, and at the same time reinforce technological search efforts aimed at extending the life-cycle of specific pieces of equipment. These stretching efforts are of course efficient in the short run, but at the cost of paralyzing technological development. By inhibiting investment in fixed capital they reduce the possibilities of optimizing the existing technological regime. And in the longer term, it blocks out investment in riskier, more uncertain and less profitable niche alternatives. In this way, the technological structure and investment behavior reinforce each other.

The relationship between public finance and the fossil fuel regimes is especially worrying in oil producer countries. With the exception of Petrobras, dependency on oil revenues has tied the fiscal regimes of oil companies to the financing of government expenditure, blocking investment flows for maintenance, technological up-grading and R&D.

Income concentration and low income levels reduce diffusion rates conduces both from the demand as from the supply side, to slower diffusion rates and to a reduction in the number, variety, and speed of development of potential strategic niches for innovation. Adoption costs can hardly be shared with final users (being them industrial firms or households) with low income levels, especially during the first phases of transition when new technologies involve higher costs.

Finally, but not least importantly, financial pressures on Latin American states seriously hinder their capability of gradually increasing and sustaining government expenditure dedicated to increasing technological capabilities: education services and infrastructure, basic R&D, R&D in general-purpose and other strategic technologies, horizontal and specialized science and technology services and venture capital. The involvement of state expenditure in R&D will be especially important to attract complementary private flows and reduce uncertainty in the first stages of technology development (see Kim, 1997 for the case of Korea).

The next 30 or 40 years present already enormous challenges for financing energy systems in the region. Capital costs are going to be crucial, not only for finding ways to invest in future alternatives, but simply for sustaining the current technological regimes in oil, gas and electricity. According to the IEA, Latin America will need to invest 1.5% of its GDP every year from 2001 to 2030 only to cover its basic energy requirements (around $1,337 billion dollars in the whole period). Of this total, 25% will go to oil and 18.5% to gas. Only exploration and development in fossil fuels will account for 28% for the total energy investment.

SECTION 3

SELECTION ENVIRONMENTS

The composition of investment: from flows to stocks and backwards

In this last section we construct a simple heuristic framework to exemplify the influence of structural factors on investment flows. By comparing ad hoc examples under stylized conditions we exemplify how rigidities will impact alternative transition paths.

As we argued above, rigidities in a technological regime progressively hinder technological changes of higher order of complexity, biasing technology developments to the easier changes. Clearly, transition out of hydrocarbons implies the generalized adoption of CTs; optimizing trends within the hydrocarbons regime (through diffusion of EOP and increases in energy efficiency), offer in turn a temporary response to emission abatement requirements. Energy efficiency can come both from incremental innovation within the dominant regime of hydrocarbons (EEI) as from incremental and radical innovations in process technologies in end users (EER). Radical improvements in energy efficiency in industrial users can be considered, in turn, as a transition in their respective technological regimes.[14]

Suppose these possibilities for technological investment are assessed as constituting an investment portfolio. Firms or decision makers evaluate investment decisions comparing expected returns to adoption costs. Suppose that the investment options are: acquiring new equipment on a "business as usual" basis (BAU), projects involving adoption of EOP, increasing energy efficiency through EEI, or introducing EER or CT. All this options are graded according to the correspondent technological effort or technological "familiarity distance." Suppose, finally, that these investment options are compared to a risk-less asset (like bonds or other financial instrument) constituting a financial "hurdle" rate. A rule of investment will look like:

$$(p-r) = \alpha + \beta(TE)$$

where p are expected returns to the project; r the interest rate and TE the technological effort.

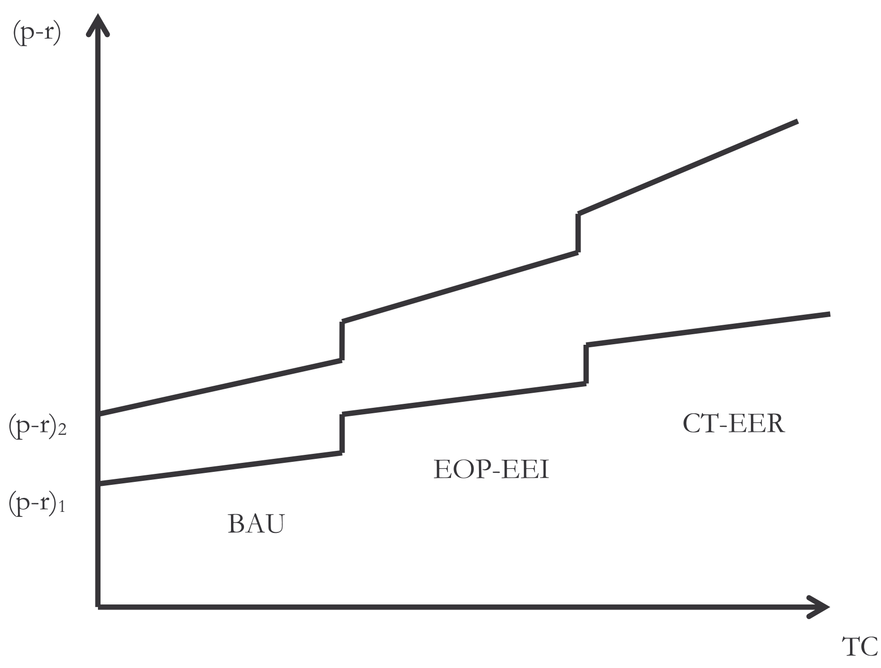
[14] CT solutions are clearly preferred to EOP solutions from both environmental and technological criteria. First, EOP technologies are perceived as an increase in cost production, even when these costs are clearly offset by environmental gains. Cleaner production methods, on the contrary, involve most of the time superior performance, but at higher adoption costs and risk. Second, EOP technologies simply shift the flow of materials creating additional costs of energy, transport and storage. Clean production eliminates (or reduces substantially) the emission of materials and reduces energy intensity by substituting inputs and incorporating more efficient forms of energy use.

If we graph the possible distributions of investment flows into EOP, EEI, EER and CT according to their expected returns and the requirements on local technological capabilities to carry them on, alternative scenarios would look like Graph 3 (below).

Uncertainty associated with distance in technological familiarity increases along the axis line; but additional "hurdles" arise from discontinuities in the nature of projects (schematically drawn like jumps in the investment distribution line). Parameter α captures "system hurdles" derived from sunken costs up-stream the energy chain or associated equipment; parameter β will be affected by the "sensitivity" to the technological effort or opportunity of appropriating technological gains (the higher the opportunity, the lower the slope of the line).

The model should be appraised not in a deterministic, but in a probabilistic way. In principle, no investment option is excluded. Some risky projects located above the portfolio investment line may be selected. But most selected projects will match the rule. The point of a model like this is to assess how different environments would affect the probability distribution of selecting different technology projects. The static conclusions of this simple exercise seem straight forward. The higher the technological effort of the project (or the less "familiar" the technology to the organization), the higher the "hurdle" impact of sunken costs, and the lower the perceived gains, the higher the floor of the expected return demanded to invest in it. The higher the level of the rule, the more projects are "screened-out."

GRAPH 5



Low interest rates, local technological environments conducive to a high perception of technological opportunities and accumulated experience in technical change would increase the probability of having a more distributed profile of technology investments (more "hits" along the whole range of options). Still, niche nurturing will be necessary to extend the distribution to the upper-right area of the graph. On the contrary, fragile financial systems and stringent access to financial resources, slow market growth, incomplete technological systems and high adoption costs, will bias the distribution of projects to the origin, screening out first CT and EER projects, then incremental advances, and eventually all equipment investment.

Within a technological regime, investment decisions of independent investors will collide and affect each other. The aggregated distribution of investments at a point in time will configure an investment pattern reflecting the "momentum" of a regime, its drive for optimization and the strength of transition drivers. Structural macro and meso-economic conditions influence the parameters of technology selection, which by allocating investment flows reinforce or weaken the nested persistence of technological configurations.

More interestingly is how different scenarios would *evolve* through iterative investment rounds. As we stated above, there exists a feedback process between capability accumulation and resource allocation to technology projects: 1) local capabilities are a critical component in investment decisions: they illuminate promising areas of technological development, assess risk and opportunities, and reduce transfer and development costs; 2) investment decisions feed capability accumulation: capability is embedded in processes that use and consume resources. This means that the position of the curves (the distribution of technological projects), would depend on previous investment patterns, generating complex, non-linear dynamics and path-dependent trajectories. Developing a formal model is part of our current research.

For the moment we can infer that the technology profile of a country's capabilities would follow closely the aggregated technology investment profile in a clear circular causation relationship. Sunken costs and capital costs are evaluated by agents through parameters defined both at the macroeconomic level (interest rates, demand growth, credit availability) and at the meso-economic level (input prices, and the base of technological capabilities). In this way, signals from the entire economic system are translated into selection pressures that foster or hinder adaptive responses or shifts in technological regimes.

Selection environments: Mexico and the Latin American context

Changing the profile of technology investments in a country will depend at a good extent on the interplay between financial constraints and the capacity of local systems and organizations to unveil technological opportunities. In this last section we examine *grosso modo* the magnitude this two forces in Latin American countries.

Table 5 provides an estimate about the cost of credit in the Latin American region. Average interest rates in Latin America were 3.6 times as big as the U.S. prime rate during the nineties. This difference diminished after the 1994 Mexican crisis but started growing again since the year 2000. Financial liberalization and reform has been unable in bringing down credit prices and, most important, in increasing financial penetration into these economies. Credit scarcity combines critically with the lack of a solid institutional platform providing long-term credit and venture capital.

Table 1

Latin America: Interest Rate Differentials (local rate/US prime rate)*											
	1993	1994	1995	1996	1997	1998	1999	2000	2001	1993-1997	1998-2001
Latin America[1]	**8.4**	**4.5**	**2.5**	**2.6**	**2.5**	**2.8**	**3.4**	**2.3**	**3.5**	**4.1**	**3.0**
ARGENTINA	1.0	1.2	2.3	1.9	1.4	1.4	2.1	2.1	6.0	1.6	2.9
BRASIL	69.6	26.6	1.7	5.2	6.2	7.5	8.5	5.1	7.3	21.9	7.1
CHILE	2.7	1.4	1.3	1.5	1.3	2.7	1.4	1.6	1.9	1.6	1.9
COLOMBIA	3.6	3.1	2.9	3.3	2.2	3.0	3.0	1.7	3.4	3.0	2.8
MEXICO	3.7	2.7	3.2	0.3	0.5	1.6	1.4	1.4	1.9	2.1	1.6
PARAGUAY	3.5	2.7	3.0	3.8	3.2	2.5	3.8	2.8	4.7	3.2	3.4
PERU	10.0	5.4	3.8	3.4	3.3	3.5	5.2	4.2	5.5	5.2	4.6

* Real interest rates (deflated by the consumer price index).

[1] Regional average; includes Bolivia, Costa Rica, El Salvador, Ecuador Guatemala, Honduras, Jamaica, Nicaragua, Uruguay, and the above listed countries.

Source: Economic Commission for Latin American Countries and International Monetary Found; U.S Department of Treasury and U.S. Department of Labor Statistics.

These estimates should be accounted as the credit cost baseline due to unregistered operational costs which could easily level up the differential to the reference rate. Even in countries like Chile and Mexico, where strong inflation control has lowered interest rates credit is still almost twice as high. Higher credit costs and market uncertainty constitute enormous financial barriers for long term investment, especially for small and medium firms. According to the Bank of Mexico's Credit Market Surveys, only 18% of small and medium firms borrow from national commercial banks; 2% borrow from international banks and 2% from development banks.

The impact of high interest rates must add to the fact that capital intensive investment in developing countries is commonly assessed as less profitable and more risky (IEA, 2003). Conventional technology regimes may very likely face trouble in finding suitable financial sourcing under this conditions, leaving new energy sources and clean technologies in an even weaker competitive position.

Research and development resources in Latin America are scarce. Table 6 shows a set of selected indicators of R&D activities in the region. Total expenditure is small in absolute terms as well as relative to GDP (accounting for purchasing parity power differentials). Per capita expenditure on R&D is 20 and 35 times smaller than that of Canada and the U.S. respectively. Total human resources devoted to R&D are also much smaller than in North America and asymmetries diminish in order of magnitude only for a handful of countries (Cuba, Argentina, Brazil).

This scarcity of resources creates an adverse environment for the private appropriability of technological development, which reflects in the lower level of business enterprise share in R&D expenditure and the minuscule percentage of local patenting. Given the volume of resources, the relatively bigger percentage of R&D allocated to environmental and energy R&D in Latin America is probably insignificant.

Table 2

Latin America: Selected Research and Development (R&D) indicators[1]								
country	R&D expenditure					R&D personnel		Patents
	Total (million PPP$)	As percentage of GDP	Per capita (PPP$)	Business enterprise share	Environmental and energy share of R&D	Researchers per million inhabitants	Total S&T personnel per million inhabitants	Invention coefficient[3]
Argentina	908	0.39	25	22.5	7.1	949	1,438	3.0
Brazil	13,564	1.04	80	38.2	2.3	200	1,470	5.2
Colombia	275	0.10	6	46.9		169	299	0.2
Cuba	190	0.62	17	35.0	22.4	538	6,531	1.3
Chile	767	0.57	52	24.9	3.2	429	915	2.8
Mexico	3,321	0.39	34	29.8	23.2	261	446	0.4
Paraguay	21	0.10	4	0.0	3.7	127	438	0.2
Peru	140	0.10	5	10.7	0.0	229		0.2
Venezuela[2]	463	0.38	18	20.9		222		0.4
Latin America	**19,649**	**0.41**	**27**	**25.4**	**8.8**	**347**	**1,648**	**1.51**
Canada	17,869	1.88	569	45.3		3,333	5,073	17.9
United States	276,434	2.64	960	64.6	2.2	7,125	8,545	58.6

Notes:

1 2002 data, excepting Brazil (2000), Chile (2001), and Mexico (2001)

2 Total Science and Technology expenditure

3 Patents applied by residents per 100 000 population

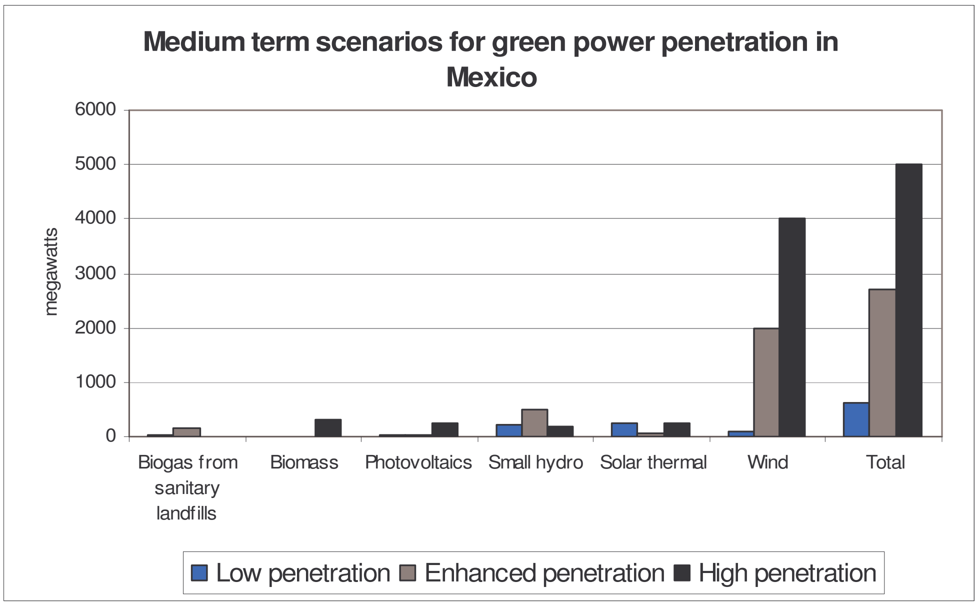
Source: Interamerican Network of Science and Technology Indicators (RICYT).

Small investment in specialized technological resources and skills diminishes the capability of transferring, adapting and developing substitute technologies. It also makes more difficult the development of new capabilities and setting up a technologically dynamic environment. This, in combination with a financial environment adverse to capital turnover exemplifies the rigid situation depicted in the heuristic model described above.

How does this relate to the development of new technological capabilities? Take the example of electric power in Mexico. This country has a relatively small use of renewable sources for electricity production due to high endowments of fossil fuels, small energy markets, and direct and indirect subsidies to oil use. Nevertheless, the perceived higher costs of renewables could be reduced by enhancing a number of complementary technological and institutional developments. Between 2004 and 2013, Mexico will need to expand the capacity of its national electric system in around 25,000MW. Technology for 73% of the new capacity has already been chosen: 52% of new electricity will be produced by combined cycle power stations, 7% by other fossil fuel stations, and 12.7% by large hydropower plants (SENER, 2004). Wind energy will contribute with 405MW. Mexico's energy dependence on hydrocarbons will this way emerge unaltered after ten years, unless new renewable sources are assigned for the remaining 6,700MW.

Estimates show, however, that renewable energy resources could in fact cover a much broader share of electric power. According to Huacuz (forthcoming), around 5,000MW could be now economically produced from wind (see Graph 6 below) and another 10,000MW may be detected through further exploration. Next to small hydropower (3,550MW), biomass (36MW) and biogas (150MW), new renewables could be delivering three times the amount of energy which technology choices have already left out.

Graph 6



Source: Based on Huacuz (forthcoming).

A concert of technological and organization efforts could reduce the perceived cost of new renewables: augmenting the "hardware" stock through pilot plants; increasing the availability of "software" (technical norms and procedures, best practice manuals for project replication, development guidelines); achieving institutional changes at all government levels; and investing in specialized human resources.

Conclusions

The energy transition demanded from environmental concerns and limited availability of resources is fundamentally a technological transition. Sunken costs, high capital intensity, laid distribution networks, nested engineering practices and knowledge, as well as the relative inefficiency of alternative technologies and a strong institutional power, are all factors built in hydrocarbon-energy systems that constitute a front of selective pressures hindering energetic transition. Macroeconomic and structural features acting on investment decisions can amplify the selective pressure from built-in barriers to innovative diffusion and replacement in energy systems and energy intensive industries. In the case of Latin American countries, this will likely be the case under present trends.

Three aspects of the "technological regime transition" are important to highlight. First, its implicit systemic view: technologies are viewed as a hierarchical structure of interrelated, specialized components, production methods and patterns of technological design. Second, the nature of such a system as a "regime"; regimes are not the product of a master design (even when a design may be at its core, e.g. the combustion engine); rather they are the product of a historic process of interlocking decisions, commitments and interests; regimes are societal products, and as such traversed not only with conflict and power relations, but also with a significant degree of indeterminacy. Finally, the concept already incorporates a theory of cumulative, gradual change with radical discontinuities, highlighting critical moments and necessary phases of development.

Economic environments that punish long term investment and investment in specialized equipment and specialized skills will tend to reinforce the existent technological regime, sinking capital into it and blocking resources to the development of niches for substitutes. Perceived costs of untapped substitute technologies will remain high due to the absence of ancillary investments and supporting technologies. Lagging behind in developing a more flexible capability base will increase the economic costs of adoption and reinforce historical patterns of passive technological transfer, creating stronger rigidities to industrial growth and adaptability, and increasing GHG concentration and environmental impact.

The stability of regimes is, nevertheless relative. They are subject to selection pressures exerted by established competitive regimes and by new configurations in niches, but also by policy coordination and regulation. The reliance of adoption of EST on the local base of capabilities calls clearly for active education, industrial and technology policies. In turn, a perspective on energy transitions based on the concept of technological regimes can offer insights for gearing those policies with energy policy. On the contrary, an economic environment that punishes long term investment, investment in specialized equipment, and specialized skills is the worst possible in a transition scenario, because it will tend to reinforce the existent technological regime sinking capital into it and blocking resources to the development of niches for substitutes. Lagging behind will increase the economic costs of adoption, reinforce historical patterns of passive technological transfer, creating stronger rigidities to industrial growth and adaptability, and increasing GHG concentration and environmental impact.

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