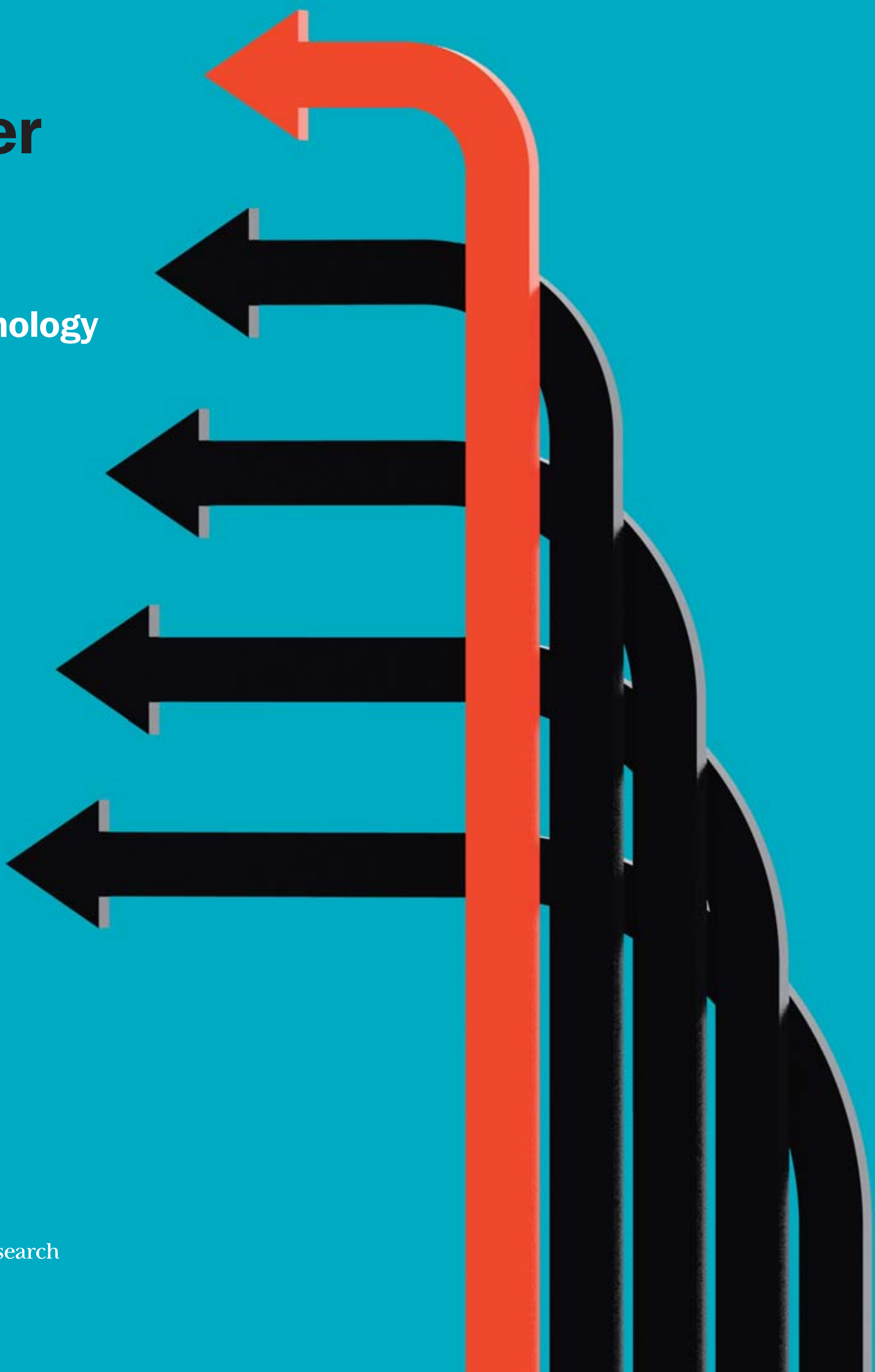
Technology Leapfrogging: A Review of the Evidence

A report for DFID



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Summary

The aim of this report is to contribute to a better understanding of the term ‘environmental leapfrogging’ and its policy implications. It identifies relevant concepts and reviews the literature on barriers, risks and opportunities for leapfrogging by developing countries, with a particular emphasis on low carbon energy technologies. The general definition of ‘environmental leapfrogging’ used in the report is the possibility that developing countries might be able to skip some of the dirty stages of development experienced by industrialised countries. Three different types of ‘environmental leapfrogging’ are distinguished: leapfrogging within overall development pathways, leapfrogging within industrial development, and leapfrogging in the adoption and use of technologies.

Many of the studies reviewed in this report investigate the conditions under which latecomer countries can catch-up or even leapfrog development paths of industrialised frontrunner countries. A sufficient level of absorptive capacity – ie the ability to adopt new technologies – is a core condition for successful leapfrogging. This capacity includes technological capabilities, knowledge and skills as well as supportive institutions. There are a range of policies that can be implemented to develop this capacity. The evidence suggests that a mix of generic functional policies (eg to strengthen levels of education) and more specific policies (eg to stimulate innovation in a particular sector) are required.

Any leapfrogging strategy involves risks. Latecomer countries can, however, benefit if initial risks of developing new products and establishing markets have been borne in ‘frontrunner’ countries. Once a market is established, developing countries can catch up through rapid adoption of new technologies and/or the development of manufacturing capacity. For a sustainable growth strategy within developing countries, such manufacturing capacity needs to be complemented by investments in domestic technological capabilities to develop imported products further. More radical innovation – due to a shift in technological paradigms – can provide additional ‘windows of opportunity’ for developing countries.

The four case studies covered in the report show that technology and environmental leapfrogging is possible. Different factors have been identified for the success of this process. In the case of developing countries that have partly skipped landline phone systems in favour of mobile phone systems, early adoption in industrialised countries enabled leapfrogging. Developing countries had access to a competitive international technology market which had already reduced costs. They could also adopt recognised standards and a proven technology. Leapfrogging in the Korean steel and automobile industries was enabled by investments in technological capabilities in the countries concerned. This was enhanced by a balanced and coherent policy mix of economic, industrial and R&D policies. The success of the Indian and Chinese wind industries illustrates the benefits of incentives for the deployment of wind technology. This market creation was allied with the development of domestic wind manufacturing industries. This, in turn, was enabled by access to external knowledge and the creation of knowledge networks.

The evidence reviewed in this report underlines that key factors for success in leapfrogging are different in each case. It is therefore not possible to generalise to a large degree. This echoes the result of earlier studies of the ‘Asian tiger’ economies which concluded that there is no standard model of development or catching-up. Instead a country’s distinctive resources need to be taken into consideration, and trial-and-error learning needs to be accepted as part of leapfrogging strategies.

Contents

1 Introduction

‘Environmental leapfrogging’, ie the skipping of pollution intensive stages of development, has attracted increasing attention in recent energy and climate debates. It has been suggested that ‘environmental leapfrogging’ – both at the level of industrial development and the adoption of cutting-edge technologies – would prevent latecomer countries from going through the same pollution intensive stages of industrial development as industrialised countries have experienced in the past. Within the current debate about responses to climate change, the idea that developing countries might be able to follow more sustainable, low carbon development pathways is particularly attractive.

The aim of this report is to review the evidence for ‘environmental leapfrogging’, and to draw out some insights for current policies for international development and climate change mitigation. The report examines different definitions of ‘environmental leapfrogging’ and highlights barriers, risks and opportunities for ‘environmental leapfrogging’ strategies. It shows that barriers and challenges are considerable. At the same time important opportunities exist if sufficient capacity to innovate is available within developing countries. This capacity includes technological capabilities - ie the resources necessary for generating and managing technical change. These are built upon skills and knowledge and supported by appropriate national and international institutions.

The report is structured as follows. The next section discusses definitions of ‘leapfrogging’ and clarifies the meanings of ‘environmental leapfrogging’. Section 3 reviews the existing literature on barriers, risks and opportunities involved in catching-up and leapfrogging by latecomer countries. These insights are then discussed further with respect to four brief case studies of leapfrogging in section 4. The technology case studies focus on the diffusion of mobile phones in developing countries, the Korean steel and automobile industries, and the Indian and Chinese wind industries. The report concludes with a summary of the literature’s main points, some tentative implications for policy, and some recommendations for further research.

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2 Defining 'environmental leapfrogging'

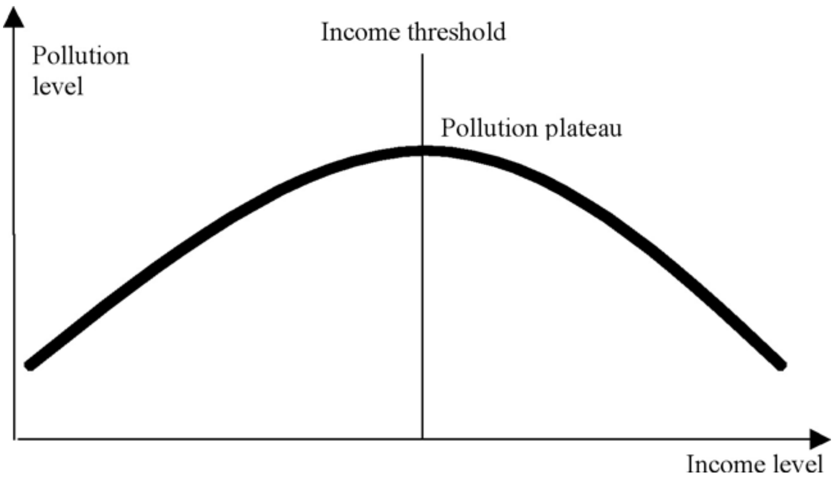
In this section, three different perspectives on leapfrogging are explored: first, a country's overall development pathway; second, leapfrogging through the development and manufacture of new technologies within developing countries; and finally leapfrogging that involves the early adoption and use of new technologies.

2.1 Leapfrogging Development Pathways

A broad definition of leapfrogging is not just concerned with particular technologies or industries. Instead, it focuses on the overall pathway that could be followed by developing countries – and the extent to which they might be able to avoid the 'polluting' economic development pathways that have been taken in the past by many developed economies. Instead, there may be scope for them to move more quickly to a cleaner mode of growth with lower environmental impacts (Gallagher 2006).

One way to analyse this prospect is the Environmental Kuznets Curve (EKC) hypothesis (Grossman and Krueger 1995; Stern 2004). This hypothesis attempts to characterise the relationship between average incomes and pollution levels as a country develops. It foresees a pattern in which environmental damage rises with income, but then plateaus when a 'threshold' level of income is reached – followed by a decline (see Figure 1).

Figure 1: Schematic of an Environmental Kuznets Curve



Source: Authors' elaboration

This hypothesis therefore characterises pollution as a 'transitional phenomenon' rather than an inevitable, increasing side effect of economic development. There are a number of explanations put forward for this relationship. Those that are borne out to some extent by the evidence include an increase in environmental awareness and resources to reduce pollution as incomes rise, displacement of one pollutant by others as economies develop, and the impact of technological progress (Lieb 2003). There are also explanations which are not supported so strongly by evidence – including the argument that dirty industries migrate to other less developed countries as incomes rise.

There is also considerable debate about the extent to which the EKC hypothesis is applicable to all types of pollutant. One comprehensive survey shows that for some air pollutants such as sulphur dioxide, the evidence is reasonably strong (Lieb 2003). However, there is a question about whether this evidence is replicated for water pollutants and stock pollutants such as carbon dioxide (Lieb 2004). The stronger evidence for pollutants like sulphur dioxide might be explained by the fact that detrimental environmental effects are felt locally (or at least regionally) and thus individual countries have a stronger incentive to curb emissions. By contrast, emissions of carbon dioxide and other greenhouse gases have global consequences. Thus countries' efforts to curb carbon emissions might be costly but could also have little effect if other countries do not follow suit (the so called 'free rider' problem). Decreases in carbon emissions appear to be more strongly related to exogenous historical shocks than income levels (Moomaw and Unruh 2001).

Overall there is rather weak or even contradictory evidence for the EKC for carbon emissions in developing countries. A recent study asserted a inverted U-shaped relationship between national income and carbon emissions for OECD countries, but could not find similar evidence for non-OECD countries (Galeotti, Lanza et al. 2006). Another recent study appears to confirm doubts about the EKC hypothesis with respect to carbon emissions in China (Auffhammer and Carson 2008). It examined accelerating carbon emissions in China in recent years and rejected the EKC as an explanation. This is because emissions have continued to rise – and accelerate – despite significant income growth:

> 'At the end of the last century, it was conceivable that China's CO2 per capita emissions growth rates were slowing down, suggesting a moderate growth emissions trajectory as income in China increased. Our paper suggests that until 2010 such a downturn is highly unlikely unless there are substantial changes in China's energy policies. In addition, our results clearly reject the static EKC specification. Each new year of data over the last five years further increases the anticipated emissions path.'

So what is the relevance of this debate for leapfrogging? If the EKC hypothesis is accepted to some extent, one definition of leapfrogging might be that a country passes the peak of the EKC and reduces its pollution more quickly than more developed countries have done. However, given the conflicting empirical evidence – especially with respect to carbon emissions – it is difficult to make this argument too strongly. There is perhaps a lack of longer-term historical data on the relationship between incomes and carbon emissions in developed countries to understand what kind of pathway would be a genuine 'break' from their experience.

2.2 Leapfrogging industrial development

In contrast to the rather scarce evidence for macroeconomic leapfrogging within development pathways, most of the leapfrogging literature deals with the question of how latecomer countries can catch up with industrialised countries and their level of industrial development – also by potentially skipping stages of their past development. This strand of literature considers technologies as key to industrial growth. Hence technology diffusion is of central interest. An important question is how to explain the catching up of latecomers and the opportunities for latecomers as compared to frontrunner countries.

In his seminal paper on technological leapfrogging Soete (1985: 416) defines technological leapfrogging as follows:

> "Far from developing factor proportions, appropriate industries and technologies both for the domestic and export world market, the opportunities offered by the international diffusion of technology to jump particular technological paradigms and import the more if not most, sophisticated technologies that will neither displace the capital invested nor the skilled labor of the previous technological paradigm, constitute one of the most crucial advantages of newly industrializing countries in their bid for rapid industrialization."

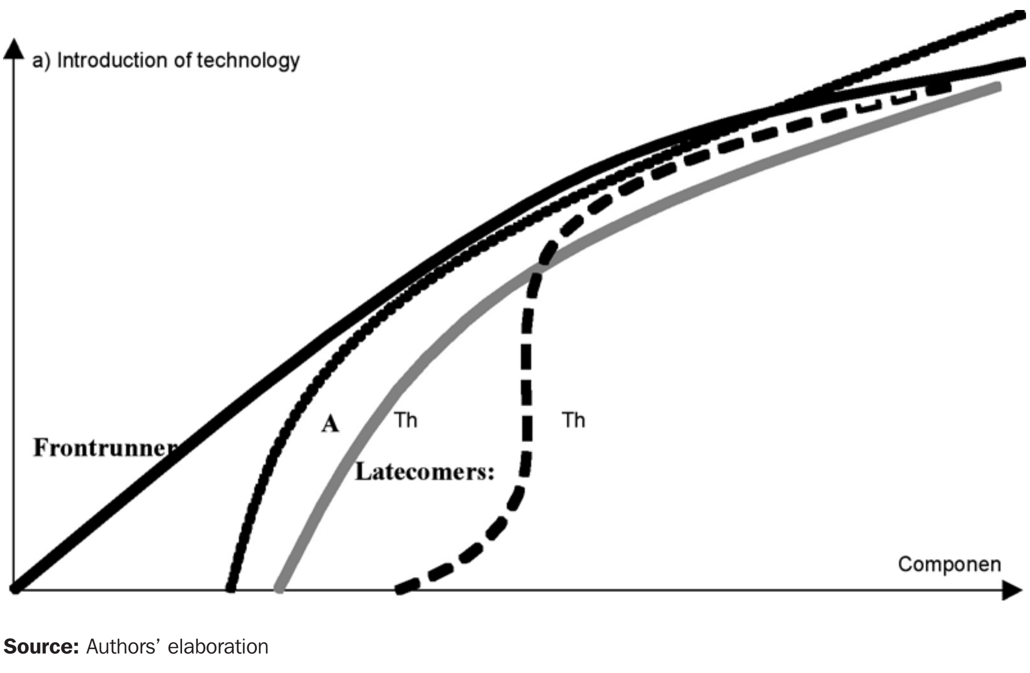
As reflected in the definition, the main interest is in the factors that enable rapid economic growth of industrialising countries. The starting point is theories of technology diffusion where technical change is considered as a key factor in the development of most industrialised countries.

The literature builds upon the historical evidence of the importance of foreign technology in the industrialisation and economic growth in both Europe and the United States in the second half of the 19th century and particularly Japan in the 20th century. Latecomers to the diffusion of a new technology can expect mainly two advantages: they avoid adopting technologies at an early phase of diffusion when they might still be subject to major improvements; and they have access to cheaper technologies at a later stage of their development. The fact that no or low levels of capital and skills were accumulated in previous generations of technology can constitute a major opportunity for latecomers.

Latecomers could therefore leapfrog vintage technologies, avoid heavy investments in older technologies, invest directly in affordable up-to-date technologies and finally, catch up with advanced industrialised countries through further innovation (eg Perez and Soete 1988). Three different patterns of catching-up can be distinguished (Lee and Lim 2001): First, path-creating catching-up where the latecomer catches up with the frontrunner but then embarks on a new development path. Second, path-skipping catching-up where the latecomer skips stages of the frontrunners' development trajectory. The third is 'simple' path-following catching-up. The former two development paths can be considered as leapfrogging since they either go beyond the frontrunners' level of development and take technological leadership (Brezis, Krugman et al. 1993; Chen 1999; Amiti 2001) or following this path by skipping earlier stages of development.

Figure 2 shows four stylised industrial development paths. Three latecomer countries (A, B and C) catch up with the industrial development level of the frontrunner country over time. While country B catches up slowly over time, country A leapfrogs by over-taking the frontrunner country in terms of its level of industrial development. Country C skips stages of the development of the frontrunner country to catch up in a relatively short period of time. These development paths are not mutually exclusive and should not imply that one development path is linked to a certain technologies. By contrast, the wide spectrum of technologies available – and their varying and sometimes unpredictable potential for incremental or disruptive change over time – underlines the likelihood that hybrid pathways might be followed.

Figure 2: Catching-up and leapfrogging



Source: Authors' elaboration

In most definitions of leapfrogging the skipping of certain stages of technological development is a key element as reflected in the following examples:

- In the context of information and communication technologies (ICTs), Steinmueller (2001: 194) defines leapfrogging as "bypassing some of the processes of accumulation of human capabilities and fixed investment in order to narrow the gaps in productivity and output that separate industrialized and developing countries"
- In his analysis of the leapfrog potential for energy technologies Goldemberg (1998: 730) argues that developing countries "can leapfrog over some of the steps originally followed by industrialized countries, and incorporate currently-available modern and efficient technologies into their development process". This can refer to both production and use as reflected in the adoption of mobile phones in Manila and China, the adoption of modern educational techniques in South Africa, as well as the restructuring of the world steel industry. The first and third of these examples are discussed in more detail in the case studies in section 4 of this report.
- Referring to Goldemberg's work Gallagher (2006: 383) provides the following definition: "the concept is that industrializing countries can avoid the resource-intensive patterns of economic and energy development by leapfrogging to the most advanced energy technologies available, rather than following the same path of conventional energy development thaw as forged by the highly industrialized countries". She distinguishes between leapfrogging in terms of skipping over generations of technology and in terms of moving ahead of existing technologies to become technological leader (eg as the Korean steel industry has done).
- From an environmental leapfrogging perspective Perkins (2003) notes that "the consensus is that leapfrogging implies a development strategy for industrializing countries to bypass the 'dirty' stages of economic growth through the use of modern technologies that use fewer resources and/or generate less pollution" (Perkins 2003: 178). Perkin's perspective on leapfrogging refers to both cleaner production processes and the deployment of less polluting technologies. Others referred in a similar context to "*climate-relevant leapfrogging* as the adoption of zero emission technologies" (Unruh and Carrillo-Hermosilla 2006: 1186).

2.3 Leapfrogging adoption and use of technologies

On the technology deployment side, technology leapfrogging refers more explicitly to "the implementation of a new and up-to-date technology in an application area in which at least the previous version of that technology has not been deployed" (Davison, Vogel et al. 2000: 2). Depending on the technology in question, the adoption of new technologies can either be user demand driven or infrastructure driven as the result of policies to modernise infrastructure, for example, in the telecommunications sector (Mody and Sherman 1990).

This dimension of leapfrogging applies to a broad range of users. It includes end-users who need to adopt and use new consumer goods in their daily lives and integrate them in their local context and daily routines (mobile phone networks is one example which is elaborated further in the case studies section of this report). At the other end of the spectrum, this refers to firms who are the users of new capital goods (eg manufacturing and process technologies) or public bodies as the users of new governance structures or policies. Leapfrogging on the user side might appear rather simple as compared to the creation of entire new industrial sectors. It requires however a broad perspective on technology adoption and use that takes into account of a complex set of factors (Murphy 2001).

2.4 Summary

In sum, the key element of 'environmental leapfrogging' is the skipping of pollution intensive stages of development pathways. Due to the scarce evidence for leapfrogging of entire development pathways, the major focus in the remainder of this report is on more specific types of leapfrogging related to industrial development and the adoption and use of new technologies. In both areas, the adaptation of technology to the local context is a necessary condition for successful leapfrogging strategies. This is a continuous process in parallel with ongoing social, economic and institutional changes.

In both of these types of leapfrogging, the term 'technology leapfrogging' cannot be restricted to the physical artefact involved, but needs to include other important dimensions such as human capabilities or organisational frameworks (Sharif 1989). Not only can or should leapfrogging refer to the skipping of technological stages of development, but it needs and in most cases must involve leapfrogging in other areas such as policy (Perkins 2003) or organisational structures (Steinmueller 2001). The embeddedness of technology into the socio-institutional context requires leapfrogging in broad terms.

The transfer of technologies from industrialised to less developed countries is a common feature in the (energy) leapfrogging literature, where technology transfer is considered as one important component of leapfrogging (eg Goldemberg 1998; Steinmueller 2001; Gallagher 2006; eg Lewis 2007). Although technology transfer can lead to leapfrogging, the use of the best technology available without skipping over older generations of technology does not necessarily count as leapfrogging (Gallagher 2006).[1]

[1] For a more detailed discussion on technology transfer between industrialised and developing countries see Ockwell, D., J. Watson, et al. (2007). UK–India collaboration to identify the barriers to the transfer of low carbon energy technology. http://www.sussex.ac.uk/sussexenergygroup/documents/uk_india_pb12473.pdf, University of Sussex, TERI, IDS.

3 Review of the evidence on technology leapfrogging

Having discussed the different types of leapfrogging and their distinctive features, this section reviews the theoretical and empirical evidence on technology leapfrogging. It distinguishes between barriers, risks and opportunities for leapfrogging in developing countries. Most of the evidence applies to all types of leapfrogging identified above. The subsequent discussion does not therefore distinguish between different types of leapfrogging, but is structured by distinguishing between key themes from the literature. Where possible and appropriate, the discussion refers to the distinction between leapfrogging for industrial development and leapfrogging in technology use. Section 4's discussion of leapfrogging case studies will come back more explicitly to the different types of leapfrogging and their policy implications.

3.1 Barriers and challenges

Barriers to leapfrogging in developing countries can be divided into six categories: absorptive capacity, technological capabilities, knowledge, institutions, the accumulative nature of knowledge, and the international technology market.

3.1.1 Absorptive capacity

Absorptive capacity is the most critical factor for success or failure in technology leapfrogging by developing countries: "In all cases, the problems of absorptive capacity are irreducible prerequisites for success in technological leapfrogging" (Steinmueller 2001: 206). This was confirmed by a recent World Bank study concluding that slow progress in developing countries' absorptive capacity was a major barrier for technology diffusion (World Bank 2008).

Absorptive capacity is a rather vague concept and includes a broad range of elements. The concept was initially introduced in the literature on firms where it was argued that latecomer firms need sufficient absorptive capacity to catch-up with frontrunner firms. The term was then expanded to encompass the notion of *national* absorptive capacity.

At the firm level absorptive capacity is defined as the "ability to recognize the value of new information, assimilate it, and apply it to commercial ends" (Cohen and Levinthal 1990: 128). This ability builds inextricably upon prior related knowledge. From this perspective a firm's absorptive capacity can be a by-product of a firm's R&D investments or manufacturing; it can also result from special training of the workforce. Due to the evidence that prior knowledge is a basis for the creation of absorptive capacity over time, it is strongly path-dependent. Low levels of investment in absorptive capacity at an early stage of technological development can lead to "lock-out" (Cohen and Levinthal 1990: 136) of a firm from a certain development path since it lacks the capabilities to recognise the value of new developments.

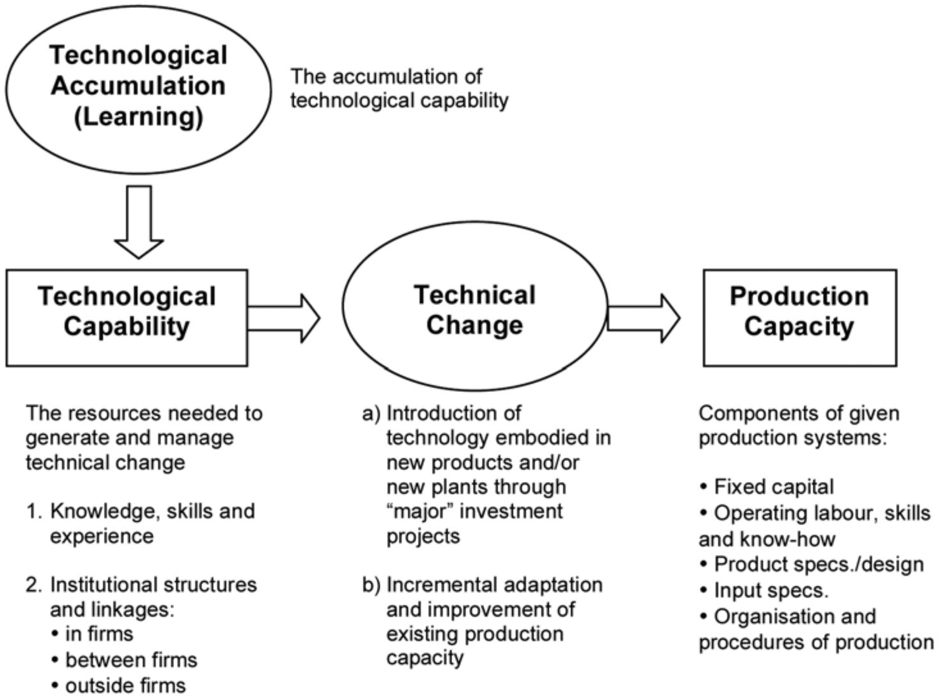
Similar inter-linkages apply to a country's national absorptive capacity which can be defined as "the ability to learn and implement the technologies and associated practices of already developed countries" (Dahlman and Nelson (1995) in: Criscuolo and Narula 2008: 57). As in the case of firms one major barrier for latecomer countries is the lack of an initial threshold of absorptive capacity which enables rapid absorption and catching-up (Criscuolo and Narula 2008). A country's absorptive capacity stems from the actions and capabilities of a broad range of actors including firms, researchers, end-users and policymakers.

The following three sections discuss a number of factors that contribute to or hinder the development of national absorptive capacity: technological capabilities, knowledge and institutions.

3.1.2 Technological capabilities

Important contributions to a country's absorptive capacity are made by its technological capabilities; ie the stock of resources for generating and managing technical change (Bell and Pavitt 1993). In their conceptualisation of technological accumulation (or learning) Bell and Pavitt distinguish between the resources and processes involved (see Figure 3). Resources are split into production capacity and technological capabilities in order to fully capture the dynamics of industrialisation. Processes involve technical change and technological learning. Resources include knowledge, skills and experience as well as institutional structures that enable exchange within and between different actors.

Figure 3: Technological accumulation: Basic concepts and terms



Source: Bell and Pavitt (1993: 164)

While in earlier examples of industrialisation the accumulation of technological capabilities went hand in hand with the expansion of production capacity, this automatic relationship has changed. Bell and Pavitt (1993) argue that the long-term trends of increasing scale of production and increasing specialisation result in the fact that technological accumulation has been less and less 'built in' to the process of industrialisation than in the past. This trend makes it more difficult for latecomers to catch up with industrialised countries. It particularly highlights the need for explicit investments to enhance technological accumulation. Both export-oriented trade policy as well as import-substitution contributed in the past to technological accumulation.

Such policies can, however, only be part of a set of measures. These need to be focused on the creation of intangible capital necessary to choose the right technology, operate it, improve its performance and further develop it. For example, education and training institutions need to be backed up by learning within and between firms (Freeman 2002).

Despite the focus on industrial development the concept of technological capabilities applies equally to the use and adoption of technologies beyond the production of goods and services. Technological capabilities to deal with technical change are also required on the consumption or user side. Developing countries need to be able to adapt, operate and maintain technologies originally developed and applied in industrialised countries within their new context. The ability to deliver this depends also on knowledge and skills.

3.1.3 Knowledge

Knowledge is another necessary condition for the successful absorption of new technologies – both in the industry sector and among end users. Any attempt to leapfrog to the best available technology can easily fail due to the lack of knowledge about how a technology works. This lack of knowledge might even lead a firm or country to gradually revert to earlier generations of technology for which sufficient technological capabilities are available (Gallagher 2006). Case studies of successful leapfrogging have shown that the build-up of internal knowledge but also the access to external knowledge is crucial (eg Lee and Lim 2001; Lewis 2007).

Increasing specialisation in global markets combined with other factors can make it increasingly difficult for developing countries to gain access to external knowledge. The access becomes a particular challenge in the later phases of a leapfrogging pathway. This is highlighted in Table 1 which distinguishes between different patterns of catching-up with respect to four stages of technological development (Lee 2005).

Table 1: Patterns of Catching up and Stages of Technological Development

	Stage I	Stage II	Stage III	Stage IV
Stages in Catching-up	Duplicative Imitation	Duplicative Imitation	Creative Imitation	Real Innovation
Patterns of Catching-up	Path-following	Path-following / stage skipping	Stage skipping	Path-leading / Path creating
Learning Object	Operational Skills	Process Technology	Design Technology (for existing products)	New Product Development Technology
Learning Mechanism	Learning by doing (production following manuals and guidance)	Learning by doing (production following product designs)	How to learn? (crisis and switches to in-house R&D, R&D consortium, and overseas R&D outposts)	Co-development Strategic alliances

Source: Adapted from Lee (2005: 103)

The first two stages focus on duplicative imitation by the latecomer and path-following catching-up which can involve stage skipping. Knowledge is mainly acquired through 'learning by doing'. The third stage involves changing the design of existing products and plants, while the fourth stage stands for the creation of new products. Thus stages three and four have a high potential for leapfrogging while at the same time access to knowledge can become very difficult. Frontrunner firms are generally reluctant to share knowledge with catching-up firms who might become the direct competitors. This can constitute a major barrier for further industrial development in general and leapfrogging in particular. It can however lead to a situation where the latecomer country might be forced into a leapfrogging strategy if the necessary resources are available and allow for such a strategy to be pursued (see case studies in Section 4).

It is important within the context of this discussion to distinguish between "know how" and "know why". "Know how" is sufficient to use advanced technologies efficiently, whereas "know why" is required to deal with more complex technologies and to be able to innovate autonomously (Lall 1998).

Within the process of knowledge accumulation, the opportunity to gain access to external knowledge might strongly differ among developing countries. It can be particularly challenging for smaller developing countries with a domestic market of limited size 'to offer' to technology frontrunners. Developing countries with a large domestic market have successfully applied a strategy of "trading market for knowledge" (Jung, Anchna et al. 2005). In exchange for access to future markets technology, international frontrunner firms are likely to be more willing to transfer cutting-edge technologies and knowledge to latecomer countries like China.

On the use and adoption side, knowledge and skills are equally required to manage a new technology in its new context, but also to operate and maintain the technology appropriately to ensure long-term benefits. Local knowledge is in particular required to adapt a new technology that was initially developed in industrialised countries to the new environment in developing countries. For an adequate consideration of the local context, for example, some argue that it is necessary to ensure the involvement of all stakeholders (Murphy 2001; Forsyth 2005). This is however particularly challenging in less developed countries which often lack the institutions and local structures for wide-ranging participation exercises, but also institutions related to the creation and exchange of knowledge.

3.1.4 Institutions

Institutions provide a fundamental framework that can enable or inhibit the innovations required for leapfrogging. In innovation studies the importance of national institutions has been reflected in the concept of "national systems of innovation". This concept has been defined in various ways and can be summarised as an attempt to deal with the problems of social and institutional capabilities necessary for technical change (Freeman 2002). In the context of innovation studies, institutions can be defined as "sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups" (Edquist and Johnson 1997: 46). This definition goes beyond a narrow concept of institutions in terms of rules and laws, but includes more tacit institutional elements such as habits and routines that are fundamental for interactive learning. The latter constitutes a central link between institutions and innovations.

Latecomer opportunities can only be fully exploited if they are complemented by an appropriate national innovation system that allows for technical and institutional changes in education, training and R&D. Besides the provision of basic functions necessary to attract (foreign) investments such as political stability or the rule of law (eg property rights) (Keefer and Knack 1997), there need to be institutional structures in place that enable knowledge flows between the private and public sector nationally and internationally. These institutions may also need to deal with the issue of risk. A culture of risk averseness where failure is considered as unacceptable can be a major barrier for technology leapfrogging (Gray and Sanzogni 2004).

Furthermore, the state needs to be in a position to assess the potential for leapfrogging, to develop a leapfrogging strategy, and to support the implementation and evaluation of this strategy over a longer period of time. Public interventions in support of leapfrogging require policy integration since they concern various policy areas, including trade or educational policies, industrial policies (eg protection of infant industries, promotion of exports, subsidies to specific firms and the promotion of R&D) (Freeman 2002).

Interventions in support of technology catching-up can be functional or selective (Lall 1998). Functional interventions address generic market failures, for example through education or infrastructure policies. Selective interventions allocate resources to specific activities, such as trade policies, subsidies or restrictions on the import of foreign technologies. The adoption and implementation of any public intervention needs to be assessed against the general country-specific conditions and the objectives pursued. Developing countries, for example, might lack the necessary institutional capacity for certain interventions and to ensure an integrated approach for a coherent 'leapfrogging policy'.

Experience in South-Asian 'tigers' shows that quite diverse policy interventions resulted in successful catching-up and that no general model or set of policy interventions can be derived (Lall 1998; Hobday 2003). The most challenging task for the design of a sound mix of policy interventions is to find the right balance between early exposure to global competition to ensure entrepreneurial and R&D activities at the cutting-edge and the protective support of emerging industries. This also needs to be seen in the light of rather disappointing results of the import-substitution policies pursued mainly in Latin America.

Any leapfrogging strategy cannot only envision the latest technology to be 'absorbed' in a given national context, but also needs to focus on the policies by which this is to be achieved. The latter can also draw on successful policy designs applied in frontrunner countries Thus it might involve 'policy leapfrogging' to move to new policy instruments (Perkins 2003) or even new policy-making processes. These policies need to be responsive to the particular context in developing countries. Small and medium-sized enterprises with a very low capital base, for example, might not have the financial means to implement stringent environmental regulations (Ho 2005).

In addition to national institutions, international institutions can be an equally important barrier to leapfrogging. This has been highlighted in the context of international technology transfer where industrialised countries or international organisations provide and finance technology for developing countries. The transfer of technology can, for example, prevent climate-relevant leapfrogging due to the influence of the vendor and its technological capabilities as well as the preferences of the financing organisations if they are focused on carbon intensive or second best technologies. This would imply the export of the carbon lock-in observed in industrialised countries to developing countries (Unruh and Carrillo-Hermosilla 2006).

Similarly at the international level, while intellectual property rights (IPRs) are generally considered as a necessary protection by leading firms (Goldemberg 1998), IPRs can at the same time constitute a major impediment for technological leapfrogging. While they do not necessarily prevent the diffusion of cutting edge technologies, they can be used by their owners to keep competitors away from their markets and prevent others to make useful experience for further developments and improvements of the technology (Steinmueller 2001). Such learning processes are fundamental for the creation of knowledge and skills – an important element of technological capabilities required for the leapfrogging of industrial development pathways.

3.1.5 Accumulative processes

The accumulative nature of building up absorptive capacity has already been highlighted. Prior knowledge plays, for example, a critical role in enabling (or 'locking out') new development possibilities. National technological capabilities in production, operation and maintenance often build upon knowledge related to previous technologies (Hausmann and Klinger 2007). This interdependence can be considered as a major barrier for any leapfrogging strategy. It raises questions about the extent to which leapfrogging is possible if the necessary knowledge is reliant upon previous stages of development. Hobday's analysis of Singapore's electronics industry strongly questions the idea of leapfrogging since it highlights the role of gradual technological accumulation over time (Hobday 1994).

Hobday argues that most learning in this case occurred in pre-electronic industries which fed that into a cumulative learning process over time.

Similarly, the scope for leapfrogging has been questioned with respect to household energy use in developing countries. One study argues that "energy technology leapfrogging itself is a misconception. Energy technology leaps – or any rapid, sudden, and significant technological change in rural areas – do not occur in reality, particularly at the household level" (Murphy 2001: 175). Murphy continues that "rural people, especially the poorest, cannot be expected to rapidly acquire or develop these skills, firms, resources, and institutions or to be able to simply 'leap' into using new technologies. Absorption will not occur unless there is a sufficient accumulation of technological know-how and the right social, cultural, and economic conditions to institutionalize this knowledge" (Murphy 2001: 188). Instead, technology diffusion is considered as an incremental process where new technologies need to be compatible with technological capabilities at the local level: "These capabilities are manifest in an individual's capacity to adapt to new technologies, their ability to take economic risks, and in their desire to modify their behaviour" (ibid.). The example of the diffusion of the *maendeleo* improved cookstove in East Africa is put forward as an example of "hard slog, rather than leapfrog" (Murphy 2001: 188). Although these impediments to leapfrogging are relevant in certain circumstances, they are not a general argument against leapfrogging *per se*.

The challenge of overcoming barriers due to accumulated knowledge for certain technologies or technological trajectories can be pervasive in some cases. Technological complementarities such as the availability of reliable electricity infrastructures are often a necessary condition for leapfrogging. Yet many developing countries do not have these complementary infrastructure systems (World Bank 2008).

The accumulative built-up of knowledge and cumulative effects of learning processes imply a non-linear relationship between absorptive capacity and catching-up (Criscuolo and Narula 2008). Achieving the threshold level of absorptive capacity required for catching up to (or beyond) the technological frontier is a slower and more complex process than the early stages of catching-up. The later stages of catching-up, where learning moves from producing and imitating to developing original products, are more complex and time consuming (see also Table 1).

3.1.6 International technology market

The international technology market can lead to further barriers to technology leapfrogging. This is particularly the case when an international technology market is characterised by market dominance by a few large firms. In contrast, a buyer's market increases the opportunities for leapfrogging. For example the international microelectronics market in the 1980s provided a good opportunity for countries to leapfrog if they had sufficient absorptive capacity. The main features of this particular context were: high competition and a buyer's market, rapid growth in both labour and capital productivity, as well as "'deskilling' effects" in industrialised countries which can create resistance to the diffusion of new technologies in these countries (Soete 1985).

Furthermore, multinationals' unwillingness to transfer cleaner technologies beyond legal requirements to developing countries can constitute an important barrier for leapfrogging (Gallagher 2006). While the international diffusion of technologies constitutes a major opportunity for developing countries, technology leaders might be worried about "how to prevent the competing away of [their] international technology monopoly position" (Soete 1985: 414). Strategically, firms in industrialised countries can try to keep their technology lead by investing in R&D or by restrict the international diffusion of their leading technologies. This restriction can mean only transferring knowledge at the early stages of technological development which involves only duplicative imitation (see Table 1). However, some latecomer countries have in the past partly solved this problem by reverse engineering. On the basis of an initial threshold of knowledge and skills they learned from the imported technology and expanded their technological capabilities to improve existing technologies and even develop new products and product designs. Korean firms, for example, used 'reverse engineering' to learn from imported products how to design and develop new products. After having assembled imported parts, existing products were first modified and then new product concepts developed (Lee and Lim 2001).

3.2 Risks

Leapfrogging involves two main sets of risks: the risk of picking losers which leads to an early 'lock-out' from critical technologies, and the risks that the wrong policy priorities will be implemented.

3.2.1 Picking losers and early lock-out

From one perspective, leapfrogging by developing countries can be interpreted as a low risk strategy. As latecomers they leave the technical and financial risks involved in the commercialisation of new technologies to industrialised countries who have the means to bear the risks related to choice of the right technology or standard and to the creation of an initial market (Kojima 2003). At a later stage, developing countries can fully exploit scale effects, which allow them to compete in the market with lower prices.

Despite this apparently comfortable position for latecomers, there are still two major risks involved. Even entering a market at a later stage of development does not prevent the risk of picking losers. The risk of picking losers is, for example, particularly high in an area with a high frequency of innovation. In the worst case new production facilities that were built on a large scale to benefit from scale effects may not be able to compete with the latest cutting-edge technology. On the other hand the entry into a new technology with a lower frequency of innovation might lead to early 'lock out' if competitors with similar competitive advantages are quicker to enter the market. The choice between a high and low risk strategy is particularly difficult for developing countries with scarce resources that might be needed in other areas. In order to limit initial risks related to the choice between alternative technologies at a very early stage and the creation of an initial market, the setting of standards to stimulate general market demand can be critical factor (Lee, Lim et al. 2005).

3.2.2 Policy trade-offs

The entry into new technology markets or the adoption and use of new technologies such as information and communication technologies in developing countries generally needs to face difficult policy trade-offs between development priorities. Some might argue for a hierarchical order of development objectives where basic needs such as education and health need to be met before scarce resources are diverted into 'new' technology areas. Related to this is the common policy objective of rapid industrialisation in developing countries that can be in conflict with the implementation of long-term strategies to build up the absorptive capacity necessary for leapfrogging.

3.3 Opportunities

Despite these considerable barriers, challenges and risks for technology leapfrogging there are also important opportunities for developing countries. These stem from latecomer advantages, and the 'lock in' of industrialised countries into 'old' technologies and new technological paradigms.

3.3.1 Latecomer advantages

As mentioned earlier, countries, firms or users which enter a market at a later stage of development can avoid uncertainties and costs linked to the creation of an entirely new market. Firms benefit from already established markets where they can sell products whose manufacturing costs benefit from large scale production. Users benefit from proven and more affordable products.

Structural features within the leapfrogging country can also provide latecomer advantages due the absence of lock-in to previous generations of technology. This "installed base effect" (Mody and Sherman 1990) could lead to slow leapfrogging because the costs of a new, replacement technology are likely to be assessed against the operating costs of the existing system, which has sunk capital costs. Thus the technology in use might be favoured due to the lower overall investment required. This advantage can, however, be outweighed by restrictions in developing countries (eg as a result of low incomes). These restrictions can lead to a lack of demand for the deployment of a new technologies – and hence, no economies of scale for new entrants.

3.3.2 'Lock in' of industrialised countries

While the lack of knowledge is a major barrier for leapfrogging, extensive and highly specialised knowledge related to an 'old' technology within industrialised countries can constitute an opportunity for firms that are catching up. Due to their comfortable position with the old technology, new opportunities might not be taken advantage of by a leading firms. One reason for this might be the "deskilling effect" related to new technologies. Workers sometimes oppose moves to integrate a new technology into their production processes because they fear that a new technology requires considerable new knowledge and thus 'unlearning' which could make them redundant. Similar effects can also apply to end users.

Instead a less developed country with low labour costs and an initial threshold of absorptive capacity can enter an emerging technology field that promises to be better than the established technology. Over time it gains experience and reaches higher productivity than the former leading country, and takes technological leadership (Brezis, Krugman et al. 1993). However, to achieve technological leadership, the new technology needs to be superior to the established technology, and the potential level of productivity needs to be clearly above the productivity of the established technology in the longer term.

3.3.3 New technological paradigms or disruptive innovations

Finally within this discussion of barriers, risks and opportunities it is important to consider the particular features of more disruptive innovations that may be part of broader shifts in the 'technological paradigm'. Such shifts happen when a set of innovations (eg advances in ICTs) have a pervasive effect across the whole economy (Freeman and Louca 2001). The emergence of disruptive innovations, perhaps as part of new technological paradigms, can provide a crucial window of opportunity for developing countries to leapfrog. The more different a new technological paradigm is from the previous technological paradigm, the more opportunities there are for less industrialised countries to compete with industrialised countries. Although the generally higher absorptive capacity in an industrialised country will still be a major factor, the leapfrogging potential for developing countries can be much higher when compared to incremental technological changes that build directly on existing technological capabilities and knowledge.

Furthermore, although accumulative processes over a longer period of time are an important feature of technology diffusion and therefore of technological leapfrogging, the extent to which previous skills and knowledge are necessary is highly technology specific. There are areas where earlier technologies as well as associated skills are bypassed. The ICT sector is an example for this. The easy access to information in the ICT sector in comparison with the chemical or manufacturing industry provides an opportunity for leapfrogging. Overall the potential for technological leapfrogging needs to be assessed against the ability to acquire knowledge and skills related to contemporary technology. This needs then to be successfully applied which often requires complementary technological capabilities (Steinmueller 2001). In addition, access to external knowledge can, for example, be gained through licensing agreements, the so-called 'reverse brain drain', or R&D outposts abroad.

Low carbon technologies, and more specifically renewable energy technologies, seem to confirm this. A PV system, for example, requires considerably different skills and knowledge to traditional thermal power plants. However, spillovers - the transfers of knowledge and experience from related technologies or technological sectors - might result from accumulative processes over time. For example, the micro-electronics industry and the PV industry are both based on silicon.

3.4 Summary

There are considerable barriers and challenges for catching-up, and even more so for leapfrogging, by less industrialised countries. At the same time, important opportunities exist. A sufficient level of absorptive capacity is necessary for successful leapfrogging. This includes technological capabilities (the resources necessary for generating and managing technical change), which are built upon skills and knowledge, and supported by appropriate national and international institutions.

Latecomer countries or firms do have some opportunities. The absence of 'lock in' to old technologies and the chance to skip early, risky stages of technological development allow countries or firms to exploit comparative cost advantage in terms of low labour costs when producing modern technologies at a large scale. New technological paradigms or innovations that are disruptive provide a further entry opportunity for latecomers.

However, any leapfrogging strategy involves risks. Even at a later stage of technological development a technological pathway can prove to be wrong, and can be in conflict with other basic development policy objectives. The factors discussed in this section are summarised in Table 2 which distinguishes between those that are internal to a firm or country and those that are external.

Table 2: Relevant factors for leapfrogging

Dimension	Factors
Internal	• absorptive capacity • knowledge / technological capabilities (eg skills, both to operate and maintain the imported technology) • appropriate managerial, education and training levels • risk readiness • capacity to asses technologies' value and profitability to adopt • ability to deal with the cumulative nature of technical change • long-term vision / planning
External	**International technology market:**
	• buyers market / non-monopolistic structure • rapid growth in both labour and capital productivity • "deskilling effects" in industrialised countries

Source: Authors' elaboration on the basis of reviewed literature

4 Case studies: leapfrogging in different contexts

In this section four successful leapfrogging case studies are discussed to further illustrate the insights from the literature review. The case studies were selected to reflect the different types of technological leapfrogging discussed in section 2. The first case study explores the adoption of mobile phones in developing countries. It examines how and why it was possible that some areas skipped landline telephony and adopted mobile telephony. The stage-skipping catching-up of the Korean steel industry is discussed in the second case study. It represents a case where a country has successfully created a leading industry at a large industrial scale. A similar example, although with important differences, is the Korean automobile industry, which is the third case study. The fourth case study discusses the experience of catching-up in the Chinese and Indian wind energy industries. This case includes leapfrogging at the level of industrial development and at the level of technology adoption and use. For an overview of these four cases, see Table 3.

Where possible within these case studies some less successful examples are briefly reviewed to help identify the reasons for success and failure. Ultimately, the aim of the case studies is to draw some lessons for low carbon technologies – particularly those that can be deployed in the energy sector on either the supply or demand sides. Some, such as the wind energy case study, are already low carbon technologies. For other non-energy examples, such as mobile telephony, the lessons are related to specific kinds of low carbon technology where possible.

Table 3: Key features of successful leapfrogging case studies

Case study	Mobile phones	Korean steel industry	Korean automobile industry	Chinese/Indian Wind industry
Type of leapfrogging	Adoption and use	Large-scale industrial development leading to technological leadership	Industrial development	Industrial development and adoption
Major driver	Demand pull	National flagship project	Strong commitment at firm level	Supply push
Technological capabilities	No major capabilities required apart from O&M	Explicit state driven strategy to build up indigenous technological capabilities	Firm driven strategy to build up new technological capabilities	Firm strategy to build in-house manufacturing and engineering capacity
Knowledge and skills		Initial low knowledge base gradually expanded on the basis of imported technologies	• Huge R&D investments • Access to external knowledge	Use of national and global learning networks: • Licensing agreements • R&D outposts
Institutions and policies	• Standards imported from frontrunners • Competitive market frameworks enabled new business models to respond to local needs (Pre paid SIM cards)	• Strong national innovation system • Supportive institutional changes for education, training and R&D • Policies not limited to protect domestic market, but export led • Integrated policy approach	• Strong national innovation system • Supportive institutional changes for education, training and R&D • Protection of domestic market	• Policy integration led to a coherent set of policies and regulations • Creation of domestic markets • Support policies for domestic manufacturing industry in China • Public R&D
Accumulative processes	Initially mobile phones were complement to landlines / spillover effects	The initial minimum threshold of technological capabilities was continuously developed	"Unlearning" –capabilities acquired from adapting imported technologies were of limited use	Industries were created from scratch within 10 years
International technology market	Competitive buyers market	Overcapacity in the world market enabled import of technologies	Competitive supplier industry	Non-consolidated competitive market
Risks	• Very low risk involved since proven technology • Potential lock out from broadband internet until reliable wireless broadband is available	High risk strategy was defended against external pressure despite overcapacity in global markets that enabled this strategy at the same time.	Low risk due to clear target	
Latecomer advantages	• Scale effects (affordability) • Proven technology • Best practice in regulatory standards and design • Not 'locked in' to landline telephony	• Low cost producer due to large scale modern production facilities • Existing world market	• Low cost advantage • Jump to new electronic injection-based engine instead of following carburettor-based engine	• Companies shifted manufacturing facilities to India to meet he local market demand

Source: Authors' elaboration

4.1 Mobile phones

The diffusion of mobile phones in developing countries has often been referred to as a successful example of leapfrogging. The speed of mobile phone diffusion has been surprisingly rapid in many cases. According to some estimates, the African continent had the highest mobile phone growth rate of all continents between 1999 and 2004, with an average annual growth rate in mobile phone subscriptions of 60% (Kyem and LeMaire 2006). In 2005, the fastest growing mobile phone markets, China and India, added 1.3 million mobile phone subscribers every week and 1.77 million subscribers every month respectively (Kumar and Thomas 2006: 298).

Such numbers have often been used to highlight the potential for leapfrogging in other areas including the use of low carbon technologies. However this analogy needs closer examination: What were the main features of the diffusion of mobile phones in developing countries and what are the implications for low carbon energy technologies? Within the scope of this study it is only possible to highlight a few key features that are relevant to draw some initial conclusions. It shows that the case of mobile phone diffusion cannot unequivocally be interpreted as technology leapfrogging in all cases. Instead it underlines some barriers for leapfrogging discussed earlier, particular technological complementarities at the early phase of diffusion. Furthermore it needs to be pointed out that leapfrogging that occurred in the case of mobile phones in developing countries was predominantly on the user-side. There were no major technological developments involved – neither in terms of technology imitation (eg local manufacturing), nor technology creation as had happened in South Korea.

While there are some parallels between low carbon distributed energy technologies and mobile phones, serious doubts have been raised about this comparison (Unruh and Carrillo-Hermosilla 2006). Like mobile phone technology, low carbon distributed energy technologies can be built independently of an extensive grid network. Their modular features make them flexible to respond to demand and they can be applied in both urban and rural areas. However, mobile phone technology had been developed and successfully commercialized by industrialized countries many years before a developing country started to invest in this technology. It had thus been proved as a mature mass market product at relatively low prices due to scale effects, which strongly enabled the transfer to developing countries. Thus there were clear benefits for latecomer countries who adopted this technology (Rouvinen 2006). This was also supported by a competitive international technology market.

However, the literature indicates that at the early stage of diffusion, the mobile phone did not leapfrog landline telephony but was rather a complement to landlines in developing countries. This somehow weakens the general assumption that leapfrogging occurred in this area. One explanation for this complementarity is that landlines were the initial communication target for mobile phone users (Kamssu 2005). In the earlier phase of mobile phone diffusion, most phone calls from mobile phones were made to fixed landlines. Furthermore, the relatively high costs of mobile phone calls were initially an impediment for leapfrogging in poor regions (Hamilton 2003). The complementary between mobile phones and fixed lines has also been confirmed in a study of the early diffusion of mobile phones in Africa (Gebreab 2002). It suggests that mobile phones are perceived as complements to landlines since there might be spillovers from the fixed network to the mobile phone network. Gebreab concludes – also referring to earlier studies – that while mobile phones were perceived as substitutes in developed countries, they were initially rather a complement to fixed lines in less developed markets.

Furthermore diffusion of mobile phones in Africa was in the early stages concentrated in urban areas, which strongly indicates that “mobiles are following the footsteps of the incumbent fixed-line operators” (Gebreab 2002: 27), which are underrepresented in rural areas. Despite the huge increase in mobile phone subscriptions in India and China, the mobile phone remains largely concentrated in urban areas in these countries due to the lack of the necessary mobile phone infrastructure in rural areas (Kumar and Thomas 2006).

Generally competition increased the rate of diffusion which spurred the introduction of new business models for mobile phone use in developing countries – an important driver for its uptake. Pre-paid SIM cards made the mobile phone accessible to the poorer population since it did not require a monthly subscription for which a bank account and physical address is necessary. It also enabled people to circumvent long delays for landline connections (ITU 2003). In addition, new usage patterns emerged in developing countries based on private and commercial sharing (James and Versteeg 2007). These new usage patterns enabled the substitution of landlines in some areas. It saves considerable infrastructure costs and can make the use of the phone as telecommunications medium more convenient for customers. Whereas competition in terms of the number of operators active in a country increased the diffusion of mobile phones in developing countries, competition in standards seems to hinder the diffusion of mobile phones (Koski and Kretschmer 2005; Rouvinen 2006). This seems to confirm the potential advantage of a latecomer country by adopting standards that have proved to be successful in frontrunner countries from early on.

Whilst leapfrogging in the case of mobile phones occurred in some rural areas that skipped landline phones for mobile phones in the later stages of their diffusion, the brief discussion shows that a certain technological level within a country was an important prerequisite for the diffusion of mobile phones. Thus the early stages of mobile phone diffusion can be interpreted as incremental change in urban areas that was then spread to rural areas, where successful leapfrogging occurred.

On the basis of their analysis of the mobile phone case Unruh and Carillo-Hermosilla (2006) conclude that leapfrogging appears possible when technological leaders – in most cases industrialised countries – have adopted a technology successfully in the first place. This is generally not the case for low carbon energy technologies – maybe with the exception of wind energy, PV and solar thermal applications in some countries. In addition to this external condition for technology leapfrogging, some internal conditions appear important for the leapfrogging success in the mobile phone sector: strong cost and market incentives, high consumer demand, no threat to existing players. Maybe most important, the construction of a costly wire-based infrastructure was avoided. This appears to be not only more attractive in terms of absolute costs – particularly in rural areas – but also due to contextual factors. State-owned companies responsible for wire-based infrastructure might be less efficient and customer focused than privately run companies. Planning applications might be much more time consuming and thus more costly for wire-based infrastructure as compared to decentralised or stand-alone low-carbon technologies.

In summary, early adoption in industrialised countries enabled leapfrogging due to a competitive international technology market, which led to low costs, recognised standards and a proven technology which could be introduced in developing countries at very low risk. Furthermore, it met the basic need for communication and could thus benefit from a fairly good market potential. This also helped to avoid expensive investments in landline networks – although this resulted in a temporary lock out from landline-based broadband internet. Due to the relatively low investment costs involved, the need for third party financing was limited and thus external influence that might have prevented the adaptation of the technology to the local context, eg specific user modes. Thus the role of public interventions was rather low and concentrated on the creation of a competitive market framework that allowed for new business models to flourish.

By comparison, low carbon energy technologies are still at an early stage of diffusion. Adoption and use in developing countries depends on public policies for their promotion. In addition to financial and training support, policies need to deal with issues of social acceptance. As opposed to mobile phones, which were an additional 'gadget' in most rural areas, some low carbon energy technologies substitute traditional technologies, eg in the case of cookstoves, which can lead to problems of social acceptance (Murphy 2001). However, in common with mobile phones, high costs for the extension of the electricity network can constitute a major driver to leapfrog to renewable off-grid technologies in rural areas. In Kenya, for example, costs for the grid connection of a rural home are seven times the national per capita income (REN21 2008: 35). Also in common with mobile phones, the introduction of low carbon technologies does not necessarily mean local manufacturing or the build-up of technological capabilities that goes beyond the installation and operation of these technologies. Yet, the example of China's Suntech (a leading PV company) shows that technology leapfrogging that includes manufacturing is possible.

4.2 Korean steel industry

The catching-up of the Korean steel industry is another example often referred to in the leapfrogging literature (eg Gallagher 2006). As opposed to the case study of mobile phones that was mainly an example of leapfrogging on the user side, the Korean steel industry case study exemplifies leapfrogging in industrial development at a large scale. South Korea as a latecomer country managed not only to catch up with frontrunners in this industry sector. It succeeded in developing a virtually non-existent industrial sector in the 1960s into a technologically leading sector by the 1990s.

Due to large plant sizes and the use of start-of-the-art technology – easily accessible in a world market characterised by overcapacity – it was able to establish itself as a low cost producer in an existing world market for steel and thus to eventually leapfrog the European and American steel industry. Yet, most important for this success story were the intangible investments in the Korean national system of innovation (Freeman 2002). Institutional changes with a particular emphasis on education, training and R&D were crucial, and a necessary condition for this leapfrogging to take place.

An autonomously strong state was an important underlying factor for the leapfrogging success of the Korean steel industry (D'Costa 1994). The state was instrumental in initiating and keeping up the momentum in this flagship project against external pressure from international organisations, limited financial resources and a low knowledge base on modern steel making. An explicit strategy to build up indigenous technological capabilities and adequate economic and industrial policies were implemented. Technological capabilities as reflected in the Korean national innovation system enabled Korea to adopt imported technologies available in a global steel market characterised by overcapacity. They also enhanced learning and eventually fostered technological innovations by Korean firms. Economic policies protected domestic infant industries, but did not stop there. Policies aimed from the beginning at export-oriented competitiveness. In other words policies were "highly interventionist, yet market-conforming industrial policies that supported foreign technology assimilation and eliminated duplication" (D'Costa 1998: 277). The emerging steel sector was thus strongly encouraged, if not forced, into the development and production of cutting-edge technology to gain a competitive position. The Korean case study underlines the need for an integrated policy approach across different policy areas.

One further observation is important in the context of this report. The late entry of the Korean steel industry does not appear to have resulted in a highly polluting development pathway when compared with other major steel producing countries. A decomposition analysis of CO2 emissions of the iron and steel industry over time, comparing different countries including frontrunners and latecomers, shows that the carbon intensity of the industry is not related to the entry time of a country into this industry. Latecomer iron and steel industries show a rather low carbon intensity – lower than that in the US, but higher than in Japan (Kim and Worrell 2002).

In contrast to the Korean experience, the Indian steel industry was constantly behind the technological frontier. One major factor for this lagging behind was technological fragmentation in the Indian steel industry (D'Costa 1998). Technological divergence was caused by the influence of various external funding sources all pushing for different technologies. It was also a political aim to prevent dependence on a few technology providers. This technology divergence was, however, a major impediment for cumulative learning processes. As argued above, the acquisition of knowledge and skills at the early stage of catching-up are crucial in order to be able to enter into later stages of technology development, ie adaptation and creative innovation. As the Korean case shows, an integrated approach to technology evolution based on a few technology designs might have prevented fragmentation (D'Costa 1998). In addition, a strongly regulated and protected Indian steel market did not provide sufficient incentives to use and further develop the most efficient cutting-edge technologies.

4.3 Automobile sector

The catching-up of Asian automobile industries constitutes another example of leapfrogging in the area of industrial development.

A successful example for technology leapfrogging in this sector is the Korean firm Hyundai Motors (Lee 2005). It entered the automobile industry only in the early 1970s and has managed to take a share of the global market. The example underlines the role of investments in R&D at firm level but also the need for access to external knowledge. While Hyundai was initially supported by the Japanese car manufacturer Mitsubishi within the scope of a joint-venture, Mitsubishi refused to support the design and production of independent engine technologies within the Hyundai group. In response, Hyundai invested heavily in R&D to develop its own engine design. These high R&D expenditures were complemented by access to external knowledge. The English company Ricardo was willing to assist Hyundai since Ricardo's core business was not to produce and sell cars but to sell technologies and services (Lee 2005). Another significant factor in Hyundai's leapfrogging strategy was the 'right' technology choice at an early stage of development on the basis of expectations about future market trends. Hyundai did not invest in the development of the then standard carburettor-based engine technology but in electronic injection-based engines which became the standard design.

The leapfrogging success of the Korean automobile industry was mainly enabled by significant R&D investment by a financially strong private actor, Hyundai motors, and low state involvement apart from domestic market protection. It shows also a case of "unlearning". A completely new R&D centre was built-up for the accumulation of new capabilities since the old capabilities related to the adaptation of imported technologies were only of very limited use for the development of a new engine (Lee and Lim 2001)

As compared to the Korean automobile industry, China is still a latecomer who relies mainly on product transfer from industrialised countries on the basis of joint-ventures or licensing agreements. Gallagher (2006) analysed the barriers and challenges within the Chinese automobile industry to environmental leapfrogging. In the past the potential for environmental leapfrogging was mainly underexploited due to a low level of technological capabilities, the lack of coherent policies and insufficient environmental regulations. Overall R&D expenditure – a major driving force in the Korean case – has been rather low and often loosely connected. Furthermore the high influx of foreign direct investments diminishes incentives to invest in domestic innovation capabilities.

In the past the Chinese government feared that more demanding environmental regulations would put enormous pressure on national firms who would lack the technological capabilities to comply with such standards. By contrast, international firms could use their readily available technologies. The important role of environmental regulations could be observed when China introduced Euro light vehicle emission standards EURO III in 2007 (EURO IV will be introduced in 2010). Toyota, for example, established manufacturing facilities for its cutting-edge hybrid technology also in response to these new environmental regulations (Ockwell, Watson et al. 2007).

Comparing the quite different experiences with catching-up strategies in the automobile industry in Asian countries underlines the role of external knowledge and early exposure to global competition. The Korean case can be considered a success story. Similarly, China recently showed good progress in building up technological capabilities in this sector by learning from the knowledge base of multinational companies. By contrast, automobile sectors in other Asian countries like Malaysia have been less successful in exploiting their catching-up potential. In the Malaysian case, this was mainly due to ineffective government policies and a lack of a long-term catching-up strategy. While Korean firms were successful in upgrading and moving up in the global supply chain, Malaysian supply firms largely failed in doing so. The Korean case also shows that catching-up strategies need to focus on creative imitation rather than duplicative imitation to increase technological capabilities (Rasiah 2008).

Another potential example of energy technology leapfrogging in the automobile sector is the Brazilian ethanol programme – which has sought to move to a new fuel supply system in place of one based on oil (Goldemberg 1998). Strong governmental support was the key factor for the rapid expansion of ethanol production in Brazil from less than 1 billion litres per year in 1975 to more than 12 billion litres in 1995. The ethanol programme was mainly a response to the oil crisis in 1973 and to declining world sugar prices which caused problems in the Brazilian agricultural sector. The main supporting policies included economic incentives for producers, an obligation on the national oil company PETROBRAS to purchase a certain amount of ethanol, as well as regulated low end-consumer prices for ethanol (Moreira and Goldemberg 1999). Therefore, policies mainly concentrated on the creation of a domestic market. Deregulation in the 1990s put ethanol producers under strong competitive pressure and raised questions about its long-term strategy and viability. The recent increase in global demand for biofuels in response to energy security concerns and high oil prices has opened a new window of opportunity for the Brazilian biofuels industry as the current technological leader in this sector. It has been suggested as an example to follow for other developing countries keen to develop their agricultural sectors and create new economic opportunities (Thomas and Kwong 2001). Nevertheless, increasing doubts about the sustainability of biofuels – particularly the extent to which they can lead to lower carbon emissions, and can avoid adverse impacts on land use change - will be an important challenge for this industry.

4.4 Wind energy industry

The wind energy industry has emerged as a major growth sector in a number of countries. It can serve as an example for environmental leapfrogging in terms of industrial development and in terms of technology adoption. While leading wind turbine manufacturers are based in industrialised countries like Denmark, Germany and Spain, India and China have caught up very rapidly– both through building up their own wind industries and through support for wind energy deployment. Within 10 years they managed to progress from having no wind turbine manufacturers to hosting leading companies capable of manufacturing whole wind energy systems with most of the components produced locally (Lewis 2007).

China, for example, had a total grid-connected installed wind power capacity of nearly 2600 MW by the end of 2006, out of which around 1300 MW had been installed in 2006 alone. In addition there were over 200,000 stand alone small-scale wind turbines installed mostly in rural areas (Junfeng and Lingjuan 2007). Take-off in 2006 coincided with increased policy support via the Renewable Energy Law. In 2007, China added 3.4GW of wind capacity (the third largest addition behind Spain and the USA) (see Figure 4). 1.4GW of this was produced by two domestic companies, Goldwind and Sinovel (Global Wind Energy Council 2008). Official targets were set for 5GW by 2010 and 30GW by 2020 in National Plan for Renewable Energy Development (2007). The 2010 wind capacity target has already been exceeded, and a senior Chinese government official recently predicted that China would reach 10GW installed by the end of 2008[2]. The National Development Reform Commission (the major Chinese government planning Ministry) has also revised its 2010 target upwards to 10GW. Looking further ahead, one forecast from a Chinese trade association is quoted as predicting an increase to a total capacity of 50GW by 2015. The GWEC 2007 report itself expects that China will be the largest national wind market by 2010.

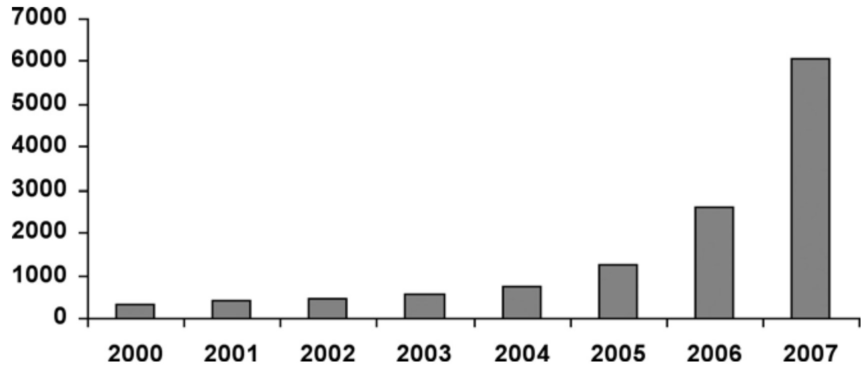


Figure 4:
Total installed wind capacity (MW) in China

Source: Global Wind Energy Council (2008)

[2] http://www.chinadaily.com.cn/bizchina/2008-03/24/content_6560381.htm

Chinese wind power manufacturing was very low in the 1990s when over 90% of installed wind turbines in China were still imported (Lema and Ruby 2007). By contrast, in 2007, domestic suppliers achieved a market share of 45% within China. The country has around 20 domestic manufacturers in the wind power sector with firms mastering up to 1.5 MW turbine designs and developing larger scale turbines (Junfeng and Lingjuan 2007).

Analysis of the development of the Chinese wind sector over the last decade underlines the pivotal role of integrated policy-making leading to coherent policies and regulations (Lema and Ruby 2007). Initially contradicting policies, for example on the role of imported and domestic wind turbines, were eventually developed to form a coherent policy framework. Thus a domestic market for Chinese wind turbines could develop. Furthermore, barriers related to the financing by international donors were addressed. These donors required the use of imported wind turbines as well as customs duty exemption, which inhibited the development of domestic production capacity. The increasing awareness of the large wind resource in China and its potential contribution to its electricity supply mix led to systematic wind resource assessments and the initiation of publicly-funded R&D, with the clear objective to benefit from this energy source – both on the manufacturing and the user side. Direct initiatives in the wind sector were complemented by other economic and industrial policies in support of domestic industries - eg the requirement for a 70% local equipment share since 2004.

A comparison of the Indian and Chinese experience further underlines the importance of managing access to external knowledge and of enabling learning networks (Lewis 2007). While both China and India implemented strong support policies for wind energy in general, and domestic wind energy in particular, the use of national and global learning networks by the companies was quite different in both cases. India's Sulzon very successfully used international learning networks, while China's Goldwind followed a strategy that was based on licensing agreements, and learning efforts were largely restricted to China. Lewis concludes that "Suzlon's growth model particularly highlights an increasingly popular model of innovation practices for transnational firms: a model of globally dispersed operations that utilizes regional variation in technical expertise and low input costs to its advantage" (Lewis 2007).

These case studies show that advanced developing countries are not only interested in using a technology developed and produced elsewhere but are also interested in developing domestic capacities for the further development and production of a mature technology. Both approaches can be considered as leapfrogging, although at a very different scale. These examples refer back to the increasing separation between production capacity and technological capabilities in different countries and thus the importance of finding strategies for access to, and absorption of, external knowledge. Furthermore, the examples from the wind industry point to how a successful leapfrogging strategy should address both dimensions of leapfrogging: industrial development and technology adoption. A domestic market is an important test market for new players, although competition with the global market is important to ensure the development of technologies capable of competing at the domestic and international level.

5 Conclusions

5.1 Summary of the literature review

The aim of this report was to contribute to a better understanding of the term 'environmental leapfrogging'. It has identified key concepts and has reviewed the literature on barriers, risks and opportunities for developing countries to leapfrog, with a particular interest in the implications for low carbon energy technologies. The skipping of dirty stages of development experienced by industrialised countries served as definition for 'environmental leapfrogging'. In addition three different types of 'environmental leapfrogging' were distinguished: leapfrogging as part of entire development pathways, leapfrogging through industrial development, and leapfrogging via the adoption and use of new technologies.

Many studies reviewed in this report investigate the conditions under which latecomer countries can catch-up or even leapfrog development paths of industrialised frontrunner countries. It is assumed that technological innovations are the key to macroeconomic growth. Their major focus is on technology leapfrogging. A sufficient level of absorptive capacity - ie the ability to adopt, manage and develop new technologies - is a core condition for successful leapfrogging. Absorptive capacity is often built up over a significant period of time and countries tend to build capabilities in fields related to existing strengths. It includes technological capabilities (ie the resources for generating and managing technical change), knowledge and skills, as well as supportive institutions in terms of laws and regulation, but also informal habits and routines.

Any leapfrogging strategy involves risks. An early decision to embark into a certain technological area can lead to picking a losing technology. Late entry into an emerging market can result in 'lock out' if firms within other countries develop faster. Besides technical risks, financial risks are critical for many developing countries with scarce financial resources. Developing countries face difficult policy trade offs between long-term leapfrogging strategies that aim to build up a sufficient level of absorptive capacity and the provision of immediate basic needs.

Latecomer countries can, however, benefit from substantially reduced risks. They can leave the initial risks of developing new products and establishing a market for a new product to industrialised frontrunner countries. As soon as a market is established, developing countries can enter the market by developing manufacturing capacity and benefit from large-scale advantages. For a sustainable growth strategy, the development of such manufacturing capacity depends on investments in domestic technological capabilities to develop imported products further. Another opportunity for developing countries arises from the 'lock in' of frontrunner countries into the predominant technological paradigm, which may make it more difficult for them to enter new technological areas. Such windows of opportunity are linked to the emergence of new technological paradigms or disruptive innovations.

Against this background four case studies have shown that technology and environmental leapfrogging is possible. Different factors have been identified for their success. In the case of the landline-skipping diffusion of mobile phones in some developing countries, earlier adoption in industrialised countries enabled leapfrogging. Developing countries had access to a competitive international technology market, which led to low costs, could adopt recognised standards and a proven technology. It was thus linked to very low risk. Yet, at the early diffusion stage of mobile phones in developing countries it was a complement to landline telephony – mainly in urban areas. Hence, it became only eventually a case of leapfrogging in some more rural areas, and was only an example of leapfrogging related to the use of the technology rather than its production or development. Leapfrogging in the Korean steel industry and automobile industry was enabled by investments in technological capabilities over a long time period and a balanced and coherent policy mix including economic, industrial and R&D policies. The success story of the Indian and Chinese wind industries point to the mutual benefits between the creation of a domestic market for the adoption of a new technology, and the creation of a new domestic industrial sector. The access to external knowledge and the creation of knowledge networks were key elements here.

The evidence reviewed in this study underlines that key factors for catching-up or leapfrogging success are different in each case. It is therefore not possible to generalise to a large degree. This confirms the results of early studies on the newly industrialising economies in Asia in the late 20th Century. These concluded that there is no standard model of development or catching-up and that the process is often long-term (eg Hobday 2003). Instead, a country's distinctive resources need to be taken into consideration, and trial-and-error learning needs to be accepted as part of leapfrogging strategies.

A common feature of successful leapfrogging is a coherent set of public interventions in support of a long-term leapfrogging strategy. Balanced public interventions to support catching up should be both functional (eg generic support for education and critical infrastructures) and selective (eg support for specific sectors or industries). In addition, it is important to support emerging industries without disconnecting them entirely from global competition as well as international learning and knowledge networks.

5.2 Policy implications

These insights lead to a number of tentative implications for policy:

- Any leapfrogging strategy needs to clarify its objectives and distinguish between the different types of leapfrogging. Despite many common elements, leapfrogging in industrial development is distinctive from leapfrogging in technology adoption and use. One major difference is the potential involvement of many end-users in the latter category of leapfrogging – perhaps numbering millions in the case of consumer goods. The adoption of new technologies by these users might have important ramifications in terms of required knowledge and skills or daily routines.

- Leadership by industrialised countries is not only necessary for the political and ethical reasons often cited in climate change debates. It is also helpful since it can demonstrate the feasibility and commercial availability of new technologies (such as mobile phone systems). This in turn can create an internationally competitive technology market that makes it possible for latecomers to leapfrog in terms of technology, but also in terms of regulations and policies.

- The capacity for leapfrogging clearly varies from country to country, and from industry to industry. From the evidence discussed in this report, it may be tempting to distinguish two categories of developing country for policy purposes. One possibility is that less developed countries might find it easier to leapfrog in the adoption and use of technologies, whilst 'middle income' developing countries could also leapfrog in industrial production. Such a classification is risky, however, and may unfairly pigeonhole less developed countries. It is important to recall that many of today's middle income countries (eg Korea) were once less developed countries, and have demonstrated the capacity to catch up (if not leapfrog) in both dimensions.

- For any leapfrogging strategy it is helpful if it is clear who are the frontrunners and on what basis – what would it mean to leapfrog? The evidence in this report shows that it is difficult to identify examples of frontrunner countries with respect to long-term, rapid decoupling between development and greenhouse gas or carbon emissions. It is perhaps easier to focus on specific low carbon technologies or sectors.

- Given the general importance of technological capabilities the priority should be on the creation of a general economic environment in developing countries which is favourable to technological learning and innovation. This is the case at a general level, but could also involve targeted capacity building which relates to specific sectors or technologies.

- Any catching-up strategy involves risk. Latecomer countries therefore need to be assisted in the assessment of their specific opportunities to enter into a certain technology sector. Such assessments also need to take into account the country's natural resources and the energy needs of the geographic region in question (eg lower need for space heating in Southern regions). Such an assessment is crucial to prevent a 'one size fits all' policy approach. The evidence suggests that general models or prescriptions are of limited use.

- Before any leapfrogging is possible in the development and manufacture of new technologies, latecomer countries need to have access to cutting-edge technologies. This is necessary for firms and organisations in these countries to upgrade their technological capabilities and – most importantly – adapt new technologies to the local context. The literature on technology transfer shows that the ease with which this access can be gained varies by technology and by country. The examples given in this report of wind energy in China and India show what is possible in some circumstances.

- Consideration of the social context and thus acknowledging the two-way relationship between technology and society is important. Technical and social issues will be different for various social contexts. The creation of an enabling legislative, financial and regulatory environment for low carbon technologies is therefore as important as a focus on the technologies themselves. This is challenging everywhere, but particularly so in developing countries with often weak governance structures in place. One possible route for action is to implement an appropriately timed phase-in of higher standards and regulations.

- A final related point is that strategies to create the right enabling environment for industrial development, catching up – and perhaps eventually, some leapfrogging – are often long term. The Korean steel and automotive industries discussed in this report are good examples of the need for a long-term, patient strategy to catch up and become internationally competitive. In some cases catching up has been facilitated by strong States who have strategically protected new industries. However, there is also the associated risk that too much insulation from international markets can inhibit innovation.

5.3 Further research

This study highlights some important issues that have not attracted sufficient attention in the literature on low carbon technologies so far. Further research in the following areas could provide new insights for policies to support successful catching up – and perhaps environmental leapfrogging - within developing countries:

- There is a need for further work to identify the characteristics of long term development pathways of developed countries – particularly the relationship between growth and greenhouse gas emissions. This would serve as an important starting point for the analysis of sustainable, low carbon development in developing countries – and what the scope is for these countries to (at least partly) avoid high carbon pathways

- In order to clearly pinpoint the leapfrogging potential in the area of low carbon energy technologies, it might be useful to establish a thorough taxonomy of low carbon energy technologies which would include an analysis of i) frequency and speed of innovation, access to external knowledge, and their expected contribution to low carbon targets; ii) who is in the lead in their development and production; and iii) which countries are leading in their deployment and use. This could be used as a basis for policy interventions to selectively develop appropriate absorptive capacity within a country or industry.

- The role of policy processes and institutions in leapfrogging strategies need to be better understood – particularly which policies have been successful in developing critical absorptive capacity. While certain policies are a common theme in the literature (eg trade policies, industrial policies and R&D policies), the role of policy processes and how they affect policy outcomes are poorly understood. Further understanding is required on how to best support the formulation and implementation of policies in a rapidly changing context. Within this, research might also investigate the balance between policies of open-ness to international competition (which can foster innovation) and policies that protect local industries and markets (which can help these to grow in their early phases).

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