INTERNATIONAL
SERIES ON
TECHNOLOGY
POLICY AND
INNOVATION

REGIONAL DEVELOPMENT AND CONDITIONS FOR INNOVATION IN THE NETWORK SOCIETY

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Purdue University Press

International Series on Technology Policy and Innovation

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Purdue University Press
West Lafayette, Indiana

Printed in the United States of America.

Library of Congress Cataloging-in-Publication Data

Regional development and conditions for innovation in the network society / edited by Marina van Geenhuizen, David V. Gibson, and Manuel V. Heitor.

p. cm. -- (International series on technology policy and innovation)

Includes bibliographical references and index.

ISBN 1-55753-355-5 (alk. paper)

1. Regional economics. 2. Regional planning. 3. Information society--Economic aspects. 4. Information technology--Economic aspects. 5. Technological innovations--Economic aspects. 6. Knowledge management--Economic aspects. I. Geenhuizen, M. S. van II. Gibson, David V. III. Heitor, M. V. (Manuel V.), 1957- IV. Series.

HT388.R425 2005

338.9--dc22

2005004922

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Innovation Infrastructures

Keith Smith

INTRODUCTION

A striking empirical feature of innovation in the modern era is the role of infrastructural organizations in developing and diffusing major technologies. If we look at the histories of specific technologies, especially those generally regarded as having a major economic or technological impact, it is surprising how often the fundamentals of the technology are developed in government labs, state owned companies, universities, military R&D programmes and so on. It is often hard to understand how radical technologies in particular emerge or become established unless we take into account the roles of supporting infrastructures.

There seem to be two broad roles for infrastructures in shaping large-scale technologies. On the one hand, such technologies often involve significant accompanying infrastructures. Automobiles, consumer electric technologies, information and communications technologies, aeronautics and so on all rely on extremely substantial infrastructure investments—highways, electricity distribution networks, cable networks. The provision and economics of these infrastructures appear to have powerful effects both in initiating and driving the rise to dominance of new radical technologies. On the other hand, turning to knowledge infrastructures, the major technological innovations that have shaped the modern world mostly originated or developed in public-sector infrastructural organisations (Faulkner and Senker, 1995).

Radar, telecommunications, microelectronics, nuclear power, biotechnology, advanced aircraft, space-based communications, new materials, the Internet—in these core technologies of the modern industrial economy many or most of the important developmental decisions were made, in one way or another, in government or public infrastructural agencies. Of course the decisions came from a variety of organisations—the military, research councils, civil ministries, universities—and the key choices and decisions were not necessarily made in any rational or consistent way. However none of the qualifications that we might make about the role of the public sector should obscure the extraordinary importance of public-sector decision making at key stages in the evolution of these technologies. It might be argued that radical breakthroughs which have occurred in industrial R&D labs are by contrast noticeable by their rarity, although they may be of great economic importance. Given the prevalence of such infrastructural inputs to modern technology, it seems unlikely that the infrastructural role is merely accidental, and it is therefore worth asking whether there is anything essential (or indeed systematic) about infrastructures and large-scale innovations.

Asking such a question immediately confronts us with the fact that we have neither a good economic theory of infrastructures, nor enough empirical studies of how they operate. This chapter explores the problem of conceptualising infrastructures and describing their effects on the economic performance of innovation systems, with a focus on the role of public policy in developing and maintaining such infrastructures.

AN EXAMPLE OF THE ROLE OF INFRASTRUCTURES: MOBILE TELEPHONES

Infrastructural factors in innovation are often neglected. In fact the roles of infrastructural organizations are often completely forgotten once a technology is fully developed and diffusing rapidly. As an example of this, let us consider one of the most dramatic innovations of the modern era, mobile telephony (for more detailed discussion, see Hauknes and Smith, 2002; Lindmark, 1995). If we look simply at the Nordic area in recent years, then most of the attention in this field has gone to such dynamic firms as Ericsson and Nokia. In 2000 Ericsson supplanted Lucent as the leading producer of telecom equipment, mainly because of its position in mobile networks. Ericsson now has a 40% global market share in GSM (Global System for Mobile Communications) infrastructure systems, a strong position in other major mobile standards (such as TDMA [Time Division Multiple Access]) and was by the end of May 2001 involved in 31 of 50 3G-infrastructure agreements announced, in many cases as sole supplier. Its alliance with Sony (announced in October 2001) is leading to a rapidly growing share of the mobile handset market. Nokia has continued to increase its lead in global handset markets. In 2000 Nokia's market share was more than 30%, more than double the share of second-place Motorola. Its market share had increased to more than 35% by the end of the first quarter of 2001, approaching the goal set by Nokia of a 40% global market share.

Yet if we wish to understand the evolution of the technology, and the growth of the firms themselves, it is essential to look behind the firms, at the long-run commitment of resources into telecommunications in the Nordic area. The key organizations that developed this technology were the Nordic telecommunications services companies, all of which were publicly owned infrastructural organizations. Their investments in mobile telephony have now lasted more than a century, and have shaped the overall capabilities of the region, as well as the dynamics of such firms as Ericsson and Nokia. These infrastructural organizations provided both physical infrastructures (networks, switching equipment, telephone sets etc.) and also major knowledge infrastructures in the form of very-large-scale R&D labs, and long-term R&D investments. It was the infrastructural organizations that made the big commitments to mobile telephony, and indeed they had modern cell-concept networks running in the Nordic countries by the mid-1960s. The long-term roles of telecommunications service providers—firms such as Telia, Telenor and Sonera—were central to the development of the technologies and standards that culminated in satellite communications, in the NMT technology (Nordic Mobile Telephone System—the first modern mobile standard), and then in GSM. These telecom enterprises played central formative roles in *all* of the major innovation decisions, such as the cellular concept for mobile phones, roaming capabilities, handset capacities and the like.

We have noted that Telia, Telenor and Sonera are former publicly owned firms—indeed they were monopolists—but why did this matter? Essentially it was because their governance was shaped by complex social, regional and industrial objectives that permitted the emergence of far-sighted technological cultures. It could be argued that it was precisely the publicly owned structure of these enterprises that enabled the long-term financial, technological, engineering and skill commitments, in the face of sustained uncertainty, that made the radical innovation of mobile telephony possible. It is hard to envision privately owned companies making the very long-term and highly risky decisions that culminated in modern mobile telecommunications technologies.

It was not only their decisions that shaped the technologies brought to fruition by Ericsson and Nokia, but in effect they decided which firms would win and lose, for some key equipment suppliers disappeared along the way. So in evaluating this radical technology, we must take infrastructures into account, on several levels—in terms of their physical networks, but also in terms of their organization, finance, governance and knowledge-creating capabilities.

THE NEED FOR A CONCEPT OF INFRASTRUCTURE

A further primary reason for looking more closely at infrastructures is that in the modern economics of innovation, and particularly those theories that use a systems approach, the term is very widely used. There is frequent reference to institutional infrastructures, knowledge infrastructures and so on. But the characteristics and roles of such infrastructures are frequently unclear—often "infrastructure" seems to be used as a kind of shorthand reference for a wide range of framework conditions, institutional setups, collective inputs, public utilities and so on. This rather loose way with the term is shared by the economics literature generally—the term infrastructure is widely found, but it has no agreed conceptual underpinning, and is therefore generally deployed in a flexible but unrigorous way.

The view taken here, however, is that we need a more developed concept of infrastructure, particularly when thinking about the characteristics and performance of innovation systems. The analysis here focuses on collective capital: we look not at infrastructural institutional frameworks, but rather at collective resources for production which require investment decisions. The argument is that we can define a class of such resources, which provide either tangible inputs to production or, more important, shape the knowledge background to production. These inputs can be called infrastructure because they possess technical and economic characteristics which are significantly different from the characteristics of the capital stock in general, and which help to define important characteristics of systems.

Why should a concept of infrastructure be necessary for theories of innovation and economic performance? For much economic analysis it may be that the absence of an elaborated concept of infrastructure is not a serious problem. After all, many theories incorporate fringe notions of various types which refer in a broad way to phenomena which are not conceptually central, yet which are important in some way to what Deirdre McCloskey (1998) calls the "rhetoric" of a discourse. It could be that infrastructure is a notion of this type. Whether it should remain so, however, depends not on the objectives and problems of economic analysis in general, but rather of specific types of analysis.

Neoclassical theories which explore private decision making and allocation effects in the context of given technologies and strict independence of utility and production functions can treat the broad institutional and technological framework as given, and therefore probably have little need of a concept of either infrastructure or institutions (at least as long as they do not have any ambition to produce a descriptive theory of any particular economy). But this can hardly be the case with any theory which stresses interdependence among economic agents, or which aspires to descriptive adequacy.

Suppose agents are reciprocally dependent on each other for specialised inputs, or reciprocally dependent in terms of learning and technology creation or jointly dependent on shared inputs of some kind. Then we can begin to speak in terms of systems, systemic interactions and so on. This leads to three broad problems: first, what is it which encourages or compels coherence or cohesion in the system (what is genuinely systematic about the system?); second, what is it which establishes the specificity of a system (and by implication defines its boundaries); and third, what kinds of factors shape the overall performance of the system?

Although it is clear that there is no simple answer to such questions, the suggestion here is that infrastructures are important to each of these three problems. Of course there is more to such questions than infrastructure, since systems are complex. Systems rest on definite institutional foundations (the specific forms of which have complicated links with cultures and social values); they have legislative and regulatory foundations, which rest on political boundaries, sovereignties and political cultures; and they are also to some extent shaped by natural resource conditions and geophysical considerations. But the argument here is that they are also constructed and shaped by discretionary investments in collective capital inputs which can be understood as infrastructure: that is, that the cohesion, specificity and spatial character of systems can be seen in terms of the characteristics, opportunities and constraints which flow from historically cumulated patterns of overhead capital. This implies that one component of the general performance of a system will be the nature and amount of infrastructural resources available.

INFRASTRUCTURE AND THE CAPITAL STOCK

If infrastructure is to have any rigorous meaning in this context, it must be carefully distinguished from two other features of any system: the institutional foundations and the general capital stock. The concept of "institution" that is used here refers to the distinction between processes, which regulate economic behaviour (the rules of the game) on the one hand, and organisations, which operate within these rules on the other. From this perspective, institutions can include culturally developed rules, but also such phenomena as systems of law. These types of institutions are not part of the infrastructure as it is discussed here. This is because although they are a tangible and extremely important part of the framework, within which economic activity occurs, they are socially constructed, usually originating via evolutionary processes of cooperation or by political decisions and legislation.

It is difficult, though by no means impossible or unheard of, for institutions in the cooperative sense to be objects of policy action. On the other hand, we have infrastructures, which are the outcome of conscious policy decisions and investment programmes, and these are the types of infrastructure on which we focus here. That is, we consider organisations or structures requiring substantial (and usually sustained) capital investment, such as utilities, health organisations, transport systems, universities, government laboratories and so on. A key question, to be addressed later, concerns the extent to which the capital assets, which result from such investment, differ from the general capital stock. Can we identify infrastructure as a specific class of capital goods, and if so what are the implications?

TYPES OF INFRASTRUCTURE

We are concerned here with two types of tangible infrastructure—on the one hand physical infrastructures such as roads, harbours, electricity production and distribution systems, telecommunications networks, and on the other hand knowledge infrastructures such as universities, research labs, training systems, organisations related to standardisation and intellectual property rights protection, libraries, databases.

A related reason for examining the role of infrastructures concerns not their technological roles but their economic effects. As will be argued later, infrastructures can involve major network externalities, and they are often the place within a system where scale and scope economies are very significant. This implies that their existence or nonexistence can significantly shape the fates of competing technologies, and thus the evolution of overall technoeconomic systems.

How should we think about the past and future of the infrastructural organisations, which generated these technologies? This chapter follows a systems approach which sees public and private organisations as part of an overall system rooted in specific geographical and cultural contexts. Science and technology, like economic forces generally, are international; but how these global forces actually operate depends on how they interact with specifically national or regional institutions and environments. In particular the innovation behaviour of industries takes place within national or regional environments in which many agents are interacting. One component of this innovation system can be thought of as infrastructure—a stable framework of collective inputs including scientific and technological activities and institutions which private industry uses. The infrastructure enters—sometimes intermittently, sometimes routinely—as a contribution to a wide range of apparently private activities. Understanding this contribution seems to be an essential precondition for future thinking about the financing and management of the knowledge infrastructure.

There seems to be a necessary convergence between systems approaches to innovation and analyses of infrastructure. It is increasingly recognised that innovation decisions (including decisions involving the diffusion of a new technology) do not occur in isolation. The actions of an innovating firm should be seen in the context of the economic and technological relationships in which it exists. That is, any firm exists within a more or less complex network of suppliers and customers, of sources of labour skills, of suppliers of specialised inputs, knowledge, finance and so on. These networks consist in large part of interfirm relationships, but they also involve a set of overhead capital inputs and a range of organisations engaged in the production, distribution and management of knowledge.

The cohesion of any system thus appears to rest on two sets of infrastructure: physical infrastructures usually related to energy and communications, and science-technology or knowledge infrastructures such as universities, publicly supported technical institutes, regulatory agencies, libraries and databanks or even government ministries.

This overall set of institutions in turn operates inside a framework of regulation, which can also be regarded as infrastructure: technical standards, risk-management rules, health and safety regulations and so on. The regulatory system includes not just formal rules, but also the general legal system relating to contracts, employment and intellectual property rights (patent and copyright law) within which firms operate. Finally there is the wider context of political culture and social values, which shapes public policy objectives and particularly the macroeconomic policy environment. Taken together, this integrated set of public and private organisations, regulatory systems and the policy system makes up a "national system of innovation": an overall context of economic and technical behaviour which shapes the technological opportunities and capabilities of firms. It thereby shapes firms' economic performance and the macroeconomic evolution of the economy as a whole. Attempts to conceptualise such systems, and to understand their capabilities and dynamics, are at the core of much modern theory of innovation.

ANALYSES OF THE ECONOMIC INFRASTRUCTURE

Before we can discuss the role of infrastructure in national innovation systems, it is necessary to clarify its distinctive economic characteristics. The main problem here, noted above, is that although the term "infrastructure" is frequently used in economic discussion, its use is casual and untheoretical. Infrastructure usually refers to the complex of nonnatural resources, which are collectively used by industry in the production and distribution of products. This includes energy supply systems, water supply, transport systems (roads, airports, harbours etc.), telecommunications systems and so on. As noted above, the infrastructure can also involve nonphysical components (often in the form of public-sector services) such as technical standards, educational provision and legal systems (particularly the framework of contract law). A fundamental difference between these types of infrastructural institutions lies in the ways in which they come into existence: on the one hand, on the basis of major investment decisions, and on the other via the evolution of cooperative institutions.

How can we characterise the activities or products which make up the infrastructure? Although economics has no accepted definition of this term, within recent years a substantial literature has emerged, of two types. One is econometric, looking at the links between total factor productivity growth and changes in the infrastructural capital stock. However, within this literature infrastructure is defined in a somewhat mechanical way, presumably in order to facilitate measurement and ease the data problems; it is defined and measured either as public-sector capital or as some combination of the capital stocks for "producers of government services", electricity, gas and water, transport and communications structures. In an influential paper, Aschauer (1992) showed that changes in the infrastructure stock were closely correlated with changes in private-sector productivity; he concluded that infrastructure had a positive impact on such productivity.

This conclusion was challenged by Ford and Poret (1991, p. 56) who nevertheless concluded that "infrastructure investment has a large estimated return in the United States and four other OECD countries; the estimates imply widely differing production structures from country to country; there is no evidence that infrastructure and productivity are related in the United States outside the post-WW2 period; there is some cross section evidence that countries with high infrastructure investment in the post-war period also have had high productivity growth." These studies are by no means conclusive: they concentrate on relatively simple correlations, they ignore lag structures and they do not discuss factors (such as geophysical characteristics) shaping infrastructures. Above all, they ignore the scientific and technological dimension. Nonetheless they suggest economic effects which deserve further research; recent surveys can be found in Munnell (1992) and Gramlich (1994).

But a wider literature has emerged, seeking to develop a more nuanced view of knowledge infrastructures. In terms of technological infrastructure, Justman and Teubal (1996), and Tassey (1994) have offered two recent definitions. Justman and Teubal define infrastructure in terms of "a set of capabilities and market links which firms need in order to function on an efficient competitive basis, yet which transcend the needs of any individual firm"; the specifically technological dimensions of this are returned to later.

The Justman-Teubal-Tassey approaches are productive, but they do not involve an analysis of the technoeconomic characteristics which serve to place these activities as infrastructure; it seems to me that a key issue concerns why these activities tend to be developed or provided in collective, quasipublic forms, rather than as private activities—what is it about the activities, as activities, which makes the term infrastructure appropriate?

A very different analysis is offered by Richard Day (1994). Day argues that differentiated technologies involve a problem of cohesion in the workforce, which is not solved by market relations, and is related to the evolutionary stage of society. Suppose that the technology can be effective only if a part of the population forms a social infrastructure upon which the use of the given technology depends. Such an infrastructure mediates the human energy devoted to coordinating production and exchange, so providing social cohesion for effective cooperation, for training and inculturating the workforce and for producing the public goods, such as waste disposal and public safety required for the well-being of the workforce (Day, 1994, p. 48).

Day's model incorporates infrastructure in this sense into a stages theory of economic growth. This notion of cohesion in the face of complex technologies (which also relates to much wider debates concerning the role of market coordination versus forms of hierarchical command or administrative coordination) is surely grasping a central functional feature of infrastructures. But it leaves open the question of why some processes or activities fall into the category of infrastructure. The approach taken here is not to give a prior definition of infrastructure, but to try to define some of the technical characteristics of activities or organisations which are usually considered as part of the infrastructure, and to explore whether those technical characteristics translate into economic characteristics which in some way distinguish infrastructure from other types of capital input.

TECHNICAL AND ECONOMIC CHARACTERISTICS OF INFRASTRUCTURE

What is it that justifies thinking of some input in terms of infrastructure? Taking an inductive point of departure, we can suggest that technical characteristics of scale, indivisibility, multiple users and generic functions distinguish infrastructure from other components of the capital stock, and from other widely used inputs. These attributes imply economic characteristics, which distinguish infrastructures from other categories of capital goods.

First, there is indivisibility—the fact that a harbour or electricity supply service must normally be constructed as a complete system or set of systems. It is this feature which has led Thomas Hughes (1983, p. 17) to argue that the history of the construction of major modern technologies, and in particular electrical power systems, should be conceptualised in terms of "systems, presided over by systems builders". The systems, which are constructed often, serve not a particular market, but rather the entire industrial base of a region, country or even continent.

Second, infrastructure is multiuser in the sense that there are many users of the same supply system: many users of the same road, rather than many users of individual cars. This implies that firms or consumers use the infrastructure capital stock directly; in the case of "normal" capital they use the capital stock indirectly by using its products. The multiuser characteristic means that, within limits of congestion, only one infrastructure system need be provided: duplication is unnecessary and results in social losses. (This is of course a key element in establishing the dominance of a technological regime, since it implies a "first-mover" advantage to any technology, which can begin infrastructural construction.) The combination of indivisibility and multiple users means scale is often large, and infrastructure investment requirements are often very large relative to most industrial investment. The investment costs of the Channel Tunnel, for example, are several orders of magnitude higher than even the investment costs of a new large commercial aircraft, which is probably the single most investment-intensive industrial product.

Third, infrastructure is generic, in the sense that it is a core requirement for many or all activities: it consists of the provision of resources, which enter as fundamental inputs into virtually all economic activity. Energy, the flow of information, the movement of products, the social and legal framework for production: these are among the very few inputs to all production. The infrastructure is therefore a kind of social overhead capital, related to fundamental "enabling" technologies, which are basic conditions for production to take place. It should be noted that there are, of course, some fundamental activities, which can be provided either on a decentralised basis like most goods, or on an integrated systemic basis like the infrastructure described here. Important examples would be medical care and education. In such cases, most countries have some combination of infrastructural and private provision, the emphasis depending on values and political choices.

What do the technical and systemic characteristics of infrastructure imply in economic terms? The combination of size and indivisibility often means increasing returns to scale. This is why natural monopoly is common in infrastructure. Multiuser characteristics in many cases imply network externalities. Network externalities arise where the benefits to an individual user rise with the number of users. Not true in the case of a road or an airport, but true of telecommunications systems, data networks and the like.

Next, recall that the infrastructure need not be physical; it can include organisational systems such as the framework of contract law, or regulation of the physical environment. These are public goods (and it could be argued that, within limits of congestion, many elements of the infrastructure are "quasi" public goods). Subject to choices about methods of finance and management (i.e., subject to economic organization), and within congestions limits, a road can, for example, be nonrival or nonexcludable. So there is the potential for significant productivity spillovers from the infrastructure to the private sector. Finally, the substantial investment costs have already been noted, but it should be added that some elements of infrastructure also have very long lifetimes (there are in Europe bridges built by the Romans still in use, roads first carved out by the Romans, and many cities using sewers built more than a century ago). Infrastructures involve—in both negative and positive ways—major problems of stability and path dependence in systems.

The characteristics of scale economics, indivisibilities and externalities mean that although infrastructure can be provided either by the public sector or by private firms, there is often a case for public provision. An historically important method of provision was for public organisation and ownership of infrastructure, combined with private finance. Worldwide economic development in the late 19th century relied heavily on major infrastructure construction; approximately 70 percent of all foreign investment from Britain, France and Germany, raised from private sources, went to infrastructure projects in foreign countries. However "the principal overseas borrowers for railway and other social overhead capital projects were either governments or joint stock enterprises whose dividends and interest payments were guaranteed by an overseas government" (Edelstein, 1982, p. 39).

Alternatively, the natural monopoly aspects lead to pricing problems, which require public regulation. In terms of investment, the combination of high initial cost and longevity leads to serious problems of investment appraisal and finance. The main problem is that discounted cash flow methods of investment appraisal place a very low value on benefits occurring over the long term. The scale, monopoly and externality aspects of infrastructure mean that in practice the private sector often lacks either the incentives or the financial capability to construct infrastructure; it is frequently very much a matter for public-sector decision making. Note that where private-sector provision of infrastructure occurs—such as the Channel Tunnel, or private bridges (such as the new bridge over the Thames), or private toll highways in France—there are usually complementary public-sector decisions. These can involve construction of related infrastructure (such as rail links to and through the Channel Tunnel), or links with existing road systems, or price regulation. It is worth noting that the Channel Tunnel has faced severe and persistent financing problems. From a pricing point of view, the "outputs" of infrastructural systems are often a form of joint production, a phenomenon that provides major problems in using prices to achieve optimal resource allocations.

What is the economic role of infrastructure either in the national innovation system, or on the competitiveness of different technologies? It is not difficult to see that decisions regarding either provision or pricing of infrastructure can have a major impact on economic performance and technological choice. There are more or less direct effects on industrial competitiveness, industrial structure and the international or regional location of industry. The transport infrastructure, for example, directly shapes transport costs. The major innovations in this area (bulk air cargo, the container revolution) both require serious infrastructure provision and have radically reduced transport costs with serious implications for the international division of labour. Health and education provision have important implications for productivity and the growth rate. The precise links between education and development remain a subject of much debate, however (for an overview of approaches, see Tortella, 1990). Legal systems and the regulatory environment shape transactions costs. This affects, among other things, the size distribution of firms, and the locational decisions of international firms.

The integration of computing with the telecommunications infrastructure affects interfirm relations with strong implications for industrial "clustering" and the location of firms; the combination of this physical infrastructure and international data standards sharply reduces the economic significance of distance and national boundaries. Infrastructure decisions can directly affect the industrial structure. The existence of a hydroelectric power infrastructure in Norway, and the pricing policies which are adopted for it, more or less account for the existence of an aluminium industry in Norway, and hence for a major metallurgical sector within the industrial structure of the country. Finally, it is worth noting that infrastructure provision can be an essential precondition for the diffusion of major technologies: the internal combustion engine and the automobile required road and highway construction; the electrical power generation and supply network was a precondition for diffusion of industrial and consumer electrical products; the fax machine requires a telephone system; diffusion of advanced information technology requires internationally compatible telecommunications networks.

These considerations lead us to the following provisional definition:

The economic infrastructure consists of large-scale indivisible capital goods producing products or services, which enter on a multiuser basis as inputs into most or all economic activities.

To return to the national system of innovation, it seems plain that the production infrastructure will be an important shaping factor in the *technological* competitiveness and capabilities of firms. Even at a simple level the scale and scope of the infrastructure affects the ability to diffuse and apply technologies, access to information, international linkages and the supply of skills. All of these are central elements in innovative performance. Any analysis of the technological performance of a country or region should therefore have the infrastructure clearly in focus. But we can also argue that science and technological activity are an element of the infrastructure, with an even more direct impact.

THE KNOWLEDGE INFRASTRUCTURE

Can we identify a knowledge infrastructure, which is analogous to—or a component of—the physical and organisational infrastructure of the advanced economies? And what is the public-sector role in it?

If we think of infrastructure as a generic, multiuser, indivisible enabling activity, then it seems clear that there is a "knowledge" infrastructure. There certainly exists a complex of public and private organisations and institutions whose role is the production, maintenance, distribution, management and protection of knowledge; these institutions possess technical and economic characteristics, which are not dissimilar to those of physical infrastructure.

This infrastructure is of the greatest economic significance because industrial production is based ultimately on knowledge: industrial technology consists essentially of knowledge related to material transformation. Such knowledge can be either formal (codified scientific or engineering knowledge) or tacit (embodied in skilled personnel, and/or technical routines). The distinction between formal and tacit knowledge corresponds roughly to a distinction between generic or "accessible" knowledge on one hand, and private (appropriable or secret) knowledge on the other. This distinction between generic (usually formal) and private (usually tacit) knowledge is central to innovation theory, mainly because it refers to economic characteristics of knowledge which are important for R&D performance. If generic knowledge is not appropriable, then firms have no incentive to produce it.

The part of industrial knowledge base that is public (not in the sense that it is produced by the public sector, but public in the sense that it is accessible knowledge which in principle is available to all firms), is one way of looking at the concepts of technological paradigms or regimes—that is, as a body of knowledge and practice which shapes the performance of all firms in an industry. Now this knowledge base does not exist in a vacuum. It is developed, maintained and disseminated by institutions of various kinds, and it requires resources (often on a large scale). Gregory Tassey has defined the combination of knowledge and institutional base as the "technology infrastructure", in the following way:

> The *technology infrastructure* consists of science, engineering and technological knowledge available to private industry. Such knowledge can be embodied in human, institutional or facility forms. More specifically, technology

> infrastructure includes generic technologies, infratechnologies, technical information, and research and test facilities, as well as less technically-explicit areas including information relevant for strategic planning and market development, forums for joint industry-government planning and collaboration, and assignment of intellectual property rights (Tassey, 1991, p. 351).

Justman and Teubal (1996, pp. 4-5) have a somewhat similar approach, but they distinguish between 'sector-oriented' and 'functional' infrastructures. The former include, for specific sectors, the provision of capabilities for testing and quality control; product design capabilities; and institutional capabilities for identifying and implementing new process technologies. The latter includes methods and institutions for changing fundamental technological capabilities, via the development of new generic technologies. Tassey (1991) emphasises three important aspects of the institutional basis of the infrastructure: first, that it has some of the characteristics of the physical infrastructure—such as high investment costs—which I have emphasised above; second, it can involve both public and private institutions; and third, it is independent of the (multiple) users. We should also note that since a "core" knowledge is involved, then parallel or duplicate production of such knowledge is problematic; this can be viewed either as potential waste, thus providing a fundamental economic argument for collective provision, or—from an evolutionary perspective—as a problem related to the maintenance of variety.

On the private level, technology infrastructure institutions include industry associations and conferences, training centres, trade publications, collectively established technical standards (such as architecture and operating systems in computing), branch research institutes and so on. Public-sector institutions include research councils, standards-setting organisations, patent offices, universities, research institute systems, libraries and databases. Public-sector instruments include R&D programmes, legal or administrative regulations, subsidies to capital stocks (especially structures and scientific equipment) and public procurement. We could define the public knowledge infrastructure as consisting of a combination of these institutions and the flow of resources through them. In what kinds of ways can the infrastructure have economic effects? Some main ways would include (for a more detailed discussion, see Smith, 1997, pp. 96-104):

- Production and diffusion of scientific and technological knowledge
- Education, training and skills
- Standards, regulation and protection of technical activities
- Creation of firms
- Access and dissemination functions

PUBLIC AND PRIVATE INFRASTRUCTURE PROVISION

In the past, most infrastructure has been either put in place by the public sector or put in place using indirect public revenues, mainly because, as Tassey has remarked, "A characteristic of technology infrastructure is that it depreciates slowly, but it requires considerable effort and long lead times to put in place and maintain" (1991, p. 347). There are several other dimensions here, however. One is that the public sector has a close interest in innovation. Often it is a prime user for key (radical) technologies, and this also involves it in the process of public procurement and hence as a partner in user-producer interactions. It is also a regulator and indirect beneficiary of productivity-raising innovations. So it should not be surprising that the public sector gets involved in innovation. But what can the public sector do which the private sector cannot do? There are a number of reasons why the public sector has played such a crucial role in innovation in the advanced economies. A basic argument is that the public sector has a number of advantages which permit it to undertake important innovation tasks which are closed to private firms. These include:

- Risk bearing—the public sector's ability to cope with uncertainty
- Scale—the ability of the public sector to carry out very large-scale projects, and its ability to mobilize large resources
- Multiple technology paths—the ability of the public sector to explore a range of possible innovation paths

However, many dimensions of the role of the public sector are now under explicit and implicit challenge. First, some important aspects of public-sector activity have their roots in Cold War strategic rivalry; as defence budgets are changed and reduced, there are increasing questions over the role of military-based innovation and scientific research. Second, trends towards privatization and generally diminishing public ownership raise questions about the future of innovation in such key fields as energy, telecommunications and transport. This means a need for a careful consideration of how the important facilitating role played by the public sector in the past might be continued in the future.

Privatization has played an increasing role in government industrial policies over the past 20 years (for useful discussion, see Tsuji et al., 2000; Kagami and Tsuji, 2000). Much of it has focussed on the privatization of utilities and related infrastructures: telecommunications, airports, electricity, gas, water supply and railways, for example. There is no question that private companies can successfully run many such infrastructures. Although there have been some major failures—such as railway transport in the United Kingdom—the operational record is generally good. However two major questions arise in the context of the discussion above. The first is that although private enterprises can run infrastructures efficiently, it is not obvious that they can establish them on the requisite scale in an appropriate way. Without state involvement there may be no incentives to provide at all, or there may be overprovision—so private telecommunication companies either ignore large parts of society (especially connections to private households), or they massively overprovide (as in the rush to build networks in densely populated business areas that has culminated in a number of major bankruptcies).

From the innovation standpoint, the question is whether privatized infrastructure operators will in any way replicate the past innovation performance of publicly owned infrastructure companies. There are strong reasons to doubt this, mainly because the shift from public to private also involves a major shift in corporate governance. This implies far more stringent conditions applying to returns on investment, with smaller scales and shorter time horizons than in the past. While this will avoid waste and white elephants, it will also mean that the long-run programmes that generated, for example, modern mobile telecommunications, will not be repeated. So infrastructure providers are no longer likely to be radical technology developers, and this raises interesting questions about where and how the next generation of radical technologies will emerge.

CONCLUSIONS

The discussion in this chapter suggests a number of tentative conclusions. First, however difficult the concept of infrastructure, it appears to be the case that we can identify a theoretical and operational concept which is relevant to central problems in the analysis of innovation. These problems include identifying the specificity and boundaries of innovation systems, understanding elements of system cohesion and accounting for innovation performance differences between countries. Furthermore we can identify a knowledge infrastructure which is a central component of the wider economic infrastructure, and therefore a central component of the national innovation system. Knowledge infrastructures will affect the performance of both national and regional systems, depending on the extent to which they actually deliver the outcomes sketched above.

There are four outstanding policy issues concerning the knowledge infrastructure: these concern the level of funding, the composition of infrastructural activity, the internal organisation and management of infrastructure, and policy integration across government agencies.

The level of provision should be increased only if it will generate benefits greater than costs. It is one thing to show, either through example or statistical analysis, that the infrastructure can have economic effects. It is something quite different to estimate how changing the scale of provision will affect subsequent economic performance in terms of output or productivity growth. A serious issue before us is whether existing levels of funding for infrastructure are in some sense "adequate", and this requires a much more sustained effort to analyse how marginal changes in provision are likely to affect industrial users.

The second problem concerns the composition of the infrastructure. What is the appropriate balance between the types of activities outlined above? At the present time, research and higher education are the most heavily supported elements of infrastructure, although there are wide disparities among countries. In some cases public research programme budgets—strongly oriented towards the military in the United States, Britain and France—are central elements in infrastructure systems, while others focus more on public-private coordination agencies.

Library and database provision likewise varies sharply among countries and regions. We really know little about the combined effects of infrastructural organisations, and thinking about the system as a system is an important challenge.

Third, there is the question of management and organisation within the infrastructure. The term "university" means different things in different countries; the objectives, cultures and self-images of universities vary widely, and this may be linked with variations in economic role. But similar points apply to regulatory organisations, to library systems (where differences in operating practices shape whether knowledge is accessible or inaccessible). This is not simply a matter of deciding which methods of administration and management are most "efficient", because there are differences among cultures in what people want from a library, for example. But nevertheless these internal aspects of infrastructural organisations will be an increasingly important policy question.

Finally, perhaps the most important issue. How can a coordinated infrastructure policy be developed and implemented? The infrastructure is a system, and policymakers should see it as such. But the elements of the system, which have been described above, usually fall within the competence of different ministries or public agencies. Intersectoral problems within public administration are a well-known issue, which needs no repetition here; but it is clear that any integrated approach to the knowledge infrastructure will require organisational innovation with the public sector itself. The knowledge infrastructure activities described here absorb somewhere between 5 and 10% of national income in most OECD economies. If the knowledge infrastructure is important enough to deserve these kinds of resources, it probably deserves an integrated policy approach as well. A key issue in this is the balance between national and regional provision, and how national and regional knowledge infrastructure policies can be coordinated.

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