TECHNICIANS AND INNOVATION: A LITERATURE REVIEW

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EXECUTIVE SUMMARY

Innovation involves both the invention of completely new ideas and also the use of existing ideas by organisations that have not hitherto employed them. It is the means through which new knowledge is applied to economic processes in order to increase productivity and add value to economic activity. As such, it is the engine of long-term economic growth and development, and the major source of productivity and rising living standards.

However, a shortage of technicians is hampering innovation in the UK.

This is the principal conclusion of this report by Paul Lewis, who has examined the supply and training of technicians who contribute to the development and use of technologies that are key to the future success of advanced manufacturing in the UK.

Technicians make significant contributions to innovation. Perhaps most important of all, they have a critical role to play in enabling firms successfully to exploit new technology. In the UK, however, the critical role played by technicians all too often goes unrecognised.

Innovation has often been thought of as linear process, whereby new knowledge is created through fundemental scientific research and is then applied to create novel products and production processes. On this view, the creation of the knowledge involved in innovation is the exclusive preserve of highly-educated scientists and engineers. However, evidence suggests that the linear view is mistaken and that innovation is in fact non-linear in nature, characterised by complicated feedback mechanisms and interactive relations involving science, technology, production, and use. For example, rather than simply implementing ideas developed by the scientists and engineers involved in R&D, technicians draw on their experience of using and maintaining technology to provide suggestions about how it can be improved. According to this perspective, technicians make an indispenable contribution to innovation.

The innovation systems approach uses the evidence on the non-linear nature of innovation to identify a whole range of aspects that are critical to innovation, including the practical and theoretical knowledge embodied in skilled workers at all levels, including technicians.

In the UK, a commitment on the part of policy-makers to a linear view of innovation over-emphasises fundamental research and development, and so neglects other important influences on innovation, in particular those stemming from technicians, obscuring the critical role they play.

The author suggests that an important step change required to drive innovation in the UK is to improve the quality of technician training, which currently all too often fails to provide firms with a workforce possessing the right quantity, and blend, of practical and theoretical knowledge to make the best use of new technologies. One of the reasons that technician training has been neglected is that an over-supply of graduates has masked technician shortages, but these graduates are unlikely to have the practical experience and skills which are so critical to the technician role.

The report goes on to suggest that centres of innovation, such as Catapults, which are at the forefront of technology development, should play a role in the training of technicians and that these centres could make a significant contribution to training for innovation by working with training providers to ensure they understand the skills requirements of emerging technologies and enabling access to training on the latest equipment and facilities.

The report then concludes with the following recommendations:

a) Greater consideration should be given to the importance of technicians in the innovation system by firstly ensuring that the funding regime does not discourage colleges and other providers from offering technician training courses; and secondly by requiring Catapults to include workforce planning alongside technology development within their remit

b) Centres of excellence, possibly the new Institutes of Technology, should work with Catapults to develop courses on emerging technologies which could also be delivered through distance learning

c) Policymakers should ensure that apprenticeships and other forms of technician training develop the broad occupational competence and underpinning knowledge so that technicians can assist in the deployment and development of new technologies involved in innovation

d) Further research should be conducted to explore how high-performance working can contribute to innovation in the UK

1. INTRODUCTION AND BACKGROUND

Innovation is the process whereby new technologies are created and diffuse throughout the economy so as to create new commercially-viable products and novel methods of producing existing goods and services. It involves both the invention of completely new ideas and also the use of existing ideas by organisations that have not hitherto employed them. It is the means through which new knowledge is applied to economic processes in order to increase productivity and add value to economic activity. As such, it is the engine of long-term economic growth and development, and the major source of productivity growth and rising living standards (OECD 2005: 46-52, 2015: 3-4; BIS 2011: 1-2, 7-22).

Skills are critical for innovation (Lloyd-Ellis and Roberts 2002; BIS 2011: 111-14; 2017: 97-119; Makkonen and Lin 2012; 2015: 13-14). Most obviously, highly-qualified research scientists and engineers make a vital contribution to the research and development through which new ideas are developed. Academics and policy-makers have therefore devoted a good deal of attention—perhaps, it might be argued, too much attention—to the high-level skills needed for work of this kind (Tether *et al*. 2005; Toner 2011). Good managerial skills are also critical for ensuring the effective use of new knowledge and novel technologies (BIS 2012: 24-25; DBEIS 2018: 22). But there is another category of worker who also makes an important contribution to innovation, namely technicians. Technicians are workers occupying roles that require 'intermediate'—that is, level 3-5—skills in science, technology, engineering and/or mathematics. The category encompasses both 'skilled trades', such as laboratory technician and maintenance engineer, and also 'associate professional/technical' roles (which include some varieties of manufacturing technician and production engineer) (Jagger *et al*. 2010; Mason 2012).[1]

Technicians use their knowledge of science, technology, engineering and mathematics to solve practical problems arising in research and development, production, and maintenance. This report will explore how technicians deploy their skills and knowledge to contribute to innovation. As we will see, technicians make critical contributions both to the development of new technology and also to its effective deployment and use. The report will also investigate the role of the organisations involved in technician training in helping to ensure that innovative firms have the skills they need to develop and exploit the potential of new technology. In this way, the report explores one important but hitherto largely neglected set of organisations that helps to shape an economy's capacity to innovate, namely those connected with vocational education and training. It will be argued that in the case of the United Kingdom, deficiencies in the rules governing the provision of vocational education and training mean that that firms cannot always obtain the skilled technician labour they need to develop and utilise new technologies to good effect, impeding their ability to innovate.

1 More detailed descriptions of such roles, drawn from the space, composites, and industrial biotechnology sectors, can be found in Lewis 2012b: 11-20, 2013b: 15-26, and 2016a: 14-29.

The structure of the report is as follows. Section 2 explores the meaning of the term 'innovation', while Section 3 sets out the main theoretical framework currently used to analyse and guide policy on innovation, namely the innovation systems approach. Section 4 discusses innovation policy. Section 5 draws on the previous sections by using them to provide a framework for analysing the contributions technicians made to innovation and the scope for policy to ensure that firms are able to access the skilled technicians they need if they are to innovate. Section 6 summarises and draws conclusions.

2. INNOVATION

Innovation is the process whereby new technologies are created and diffuse throughout the economy so as to create new commercially-viable products and novel methods of producing existing goods and services (OECD 1997a: 47, OECD 2005: 46-52; BIS 2011: 1, 7-22).

Two broad kinds of innovation may be distinguished:

- *radical* innovation involves the creation of entirely new products and technologies that transform existing markets and/or industries, usually based on the creation of new knowledge through research; and
- *incremental* innovation involves the gradual improvement of existing products and technologies, often through knowledge creation in the workplace (BIS 2011: 2, 30-31).

On this view, innovation involves not only the invention of completely new ideas but also the application of existing ideas by firms that have not hitherto employed them, so that they are deployed in workplaces to transform practice in the relevant organisation, thereby diffusing more widely through the economy.[2]

An important theoretical framework for understanding innovation, which is influential both in academia and also among policy-makers, is the *innovation systems* approach.[3] The key insight is that the extent and kind of innovation occurring in an economy is crucially shaped by the rules governing how firms and other organisations involved in innovation interact with one another. Under the influence of this approach, as we shall see, those rules have become a central focus of attention, both among academics striving to understand the determinants of innovation and also on the part of policy-makers seeking to improve the performance of their economies. It is upon this approach that the next section of this report will focus.

2 Put slightly differently, the technology whose diffusion constitutes innovation need only be 'new to the user' and not necessarily 'new' or 'advanced' in any wider sense.

3 The seminal contributions were written in the late 1980s and early 1990s. They included Christopher Freeman's 1987 book on *Technology Policy and Economic Performance: Lessons from Japan*, along with three volumes edited by Dosi *et al.* (1988), Lundvall (1992), and Nelson (1993). A slightly later milestone was the publication in 1997 of a volume edited by Edquist, in which a group of authors sought to reframe the ideas advanced in the earlier studies in a conceptually unified way.

3. THE INNOVATION SYSTEMS APPROACH

One of the main factors encouraging the development of this literature was dissatisfaction with 'linear' views of innovation and technological change (Sharif 2006; Weber and Truffer 2017: 103-04). We shall consider first the critique of the linear view of innovation, before going on to explain the innovation systems approach to which that critique gave rise.

3.1 LINEAR VERSUS NON-LINEAR VIEWS OF INNOVATION

According to the 'linear' view, innovation essentially involves a fixed sequence of activities, whereby new knowledge is created through basic scientific research and is then applied to create novel products and production processes. (Bush 1945). On this view, scientific progress is the principal cause of economic progress, so that the main policy challenge is that of catalysing scientific activity, whose economic benefits would—it was thought—be realised more or less automatically (Smith 2000: 85-86, 92-93; Weber and Truffer 2017: 103).

However, it is now widely accepted that innovation does not follow a simple 'linear' path from fundamental to applied research and thence to the development of new products and processes at a commercial scale. On the contrary, evidence suggests that innovation is a non-linear process, characterised by complicated feedback mechanisms and interactive relations involving science, technology, production, and use. Two stylised facts support this non-linear view.

First, case studies indicate that, far from always involving the application of given scientific knowledge, technological innovations have in fact often taken place *before* the development of the relevant scientific theory, being based on practical rather than scientific knowledge. Indeed, by drawing attention gaps in basic knowledge, technological developments have at times driven the growth of science, as for example when thermodynamics was developed to understand the factors determining the efficiency of steam engines, or when advances in solid state physics took place as scientists strove to understand how the first transistors worked. Far from being something that occurs autonomously, therefore, the development of scientific knowledge is often stimulated by the need to understand already-existing technologies. On this view, technological developments occurring in the later stages of the innovation process can help to shape basic scientific research, undermining the linear model's claim that scientific advances always precede and drive technological change (Rosenberg 1983: 141-59; Nelson and Rosenberg 1993: 6-9; Dosi and Nelson 2018: 42-43).

Second, the evidence also shows that requests and recommendations made by actual and/or potential users of new products and technologies, especially early or 'lead' users, are often fed back into the research process through which those products and technologies are developed. Related to this, suggestions made by salespeople who try to find buyers for new products and equipment are incorporated into research and development, again informing the learning involved in innovation (Rosenberg 1982: 193-241; Lundvall 1988; von Hippel 1988, 2005; Dosi and Nelson 2018: 46-47, 67-68).[4]

4 We will consider a third example of such feedback from the later to the earlier stages of the process through which innovation takes place below, when we consider how the technicians who install and operate new technology can also make important contributions to innovation.

What these stylised facts indicate is that the learning through which the new knowledge involved in innovation is generated derives not just from pure scientific research but also from several other sources, located at various stages in the innovation process (rather than just at its outset). Contrary to the linear view, therefore, innovation appears to be a complex, non-linear, interactive process of knowledge creation, characterised by complicated feedback mechanisms and interactive relations involving science, technology, production, and use (Kline and Rosenberg 1986; Edquist 1991: 1, 13, 16; Fagerberg 2017: 499-502).

A significant implication of this non-linear model is that innovation involves interactions between firms and several other kinds of actor (including customers and organisations involved in scientific knowledge creation, such as universities and government research institutes). Those other organisations serve as sources of the information, finance, skills, and other resources required for new knowledge to be developed and to diffuse through the economy. And if innovation involves interactions between a variety of organisations, then in order to understand it, it will be necessary to analyse the rules that govern those interactions and thereby shape knowledge creation and diffusion. The theoretical perspective that has been developed to understand those interactions, and the rules that structure them, is known as the *innovation systems* approach.

3.2 THE INNOVATION SYSTEMS APPROACH

When firms innovate, they rarely if ever act in isolation. Rather, they interact with other organisations in order to generate, acquire, and develop the knowledge used in innovation. Those organisations will often be other firms; but they also include universities, banks, government departments, regulatory agencies, venture capital funds, technical standards institutions, schools, and other providers of education and training, to name but a few. Those organisations act as sources of knowledge, finance, skills, and other kinds of resource, thereby contributing to the process through which innovation takes place.

The organisations in question, along with the rules governing their interactions, constitute what is known as an *innovation system* (Edquist 1997a, 1997b; BIS 2011: 2, 10, 28-30; President's Council of Advisors on Science and Technology 2014: 2, 18). As one of the founders of the innovation systems approach, Bengt-Åke Lundvall, has put it, "A system of innovation is constituted by elements and relationships which interact in the product, diffusion and use of new and economically useful knowledge" (Lundvall, 1992: 2). In a similar vein, another prominent contributor to the literature, Charles Edquist, has stated that, "Innovation processes … occur in interaction between institutional and organisational elements which together may be called 'systems of innovation'" (1997a: xiii). The elements or parts of the system are the organisations that contribute to innovation; while the institutions are the rules that govern how those organisations interact with each other. The institutions or rules in question include:

- financial rules, such as accounting standards (which govern how organisations' financial performance will be evaluated) and the rules of corporate governance (which specify the terms on which funding will be provided to the organisations that play a part in innovation);

- legal rules, relating to contracts, employment and perhaps most notably intellectual property (which concerns who owns the new technologies being developed, who is allowed to use them and on what terms, and who is entitled to the income they generate);
- regulatory rules governing the kind of research that can take place and production methods that can be used;
- risk-management rules;
- rules governing the application of various kinds of technical standards;
- environmental, and health and safety, regulations, which influence the demand for certain kinds of technology;
- rules governing public procurement, which also help to shape the demand for innovative technologies and goods; and
- educational rules, governing for example the terms on which government support will be given to organisations that engage in various kinds of training.

By structuring how firms interact with each other, and with the other organisations that contribute to the innovation process, these institutions or rules are an important influence on the quantity and kind of innovation—understood as learning about new products and methods of production—that takes place (Lundvall and Johnson 1994). As summarised by one of the pioneers of the innovations system approach, Stan Metcalfe, a system of innovation is "that set of institutions [rules] which jointly and individually contribute to the development and diffusion of new technologies ... As such it is a system of interconnected [organisations] to create, store and transfer the knowledge, skills and artefacts which define new technologies" (Metcalfe 1995: 38).[5]

The key question that may be asked of such systems concerns the extent to which they generate the information and incentives required to encourage and enable firms successfully to innovate by accumulating and putting into practice at a commercial scale new products and methods of production. Considering this question gives rise to the issue of what role, if any, there is for government policy to support innovation. As we shall see, the innovation systems approach gives rise to a distinctive set of arguments in favour of government intervention, including concerning vocational education and training.

5 Also see: Freeman 1987: 1; Lundwall 1992: 9, 12; Edquist and Johnson 1997; Smith 1997; Woolthius *et al*., 2005: 610-11; Edquist 2005: 182, 187-88; Metcalfe 2007: 447-48.

4. INNOVATION POLICY: THE 'SYSTEM THEORETIC' RATIONALE FOR GOVERNMENT INTERVENTION TO SUPPORT THE DIFFUSION OF NEW TECHNOLOGIES

The innovation systems literature focuses on how the rules governing the interactions between firms and other organisations constrain and enable innovation. This approach gives rise to the notion of 'system failure', which is quite distinct from the conventional notion of market failure associated with neoclassical economics.

The best-known rationale for government intervention to support innovation is provided by standard, neoclassical economics and is based on the old, linear view of innovation (according to which new knowledge is created through basic scientific research and then applied, more or less automatically, to develop novel products and processes). The neoclassical approach suggests that, if the process of scientific knowledge creation that (on this account) drives innovation is left to market forces, then too little knowledge creation—and, therefore, too little innovation—will take place. The reason is that the benefits arising from knowledge creation are enjoyed not only by those actors who actually create that knowledge in the first place but also by third parties who subsequently acquire it. However, in deciding how much to invest in knowledge creation, private sector actors only take into account the returns they themselves receive from their investment, ignoring the external benefits accruing to third parties. The resultant divergence between the private and social returns to knowledge creation—or externality, as economists term it—implies that private actors have what is from the point of view of society as a whole too weak an incentive to invest in generating new knowledge, so that too little knowledge creation, and therefore too little innovation, take place (Nelson 1959; Arrow 1962; also see Smith 2000: 84-85; Chaminde and Edquist 2010: 97-99; Edler and Fagerberg 2017: 6-8; and Dosi and Nelson 2018: 50-57).

This 'market failure' provides a rationale for government intervention designed to raise the level of investment in research and development up to the socially optimal level. A number of different policies might be used, including: direct government production of knowledge, via publicly-funded research institutes; the use of subsidies for research in non-governmental research institutions such as universities; and the establishment of a system of patents to protect the intellectual property created by R&D. This 'public good' type justification for government intervention remains influential in policy circles (DBIS 2014: 11-14; Government Economic Service 2014: 9-10).

System failures arise when there is a failure to disseminate the information and other resources, and to coordinate the activities, required to ensure that new technologies are developed and diffuse properly through the economy. This may be because some of the relevant organisations or elements of the system are absent, or because some of the connections linking them are missing or inadequate, so that the informational and other resources required for innovation are not available in sufficient quantities. As one prominent contributor to this literature has put it, "A system may fail to operate in the desired way because knowledgeable actors are missing, because connections are absent or because system boundaries are drawn in the wrong place. Attention to these issues provides the basic rationale for innovation systems policy" (Metcalfe 2007: 447; also see Metcalfe 2005: 54-63, 2007: 447-48; Smith 2000: 93-100; Edler and Fagerberg 2017: 5, 8-10; Weber and Truffler 2017: 112).

For instance, if the legal rules governing intellectual property are too lax, then organisations may doubt that they will earn a sufficient return on their investment in developing new products and production techniques, deterring them from making such investments and thereby deterring innovation. But if the rules are too harsh, then the diffusion of knowledge required for innovation will be impeded. To take a second example, if a country's system of corporate governance—the rules governing the provision of finance and the possibility of takeovers—is such that firms rely heavily on equity capital and have to focus on the short-run price of their shares, then they may be reluctant to undertake the long-term investments required to support innovative activities (Woolthius et al., 2005: 613; BIS 2011: 29).[6]

The possibility of such 'systemic' problems implies a possible role for the state, not just in correcting market failures, but in improving the institutional framework—the set of rules—within which innovation takes place (Metcalfe 2007: 448-52; Edler and Fagerberg 2017: 9-10). Just as system failures may reflect the fact that some of the relevant organisations may be missing entirely, or that they are governed by rules that discourage them from doing what is required to generate and use new technologies, so too there are two broad sets of policy responses:

- policy can focus on the organisations that are the elements in the system, through the creation of 'missing' organisations or by building their individual capabilities to develop and exploit innovations; or
- it can focus on the rules governing how those organisations interact with each other—i.e., it can focus on the connections between the elements, rather than the elements themselves—by seeking to bring the different organisations together to facilitate more effective development, diffusion, and use of knowledge (Edler and Fagerberg 2017: 5; Fagerberg 2017: 502).

The innovation systems literature has acquired a significant following among policy-makers, not least because of its adoption by the OECD (1997b, 1999, 2002). It has also received attention from policy-makers in the UK (see, for example, BIS 2011: 10, 28-30; DBIS 2014: 11-26; GES Group on Growth 2014; Hauser 2014: 10, 45). As least part of its appeal derives from the fact that—compared to neoclassical approaches to policy—it encompasses a greater range of influences on innovation and so affords policy-makers a wider scope for possible policy intervention (Mytelka and Smith 2002; Sharif 2006; Weber and Truffler 2017: 106-09).

6 We shall explore in greater detail below a training-related example of system failure.

5. THE INNOVATION SYSTEMS APPROACH AND TECHNICAL EDUCATION

An important influence on innovation is a country's education system, which is a key element in shaping the economy's ability to generate the skills required to develop and make effective use of new technologies (Nelson 1992: 351, 358-59; Metcalfe 2005: 68-69, 2007: 449-50; BIS 2011: 5, 29-30, 111-17). However, while contributions to the innovation systems literature occasionally mention vocational education and training, and the organisations through which it is provided, attention tends to be concentrated primarily on universities and graduates (see, for example, Nelson and Rosenberg 1993: 13; Edquist 1997b: 20; Edquist and Johnson 1997: 47; Edler and Fagerberg 2017: 11-13; Fagerberg 2017: 504).

This gap in the literature has not gone unnoticed. For instance, Edquist (2005: 195) has observed that there is "little systematic knowledge about the ways in which the organization of education and training influences the development, diffusion and use of innovations". Similarly, Shapira *et al*. (2010: 462) remark that "innovation scholars have hardly addressed the educational system. Research in the requirements the knowledge society asks from the education system is scarce." In a survey of work on the relationship between skills and innovation, Jones and Grimshaw note that while those two factors are commonly held to be key determinants to economic growth, "there is a surprisingly limited appreciation of how these core features combine and interact both at the firm level and at the interface between tertiary education and industry … for the most part the training/skill-innovation inter-linkages remain under-researched" (2012: 3; also see p. 7). One key question, they suggest, concerns the relative merits of high-level, tertiary education as opposed to intermediate, vocational education for innovation (Jones and Grimshaw 2012: 3, 6-7). Most recently, Borras and Edquist (2015: 225) refer to "important gaps in the literature that warrant further research efforts in the near future" such as "the lack of empirical studies that look at the effects of vocational education and training schemes." Finally, two authors of a recent paper on the link between university education and innovation note that, "[I]n focusing on firms, investors, and elite research institutions, innovation scholars have neglected the dynamics of skills and the key role of educational institutions" (Vona and Consoli 2014: 1395).

5.1 INNOVATION AND THE INSTITUTIONS GOVERNING TECHNICAL EDUCATION

The aim of this section of the report is to begin to help fill that gap in the literature, by examining the importance of technician skills and training in developing the capacity of firms to innovate, and the role of organisations involved in vocational education and training in supplying those technicians. As noted above, technicians are workers occupying roles that require 'intermediate' skills in science, technology, engineering and/or mathematics. They use their knowledge of those disciplines, and related practical skills, to solve practical problems arising in research and development, production, and maintenance.

The following section of this report will explore both the contribution that technicians make to innovation and also the role of the organisations involved in technician training, along with the rules governing their behaviour, in helping or impeding efforts to ensure that innovative firms have the technicians they need to develop and exploit the potential of new technology.

5.2 THE CONTRIBUTION OF TECHNICIANS TO INNOVATION

This section considers two key ways in which technicians can contribute to innovation. The first concerns how technicians contribute to what is known as the *absorptive capacity* of firms (that is, to firms' ability to understand and make effective use of new knowledge about products and production processes). The second concerns the contribution that technicians can make to the generation of new knowledge about products and methods of production.

5.2.1 Absorptive capacity

The term 'absorptive capacity' refers to "the ability of a firm to recognise the value of new, external information, assimilate it, and apply it to commercial ends" (Cohen and Leninthal 1990: 128; also see Zahra and George 2002). A firm's absorptive capacity is therefore its ability to understand and make effective use of new knowledge and innovative technologies. One of the key determinants of absorptive capacity is the technical skills and knowledge of a firm's workforce (Cohen and Levinthal 1990: 129-33; Jones and Grimshaw 2012: 4, 20-16: 113; Government Economic Service 2014: 3 n. 1, 20, 24-25; Mason *et al*., 2017). The capacity for successful innovation—and, in particular, for the successful commercialisation of new technology—depends upon employers having workers who can deploy and use that technology to good effect, thereby helping to ensure that its potential is realised. While highly qualified engineers and scientists are likely to play a very significant part in identifying the relevant knowledge in the first place, evidence indicates that technician-level workers also make important contributions to firms' efforts to apply that knowledge successfully in the workplace. More specifically, it is possible to distinguish between *potential* absorptive capacity, defined as the ability to identify and acquire relevant external knowledge of new technologies, and *realised* absorptive capacity, which refers to the ability to apply that knowledge to good effect within the organisation (Zahra and George 2002). This distinction parallels that between 'exploration', understood as the search for new technologies and 'exploitation', centrally involving the application and refinement of known technologies, drawn by March (1991). It is to a firm's realised absorptive capacity that technicians mainly contribute (Mason *et al*. 2017: 8).

The reason is straightforward; the effective deployment of technology to bring about improved operational performance depends upon the ability of technicians to install, adapt, operate, trouble-shoot, and maintain the technology in question. A few illustrative examples are as follows:

- Technicians are involved in the installation, commissioning, maintenance and improvement of plant and facilities in the chemical industry and in industrial biotechnology (Lewis 2013: 13-15, 2016a: 20-22, 25).
- In the automotive industry, technicians play a critical role in helping firms realise the potential for changes in technology and work organisation to reduce costs and improve output quality (Mason and Wagner 2005).

- In the garment industry, machine operators who are more skilled at reading technical drawings take less time, and require less supervisory assistance, when putting a new style into production (Prais 1995: 69).

A firm's absorptive capacity will be greater if its technicians have broader, occupationally-oriented skills, coupled with a sound grasp of the relevant theoretical principles, rather than narrow, job-specific skills with little underpinning knowledge. Technicians with a wider range of skills and good underpinning knowledge are better placed to incorporate the use of new technology into their routines and thereby to facilitate its effective use (Tether *et al*., 2005: 6-7, 60-61; Toner 2011: 47). Evidence indicates that higher-level technician skills in particular make a significant contribution to firms' performance in the area of innovation, by enabling them to exploit new knowledge (Mason *et al*., 2017).

If there is a shortage of technicians, if their skills are tailored to the requirements of a specific role, or if they lack a good grounding in the relevant theoretical knowledge, then the technician workforce will be ill-equipped to adapt to new technologies and to exploit their potential to the full. In such cases, firms will have poor absorptive capacity, suffering from a deficient capability to innovate because they do not have enough appropriately trained and educated technicians to make the best use of new technologies. Some examples of the kinds of problems that can arise include the following:

- Difficulties with the technician workforce have in the past made it hard for firms in the UK automotive industry to respond to the advent of new technology and the demands created by the restructuring of supply chains, leading to slower innovation and lower productivity and competitiveness than would otherwise have been the case (Mason and Wagner 2005).
- Matched-plant studies have shown that historically British engineering firms have been slower than their German counterparts to use new equipment, and have tended to use simpler models, because deficiencies in the skills of their technician workforce mean that managers are not confident of their workers' ability to make good use of new technology. Such firms suffer from a deficient capacity to absorb new knowledge and innovative technologies, leading to slower innovation and lower productivity and competitiveness (Prais 1995).
- Firms in the advanced manufacturing sector that wish to shift from the use of metallic to composite components have struggled to recruit workers skilled at working with composite materials, hampering their efforts to make effective use of innovative, composite-based methods of production (Lewis 2012a: 21-22, 38, 2013b: 33-35).
- Similarly, organisations in a variety of industries that are seeking to replace methods of production based on chemical synthesis with the use of biological substances and processes have noted the difficulties caused by a lack of manufacturing technicians with the relevant skills (Lewis 2016a: 31-32).

In all such cases, to use the language of the innovation system approach, the interactions between firms and the organisations involved in vocational education and training are deficient in some key respect, implying that firms cannot obtain the skilled technician labour they need to develop and use new technologies to good effect (DBIS 2014: 22-23). We shall elaborate below on this notion of system failure in the case of vocational education and training. Before doing so, however, we shall consider two more ways in which technicians contribute to innovation, in addition to facilitating the diffusion of new technologies, both of which involve them contributing to the creation of the new knowledge upon which innovation is based.

5.2.2 Technician-driven (bottom-up) innovation

Evidence suggests that, in addition to playing a key role in putting new technologies to good use, technicians also make a direct, and important, contribution, to the creation of the knowledge that informs both radical and incremental innovation.

5.2.2.1 Radical innovation

Studies of R&D indicate that while highly qualified research scientists and engineers play the principal role in the creation of the knowledge involved in radical innovation, technicians also make a significant contribution in two ways.

First, technicians make a direct contribution to knowledge creation by designing and building many of the instruments and experimental rigs involved in research. Researchers often do not provide the technicians with detailed technical drawings of the kind of instrument or apparatus required to bring the experimental part of the research projects to a successful conclusion. On the contrary, they often provide technicians with no more than a rough sketch of the kind of instrument or apparatus required to solve the technical problems that arise in the course of their research. It is then up to the technicians to draw on their knowledge and practical expertise of engineering—their knowledge of the properties of different kinds of material and their understanding of what particular tools can be used to achieve—along with their general problem-solving skills in order to design and build the requisite instrument or experimental apparatus. The process through which the final design of the experimental apparatus or instrument emerges is therefore perhaps best described as a dialogue or iterative process in which researchers and technicians work as a team in order to develop the instrument or experimental apparatus required to give practical effect to researchers' ideas. Through such informal interaction with researchers, technicians make an invaluable, if all-too often unheralded, contribution to research (Toner *at al*. 2010: 3-5; Lewis and Gospel 2011: 16-17; Herrmann and Peine 2011: 698).

Second, technicians' experience of operating and maintaining machinery, and of manufacturing products, affords them important practical knowledge of what designs work well and which give rise to problems. This information enables technicians to provide advice to the scientists and engineers involved in R&D about which designs are likely to work well and so should be adopted and which will be hard to realise in practice and so should be dropped. Some examples of the kind of contribution technicians can make are as follows:

- In industries that use composites materials, technicians' experience of how work is actually carried out on the shop floor—and, in particular, their awareness of the difficulties that can arise in realising certain kinds of design—enables them to provide valuable advice and feedback to ostensibly better qualified, but in terms of hands-on laminating often less knowledgeable, graduate engineers about how to design components in ways that make them as easy to manufacture as possible. For example, one high-end automotive company reported that it had greatly improved the process through which new composite components were made by having technicians in its design office who 'have a feel for' what composite materials can and cannot be made to do and what kinds of design can be made quickly and reliably and which cannot (Lewis 2013b: 22-23).
- Skilled technicians play a key role in the development of new goods by high-end producers of kitchen and tableware such as Alessi, by acting as intermediaries between designers and manufacturing engineers in order to ensure that the designs chosen can readily be manufactured (BIS 2011: 16-17; D'Ippolito 2014: 1335, 1343-44).
- An organisation involved in the maintenance, repair and overhaul of commercial aircraft described how its technicians pointed out to a chartered design engineer that the repair he had designed for an aircraft structure would not be feasible, because in practice the pipes and wiring looms on the aircraft precluded the kind of access needed to effect it (Lewis 2012a: 9).

These examples illustrate how technicians make their own distinctive contribution to the knowledge creation required for R&D. This is of course consistent with the non-linear view of innovation; rather than simply implementing ideas developed by the scientists and engineers involved in R&D, technicians draw on their knowledge of what designs can be turned into reality at later stages of the innovation process to feed back on and inform underlying research and development.

These examples have important implications for the organisation of work in organisations carrying out R&D, namely that firms seeking to innovate should not leave their R&D department to operate in isolation from their manufacturing operation, lest they end up designing products that do not lend themselves to manufacturing in a straightforward way. As Cohen and Levinthal (1990: 134) put it: "a process in which one unit [R&D] simply hands off the design to [another unit] is likely to suffer greater difficulty" than one where R&D and manufacturing and work together, with technicians incorporated into R&D departments (also see Toner *et al*. 2010: viii-xi, 28).

5.2.2.2 Incremental innovation

It is also increasingly widely recognised that, in addition to contributing to and facilitating the diffusion of radical innovations, technicians also play a key role in incremental innovation (that is, the gradual improvement of existing products and technologies). In the words of the historian of technology Nathan Rosenberg, incremental innovations "involve endless minor modifications and improvements in existing products, each of which is of small significance but which, cumulatively, are of major significance" (Rosenberg, 1994: 14-15). They require an "intimate familiarity with the minutiae of the productive sequence" of the kind technicians acquire through their experience of installing, operating, maintaining, adapting, and solving problems with, the machines and processes in which technology is embodied (Rosenberg 1982: 122). In performing their duties, therefore, technicians learn how the technologies in question can be improved, enabling them to contribute to the creation of the knowledge that gives rise to incremental innovation. Such incremental innovation is highly significant, suggesting another important route through which technicians have an important contribution to make to innovation (HØyrup 2010: 144, 149; Toner 2010: 78-79, 2011: 3, 26-29; also see Dahlman and Nelson, 1995: 95).

The degree to which a firm's workforce actively engages in such bottom-up, incremental innovation is strongly influenced by the way in which work is organised, in particular by the extent to which technicians are allowed and encouraged to make suggestions for how technology can be improved (Høyrup 2010: 150; Toner 2011: 3; Jones and Grimshaw 2016: 110). The organisational policies which facilitate technician-driven innovation often fall under the heading of 'high-performance work systems' (HPWS). These can be defined as organisational practices and arrangements that enhance a firm's capacity for making incremental improvements to the efficiency of its work processes and to the quality of its products and services (Arundel *et* al. 2006: 1178-79; Toner 2011: 53). Features of HPWS include the following:

- broad-based job descriptions and occupationally-oriented training which, when coupled with extensive job rotation, increases both the flexibility of workers and also their capacity to understand the production process and thereby contribute to its improvement;
- the granting of significant autonomy to workers involved in production, so that they have the scope to act on their practical knowledge of how production might be improved;
- the development of trust between workers and management, so that the former are willing to advance their ideas for how improvements can be made; and
- rewards in the firm of bonus payments and/or enhanced prospects for promotion when the active participation of front-line workers in innovation leads to improvements.

These HRM practices are often complementary or mutually reinforcing in the sense that the impact of any one of them is greater if it is combined with others than if it is adopted in isolation. For instance, autonomy and training are complementary because affording workers the opportunity to take the initiative in making incremental improvements in production is typically more effective if they have the skills and knowledge required to identify and enact such improvements (Michie and Sheehan 1999; Laursen and Foss 2003; Jensen *et al*. 2007: 684; Toner 2011: 54-56; Sung and Ashton 2015: 134-69; OECD 2017: 11, 74-75).

What the evidence reported in this section suggests, therefore, is that the knowledge creation involved in innovation is no longer regarded as the exclusive preserve of people educated at graduate level and above, working in R&D facilities, but rather is conceptualised as issuing from several levels of the workforce, including technicians. The practical experience gained by technicians in carrying out their duties can be harvested and made explicit, leading to a change in the firm's working routines so that technology is better used. This is, of course, of a piece with the non-linear model of innovation described above, in which the learning that gives rise to innovation is generated not just from pure scientific but also from several other sources of the process through which new technologies come to be developed and deployed, including the production stage in which technicians are so intimately involved (Jensen *et* al. 2007; HØyrup 2010: 151-53; Toner 2010: 78).

This type of analysis arguably leads to the view that the scope of public policy ought to extend beyond a focus on the supply of skills towards a concern with how skills are deployed in the workplace and, in relation to this, with employers' demand for skills. For if the impact of an increase in skills on innovation is contingent on the other practices adopted by firms, such as how they organise work and whether they adopt a low skill/low cost/low value business strategy, competing principally on the basis of price, or a high skill/high cost/high value one, competing on the basis of quality, then it might be argued that government ought to encourage business strategies and forms of work organisation that mobilise high levels of skill and high value added (Finegold and Soskice 1988; Ramstad 2009; Campbell 2012: 33-35; Keep and Mayhew 2014; Keep 2013; Sung and Ashton 2015).

5.3. TECHNICAL EDUCATION AND SYSTEM FAILURES

In this section we draw on the notion, outlined above, of 'system failure' to analyse some of the problems that can arise when the organisations and rules governing the provision of vocational education and training fail to disseminate the information and other resources, and to coordinate the activities, required to develop the technician workforce needed to make good use of new technologies.

5.3.1 Education and training organisations, 'skills systematisation' and coordination failures

Standard human capital theory, on which the economic analysis of vocational education and training is based, typically assumes that education and training providers alter their offerings seamlessly to the availability of new technologies, however novel, and automatically offer the right kind of training to enable firms to build the absorptive capacity to exploit them (Nelson and Phelps 1966; DBIS 2014: 22-23). It therefore ignores the possibility that the organisations involved in education and training may fail to adjust their offerings appropriately, thereby hindering the adoption of the technology in question, with detrimental consequences for innovation, productivity and economic growth (Andreoni 2014: 58, 60; Vona and Consoli 2014: 1394-95, 1400).

Recent work has attempted to fill this gap by considering explicitly the role of educational organisations—such as schools, universities and training providers—in facilitating, or hampering, the development of the skills required to realise fully the potential of new technologies (Vona and Consoli 2014). Instead of simply assuming that such organisations seamlessly adjust their offerings to match the requirements of new methods of production, this literature examines the effectiveness of those organisations, and the rules governing their behaviour, in facilitating or hampering the development of the workforce required for the successful diffusion of new technology. As two of the researchers who have developed this approach put it, their goal "is to articulate in detail the link between the emergence of new skills closely tied to radical new technology and the adjustments that are made in formal education to reap the potential benefits of innovation" (Vona and Consoli 2014: 1393; also see p. 1397).

A key concept in this literature is that of 'knowledge systematisation', which is used as a conceptual device for connecting technology, organisations and human capital. Initially, as a new technology is first being developed, the activities associated with it tend to be complex, ill-structured, and the preserve of a small number of specialist researchers. The relevant knowledge is mostly tacit, and therefore difficult to transfer without personal interaction between those who already possess it and those attempting to acquire it. As the technology is developed, however, it becomes possible to articulate, systematise and standardise the production techniques in question, so that they can be reduced to a series of explicit, routine work instructions or standard operating procedures of the kind that can be carried out by a skilled technician (as required for the efficient scaling-up of production from an R&D facility or process development plant to full scale manufacturing).[7] As this process of 'knowledge systematisation' takes place, the education system has an important role to play in ensuring the availability of the skills required for the effective exploitation of this developing technology. In particular, the organisations involved in education and training must offer the relevant programmes, so as to facilitate the training of workers with the skills required for the widespread exploitation of the new technology (Vona and Consoli 2014: 1394-99; also see Tether *et al*., 2005: 8, 97, Toner 2011: 29, and D'Ippolito *et al*. 2014: 1335-36).[8]

If they do not do so—if the relevant education and training organisations are absent, or if the institutional rules governing their behaviour are inappropriate—then there arises the possibility of coordination failures, whereby the education system fails to align the accumulation of human and physical capital, focusing on one kind of skills (graduate, say) and neglecting others that are needed to exploit novel technology (for example, technician-level skills).[9] Such coordination failures lead to structural mismatches between the stocks of physical and human capital. These manifest themselves along the lines described in Section 5.2.1 above and Section 5.3.2 below, in problems such shortages of technicians, deficiencies in technician skills, and/or the use of over-qualified but under-skilled graduates in technician roles, that hamper the 'absorption' of new technologies and thereby inhibit productivity and economic growth (Amendola and Vona 2012: 633-34; Vona and Consoli 2014: 1400-05; Andreoni 2014: 60-62, 65; Borras and Edquist 2012: 223; Smith 2010: 89-90; Weber and Truffler 2017: 112).

Failings of this kind are 'systems failures' in the sense in which that term is used in the innovation systems literature; the system of organisations and rules within which innovation occurs is inadequate to coordinate all the activities required to ensure that new technologies are developed and diffuse properly through the economy, in this case because the organisations governing vocational education and training do not supply firms with the specific types of human capital required to make best use of the technologies in question. Put slightly differently, if it is indeed the case that one of the attributes of a well-functioning innovation system is its "capability to ensure timely access by innovators to the relevant stocks of knowledge" (Smith 2000: 78), and if those stocks of knowledge including the practical and theoretical knowledge embodied in skilled workers at all levels, including technicians, then where the

7 For discussions of this process in the case of cell therapy and regenerative medicine, see Eriksson and Webster (2015).

8 Earlier analyses of technology-driven economic development have underlined the significance of supportive educational institutions in facilitating the systematic updating of educational curricula for the development of the chemical and petro-chemical industries (Nelson 1994; Rosenberg and Nelson 1994; David and Wright 1997). They have, however, tended to focus on the importance of universities rather than institutions involved in vocational education and training.

9 This is in addition to the possibility, long discussed in the literature on human capital, that there may be a market failure to invest adequately in skills due to employers' fear of poaching (Stevens 1999; Lewis 2014a: 13-16).

organisations involved in vocational education and training do not supply adequate numbers of skilled technicians the innovation system can be said to have failed because it is not providing firms with the right quantity, and blend, of practical and theoretical knowledge to make the best use of new technologies.

5.3.2 Systems failures in the UK: The case of technician skills for emerging technologies

There is evidence of coordination problems of the kind just described in the case of technician skills and training for emerging technologies in advanced manufacturing in the UK. Employers seeking to deploy new technologies in the space industry, in advanced therapies, in industries that make use of composite materials, and in industrial biotechnology all report significant difficulties in obtaining the skilled technician labour they need to deploy those new technologies effectively. For example, as noted above, space firms struggle to hire experienced, high-quality manufacturing technicians, as do employers in industrial biotechnology and the advanced therapies industry (Lewis 2012b: 25-26; 2016a: 34-35). Employers in the aerospace and automotive industries who wish to make greater use of composite parts find it hard to recruit technician skilled at working with that material (Lewis 2012a: 21-22, 2013b: 33-35).[10] These shortages impose limits on the absorptive capacity of firms.

Employers in some industries have responded to shortages of genuine technicians—and the abundance of science graduates produced by UK universities—by recruiting graduates to fill technician roles. This is especially common, for example, in the case of laboratory and manufacturing technician roles in the chemical industry, industrial biotechnology, and in cell therapy/regenerative medicine (Lewis 2013a: 16-18, Lewis 2016a: 17-20, 31-32; Lewis and Gospel 2015: 10-11; House of Lords 2018: 23-25). This is a case of *over-qualification*; the level of education possessed by the graduates exceeds that required for the role.[11] The use of graduates to fill such roles is often a mixed blessing, bringing short-term benefits in the form of cheap labour—the abundant supply of such workers produced by UK universities means that they can often be hired at relatively low wages—but also giving rise to two kinds of problem in the longer term.

First, whilst graduates may possess a higher level of theoretical knowledge than is needed to fill a technician role, they are also often under-skilled, because they lack the practical skills required to apply that theoretical knowledge to good effect in the workplace and thus to do the job well. This is an example of what a recent study of over-qualification refers to as a "possibility which tends to get overlooked—that graduates are less capable in some occupations than the non-graduates they are displacing" (Holmes and Mayhew 2015: 12). This is because certain skills are more effectively produced in the workplace through supervised practice, rather than in an academic institution. However, given labour market and societal pressures and government rhetoric and information, the sort of able young person who might once have gone down a work-based vocational learning route (and successfully entered a good occupation) opts instead to apply to university, and consequently fewer new labour market entrants have those

10 This is against the background of more general evidence of shortages of skilled technicians (UKCES 2010a, 2010b, 2015: 66-71; Adonis 2014: 6-9; HM Government 2017: 37-38, 48; OECD 2017: 26-27). Evidence indicates that the share of the workforce with technician or intermediate-level skills is significantly lower in the UK than in our major competitors (HM Treasury and Department of Business, Innovation and Skills 2011: 36; BIS 2015: 17).

11 Evidence indicates that the problem of over-qualification is significant both in absolute terms, with somewhere in the region of one quarter and one third of UK employees falling into that category (Chevalier and Lindley 2009; Green and Zhou 2010; UKCES 2015: 7, 57), and also that the scale of the problem is worse in the UK than in most other European nations (OECD 2013: 171; Holmes and Mayhew 2015: 25-28).

particular skills. (Holmes and Mayhew 2015: 12; also see UKCES 2015: 46 and Jones and Grimshaw 2016: 109.)

Second, graduates often quickly become dissatisfied, both with the often mundane, highly routinised nature of much technician work and also with the relatively low wages they earn in such roles, and so often leave relatively soon after joining their employer. The combination of these two problems—a lack of practical skills, which implies that graduates require on-the-job training in practical skills, and high labour turnover amongst graduates in technician-level roles—is especially frustrating for employers who, having spent time and effort equipping the graduates with the practical skills required for technician roles, then see them leave before the firm enjoys a return on its investment.

What these findings suggest is that the UK education system is arguably producing the wrong mix of skills, with too many graduates and too few technicians being educated in some STEM disciplines. As a recent report House of Lords Report on the economics of post-school education described the situation, "There is a skills mismatch in the UK: despite the record numbers of the population with an undergraduate degree businesses are reporting a shortage of people with technical skills … Rather than a need for more STEM graduates … the greater shortages today appear to be for people with sub-degree qualifications … there is an acute shortage of technician-level STEM skills (House of Lords 2018: 15, 22; also see pp. 5-8, 23-27, 42-53, National Audit Office 2016: 8, 18, 23-26, and OECD 2017).[12] As noted above, this kind of mismatch is symptomatic of system failure, involving firms suffering from reduced absorptive capacity arising in this case because the rules governing the provision of different kinds of post-school education in the UK have encouraged too great a focus on graduates compared to technicians.

Increasing numbers of employers in emerging industries are responding to the problems posed by shortages of technicians, and the shortcomings of graduates, by turning towards apprenticeship training.[13] Where successful, this brings a number of benefits. A successful training scheme yields a supply of skilled workers to fill technician roles in the face of a paucity of skilled technicians on the external labour market, improving firms' absorptive capacities. It also produces workers who, having enjoyed significant on-the-job training as well as off-the-job technical education, have good practical skills. Moreover, having come up via a 'work-based' route, ex-apprentices are less likely to be encumbered with unrealistic, graduate-level expectations of what their job will involve. Finally, apprenticeship training gives employers an opportunity to shape their values (for example, about the standards to which work needs to be done). It also builds loyalty, as former trainees reciprocate the investment firms have made in them through greater commitment to their employer (Ryan *et al*. 2007: 140-41; Lewis 2012a: 29, 2012b 31-32).

However, many of the employers who have attempted to train apprentices to work with emerging technologies have faced serious problems obtaining the requisite education and training. Two broad categories of difficulty can be identified.

12 "The evidence suggests that there is a mismatch between the qualifications and skills provided by the higher education system and the needs of the labour market … The combination of incentives to offer and study for undergraduate degrees has had a negative effect on the provision and demand for other types of higher education … [T]he lack of sub-degree technical qualifications has led to a mis-match between the skills attained through the education system and those required by the economy" (House of Lords 2018: 9, 55).

13 An 'apprenticeship' is a contract between an employer and a young person that combines a structured programme of on-the-job training and productive work with part-time, formal technical education. Apprenticeship training, which is usually formally certificated, equips people with intermediate-level skills of the kind required by people who fill roles typically described as 'Skilled Trades' and 'Technicians/Associate Professionals and Technical Occupations' (Ryan *et al*. 2007: 129; Lewis 2014a: 1).

First, many of the organisations that are currently take apprentices, or are seriously thinking about doing so, have had difficulties obtaining the off-the-job technical education their apprentices require if they are to acquire the theoretical knowledge they need to do their job well. For example:

- Employers in the space industry have struggled to find a local college or university willing to offer the off-the-job courses their manufacturing apprentices need (in particular, HNCs in electronics);
- Employers in the composites sector have found it hard to find colleges willing to offer their apprentices modules in composites engineering;
- Firms in industrial biotechnology have found it difficult to persuade local colleges to offer courses in the underpinning knowledge required by their laboratory technicians and, in the case of industrial biotechnology, their manufacturing technicians as well.

Second, firms in the composites, industrial biotechnology, and cell therapy/regenerative medicine industries have also struggled to persuade colleges to offer high-quality, up-to-date practical training for their apprentices so that they can learn how to use new methods of production. The problem here sometimes centres on a total absence of provision, as experienced by employers in the life sciences who wish their apprentices to receive training in cell cultivation under clean room/cGMP conditions; and sometimes—as in the case of employers with apprentice aircraft mechanics and composite technicians—on inadequate provision, delivered in poor facilities by lecturers unfamiliar both with the techniques and materials currently used in industry and also with current standards of good practice (Lewis 2012b: 31-32, 2012b: 31-32,_2013b: 46-47; Lewis 2016a: 39-40).

The principal reason for these problems lies in what might be called 'the tyranny of small numbers'. The total number of apprentices wanting to take the courses in question in the relevant geographical area is too small for it to be in the interest of colleges to offer them, given the high fixed costs of providing the training in question and the prevailing funding regime under which colleges and other providers operate. As Alison Wolf has explained, the rules governing apprenticeship funding encourages providers to focus provision on shorter, cheaper, lower-level (1-2) programmes, in subjects such as customer service and business administration, rather than the longer, more expensive, higher-level (3-5) apprenticeships required by employers in advanced manufacturing. This is so, Wolf argues, for two main reasons: first, because such courses are easier to pass, so that it is easier for providers to claim funding for them under the current 'output-related' funding system; and also, second, because for any given level of difficulty, if a provider offers a large number of shorter courses, then the risk of it suffering an unexpected shortfall of income because of an unusually high number of failures in any one group is reduced if that risk is spread over a larger number of cohorts (rather than a smaller number of groups on longer programmes). One might even say that there is a skills 'valley of death', whereby training providers struggle to develop commercially-viable programmes for emerging technologies in advanced manufacturing, akin to the technology 'valley of death' that thwarts efforts to commercialise the new technologies themselves.[14] The upshot is a situation where training providers lack the incentive to offer the kinds of courses needed by

14 The 'valley of death' is the term used to describe the phase of innovation between research and the initial generation of ideas, on the one hand, and their full-scale commercial exploitation, on the other (McKinsey Global Institute 2012: 136; Edler and Fagerberg 2017: 17).

employers in advanced manufacturing who wish to train apprentices to work with new manufacturing technologies (Wolf 2015: 5-6 9-12, 32; BIS 2015: 18 30-31; HM Government 2017: 39, 41-42; House of Lords 2018: 48-50, 74-75; York Consulting 2018: i, 5-8; also see Toner 2010: 83, OECD 2017: 21-22, 51 and NASEM 2017 106).[15] This is another example of system failure, exemplifying the kinds of difficulties that can arise when the rules governing the behaviour of education and training providers discourage them from offering the programmes required by employers seeking to deploy new technologies.

5.4 TECHNICIANS AND INNOVATION: A POSSIBLE SOLUTION

The evidence from several emerging sectors suggests, therefore, that the rules governing the relations between emerging manufacturing sectors and the educational system, in particular the system of vocational education and training, are flawed, in such a way that there are insufficient technicians with the skills required to facilitate the successful adoption of new technologies. What is required for successful innovation, in addition to the high-level scientific and engineering capability to develop new technologies, is a set of educational organisations and rules that will provide in a timely manner the technician skills needed to implement new technologies to good effect at commercial scale. Put slightly differently, the development of the technician workforce must take place in concert with, and be accorded the same priority as, technology development, rather than happening—as is all too often the case at present—as an afterthought.

Aside from undertaking a general reform of the funding regime governing FE colleges and other training providers (House of Lords 2018: 42-53), policy-makers could address this problem, and thereby help to ensure an adequate supply of skilled technicians for employers seeking to deploy innovative technologies in advanced manufacturing, by considering the following approach:

- First, develop only a small number—one or two—of centres of excellence that offer the requisite training, located in areas where there is a significant concentration of the relevant kind of manufacturer.
- Second, ensure that those organisations offer training via distance learning, supplemented by periodic residential courses or stints of block release, in order to extend their reach beyond the geographical area in which they are located (and including not just England but other parts of the United Kingdom).
- Third, as far as possible design the training courses so that they are suitable not just for apprentices from one industry—cell therapy and regenerative medicine, say—but also for two other groups of people: (i) apprentices from other, closely related industries whose training requirements may be similar (e.g. biologics); and (ii) graduate recruits and 'converts' from other industries who, while they may have already received significant education and training, may still need additional instruction in the particular requirements of working with the new technology in question (e.g. chemical process operators who are moving into industrial biotechnology). This will further increase demand for the training programmes in question, increasing their financial viability (Lewis

15 Wolf (2015: 32) highlights how most of the recent increase in apprentice numbers has been concentrated in low-cost areas, and also at below level 2 (also see Lanning 2016: 5-7). Field (2018: 52) reports that a smaller proportion of full-time students study higher-level (level 4/5) technical qualifications in the UK than in many other countries. For more general concerns about whether the incentives that encourage the FE sector to provide training in STEM disciplines are sharp enough, see Skills Commission (2011: 10-11, 23-27), Wolf (2011: 60), Westwood (2016: 47) and Sainsbury (2018: 7).

2016b: 20; Lewis and Bradshaw 2017: 5).The importance of devising training programmes for existing workers is perhaps especially important in the case of the new skills required of workers in industries where manufacturing will be transformed by innovative digital technologies associated with (so-called) industry 4.0 (Maier 2017). Further research on this issue of the need to retrain the existing technician workforce so that are equipped with the skills required to deal with these developments is urgently required.

- Fourth, reduce the initial financial outlay, and risks, associated with the provision of the practical component of the training by using existing facilities rather than building new ones.The use of existing facilities should reduce the size of the investment required to establish the training programmes because some of the relevant equipment and personnel will already be in place; and it will reduce the risk because the facilities can be used to generate income from sources other than training, such as research/process development work (Lewis 2016a: 44-45; Lewis 2016b: 20- 21).[16]

Establishing centres along the lines just described holds out the prospect of overcoming the workforce 'valley of death'—akin to the technology valley of death—that arises at present because training providers fear that there will be insufficient demand for their services to warrant them incurring the high fixed costs of establishing the relevant facilities, etc.

Prominent examples of the relevant kind of existing facility are to be found in the Catapult Centres.[17] Some Catapults, such as the AMRC and MTC, have become involved in apprenticeship training to very good effect; but others have not (Lewis 2014b; Burnett 2016; Perkins 2019: 52-53). Using the Catapults has at least two key advantages. First, it would make it possible to avoid the expense of setting up yet another new organisation, which would be wasteful and probably prohibitively costly in the current financial climate. Second, because Catapult Centres are involved in process development work, it should be relatively straightforward to ensure that training programmes and syllabuses are kept up to date and thereby remain attuned to the needs of industry (something that is especially important in an industry like cell therapy/regenerative medicine, where the pace of technological advance in manufacturing is rapid).

More specifically, it should be possible to follow the example of the one of the US Manufacturing Institutes, the American equivalent of the Catapult Centres, and develop within the Catapults so-called 'expert educator' teams to engage in the 'skills systematisation' required to develop a suitable technician workforce

16 Employers might also be encouraged to support the workforce development efforts of such centres, for example by providing up-to-date equipment.This might reflect a wider notion of 'employer leadership' than is often used in the field of vocational education and training in the UK, where all too often that phrase is interpreted to mean little more than employers being able to choose from a menu of training programmes to whose provision they have contributed little. Far from being an act of charity, this can of course be in the interests of the firms in question. Not only will employers who contribute benefit from having a better-skilled workforce; in addition, equipment manufacturers who supply kit for the training facility are likely to benefit, not least because if firms cannot be confident that their workers know how to use and maintain a particular piece of equipment, they are unlikely to buy and use it.

17 Catapult Centres are technology centres where universities, businesses and government work together to encourage the commercialisation of new technologies.Their goal is to reduce the risks associated with the development of such technologies, in particular by providing facilities and expertise to demonstrate that the technologies in question can work not just at the laboratory level but at full, commercial scale. In this way, by helping to solve some of the market failures that hamper the commercialisation of new technology, they can help firms developing new technologies to pass safely through the so-called 'valley of death' (that is, the phase of innovation between the initial generation of an idea and its full-scale commercial exploitation, through which many innovative technologies fail to pass) (TSB 2011; Hauser 2014: 10-16, 45-46). Other innovation centres, such as NPL and RAL, also arguably have the potential to play a similar role to Catapult Centres in disseminating information about the skills required successfully to exploit new technologies.

for emerging technologies. These consist of a small group of people who are knowledgeable both about science and education, and who will work with the Manufacturing Institute and employers to harvest information about the skills and knowledge needed to exploit new technology and translate it related statements of competence and job descriptions, and educational and training syllabi, so that training programmes keep pace with advances in technology (Bonvillian and Singer 2017: 235-36; LIFT 2017: 3-4; Lewis and Bradshaw 2017: 8-9).[18] They constitute a concrete example of how it is possible to develop the connections between organisations—in this instance, between employers and providers of vocational education and training—needed to facilitate the flows of information, in this case about the workforce required to operate emerging technologies, required for a smoothly working innovation system (cf. Ferrier *et al*. 2003: 27, 50, 61-62; Down 2004: 114-16; Whittingham *et al*. 2004; Metcalfe 2005: 68-71, 2007: 451).[19]

An example of an initiative developed along these lines comes from the therapy/regenerative medicine sector. Firms in that industry are just beginning to move from a focus on R&D and process development to begin full-scale commercial manufacturing. As they do so, they will need to employ increasing numbers of specialist cell therapy manufacturing technicians. Employers are adamant that the people who occupy those roles will need to be genuine technicians, rather than over-qualified but under-skilled graduates (Lewis 2016b; Lewis and Bradshaw 2017). Initial support from the Gatsby Foundation, built on by funding from Innovate UK, made it possible for employers in cell therapy/regenerative medicine to work with each other, and with the Cell and Gene Therapy Catapult Centre, to create a suitable apprenticeship training scheme. The institutional 'home' of the team that will be managing the apprenticeship seems likely to be in the Cell and Gene Therapy Catapult Centres (whose facilities may also be used for some very specialist training, and whose knowledge of new developments in the relevant technology will be essential in ensuring that the relevant training programme will be kept up to date).[20]

However, some Catapult Centres may—indeed, arguably have been—discouraged from playing a role in technician skills and training because unlike their counterparts in some other countries, they do not have (a measure of) skills development as one of their key performance indicators. Consequently, their record when it comes to skills development, especially at the technician level, is mixed. Some, such as the Advanced Manufacturing Research Centre and the Manufacturing Technology Centre, have become involved in apprenticeship training on a significant scale to very good effect. However, others have paid little attention to technician skills and training, concentrating instead on training people qualified to graduate level or above.[21] Given the importance of having a well-trained technician workforce to carry out manufacturing in general, and for the absorption of new technologies in

18 Also see http://www.aplu.org/projects-and-initiatives/economic-development-and-community-engagement/Aligning-Technology-and-Talent-Development/Index.html.

19 Bonvillian and Singer (2018: 225) make a similar point with regard to the USA's Manufacturing Institutes. Like Catapults, these organisations are responsible for facilitating the development of emerging technologies. Unlike Catapults, they have taken on board the principle that workforce development must go hand-in-hand with technology development. As Bonvillian and Singer put it, "[E]ducation and training programmes should not be a sideline but rather a key part of the technology development and dissemination effort" (p. 225; also see pp. 232-36). Also see LIFT (2017).

20 See https://ct.catapult.org.uk/news-media/general-news/cgt-catapult-announces-major-uk-investment-skills-and-capabilities and https://ct.catapult.org.uk/news-media/general-news/addressing-sector-skills-gap-first-apprenticeship-programme-advanced. Accessed 12th March 2019.

21 This failure to put technician training on a par with R&D is arguably symptomatic of the continued influence of the old, linear view of innovation, which—as we have seen—emphasises the importance of high-level scientific research and neglects the importance of other influences on the development and diffusion of new technologies, including those associated with the work of technicians (Lundvall 2007: 104; Toner 2011: 8; CIPD 2014: 7, 24-26; Filippetti and Guy 2016: 506-07, 515; also see Jensen *et al*. 2007: 690).

particular, the current approach—whereby some of the Catapult Centres become involved in training on an *ad hoc* basis—seems to be flawed. It is necessary to give the Catapult Centres a clearer remit to work with training providers to ensure the provision of high-quality apprenticeship training for emerging technologies, so as to put workforce development on a par with technology development in the Catapult Centre's list of responsibilities. This could be done through the explicit inclusion of (indicators of) skills development as one of the key benchmarks against which their performance is assessed (Lewis 2014b, 2016a: 44-45, 2016b: 21; Gatsby Foundation 2017: 7; Perkins 2019: 53). In this way, an institutional framework could be established that would help to provide an adequate supply of skilled workers for employers in advanced manufacturing, so that workforce development and technology development can be properly aligned and coordination failures and structural mismatches avoided.[22]

Involving the Catapult Centres in technician skills and training also holds out the prospect of a solution to some of the other problems that bedevil technician skills and training in emerging industries, namely that firms in such industries are often small, unfamiliar with apprenticeships, and have highly truncated time horizons. First, many of the firms that are developing and deploying emerging technologies are SMEs who may be deterred from taking on apprentices by a lack of familiarity with apprenticeships and with the precise requirements of apprenticeship training programmes. This may be especially problematic because many such firms lack a large HR team that can master the process of taking on and training apprentices. Such firms may therefore simply decide that it is easier to hire over-qualified graduates to fill technician roles rather than fight their way through what is in the UK at least a rather labyrinthine apprenticeship system. Second, those firms are also often said to have short-time horizons, being preoccupied with the immediate demands of running and developing their business and not looking far enough ahead to contemplate the need to fill technician roles in two to three years time (Sims *et al*. 2000: 1; Lewis 2014c: 505; NASEM 2017: 77). The problem, of course, is that if firms do not look that far ahead, then given the long lead time involved in technician training, the workers in question will not be available when they are needed.

The Catapult Centres may have a significant role to play in dealing with these problems. If a dedicated apprenticeship team, consisting of no more than one or two people, were employed within each Catapult, then they could play a convening or coordinating role that would see them assist SMEs in recruiting apprentices, in finding a suitable training provider, and in navigating the requirements of apprenticeship training programmes (as well as exploiting opportunities for funding). In this way, it might be possible to relieve SMEs of much of the burden of managing the apprenticeships, thereby removing one of the barriers to their

22 This imperative has already received some recognition in Scotland, where the recent Reid review of Innovation Centres (ICs)—the Scottish counterpart to the English Catapult Centres—stated the following: "The ICs were created to help bring academic expertise to business-led challenges that would have an economic impact for Scotland. The success of the college sector in Scotland can be through innovation of business products, but is more often about delivering skills, and through those enhanced skills, improved productivity and efficiency. The delivery of skills is not some sort of "secondary" innovation – developing new skills and techniques to apply alongside new technological innovation is vital if such developments are to be embedded and made truly a commercial success. Having the college sector work more closely than is currently happening with both the ICs and the university sector should strengthen the performance of the ICs" (Reid 2016: 38; also see Scottish Funding Council 2017).

participation in such programmes.[23] A more radical possibility, which might address the second of the two problems noted in the previous paragraph, would involve the Catapult Centre in actually employing the apprentices, who would then be hired out to SME 'host employers' for the duration of their training. The host would pay a fee for this service, the size of which would depend both on the apprentice's wage and also any management fee charged by the Catapult Centre.

Precisely which delivery model is best is likely to vary between sectors, so one would not expect all Catapult Centres to play their role in aligning workforce and technology development in the same way. But that they should have such a role seems clear.

23 This is not, of course, the only way in which these problems might be solved. Another possibility, which firms in advanced manufacturing have adopted, centres on what is called 'over-training'. This involves a large employer, who currently offers high-quality apprenticeships, playing a role in the training of more apprentices than they themselves require to meet their own anticipated needs, with the extra apprentices being employed from the outset of their apprenticeship by other firms (often small and medium-sized enterprises). The larger firm will typically manage the training and assessment of the apprentices, using its own apprentice managers, instructors and assessors to do so. It may also provide some of the on-the-job training itself, especially if it has its own training facilities. The smaller firms that have their apprentices managed in this way can gain access to a more experienced, and effective, way of managing and training their apprentices than they themselves could provide on their own. Moreover, the large employers that offer such over-training do not do so as a charitable act, but rather because they expect to benefit from doing so, for one of two reasons: either because the government funding and fees they gain from over-training help them to cover some of the fixed costs of running their own apprenticeship schemes; or because, by training apprentices for firms in their supply chain, they stand to gain from having better quality, and /or more reliable, input supplies. Several large employers in UK advanced manufacturing already engage in over-training and there exist some firms in sectors using emerging technologies, such as those involved in the ATMP and biologics industries, that are well situated to join their ranks (Lewis 2014c).

6. CONCLUSION

Technicians make significant contributions to innovation. They often participate in the experimental work involved in research and development. They draw on their detailed, practical experience of production to make suggestions about incremental improvements in production processes. And, perhaps most important of all, they have a critical role to play in enabling firms successfully to deploy new technology, thereby contributing to the absorptive capacity of the firms that employ them.

In the UK, however, the critical role played by technicians all too often goes unrecognised, obscured by a commitment on the part of policy-makers to a linear view of innovation that over-emphasises fundamental research and development and so neglects other important influences on innovation, in particular those stemming from technicians. The shortcomings of the institutions governing vocational education and training mean that workforce development is often poorly aligned with technology development, leading to system failures in the sense in which that term is used in the innovation systems literature. In particular, firms seeking to introduce new technology all too often struggle to find the skilled technicians they need to do so.

What is required to deal with this problem is a system of institutions that will encourage and enable the production of workers with the skills required effectively to deploy new technologies (perhaps especially those characteristic of emerging, high-value added industries where productivity and wages are likely to be high). If the benefits of those technologies are to be fully exploited, then their development must go hand-in-hand with the training of the workers—prominent amongst them the technicians—who will put them into practice in the workplace. Catapult Centres, and other innovation centres, are very well placed to respond to the demands that technological innovation places on firms' workforces, and to play a key role in enabling employers to obtain the key technician skills they require. Those organisations need to be given an explicit remit to play the critical role they can serve in workforce development so that, to borrow the terminology of the chief economist of the Bank of England, they can become 'diffusion spokes' as well as 'innovation hubs' by helping firms to develop the technician workforce required to make good use of new technologies as well as to develop them in the first place (Haldane 2018: 16).

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