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Committee for Scientific and Technological Policy

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THE NEXT PRODUCTION REVOLUTION -- AN INTERIM PROJECT REPORT

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This document contains interim findings from the cross-cutting project, led by CSTP, entitled "Enabling the Next Production Revolution". Following comments from CSTP and the other involved committees, a condensed version of this interim report will be submitted to Council for subsequent submission to the June 2016 Ministerial Council Meeting.

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2. The next production revolution (NPR) project focuses on the technologies of future production, with an emphasis on manufacturing. The background is one in which major science and technology-driven changes in the production and distribution of goods and services are occurring and diffusing widely. Other developments – possibly more significant still – are on the horizon. Such changes will have far-reaching consequences for productivity, skills, income distribution, human well-being and the environment. The more fully governments understand how industrial production could develop, the better placed they will be to prepare for the risks and reap the benefits. Through judicious policy, the opportunity exists now to shape the next production revolution.

Key messages

3. Information and communication technology (ICT) is transforming production. For instance, the combination of big data analysis, cloud computing and the Internet of Things[1] is enabling increasingly autonomous and intelligent machines.

4. Because the effects of ICTs are pervasive, government action is often needed across many areas. Access to useful data and critical ICT infrastructures has to be broadened, and barriers to diffusion lowered (many businesses, in particular SMEs, lag in adopting ICTs). Standards development and interoperability need to be supported. Skills bottlenecks have to be removed. Issues of liability, transparency and ownership require resolution (for instance, data analytics leads to new automated ways of making decisions. This can raise productivity but also raise new legal questions). Digital security and privacy risks have to be managed (for example, governments need to promote data use in ways that prevent privacy violations).

5. The tools exist today to begin **a bio-based revolution in production**. Bio-based batteries, artificial photosynthesis and micro-organisms that produce biofuels are just some among recent breakthroughs. Biotechnology also offers unique solutions to dependence on oil and petrochemicals.

6. Governments can assist the development of sustainable supply chains for bio-based production and consider supporting the development of bio-based chemicals. Demonstrator bio-refineries, built through public-private partnerships, can help resolve technical and economic questions about production before more costly commercial-scale investments are made.

7. Governments should also reduce barriers to trade in bio-based products, lower regulatory hurdles that hinder investment, and, establish a level playing field for bio-based products (such as chemicals and plastics) with respect to fossil-based and other products. More flexible regulation could help to use agricultural and forestry residues and domestic wastes in bio-refineries. Public procurement can also be deployed to support industrial biotechnology.

8. **Nanotechnology** is a general purpose technology which can enable many parts of production. Significant resources are required for nanotechnology R&D. Nanotechnology needs international collaboration, as many of the research and engineering tools are hard to gather in a single institute (or even region). Policymakers should develop multidisciplinary networks and support innovation and commercialisation in small companies. Timely and clear guidelines are needed for assessing the risk of nanotechnology-enabled products, as is international harmonisation in this area.

9. **3D printing** includes a group of technologies and processes that use a digital file to build a physical three-dimensional object. 3D printing could augment manufacturing productivity, although today the technology is most economical for small quantities of complex customised products.

10. 3D printing has potential environmental benefits. To achieve these, policy should encourage low-energy printing processes and low-impact materials. Governments can: target grants or investments to commercialise research in these directions; remove intellectual property barriers to enable 3D printing of repair parts for legacy products (for instance, washing machines no longer in production); and, support certification of 3D-printer sustainability.

11. Recent advances in scientific instrumentation, data science and computation have contributed to a revolution in **materials science**. Industrial materials will have properties not seen before. Increasingly, the desired properties will be deliberately designed into materials.

12. Policies are needed to facilitate open data and open science (for instance for sharing simulations of materials structures). Progress on new materials requires close collaboration between industry, universities, research funding agencies and public laboratories. And steps are needed to foster interdisciplinary research and education.

13. If firms which could lead the next production revolution are unable to attract the human and financial resources to grow, the development and **diffusion of technology** will be stunted. An important way in which framework policies affect the diffusion of technology is through their influence on the process of resource allocation to firms. The efficiency of this process varies considerably across countries. Inefficient resource reallocation can have many causes. These include limited product market competition, rigid labour markets, disincentives for firm exit, barriers to growth for successful firms, and a number of policy conditions, including restrictions on trade. Dedicated institutions can also enable technology diffusion. Some of these institutions, such as technical extension services (which provide information and outreach, especially for SMEs), tend to receive low priority in the standard set of innovation support measures. But there is evidence that they can be effective, if well designed.

14. **Public acceptance** could affect adoption some of the technologies addressed in this report. Some concerns exist, for instance around the control of life processes (with some bio-technologies). New societal issues might also emerge. For instance, as machine autonomy develops, who will be responsible for the outcomes that machines give rise to, and how will control be exercised?

15. Policymakers and institutions need to voice realistic expectations about technologies. Hype is too frequent. Science advice should be demonstrated to be unbiased and trustworthy, and should be used in decision making. Also, public deliberation is important for building mutual understanding between scientific communities and the public.

16. **Foresight** is a type of analysis aimed at thinking about the future and shaping it. Greater foresight in science and technology is sought by most governments. Better anticipating trends could assist policy and the allocation of research funds. The complexity of modern manufacturing and the many implications of new technologies underscore the need for foresight processes. Foresight processes can bring benefits in themselves, such as strengthened stakeholder networks. They can also encourage policy co-ordination and organisational innovation.

17. Foresight should ideally be an institutionalised practice. The links between foresight processes and decision-making should be close, but foresight exercises must also enjoy intellectual autonomy. Patent and bibliometric data can be a useful adjunct to foresight methods, but have limitations (such as sampling biases). Expert opinion can be particularly useful in exploring areas of uncertainty where data are limited

and possible outcomes are many and skewed. Professional and cognitive biases can affect expert assessments. Protocols to account for these biases must be used.

18. A number of **cross-cutting policy considerations** must also be taken into account. Specifically:

- The range of policy issues which affect future production is extremely broad. This highlights the need for policy co-ordination;
- Future production requires sound policies for science and R&D. Many of the technologies covered in this report have arisen because of advances in scientific knowledge and instrumentation. As described in the penultimate chapter of this report, many policy choices determine the strength of science and research systems and their impacts on production;
- Governments should create a context which fosters business dynamism. OECD research over recent years has highlighted the role of new and young firms in net job creation and in nurturing radical innovation. New firms will introduce many of the new production technologies;
- Helping firms to adopt new technologies is important and can be achieved through well-designed policies;
- Rapid technological change could challenge the adequacy of skills and training systems. Some new production technologies raise the importance of inter-disciplinary education and research. Greater interaction between education and training institutions is often needed, and may grow as the knowledge content of production rises. Ensuring good generic skills – such as literacy, numeracy and problem-solving – throughout the population will be important.
- The NPR may bring changes to labour market policies too. For instance, self-employment could grow, possibly requiring accommodating policies.
- Long-term thinking is essential. Leaders in business, education and government must be ready to examine policy implications and prepare for developments beyond the next ten years.
- A long-term perspective on policy also requires reflection on how policy priorities might need to evolve, for instance as a consequence of technological change itself.

19. The Secretariat will seek to secure support for a final policy-oriented project conference to be held in the autumn of 2016 in an interested member country. A final publication will be available in early 2017.

Introduction

20. This paper is an interim report on the OECD cross-cutting project "Enabling the Next Production Revolution". This project is being implemented over the 2015-2016 biennium.

21. The Next Production Revolution (NPR) project has benefitted from an allocation from the Secretary-General's Central Priority Fund (CPF). Financial support for this work has come from the governments of Australia and the United Kingdom. Thanks are also due to the government of Norway for its particularly generous financial contribution to the project.

22. The Directorate for Science, Technology and Innovation (STI) is leading the work, with inputs also provided by the Environment Directorate (ENV) and the Secretary-General's office (SGE). Within STI, the project is managed by the Science and Technology Policy Division (STP), reporting to the Committee for Scientific and Technological Policy (CSTP). Inputs to the project are also provided by the Committee for Industry, Innovation and Entrepreneurship (CIIE) and the Committee for Digital Economy Policy (CDEP).

23. Overarching policy themes addressed in connection with new production technologies were outlined in DSTI/IND/STP/ICCP(2015)8 – *Enabling the Next Production Revolution* - which was submitted for discussion at the Ministerial Council Meeting on 3-4 June 2015.

Background to the next production revolution project

24. The background to this project is one in which major science and technology-driven changes in the production and distribution of goods and services are occurring and diffusing widely. Others – possibly more significant still – are on the horizon. Such changes could have far-reaching impacts on productivity, income distribution, human well-being and the environment. But some possible developments in production also entail risks (such as labour displacement, or risks for human health). The more completely governments understand how production could develop, the better placed they will be to prepare for the risks and reap the benefits.

Future production can be analysed from a variety of perspectives

25. A range of policy, institutional, technological and broader conditions (or mega-trends) will shape the future of production (OECD, 2015a). For example, environmental conditions and the growing scarcity of some raw materials will increase pressures for materials-, water- and energy-efficient production. The continued accumulation of human capital in OECD countries, which has trended upwards for decades, could favour the production of increasingly knowledge-intensive products. Ongoing economic globalisation will augment competitive pressures that spur innovation and favour automation in high-income economies. Demographics will be important in determining what products are most demanded by consumers, and where production is located (and many other factors could also influence location, from political instability in some parts of the world to weather patterns).

The NPR project has a technological focus

26. The NPR project aims to explore the economic and policy ramifications of a set of technologies which, it is assumed, will be important for production over the near term. This focus on technologies affords the opportunity for precise thinking about technology-specific policies. A technological focus also permits tractability. Accordingly, the project's overall aims are:

- To explore – and inform governments of – possible science and technology-driven developments in selected production technologies over the next 10-15 years.

- To outline the risks and opportunities that could be created by such changes. These risks and opportunities relate to the economy, society, human well-being and the environment.
- To examine policies that could help to cope with risks and realise the opportunities.
- To assess how policymakers prepare for the future and what best-practice constitutes.

27. The remainder of this paper is structured as follows. Chapter 1 addresses the themes of productivity, work and the next production revolution. Chapter 2 examines the role of digital technologies in future production. Chapter 3 considers bio-production and industrial biotechnology. Chapter 4 focuses on nanotechnology as an enabler of future production. Chapter 5 assesses the impacts of 3D printing on manufacturing and the environment. Chapter 6 considers developments relating to new materials. Chapter 7 reviews how governments can help to foster the diffusion of new production technologies. Chapter 8 considers the influence of public acceptance on the adoption of new technologies and the options which are open to government. Chapter 9 examines what governments can do to develop foresight about future production. Chapter 10 describes the development of new technologies in Chinese manufacturing and what China's government is doing to accelerate upgrading in manufacturing. Chapter 11 discusses cross-cutting policy considerations. And Chapter 12 summarises the next steps in the NPR project.

28. Each chapter draws out possible policy directions for governments (with the exceptions of Chapters 10 and 12).

1. Productivity, work and the next production revolution

1.1 Summary

29. Much of the OECD's recent analysis of productivity has focused on framework policies, innovation and enterprise demography. One aim of the NPR project is to examine the current and potential productivity effects of emerging production technologies.

30. All of the examined NPR technologies can raise productivity. But the technologies are diverse. Their adoption and diffusion is proceeding at different rates. And each affects productivity in different ways. For example, robots increase productivity by being faster, more precise and more consistent than workers. Evidently, nanotechnology does not do this. But nanotechnology can make plastics electrically conductive, allowing more efficient spray painting during vehicle manufacture. Each of the associated productivity gains can be of different magnitudes.

31. Most evidence on the relevant productivity impacts comes from firm and technology-specific studies. Some of these indicate large productivity benefits. However, the productivity impacts of many technologies, such as nanotechnology, have not been systematically studied. Furthermore, little is known about the scale of the additional productivity effects that arise from synergies among the major technologies. In addition, new technology is only part of what is needed to achieve productivity growth. ICT, for instance, must typically be combined with other business investments in skills and organisational change.

32. Some sector-wide and macro-level studies of productivity gains from ICTs rely on multiple assumptions about adoption rates. They also often ignore other variables which could overshadow technology's effect on productivity. Nevertheless, the numbers are large. For example, for Germany, it is estimated that advanced ICTs in industry could boost productivity by 5% to 8% (Rüßmann *et al*., 2015).

33. The technologies considered in this report have more to contribute to productivity than they currently do. Often, their use is limited to larger firms. Even in larger firms their potential applications are frequently underutilised. By one well-informed estimate 'the full shift to Industry 4.0 could take 20 years' (Lorentz *et al*., 2015) (see Box 3). Unexploited opportunities are many. For instance, while a large part of food prices reflects the costs of logistics, less than 15% of the distribution process has been considered for automation (CCA/CCR, 2009). Manufacturers see many unmet opportunities for automation.

34. Advancing automation has also provoked alarm over the loss of work to machines. For instance, in 2014 the former Secretary of the United States Treasury, Lawrence Summers, argued that a limited availability of jobs will be the defining upcoming economic challenge.

35. Not all jobs have been equally affected. Digital technology has contributed to employment polarisation: employment in high- and low-wage jobs has increased, while the share of employment in middle-wage jobs has fallen.

36. Technology-driven increases in productivity benefit the economy through one or more of the following channels: lower output prices, higher workers' wages, or higher profits. While many new production technologies have novel capabilities, a historical perspective is useful. History effectively provides an experiment on the general equilibrium effects of technological change (i.e. on the effects, beyond jobs losses, of changes in output prices, wages and profits). The historical evidence is overwhelmingly positive regarding the overall economic and labour market effects of technological change (for countries, industries and firms). New technologies raise incomes, and hence demand. New technologies don't reduce the total demand for work, even when they do eliminate certain types of job.

37. Nevertheless, while new technologies bring jobs, adjustments in the labour market can be painful. The first industrial revolution eventually brought unprecedented improvement in living standards. But for many workers that revolution brought life-long hardship. Today, hardship could affect millions if rapid labour displacement were to occur in a major sector, or various sectors simultaneously. For instance, taken together, around 3 million people work as commercial drivers in 15 European Union countries. Suddenly eliminating the need for drivers would create an extraordinary labour market shock. Policymakers need to act and prepare with foresight.

38. Specifying what or where the jobs of the future will be is problematic, although a number of developments appear likely. Many remaining production jobs are set to disappear. Demand for skills that compete with machines is likely to fall, while demand for skills that complement machines is likely to rise. New jobs are likely to be increasingly skilled. Digital skills could become increasingly important for most workers. And (current) technical limits on automation suggest other skills which might predominate in future production jobs, such as adaptability, problem solving and common sense.

1.2 Productivity and the technologies of the next production revolution

39. For a number of reasons, the possible productivity effects of new production technologies are of great current policy interest. Research has established a fundamental relationship between innovation and long-term productivity. Today, raising rates of economic growth is a priority for most OECD governments. Sluggish macro-economic conditions in many OECD economies, weak labour markets and burgeoning public debt have all added urgency to the search for growth. Over the longer-term, the decline in the working-age population, combined with natural resource constraints, mean that the future of growth in OECD economies will increasingly depend on productivity-raising innovation.

40. However, many OECD economies have experienced faltering productivity growth in recent years. Some high-profile commentators have claimed that slower productivity reflects a general innovation hiatus. These voices come from academia, notably Gordon (2012), and from industry, particularly Peter Thiel, the founding CEO of PayPal. Some of the arguments made by techno-pessimists cite obstacles to productivity which are particularly significant in the United States, such as growing inequality and consumer and government debt. But other arguments are more global, particularly the claim that innovation will slow because the cost of innovation rises as technology advances (Jones, 2009; Cowen, 2011). In contrast, techno-optimists variously argue that new digital and other technologies will raise productivity (Brynjolfsson and McAfee, 2013), and that economic history provides reason to think that technological progress could even accelerate (Mokyr, 2014). A further argument of techno-optimists is that official measures of economic growth understate progress, because they poorly capture many of the benefits of new goods and services. For instance, national statistical offices usually collect no information on the use of mobile apps, or online tax preparation, or business spending on databases (Mandel, 2012), while the consumer surplus created by thousands of new digital products is absent from official data.

41. In recent years the OECD has closely studied the drivers of economic productivity. Much of this work has examined the effects of framework policies, innovation and enterprise demography (for instance, McGowan *et al.*, 2015; Andrews, Criscuolo and Menon, 2014; and, Andrews, Criscuolo and Gal, 2015). This section does not reprise that work. Rather, the following paragraphs consider the current and potential productivity effects of the technologies analysed in this report.

42. All of the NPR technologies can raise productivity. But the technologies are various. Their adoption and diffusion is occurring at different speeds. Each technology affects productivity in different ways. And the productivity effects of each technology can be of different magnitudes.

Emerging technologies affect productivity through many channels

43. Emerging production technologies affect productivity through mechanisms that are many and varied. The following examples of productivity enhancement illustrate this variety:

- By being faster, stronger, more precise and consistent than workers, robots have vastly raised productivity on assembly lines in the automotive industry. They are now doing so in warehousing and will do so again in an expanding range of sectors and processes;
- The combination of new sensors and actuators, big data analysis, cloud computing and the Internet of Things is enabling autonomous machines and intelligent systems. Such machines and systems increase productivity in many industrial and service-sector processes;
- Sensors in vehicle fleets can reduce downtime, increase maintenance efficiency and save energy (new autonomous sensors are emerging powered from ambient energy, captured for instance from wi-fi signals. These will permit more widespread benefits from sensor capabilities);
- The mix of industrial biotechnology with state-of-the-art chemistry can increase the efficiency of bioprocesses (most biological processes have low yields, which can now be improved using low temperature ambient-pressure catalysts);
- 3D printing can remove the need for assembly in some stages of production by printing already-assembled mechanisms;
- 3D printing can also shorten industrial design processes, owing to rapid prototyping, and in some cases raise productivity by reducing material waste;
- Progress in materials science and computation will permit a simulation-driven approach to developing new materials. This will reduce time and cost as companies perform less repetitive analysis. It will also shorten the time between materials discovery and their commercial use;
- The addition of carbon nano-fibres to plastics can render the latter electrically conductive. In the automotive industry this can remove the need for a separate spray painting process for plastics. This innovation could reduce manufacturing costs by USD 100 per vehicle.
- More generally, for decades, the doubling each 18 months of the number of transistors on an integrated circuit, described as Moore’s law, has raised productivity, as it has enabled firms to do more computation at lower cost.

Synergies between new technologies will also raise productivity

44. Little study has been given to the ways in which synergies among emerging production technologies could add to productivity. For instance, so-called ‘generative’ software can produce useful and counter-intuitive industrial designs by generating and evolving multiple variants of a random design. However, the resulting designs are sometimes so complex that they can only be manufactured with 3D printing. To give another example, advances in software, sensors and computation allow simulation of alternative machine arrays. In the near future such technology will combine with advances in augmented reality to permit maintenance engineers to see projections, on visors or glasses, of the inner workings of those machines.

How large are the productivity effects?

45. Evidence on productivity impacts from new production technologies come mainly from firm and technology-specific studies. A sample of these studies shows that:

- Using data-driven innovation can raise labour productivity by approximately 5-10% (although these estimates vary by sector, sometimes come from studies which suffer from selection bias, and are subject to the presence of complementary factors, such as the availability of skills).
- In the United States, output and productivity in firms that adopt data-driven decision making are 5% to 6% higher than expected given those firms' other investments in ICTs (Brynjolfsson, Hitt and Kim, 2011).
- Improving data quality and access by 10% - presenting data more concisely and consistently across platforms and allowing them to be more easily manipulated - would increase labour productivity by 14% on average, but with significant cross-industry variations (Barua *et al*., 2013).
- The Internet of Things reduces costs among industrial adopters by 18% on average (Vodatafone, 2015).
- On average, across 17 OECD countries, increasing use of industrial robots between 1993 and 2007 raised annual growth of GDP and labour productivity by 0.37 and 0.36 percentage points respectively (Graetz and Michaels, 2015).
- Autonomous mine haulage trucks could in some cases increase output by 15-20%, lower fuel consumption by 10-15% and reduce maintenance costs by 8% (Citigroup-Oxford Martin School, 2015).
- Autonomous drill rigs can increase productivity by 30% to 60% (Citigroup-Oxford Martin School, 2015).
- Other estimates suggest that successful adoption of advanced ICTs could raise growth of value added in Germany's mechanical, electrical, automotive, chemical, agriculture and ICT sectors by 1.7% a year to 2025 (BITKOM and Fraunhofer, 2014).

46. By raising productivity the new technologies can also improve financial performance among adopters. A case study commissioned for the NPR project shows that, by developing a significant IoT and data analytics capability, a leading US automaker has saved around USD 2 billion over the past 5 years (2011-2014 and most of 2015) (Box 6). A 1% increase in maintenance efficiency in the aviation industry, brought about by the industrial Internet, could save commercial airlines globally around USD 2 billion per year (Evans and Anninziata, 2012).

Some sector-wide and macro-level evidence exists, but is often speculative

47. Some sector-wide or macro-level studies of productivity gains from ICTs rely on many assumptions about adoption rates. They also often ignore other variables which could overshadow technology's effects on productivity. Nevertheless, the numbers are large. For example, for Germany, it is estimated that advanced ICTs in industry could potentially boost productivity by 5% to 8% (Rüßmann *et al*., 2015). In the United Kingdom, it is estimated that a moderate increase of £1.24bn in automation

investments could raise overall value added in manufacturing by £60.5bn over the next decade (Rigby, 2015).

There is much unexploited potential for productivity growth

48. The technologies considered in this report have more to contribute to productivity than they currently do. Often, their use is predominantly in larger firms (see Figure 4 in Chapter 2 for an example). Even in larger firms, many potential applications are underused. Unexploited opportunities exist throughout industry. For instance, while a large part of food prices reflects the costs of transportation and logistics, less than 15% of the distribution process has been considered for automation. Robotics could improve logistics and reduce the price of food and other goods by several percent (CCA/CCR, 2009). Manufacturers see unmet opportunities for automation in skilled and less-skilled fields, from manufacturing parts, to machine loading, packaging, palletisation and assembly (Rigby, 2015).

49. It could take considerable time for the productivity gains from new technologies to be realised. Moreover, the duration of this period is uncertain. The past has seen unrealistic enthusiasm regarding timescales for the delivery of a number of industrial technologies. Sometimes, as with nanotechnology and industrial biotechnology, this partly reflected miscalculation of the technical challenges. As with many technologies, advanced ICTs such as big data, cloud computing and the IoT have developed in a wave-like pattern. Rapid growth in inventive activity has followed slower activity and vice versa (OECD, 2015c). In terms of adoption, advanced ICTs remain below potential (see Figure 7 in Chapter 2). Cloud computing, for instance, was first commercialised in the 1990s, but has still only been adopted by less than a quarter of businesses in OECD countries. By one well-informed estimate 'the full shift to Industry 4.0 could take 20 years' (Lorentz *et al*, 2015). Of course, the mere availability of a technology is not a sufficient condition for its uptake and successful use. Realising the benefits of a technology often requires that it be bundled with investments in complementary assets such as new skills and organisational forms.

1.3 Work, automation and the new technologies of production

Growing machine capabilities have spurred fears of increasing joblessness and income inequality

50. Among the general public, as well as among senior policy figures and business leaders, growing concerns have recently been voiced regarding the employment implications of digital technologies. For instance, in 2014 the former Secretary of the United States Treasury, Lawrence Summers, argued that a limited availability of jobs will be the defining upcoming economic challenge (Summers, 2014). A recent survey of technology experts in the United States found that 48% were concerned that digital technologies will lead to widespread unemployment (PEW, 2014).

51. On one hand, advances in automation have stoked fears of technological unemployment. In a much-cited study, Frey and Osborne (2013) concluded that about 47% of total employment in the United States is at risk of computerisation. A spate of recent books has gone even further, warning of the eventual redundancy of most human labour (e.g. Ford, 2015; Brynjolfsson and Mcafee, 2014). On the other hand, there is concern that the digital economy is not creating employment comparable in number to that created by leading industries of the past. Lin (2011), for example, shows that 8.2% of workers in the United States were employed in new types of jobs in 1990. But this figure fell to 4.4% by 2000. And Berger and Frey (2015) estimate that less than 0.5% of workers in the United States are now employed in technology-related industries created in the 2000s. Concerns also exist that digital technologies could profoundly alter the nature of contractual relationships, to the detriment of many workers (Box 1).

Box 1. Crowdsourcing of human intelligence tasks: "Human computing"

While computing and automation technologies are steadily improving, humans still do many tasks more effectively than computers, such as identifying objects in a video, and transcribing audio recordings. For such tasks, firms have tended to hire temporary workers. But crowdsourcing a workforce for human intelligence tasks (HITs) is an increasingly used alternative. This process, which gives firms flexibility, is often referred to as "human computing" (because humans are here used solve problems that computers cannot).

Amazon is still the most prominent provider of human computing services over the Internet, since it launched its crowdsourcing marketplace for digital work called Amazon Mechanical Turk (MTurk) in 2005. Requesters advertise small projects that cannot be fully carried out by computers. Worker - called "turkers" - complete those one-time tasks, for sums ranging from as little as USD 0.01 for a short task to USD 100 for more complex jobs. Currently, some 500 000 workers from 190 countries are registered at Amazon MTurk. Especially for people living in developing countries, MTurk and similar services have been highlighted as an economic opportunity. Samasource, a nonprofit organization, provides data-related services to large companies in the United States and Europe. It divides work into small batches and sends these for completion to delivery centres in developing countries (Gino and Staats, 2012).

While they represent job opportunities for some, MTurk and similar services such as Samasource have been criticized by some as a "digital sweatshop", given that, in the words of one scholar, these services "[circumvent] a range of labor laws and practices, found in most developed countries" (Zittrain, 2009, cited in MIT Technology Review, 2010). So-called 'micro-workers' typically earn below average hourly wages (Uddin (2012); Cushing (2013); Horton and Chilton (2010)). But a survey of working conditions as perceived by 200 workers on MTurk suggests that the workers believe their chances of being treated fairly are as good or better online as they are offline (MIT Technology Review (2010); Horton (2011)).

Since 2012 Amazon has sought to verify all Amazon Payments accounts, including those of MTurk workers, in light of criticism of working conditions among its international workers, as well as risks of money laundering. This effort led to the deletion of many MTurk accounts (Ipeirotis, 2013). Requesters must now be based in the United States, and only workers in the United States and India can directly access money transferred to their accounts. Other international workers can only receive payment in the form of an Amazon gift card (Amazon, 2014b). As a result, MTurk workers now mostly live in the United States and India (Ipeirotis, 2010; Techlist, 2014).

Source: OECD (2015b)

Concerns over technology-based unemployment have a long history

52. Even before the Luddite protests against the mechanisation of textiles manufacture in early nineteenth-century England, many production technologies have raised fears of labour market disruption. Indeed, the term *technological unemployment* was coined by John Maynard Keynes 85 years ago.[2] In 1961 in the United States, the Kennedy Administration created an Office of Automation and Manpower, citing "the major domestic challenge of the Sixties: to maintain full employment at a time when automation, of course, is replacing men" (quoted in Miller and Atkinson, 2013). And workers polled in the United States in the 1970s and 1980s were constantly concerned about automation (Miller and Atkinson, 2013). Most of these fears have turned out to be unjustified. Nevertheless, many commentators argue that digital technology gives today's fears a new foundation.

Progress in computing is leading to novel machine capabilities…

53. Since the period of manual computing, and depending on the standard used, the cost of computer calculation has fallen by 1.7 trillion to 76 trillion-fold. Most of this decline happened since 1980 (Nordhaus, 2007). Such progress permits the development of some machine functionalities that rival human performance, even in tasks where humans were long thought to possess a permanent cognitive

advantage over machines (Elliott, 2014). For instance, researchers recently reported advances in artificial intelligence that surpass human capabilities in a set of vision-related tasks (Markoff, 2015a).

…and has enabled an increase in the scope and rate of automation

54. The routine tasks of most operatives in manufacturing are now automated. Cargo-handling vehicles and forklift trucks are increasingly computerized. Many semi-autonomous warehouses are populated by fast and dexterous robots (Box 2). Complex aspects of the work of software engineers can be performed by algorithms (Hoos, 2012). A version of IBM's *Watson* computer can act as a customer service agent (Rotman, 2013). Software such as *Dreamcatcher* can generate complex and novel industrial designs (as was done to design the chassis of the world's fastest motorbike, the Lightning Electric Motorcycle) (Kinkead, 2014). The *Quill* programme writes business and analytic reports and *Automated Insights* can draft text from spreadsheets. Computer-based managers are being trialled. These allocate work and schedules, with the experience well received by teams of workers to date (Lorentz *et al*, 2015). Recent softwares can interpret some human emotion better than humans, presaging new forms of machine-human interaction (Khatchadourian, 2015). And autonomous vehicles might soon substitute for large numbers of commercial drivers.

Automation has advanced most in tasks more easily defined in computer code

55. So-called 'routine' tasks are those which are more easily described by computer code. Non-routine tasks are harder to specify in code. Routine and non-routine tasks can be manual or cognitive. For example, non-routine cognitive tasks are often performed by workers in professional, technical and managerial jobs. Non-routine manual tasks - requiring personal interaction, visual and language recognition and situational adaptability - are regularly performed, for example, by janitors, personal care aides and drivers (Autor, Levy and Murnane, 2003).

Digital technology has contributed to employment polarisation

56. In recent decades, employment in OECD labour markets and industries has become increasingly polarized. Employment in high- and low-wage jobs has increased, while the share of employment in middle-wage jobs has fallen. This polarisation has been linked to the falling share of employment in occupations that involve many routine tasks (Autor, Katz and Kearney (2006), Goos and Manning (2007) and Acemoglu and Autor (2011)). In the upper pole of the labour market, ICT makes problem solving more productive, driving growth in jobs where skilled workers perform non-routine cognitive tasks (Autor and Dorn, 2013). In the lower pole, manual tasks in many services occupations are less susceptible to description in code. This has preserved jobs in such occupations, but has also contributed to a shift in employment from middle-income manufacturing to low-income services (Autor and Dorn, 2013).

The labour market effects of technology have been highlighted by the crisis…

57. Apprehension about technology's effects on employment tends to grow during economic crises (Mokyr, Vickers and Ziebarth, 2015). This may partly account for the recent upswing of technological anxiety. Some of the alarm about technology and jobs might also reflect cognitive biases: to report on job losses is easier than to report on job gains, while it is also hard to discern the nature of future jobs. But the recent recession appears to have accelerated the displacement of workers by computerised systems, and the disappearance of jobs involving routine tasks is leading to jobless recoveries (Jaimovich and Siu, 2015).

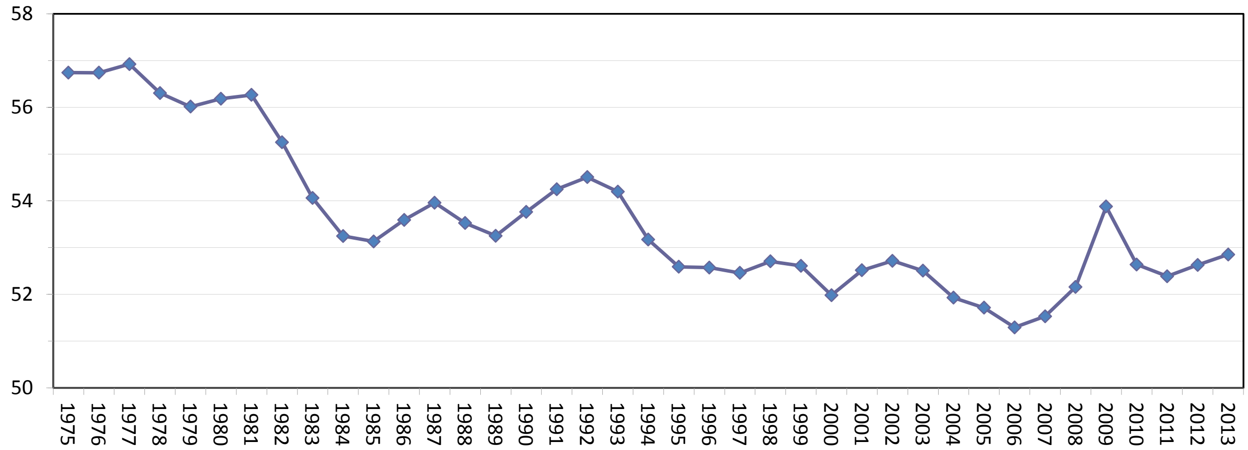
…while automation shifts gains from productivity growth to the owners of machines

58. Falling prices of ICT have spurred automation. Because the price of ICT is expected to continue to fall for some time, the currently observed decline in the wage share of GDP may also continue (figure

1). This decline is consistent with models which highlight that the returns from robotics technologies could accrue to a small number of owners of capital (Sachs and Kotlikoff (2012); Sachs, Benzell and LaGarda (2015)).

59. Frey and Osborne (2013) estimate that jobs which require low levels of skill will be increasingly susceptible to automation. Recent evidence lends support to this prediction: Graetz and Michaels (2015) find that industrial robots have reduced hours worked primarily for low-skilled workers, with less pronounced declines for workers with mid-level skills.

Figure 1. Percentage share of labour in value added in 21 OECD countries, 1975-2013



Source: OECD National Accounts at a Glance. *Note*: The figure shows a weighted average using statistics for the following 21 OECD countries: Australia, Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Spain, Sweden, the United Kingdom and the United States.

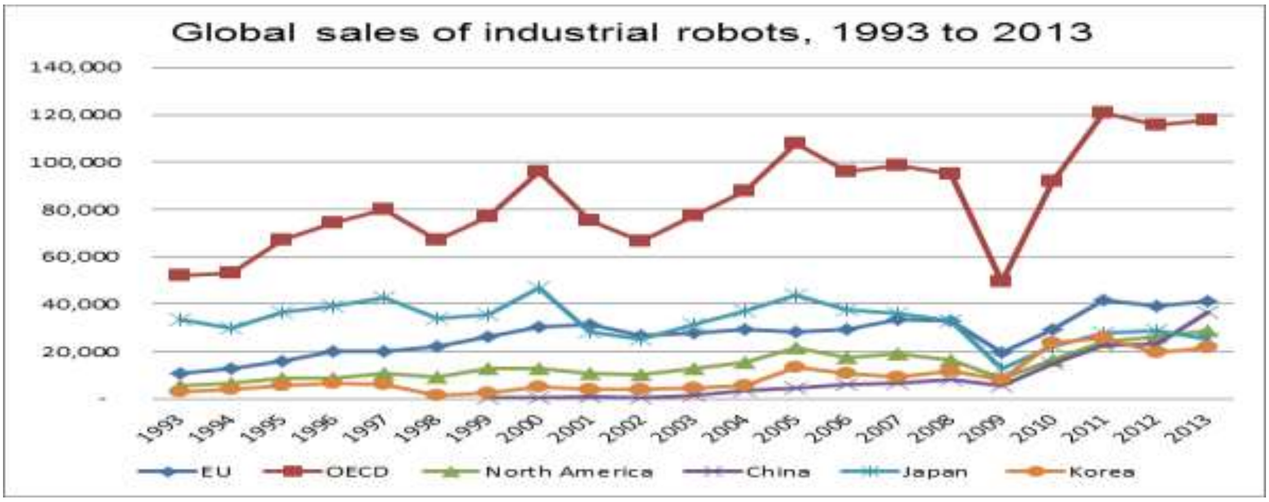
Box 2. Robots and the next production revolution

Robots first entered industry – initially in the automotive sector - in the 1960s. For decades, industrial robots were large, expensive, operated from static positions indoors, and performed one or a small number of repetitive and sometimes hazardous tasks, such as welding and machining. But a convergence of digital and other technologies has yielded a second generation of robots. These are smaller, less expensive, more autonomous, more flexible and cooperative. They can be programmed and used by average workers. Some even perform tasks by imitating workers. Robots have growing uses in manufacturing. For instance:

- BMW is testing mobile assembly robots that collaborate with workers (Knight, 2013).
- General Electric has developed robots to climb and maintain wind turbines (Robotics-VO, 2013).
- Airbus is developing a wearable soft-frame robot, or exoskeleton, to help workers manipulate loads ergonomically.
- *Kuka* makes autonomous robots that collaborate and automatically adjust their actions to fit the next unfinished product (Lorentz et al, 2015).
- Interconnected swarms of robots can map, reconstruct and analyze every tree and piece of fruit in an orchard, providing critical information to improve yields and water management.[3]
- Warehouses equipped with robots made by Kiva Systems can handle four times as many orders as un-automated warehouses. Kiva robots learn, for example, that less frequently ordered products should be stored in remote areas (Rotman, 2013).
- Robots now perform some construction tasks, particularly in Japan (Frey and Osborne, 2013).

Robots also have new roles in services. For instance, robots can fly, tunnel, swim and crawl through disaster scenes to facilitate rescue.[4] *Intuitive Surgical* makes robotic instruments that allow surgeons to operate remotely while feeling the physical sensation of what the robot touches (Markoff, 2015). Using minimally invasive robots, several thousand prostate operations a year are performed in the United States. This allows shorter admission periods, fewer infections and faster recovery (CCC/CRA, 2009).

In 17 OECD countries, from 1993 to 2007, the number of robots in industry increased by over 150%. In 6 of these countries, quality-adjusted robot prices in 2005 were only 20% of prices in 1990 (Graetz and Michaels, 2015). OECD-wide sales of industrial robots rebounded quickly after the global financial crisis (see figure below). The market for personal and household service robots is growing by about 20 percent a year, and prices are expected to decline quickly in the near future (MGI, 2013).



Robot utilisation varies greatly across countries: 48% of Spanish firms and 44% of Danish firms used at least on industrial robot in 2009, compared to just 23% of firms in the Netherlands (Fraunhofer, 2015).

An explosion in robot diversity and use may be near

In 2015 the Toyota Motor Corporation announced a five-year, billion-dollar investment to create a research center near to Stanford University to focus on artificial intelligence and robots. Gill Pratt, an eminent roboticist, leads the new center. Pratt (2015) argues that converging developments in several technologies are about to greatly enlarge robot diversity and use.

More intelligent and autonomous robots will come about through improvements currently being seen in: computing performance; electromechanical design tools and numerically controlled manufacturing; electrical energy storage and electronics power efficiency; the availability and performance of local wireless digital communications; the scale and performance of the Internet; and, global data storage and computational power. Challenges remain, particularly in perception (recognizing specific objects in cluttered environments), manipulation and cognition (Robotics-VO, 2013). But Pratt suggests that the ongoing developments could soon see the rise of:

- **Memory-based autonomy**, in which robots search online databases or video archives, or make requests from humans, for guidance as to what to do next;
- **High-speed sharing of experience**, at rates approximately 100 million times faster than humans. Already, *RoboEarth* helps robots share knowledge and experience worldwide on an online database;
- **Learning from imagination**, whereby robots simulate and examine future circumstances; and,
- **Learning from people**, with robots using the online repository of recorded human activity to better interact with the world.

Robots are essential to competitiveness in future production

The next generation of miniaturized, complex products with short life-cycles will require a level of assembly adaptability, precision and reliability which exceeds human capabilities (CCC/CRA, 2009). And as OECD populations age, robots will help to relieve demographic constraints on production. Similarly, by improving working conditions, robots can reduce expensive medical problems, benefitting firms and the wider economy. As well as increasing process reliability, robots reduce lead times for finished manufactured goods, allowing greater responsiveness to changes in retail demand. European manufacturers that use robots are more efficient than non-users. And such robot users are less likely to relocate production outside Europe (Fraunhofer, 2015).

Graetz and Michaels (2015) concluded that, on average, across 17 OECD countries, increasing use of industrial robots between 1993 and 2007 raised annual growth of GDP and labour productivity by 0.37 and 0.36 percentage points respectively. Robots were found to have no effect on the hours worked by skilled workers, but did displace low-skilled and some middle-skilled workers.

But robots are still mostly used in larger firms

Robot use increases strongly with firm size. In Europe, 36% of surveyed companies with 50 to 249 employees use industrial robots, compared to 74% of companies with 1000 or more employees (Fraunhofer, 2015). This size-sensitivity reflects the greater financial resources, experience with advanced production technologies, and economies of scale available to larger firms. Robots handling small or even single batch sizes do not yet have a significant industrial presence.

But technological development since the industrial revolution has not made human labour obsolete…

60. Firms invest in new technologies to increase productivity (and to achieve other outcomes, from increasing safety to facilitating regulatory compliance). In a given firm, this increased productivity can lower, raise, or leave unchanged the number of workers. The actual outcome depends on the price elasticity of demand for the firm's output. If demand is sensitive to changes in price, a small decline in the price of the firm's output could lead to an increase in the firm's workforce.

…and new technologies create jobs through many channels

61. A technology-driven increase in productivity benefits the economy through one or more of the following channels: lower output prices, higher workers' wages, or higher profits. Lower prices raise real incomes among consumers. This increases demand for other goods. And higher workers' wages raise demand and job creation in other markets. Even if productivity gains only lead to higher profits, or shareholders and workers save their increased income, the wider economy still benefits (Miller and Atkinson, 2013). The higher profits are distributed to shareholders, who spend all or part of this new income, adding to aggregate demand. And increased savings among shareholders and workers lowers interest rates and raises investment, eventually creating jobs. Jobs will also arise in firms that make new forms of production equipment and machinery. And economies that host many technologically-innovative firms will create markets and capture market shares abroad.

The relative importance of the routes through which new technologies affect the economy and jobs varies from country to country

62. Across countries, variation in the efficiency of markets and institutions - such as those which mediate between savings and investment - will influence the economic effects of new technologies. The labour market effects of new technologies can also vary according to: the types of tasks being automated; whether the technology complements human labour; the price and income elasticities of demand for output; and, supply responses in the labour market (Autor, 2015). For example, many manual task-intensive activities are only weakly complemented by new technologies (computers do not make waiters or cleaners significantly more reliable, rapid or inexpensive). Furthermore, manual task-intensive activities often face elastic labour supply (many people are ready to do a cleaning job, which has the effect of dampening demand-induced wage increases). But demand for manual task-intensive work is also relatively income elastic (people with high-incomes employ cleaners more often than people with lower incomes) (Mazzorali and Ragusa, 2013).[5] Consequently, the growth of high-income high-tech jobs is also important in increasing demand for manual task-intensive work. In the United States, for example, of the ten cities where waiters receive the highest pay, seven have a major high-tech presence (Moretti, 2012).

Productivity-raising technologies benefit economies

63. Fears that new technologies might harm the labour market are greatest when job losses alone are considered (the 'partial equilibrium' perspective). But history effectively provides an experiment on the general equilibrium effects of technological change (i.e. when technologies raise productivity, reduce prices, cause consumers to spend more on other goods and services and thereby create employment). Historical evidence is overwhelmingly positive regarding the overall economic and labour market effects of technological change. To cite just a few country-level studies:

- Between 2001 and 2009, while production jobs declined, more than 4.8 million white-collar jobs were created in the United States relating to interactions and problem-solving (Manyika *et al*, 2011).

- Investments in ICT had no net effect on labour demand in 19 OECD economies between 1990 and 2012 (DSTI/ICCP/IIS(2014)6). A permanent fall in the cost of ICT capital reduced labour demand per unit of output, but increased output by the same proportion.
- In the short-run, employment might decrease following productivity-enhancing technology shocks, but it grows again over the medium-term (Basu, Fernald and Kimball, 2006). Productivity-raising technology shocks reduce unemployment for several years (Trehan, 2003).
- From 1964 to 2013, against a background of accelerating automation, the United States economy created 74 million jobs (Levy and Murnane, 2013). And from 1929 to 2009, also in the United States, increases in productivity were positively correlated with increases in employment growth (Manyika *et al*, 2011).
- In England and Wales, over one and a half centuries, technological change has led to overall job creation (Stewart, Debapratim and Cole, 2014). This period saw a reduction in jobs requiring physical strength: 23.7% of all employment in 1871, to 8.3% in 2011. It also saw a shift to jobs requiring caring and empathy: 1.1% of all employment in 1871 to 12.2% in 2011. Routine jobs suffered most.
- Looking forward, Lorentz *et al* (2015) sought to assess the possible aggregate employment effects of new ICTs in industry in Germany. Under the technology adoption and revenue-generation scenario deemed most likely, the new technologies will significantly increase overall employment.

In firms and industries, the employment effects of technological change are also generally positive

64. As reviewed by Miller and Atkinson (2013), evidence at the level of firms and industries mostly shows that productivity-enhancing technology causes job losses in some cases and job gains in others. But the number of firms and industries which experience employment growth exceeds the number in which employment contracts. Employment is more likely to grow after technology shocks in firms operating in industries with low inventory costs, elastic demand and flexible prices (Chang, Hornstein and Sarte, 2009).

But adjustment can be painful

65. The first industrial revolution eventually brought unprecedented improvement in living standards. But for many workers this revolution brought hardship. Mokyr (2002) shows that while large-scale technological unemployment did not follow the industrial revolution, the translation to higher average living standards took many decades, often longer than the average working lifetime (Mokyr, Vickers and Ziebarth, 2015). Recent OECD research suggests that the negative effects of a ‘one-off’ permanent decrease in ICT user costs tend to disappear in about 10 years.

Box 3. 'Industry 4.0' and the industrial workforce in Germany

Based on extensive industry consultation, Lorentz *et al* (2015) recently studied the possible effects on Germany's workforce of the following ten new industrial uses of digital technologies: data-driven quality control; robot-assisted production; self-driving logistics vehicles; production-line simulation; supply network monitoring; predictive maintenance, machines sold as a service; self-organizing production; 3D-printing of complex parts; and augmented work. The analysis considered how these technology uses will affect the evolution of 40 job families in 23 industries in Germany to 2025. Some types of work are predicted to decline or disappear. For instance, sensor-based predictive maintenance, self-organising production and 3D-printing of complex objects will eliminate jobs, respectively, for traditional service technicians, production planners, and workers in assembly and inventory management. But those same technology uses will also give rise to new occupations. Predictive maintenance will bring novel work in system design and data science. Self-organising production will require specialised data modellers. And 3D printing will create jobs for computer-aided designers. As robots are deployed more widely, demand will rise for robot coordinators to oversee robots and respond to malfunctions. The most highly demanded new job will be that of industrial data scientist.

Many existing industrial occupations are also set to change. For instance, assembly-line workers will be assisted by robots in more of their manual tasks. Service technicians will be helped to make repairs efficiently by being able to consult details of machine performance before visiting a site and by using augmented reality technology (allowing instructions to be delivered on how to repair a part as that part is being viewed). And machine operators will be able to run several machines simultaneously.

Lorentz *et al* (2015) also sought to assess aggregate employment effects, under a variety of technology adoption and revenue-generation scenarios. Under the scenario deemed most likely, the new technology uses will significantly augment productivity. Industry 4.0 would lead to a net increase of approximately 350,000 jobs. Jobs in assembly and production would decline by around 610,000. But jobs losses would be more than offset by demand for an additional 960,000 workers, including 210,000 skilled employees in IT, analytics and R&D.

Hardship could affect many if rapid labour displacement were to occur in a major sector, or various sectors simultaneously

66. The technology of driverless vehicles might present such a threatening case. Taken together, just over 3 million people work as commercial drivers in 15 European Union countries. Suddenly eliminating the need for drivers would create an extraordinary labour market shock. However, a number of qualifying observations are relevant to such threats:

- Major technological advances in many sectors and occupations at once are improbable. Technology tends to replace human labour one task at a time, while many sectors have in fact been experiencing slow or declining productivity (Miller and Atkinson, 2015).

- Projecting the effects of new technology on even a single sector can be prone to error (witness the discussion on automated teller machines on the next page).

- The technology of driverless cars, once widely introduced, might not pose a threat to the work performed by all human drivers. For instance, at the end of a journey, many delivery drivers need to interact with customers in complex ways, hand-delivering fragile goods, ensuring the right person receives the correct delivery, etc.. Machines cannot yet perform such tasks (Markoff, 2015a).

- Automation of some knowledge-based work may even proceed more slowly in smaller countries, compared with the United States (Blix, 2015). This is because automation software is more profitable in the large United States market. Some software – such as *ediscovery*, for legal research – is developed specifically for that market.

While new technologies bring jobs, specifying what or where they will be is problematic

67. The specific types of work brought by new technology have often been hard to predict. For example, after the introduction of the personal computer in the early 1980s, more than 1,500 new job titles appeared in the United States' labour market, from web designers to database administrators (Killander, 2014).

68. New technologies can also affect employment in very indirect ways, again hindering foresight. For instance, as passenger cars displaced horse-drawn vehicles in the 1920s, the motel and fast food industries arose to serve motorists (Jackson, 1993, cited in Autor 2015). Similarly, in the future, as the safety of self-driving cars is demonstrated, insurance premia could decline, reducing the need for workers in insurance companies (Jain, O'Reilly and Silk, 2015).

69. Other workforce developments brought by new technologies can also be unexpected. Toyota, for example, has decided to put human workers back into manufacturing after realising that craftsmen also play a role in improving production processes, which robots do not (Markoff, 2015b).

70. Estimates of future labour displacement are also hindered by the fact that projected technological progress has often been mistaken. For instance, an estimate that 'general machine intelligence will be with us in 20 years' has been almost constant since the 1950s (Bostrom, 2014).

71. More generally, it is unknown whether the transformative growth in computing power which has underpinned the digital revolution will continue. With many digital devices, processing speeds, memory capacities, sensor density and accuracy, and even numbers of pixels, are linked to Moore's Law, and exhibit similar exponential improvements. But atomic-level phenomena limit the extent to which transistors on integrated circuits can be shrunk. Some experts believe a lower bound might be reached in the early 2020s (power consumption has already reached a limit). It is unclear how the end of Moore's Law might affect the pace and direction of technological change (parallel computing, the availability of massive processing power through cloud computing, clever algorithms, three-dimensional integrated circuits and other developments might more than offset the limitations that affect individual microprocessors (OECD, 2016a forthcoming)).

Nor is it precisely knowable how new technologies might transform existing jobs

72. In banking it was long believed that automated teller machines (ATMs) would cancel the need for human tellers. ATMs were introduced in the 1970s. But between 1971 and 1997 the share of human tellers among all workers in US banking only declined modestly, from just under 21% to around 18% (Handel, 2012). Numerically, the major workforce change occurred in banks' back offices, for instance with clerical jobs (Markoff, 2015b). However, the nature of the work performed by human tellers changed, coming to involve more skilled services (such as financial advice).[6]

Limits currently exist on the extent of automation

73. Automation is advancing quickly. Some authors predict machine capabilities that exceed all human equivalents. However, most see major challenges in enlarging the scope of machine substitution for workers. Frey and Osborne (2013) identify three broad categories of ability in which computer-controlled equipment is unlikely to surpass workers in the near term: creative intelligence, social intelligence (as exercised, for instance, in caring professions), and perception and manipulation (as required, for example, in jobs dealing with unstructured or changing environments). Common sense, a hard-to-define attribute which is essential to most work, has also been exceedingly hard to replicate (Davis and Marcus, 2015). In

humans, all of these abilities have evolved, rather than being developed, and therefore involve tacit understanding (Autor, 2015).

But some labour market trends might be surmised

74. While it cannot be stated with certainty how the labour market will evolve, there is reasonable conjecture on a number of likely outcomes.

- Many remaining production jobs are likely to disappear. A recent survey showed that 68% of British manufacturers see potential for increasing investment in automation in the future (Rigby, 2015). As previously noted, Frey and Osborne (2013) estimate that 47 percent of the US workforce is susceptible to computerization over forthcoming decades.

- New jobs are likely to be increasingly skilled (tasks performed within occupations have become increasingly complex since the 1980s and that complexity increased more rapidly in occupations that underwent significant computerization (Spitz-Oener, 2006)).

- Demand for skills that compete with machines is likely to fall, while demand for skills that complement machines is likely to rise.

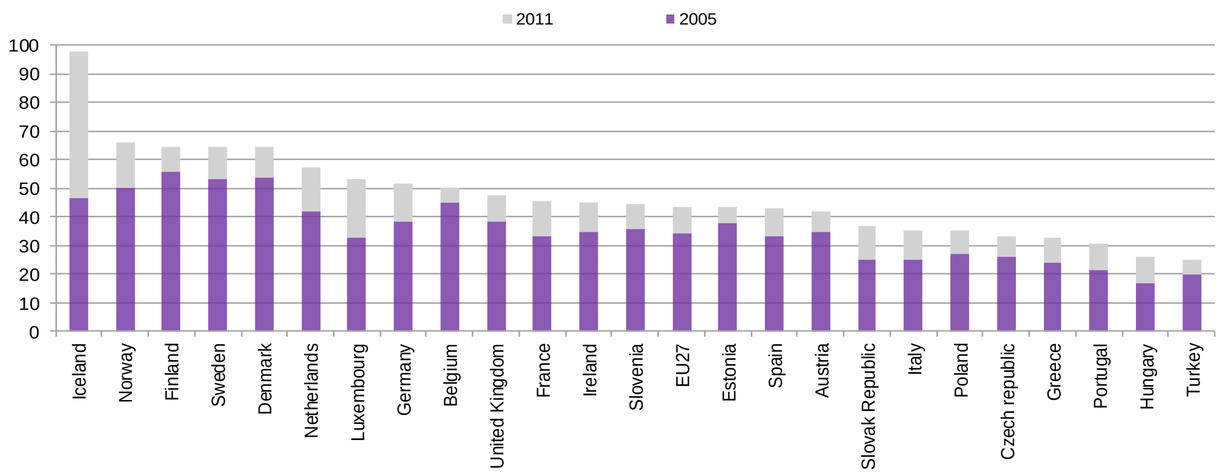
- Digital skills could become increasingly important for most workers. Some survey evidence suggests that a majority of firms consider a lack of digital skills a constraint (Capgemini, 2013). In 2013, more than 60% of European workers stated that their digital skills were inadequate to apply for a new job (OECD, 2014a) (figure 2).

- The (current) technical limits on automation suggest other skills which might predominate in future production jobs, such as adaptability, problem solving and common sense.

- Technology-driven productivity growth could bring a future in which the number of hours worked per employee declines, continuing a long-term trend. There is also likely to be greater flexibility in when and where work takes place (Mokyr, Vickers and Ziebarth, 2015).

Figure 2 Computing is becoming a more common part of the work environment

Share of employed people at work using an Internet-connected computer in 2005 and 2011



Source: OECD Internet Economy Outlook 2012.

Policymakers need to ready for worst-case scenarios

75. This chapter has highlighted the historical evidence that productivity-raising technologies lead to labour market adjustments at higher levels of income. It has also underscored that such adjustment might be highly disruptive, while the precise pace and scale of inevitable future adjustments are unknown. It may be that labour will be displaced on a scale and at a speed not seen before, that robots will make income distribution vastly more unequal than today, and that the market wages of the unskilled will fall below socially acceptable levels. Policymakers need to prepare for these extreme possibilities.

2. Digital technologies and future production

2.1 Summary

76. ICT is driving a transformation of production. Two trends make digital technologies transformational. The first is cost reduction, which has enabled wider diffusion of the technologies, including to SMEs. The second and more important trend is the combination of different ICTs and their convergence with other technologies (owing in particular to embedded software and the Internet of Things (IoT)). For instance, the combination of new sensors and actuators, big data analysis, cloud computing and the IoT is enabling autonomous machines and intelligent systems.

77. Growing use of digital technology will bring productivity and other benefits. For instance, firm-level studies suggest that data-driven innovation (DDI) raises labour productivity by approximately 5-10%, relative to non-users. And the IoT can allow efficiency-enhancing predictive maintenance, improved process efficiencies, enhanced customer service, greater speed of decision-making, and more transparent and predictable costing. For Germany, it is estimated that advanced ICTs in industry could potentially boost productivity by 5% to 8% (Rüßmann *et al*., 2015). Other estimates suggest that successful adoption of advanced ICTs could raise growth of value added in Germany's mechanical, electrical, automotive, chemical, agriculture and ICT sectors by 1.7% a year to 2025 (BITKOM and Fraunhofer, 2014).

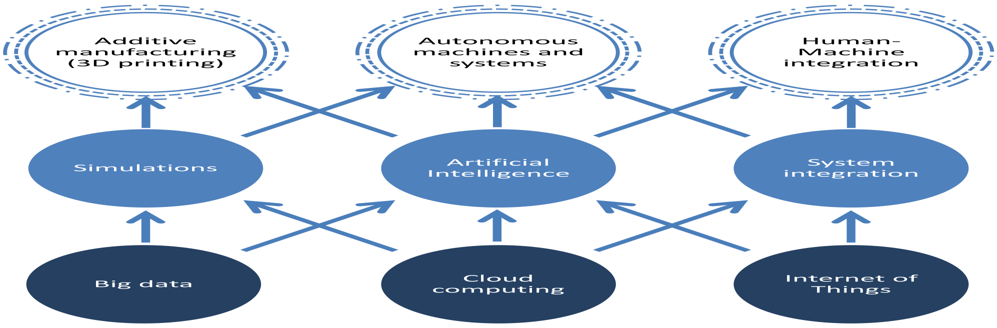
78. Digitalisation of industrial production also brings major challenges, many of which are inherited from the ICT sector. Because the effects of ICTs are pervasive, government action is often needed across a wide front, from addressing infrastructure deficits, to resolving privacy concerns, to ensuring the appropriateness of intellectual property rights. The major challenges include:

- Broadening access to data and critical ICT infrastructures;
- Reducing barriers to diffusion, developing standards and augmenting interoperability (many businesses, in particular SMEs, lag in adopting ICTs);
- Addressing potential skills bottlenecks (for example, surveys point to the shortage of skilled data specialists as one of the biggest impediments to the use of data analytics);
- Resolving issues of liability, transparency and ownership (for instance, data analytics leads to new ways of making decisions, through rapid experiments, statistics and artificial intelligence in machines and systems. This can raise productivity, but could also have novel legal implications);
- Managing issues in connection with digital security risks and privacy (for example, governments need to promote personal data use in ways that address privacy concerns).

The confluence of different technologies is driving the digital transformation of industrial production

79. Two trends make digital technologies transformational for production: (i) their falling cost, which has allowed wider diffusion, including to small and medium sized enterprises (SMEs); and, most importantly, (ii) the combination of different ICTs, and their convergence with other technologies (thanks in particular to embedded software and the IoT). Figure 3 depicts the key ICTs which are enabling the digital transformation of industrial processes (figure 3 is highly stylised and does not show many of the complex relationships and feedback loops between these technologies). All of the technologies and applications in figure 1 are discussed below.

Figure 3. The confluence of key technologies enabling the industrial digital transformation



80. The technologies at the bottom of figure 3 enable those on top, as indicated by the arrows. The technologies at the top of figure 3 - including additive manufacturing (3D printing), autonomous machines and systems, and human-machine integration - are the applications through which the main productivity effects in industry are likely to unfold. In combination, these technologies could one day lead to fully automated production processes, from design to delivery (Box 4).

Box 4. A possible manufacturing process in 2025

In a near future, possibly as early as 2025, manufacturing could become almost completely autonomous. Present-day capabilities suggest that the following hypothetical scenario is feasible:

Designers create a new device. They show 3D-printed prototypes to potential buyers and, as a result, receive a contract from an overseas retailer. The design, packaging and component list is uploaded to an online marketplace where manufacturers compete for contracts to create the parts and assemble the device. The winning contractor uses cloud-based computer-aided design tools to simulate the design and manufacturing of the device. Machine learning algorithms test which combination of robots and tools is the most efficient to assemble the device. Some components, such as systems-on-a-chip and sensors, can be sourced from existing manufacturers. Others might have to be specially created. Robotic devices execute mass production of the components.

All the components and the associated data are then sent to an assembly facility. On the assembly line, robots retool and arrange themselves. Robotic vehicles move components across the floor to the correct robot workstations and the robots start to assemble the devices. Every time a device is assembled, machine learning algorithms in the cloud analyse the sensor data and compare these to the simulations. The algorithms re-simulate and establish whether the process still fits the initial parameters and whether the process can be optimised. The finished product is packaged by a robot and put into a box, which is loaded by another robot on a self-driving truck and taken to the retailer.

At the retailer, robots place the product in the correct warehouse storage location. When the product is ordered, a smaller delivery robot transports it to the door of the customer.

If orders increase from around the world, the designers might need more production capacity. They again turn to the market, with manufacturers in regions where the product has been ordered competing to produce larger or smaller batches. The results of the earlier machine learning algorithms are communicated to the successful factories around the world, where different robots assess how to manufacture the product. When a factory is finished making a given product, the robots reorganise and retool for another.

From the moment the design is finalized, until it arrives to the customer, no worker is employed. Employees monitor the process. However, humans are unnecessary in the production, assembly and logistics. Some existing factories, such as the Philips shaver facility in Drachten in the Netherlands, are almost fully robotic (Markoff, 2012). Philips' Drachten plant employs only one-tenth of the workforce employed in its factory in China which makes the same shavers.

Source: OECD (2016a)

81. The use of the above technologies in industry has been described variously as “Industry 4.0” (Jasperneite, 2012), the “Industrial Internet” (Bruner, 2013), and “network manufacturing” (Economist Intelligence Unit, 2014).

Data-driven innovation (DDI) is transforming all sectors of the economy

82. The term ‘big data’ refers to data characterised by their volume, velocity (the speed at which they are generated, accessed, processed and analysed) and variety (such as unstructured and structured data).[7] Big data promises to significantly improve products, processes, organisational methods and markets, a phenomenon referred to as data-driven innovation (DDI) (OECD, 2015b).

83. Geo-coded maps of fields and real-time monitoring of agricultural activity, from seeding to harvesting, are raising agricultural productivity. One estimate suggests that data and analytics could increase profit on farming corn in the United States by around USD 100 per acre (at a time when gross revenue minus non-land costs stood at about USD 350 per acre) (Noyes, 2014). The same sensor data can be reused and linked to historical and real-time data on weather patterns, soil conditions, fertiliser usage and crop features, to optimise and predict agricultural production. Traditional cultivation methods are thus improved and the know-how of skilled farmers is thereby formalised and made available at a large scale. Despite these potential benefits, the digitalisation of agriculture still falls short of its potential (Box 5).

Box 5. Drivers and challenges in adopting precision farming technology - the case of the Netherlands

The concept of *precision farming* has captured the imagination of industry and policymakers, even if the market for precision farming solutions is still young.

In a survey of Dutch farmers about 55% of respondents indicated that they own tools that support precision farming (University & Research centre, WUR). Most commonly these were GPS-equipped tractors and, to a lesser extent, tools that monitor crops and soil. However, the integration of machine-generated data into business management systems (BMS) is limited. The use of BMS by farmers is primarily driven by existing regulatory and customer requirements regarding food safety. In other words, these tools are mostly used for registration purposes rather than for yielding actual management information. BMS becomes more valuable to farms as they grow in size and require better information processing. About 45% of respondents use collected data for planning fertilization, irrigation and pesticides spraying. However, planning such activities is not generally based on real-time data collected and processed automatically by machines. In other terms, the full potential of the technology is not being exploited.

The ease of use of ICT tools, and farmers’ ICT skills, are the most important factors driving the adoption and use of precision farming technologies. Other influences are farm size, the opportunities for cost reduction, total farm income, land tenure arrangements, access to information (via extension services and service and technology providers), and location (Perpaoli *et al*., 2013).

Adoption rates for precision farming vary across sub sectors. Various sources suggest that the use of data and data analytics in livestock farming, and in greenhouses, is more advanced than in crop farming. This could be because the former two sectors have shorter production cycles and operate in controllable environments, which makes precision farming solutions and automation more profitable.

Another important enabler of diffusion is the penetration of (mobile) broadband. The European AgriXchange research project concluded that the lack of broadband in many rural areas in Europe is an important barrier to innovations that build on the collection and exchange of data.

Digital technology is also making industry more services-like

84. In the 1980s, Rolls Royce stopped selling its jet engines and began selling “power by the hour”, a development made possible by ICTs (Binns, 2014). Today the IoT allows manufacturing companies to monitor the actual use of their goods and thus provide customised *pay-as-you-go* services. These services are priced based on real-time operating data. The data used to monitor products are also increasingly commercialised as part of new services. Manufacturers of energy production equipment, for instance, increasingly use sensor data to help customers optimise complex project planning (Chick, Netessine and Huchzermeier, 2014).

There is still little macro-economic evidence on the effects of DDI, but firm-level studies exist

85. Firm-level studies suggest that using DDI raises labour productivity by approximately 5-10%, relative to non-users (OECD, 2015b). In the United States, Brynjolfsson, Hitt and Kim (2011) estimate that output and productivity in firms that adopt data-driven decision making are 5% to 6% higher than expected given their other investments in, and use of, ICTs.[8] A study of 500 firms in the United Kingdom found that firms in the top quartile of online data use are 13% more productive than those in the bottom quartile (Bakhshi, Bravo-Biosca and Mateos-Garcia, 2014). And Barua *et al*. (2013) suggest that improving data quality and access by 10% - presenting data more concisely and consistently across platforms and allowing them to be more easily manipulated - would increase labour productivity by 14% on average, but with significant cross-industry variations.[9] The use of big data and analytics in some divisions of Japanese manufacturers could lower maintenance costs by almost JPY 5 trillion (corresponding to more than 15% of the value of sales in 2010). More than JPY 50 billion could also be had in electricity savings (MIC, 2013). Nevertheless, big data is still mainly used in the ICT sector. Only 30% of investments in Hadoop – the most commonly used software for managing big data - come from non-ICT sectors (Tambe, 2014). Manufacturing, however, is becoming more data-intensive (MGI, 2011).

Cloud computing enhances agility, scalability and interoperability…

86. Cloud computing allows computing resources to be accessed in a flexible on-demand way with low management effort (OECD, 2014c).[10] Many high-potential industrial applications of ICTs, such as autonomous machines and systems, and complex simulation, are very computationally intensive and require supercomputers. Especially for start-ups and SMEs, cloud computing has increased the availability, capacity and affordability of computing resources.

87. Businesses mainly adopt cloud computing to increase flexibility and decrease ICT investment costs. Accelerating project implementation, improving customer experience, and being able to rapidly adapt to market opportunities are also important benefits of cloud computing.

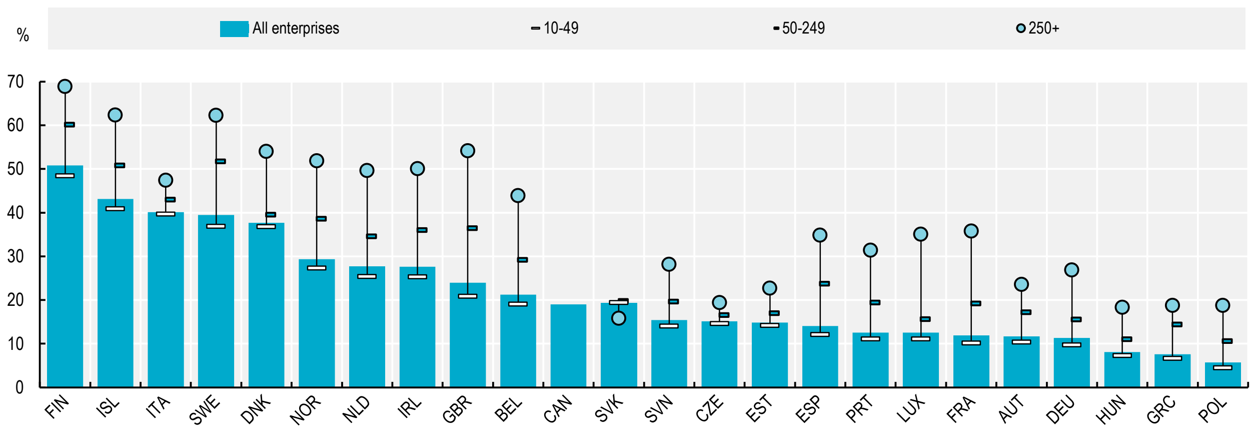
88. In addition, the ubiquity of cloud computing makes it the ideal platform for data sharing across sites and company boundaries. This enables system integration within and between organisations. Even within organisations, silos still exist today. This prevents the interoperability of production systems and creates frictions in value chains. Almost 60% of companies consider “organisational silos” to be the biggest impediment to using big data (Economist Intelligence Unit, 2012). Executives in firms with annual revenues exceeding USD 10 billion are more likely to cite data silos as a problem (72%) than those in firms with revenues less than USD 500 million (43%). Cloud computing can help to overcome these silos and make organisations more cohesive and automated (Rüßmann *et al*., 2015).

… but significant variation exists across countries and firms in the adoption of cloud computing

89. In countries such as Finland, Israel, Italy, Sweden and Denmark, almost half of all businesses already use cloud computing (Figure 4). There is also large variation in use by size of business, with larger enterprises more likely to use cloud computing. In the United Kingdom, for instance, 21% of all smaller enterprises (10 to 49 employees) use cloud computing, compared to 54% of all larger enterprises (250 or more employees).

Figure 4. Enterprises using cloud computing services by employment size class, 2014

As a percentage of enterprises in each employment size class



Note: Data for Canada refer to the use of “software as a service”, a subcategory of cloud computing services.

Source: OECD Science, Technology and Industry Scoreboard 2015. Based on data from Eurostat, Information Society Statistics and Statistics Canada.

The Internet of Things (IoT) will bring radical change

90. The term ‘Internet of Things’ (IoT) refers to the connection of devices and objects to the Internet’s network of networks. Thanks to new sensors and actuators, and in combination with big data analysis and cloud computing, the IoT enables autonomous machines and intelligent systems.

91. The precise number of devices connected to the Internet is unknown, with countries only starting to collect data. But Shodan - the world’s first search engine for Internet-connected devices – indicates that there are 363 million devices online. 84 million online devices are registered to China and 78 million to the United States. Korea, Brazil and Germany follow with 18 million connected devices each.

Equipping machines with sensors could allow efficiency-enhancing predictive maintenance...

92. A 1% increase in maintenance efficiency in the aviation industry, brought about by industrial internet technologies, could save commercial airlines globally USD 2 billion per year (Evans and Anninziata, 2012). Germany-based Schmitz Cargobull, the world’s largest truck body and trailer manufacturer, uses the IoT and sensors to monitor the maintenance, travelling conditions and routes of all its trailers (Chick, Netessine and Huchzermeier, 2014). This helps to minimise usage breakdowns. Sensors in John Deere’s latest equipment can help farmers manage their fleet, reduce tractor downtime and save energy (Big Data Startups, 2013). Among industrial adopters of the IoT, costs have been reduced by 18% on average (Vodatafone, 2015).

…as well as other benefits

93. Apart from cost savings, companies cite other benefits from the IoT, including improved process efficiencies, customer service, speed of decision-making, consistency of delivery and transparency/predictability of costs (Vodatafone, 2015). The IoT will also bring economic and social benefits not directly related to production, for instance in health, in the use of smart meters and in vehicle efficiency. The projected benefits are vast (Evans and Anninziata, 2012).

Box 6. The IoT, big data and cloud computing in a major US automaker

By developing a significant IoT and data analytics capability, a leading US automaker has saved around USD 2 billion over the past 5 years (2011-2014 and most of 2015). This automaker has achieved substantial benefits in two main areas. The first is in better controlling its supply chain. The second is in using data analytics to improve the selection of vehicles, colors and features that dealers will offer to customers.

With respect to the supply chain, it is assumed that parts constitute about one third to one half of the value of a USD 30 000 vehicle. Based on past experience, it is also assumed that the firm can reduce costs in its supply chain by about 1% to 1.5% a year by using data analytics. From current sales figures, this would result in savings of USD 200 million to USD 300 million a year, or USD 1 billion to USD 1.5 billion over 5 years. In terms of improving the selection of cars sent to dealers, one measurable gain would come from reducing the time that cars spend on dealer lots. This saving might amount to USD 50 to USD 100 per car for about 2 million cars a year, or USD 100 million to USD 200 million a year. Total cost savings of USD 1.5 billion to USD 2.5 billion have accrued over 5 years.

The investments required to achieve these cost savings were estimated to be from USD 350 million to USD 500 million over 5 years. The company had around 200 employees in the digital analytics group and these were paid USD 150 000 to USD 200 000 per year on average including all expenses (although some specialists have incomes exceeding USD 300 000 a year). This would be a USD 30 million to USD 40 million annual cost. If it is further assumed that the costs of the software and hardware for data analytics are of about the same magnitude, or possibly a bit larger, the cost of setting up the automaker's software-defined architecture to support data analytics and create an (internal) IoT would be about USD 200 million to USD 300 million over 5 years. Overall, the company has seen a roughly USD 2 billion return on an investment of USD 350 million to USD 500 million over 5 years (a rate of return of 300% to 470%).

Currently, the firm's electric vehicles generate about 25 petabytes of data an hour. The firm expects there will be about 100 times more data than this per car from new satellite technologies which could be introduced over the next two to three years. Sensors in factories and in research programs generate additional data. The company expects to be managing zettabytes of data per year by 2019 to 2020 (a rate of growth of over 250% per year from the present day).

Source : Commissioned OECD case study.

The IoT, with big data and cloud computing, are powering breakthroughs in artificial intelligence (AI) applications, like driverless cars

94. The IoT embeds physical objects in information and thereby makes them "smarter". With driverless cars, for instance, the road infrastructure, other cars and web services (such as online maps) "tell" a car what it needs to know. In this way, it is not necessary to equip a self-driving car with image processing systems comparable to those of humans, as was previously assumed. Similarly, when all the devices and machines in a factory can supply information, many new robotics applications become possible (Box 4).

2.2 Digital technologies and future production – main policy considerations

95. Data as a new infrastructure for 21st century production: Data can be conceived of as an infrastructural resource. Physical infrastructure such as roads and bridges enables benefits to 'spill over', for instance by fostering trade. But some of the spill-overs from data are not easily observed or quantified (for example, cultural and scientific exchange). As a result, governments could under-invest in the infrastructure needed to support data and data analytics, resulting in a narrower range of uses than is socially optimal.

Policy considerations 1

Governments should develop an innovation policy mix that encourages investments in data that have positive spillovers across industries while addressing the low appropriation of returns to data sharing. The combination of intellectual property rights (IPR), licences and alternative incentive mechanisms such as data citations, data donation or philanthropy need to be considered further.

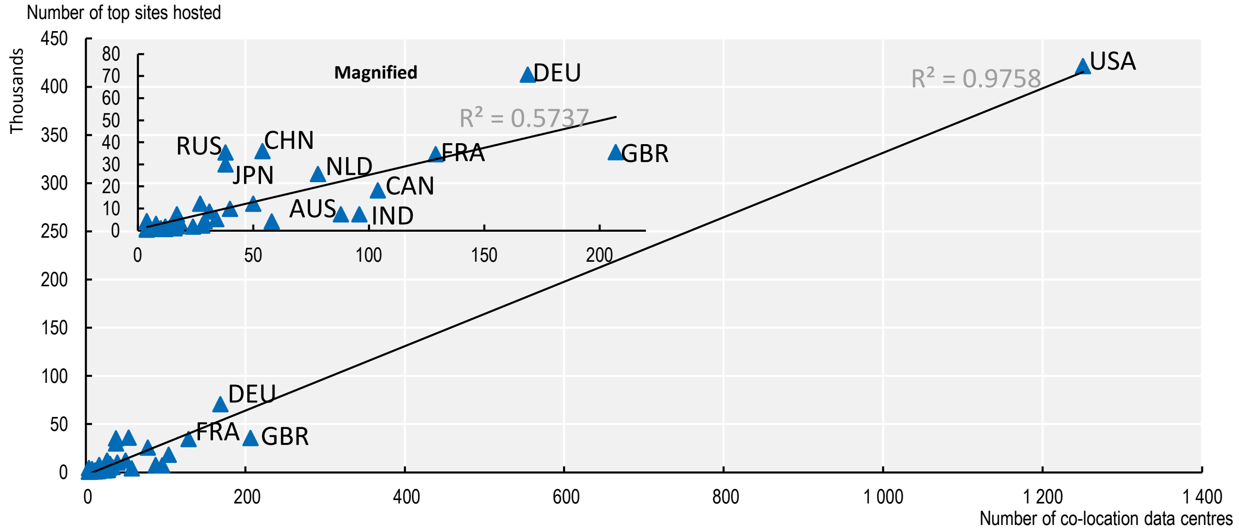
Obstacles to the reuse and sharing of data should be examined carefully. Non-discriminatory access regimes (or "access on equal terms"), including data commons or open access regimes, should be explored to support the production of goods with public and social benefits without requiring governments or businesses to pick winners (whether users or applications).

Coherent data governance frameworks should be developed. Access to data should not necessarily be free or unregulated. A balance is needed between openness (and the social benefits from access to and the reuse of data), and the legitimate concerns of those whose privacy and IPRs may be negatively affected.

96. *The open Internet and global data services*: data and digital services are increasingly traded and used across sectors and national borders. Indeed, companies increasingly divide up their digital processes – hosting, storage and processing – across many countries.

97. The precise distribution of digital services globally, and the size of cross-border data flows, are unknown. But analysis of the world's top Internet sites suggests that digital services are disproportionately concentrated in the United States, which alone accounted for more than 50% of all top sites hosted in the OECD area in 2013. Canada, Germany, France, Ireland, the Netherlands, Japan and the United Kingdom, as well as China, India and the Russian Federation are catching up as they increase their contribution to global trade in ICT-intensive services. Countries with the largest numbers of top Internet sites are also those that have the highest number of co-location data centres (data centres that are shared between users) (Figure 5).

Figure 5. Top locations by number of co-location data centres and top Internet sites hosted, 2013



Sources: OECD (2015a). Based on Pingdom, 2013; and www.datacentermap.com, accessed 27 May 2014.

98. Countries are highly interdependent in terms of data flows. Countries which are home to major providers of digital services are likely to also be major destinations for cross-border data flows (from which those digital services are constructed). Conversely, countries which host major users of ICT-related services are often major sources of the data underpinning those services.

Policy considerations 2

Barriers to Internet openness, legitimate or otherwise, can limit the impacts of the digitalisation of industrial production in particular in economies where deployment of data-driven services is poor due to failures in ICT infrastructure markets. Barriers to Internet openness can be the result of business practices or government policies. They may also have a legal basis, such as the protection of privacy and IPRs, as well as a security rationale.

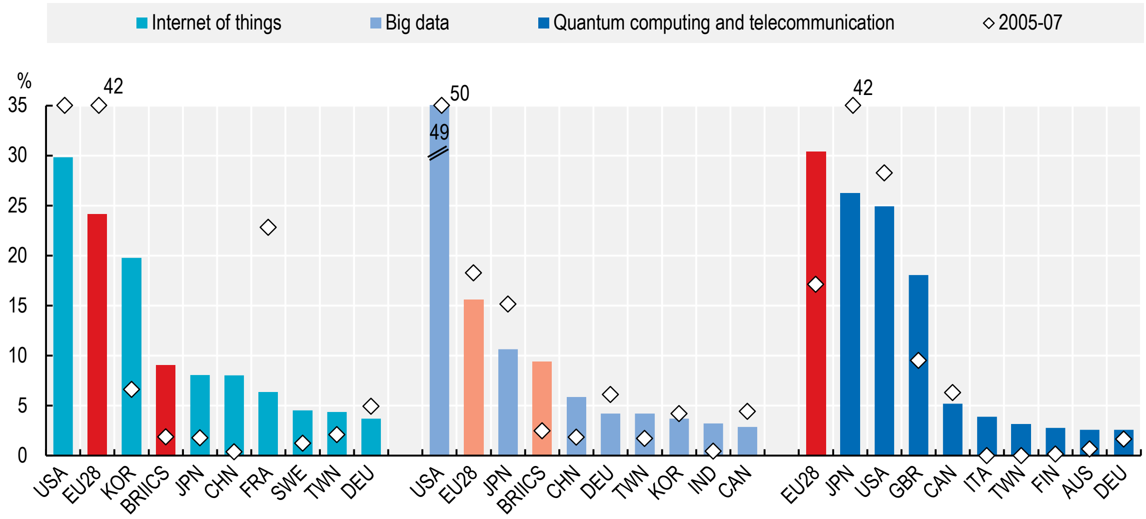
Governments looking to promote cross boarder data flows underpinning digital services should take the OECD 2011 Council Recommendation on Principles for Internet Policy Making into consideration as well as ongoing OECD work to develop a better understanding of the characteristics and social and economic impacts of Internet openness.

99. *Investments in R&D in key enabling ICTs:* The digitalisation of industrial production requires investments in research and development in fields such as the IoT, data analytics and computing. Countries with greater research capabilities in such fields could enjoy first mover advantages from the digitalisation of industrial production.

100. Figures on international patent filings show that inventive activity in digital technologies related to production is rapidly increasing. Since 2007, the number of patent filings related to the IoT, big data analytics, quantum computing and telecommunications have grown at two digit rates. In 2012, the latest year for which data are available, growth exceeded 40%. But the supply of DDI-related technologies is concentrated in only a few economies, with the United States leading in terms of filed patents, followed by Canada, France, Germany, Korea, Japan, and the United Kingdom, as well as China.

Figure 6. Leaders in IoT, big data and quantum computing technologies, 2005-07 and 2010-12

Share of IP5 patent families filed at USPTO and EPO, selected ICT technologies



Source: OECD Science, Technology and Industry Scoreboard 2015. OECD calculations based on IPO (2014), Eight Great Technologies: the Patent Landscapes and STI Micro-data Lab: Intellectual Property Database, June 2015.

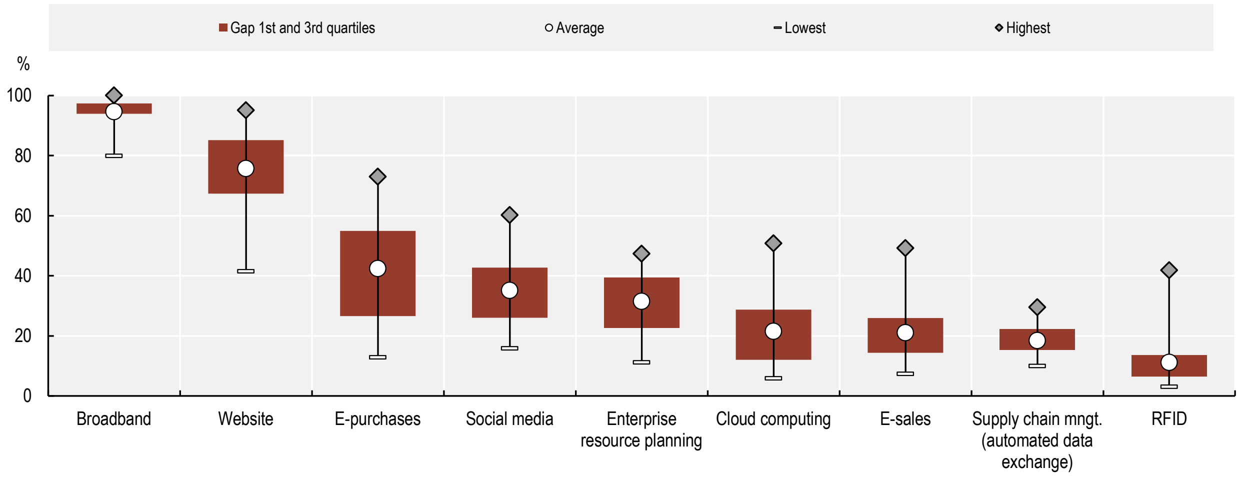
Policy considerations 3

Governments aiming to promote the supply of key ICTs should consider supporting investments in R&D in such fields as big data analytics, cloud and high-performance computing, and the IoT, as well as in security- and privacy-enhancing technologies. For instance, through its national digital economy strategy, Canada foresees investments worth CAD 15 million over three years to support leading-edge research in, and the commercialisation of, quantum technologies. And France intends to invest EUR 150 million to support R&D in five technologies identified as strategic: IoT, super and cloud computing, big data analytics, and security.

101. *Barriers to ICT diffusion, interoperability and standards:* the digitalisation of production requires the diffusion and use of key ICTs, particularly among SMEs. However, many businesses, and in particular SMEs, lag in adopting ICTs. For instance, the adoption of cloud computing, supply chain management, enterprise resource planning (ERP), and radio frequency identification (RFID) applications by firms is still much below that of broadband networks or websites (Figure 7). Nevertheless, it is these advanced ICTs that enable the digitalisation of industrial production.

Figure 7. Diffusion of selected ICT tools and activities in enterprises, 2014

Percentage of enterprises with ten or more persons employed



Source: OECD Science, Technology and Industry Scoreboard 2015. Based on OECD, ICT Database; Eurostat, Information Society Statistics Database and national sources, July 2015.

102. Factors preventing firms from using advanced ICTs include fears of technological lock-ins caused by proprietary solutions and a lack of (open) standards, as well as fears of security breaches (large firms in particular express concerns about data security). In addition, smaller firms often have difficulties implementing organisational change, due to limited resources, including shortages of skilled personnel.

103. One of the most important aspects of interoperability is identification. The IoT concerns uniquely addressable objects (things) and their virtual representations in an Internet-like structure. Billions of uniquely addressable objects are becoming a part of the existing Internet-based network. The identification of individual objects and their addressing mechanism is crucial. The interoperability of heterogeneous identifiers is a challenge for the deployment of the IoT. Governments must adapt numbering policies so that identifiers do not limit the IoT. Currently, many identification schemes exist.

104. Another interoperability issue will arise when users attempt to use IoT devices and applications from different manufacturers and suppliers. This may raise problems when using IoT devices/applications on different systems or networks, or when moving an owned device to a new service provider or network. Regulatory barriers may also prevent effective adoption of some ICTs. For example, large-scale IoT users, such as car manufacturers who need to monitor their devices with their own SIM cards, cannot do so in many countries.

Policy considerations 4

Governments should consider policies to encourage the adoption of key enabling ICTs. The Information Economy Strategy of the United Kingdom, for instance, aims to promote the use of ICTs in businesses and organisations, especially SMEs, through activities such as awareness raising, a web portal with online tools, and a network of digital advice centres offering training, mentoring and voucher schemes.

Governments should support a culture of digital risk management, as promoted by the *2015 OECD Recommendation on Digital Security Risk Management for Economic and Social Prosperity*.

Governments need to act if regulatory barriers are preventing adoption. For the IoT, for instance, removing regulatory barriers to entry in the mobile market would allow the million-device customer, such as some vehicle manufacturers, to become independent of mobile network operators and would further competition.

105. *Addressing potential skills bottlenecks:* The increasing use of advanced ICTs, such as data analytics, has raised demand for new types of skills. Surveys point to the shortage of skilled data specialists as one of the biggest impediments to the use of data analytics. In the United States, since 1999, occupations for those with advanced ICT skills are among those with the fastest growth in relative wages, suggesting (combined with other evidence) a possible shortage of skills.

106. Many countries struggle to develop the needed skills. 7% to 27% of adults in OECD countries still have no experience in using computers. Only 6% of people in the OECD have high-level ICT skills.

Policy considerations 5

National education systems, in collaboration with business, need to support the development of data-related skills, starting with basic ICT skills. The relevant skills needed extend beyond ICT to include science, technology, engineering and mathematics (STEM).

107. *Liability, transparency, and ownership:* Data analytics leads to new ways of making decisions, through low-cost rapid experiments and artificial intelligence in machines and systems. This can raise productivity.

108. But data-driven and AI-enabled decision making can also produce mistakes. This might occur because of poor data and software quality, or because of intended or unintended errors in using the data and software (in some cases, the errors might only be discovered after detailed investigation, as happened with the discovery of intended errors in software embedded in some diesel engines of Volkswagen (VW) vehicles, which were used to activate emission controls only during laboratory testing). Mistakes in data-driven decision making can also arise from unexpected changes in the environment from which data are drawn. For example, on occasion, unforeseen behaviour in algorithmic trading systems has led to significant financial losses, such as Knight Capital Group's loss of USD 440 million in 2012.

109. The risk of erroneous decisions raises questions of how to assign liability between decision-makers and the providers of data and ICTs (including software). The issue is exacerbated by complications around the concept of data ownership, which may have ambiguous applicability in some circumstances. For example, where data are considered personal, the concept of ownership can be problematic. This is because most privacy regimes grant individuals control rights over their data, on condition that these data are not restricted (for example, data generated by smart meters on individuals' electricity consumption are considered personal, but are also used by the smart meter owners who, in turn, cannot make any exclusive claims on those data).

110. As data analytics and AI-enabled applications become more pervasive, users need to be aware of their limitations, because users might unintentionally cause social or economic harm. This is especially true when incentives to minimise risks to third parties are low (such as when the analysis of data mainly benefits the application user and not the entity providing the data). For example, there may be a collision of interests when data are collected from farmers and sold to third-party analysts who use the data to project future farm prices.

Policy considerations 6

Careful examination is needed of the implications of fully automated decision making. Consideration is needed of requirements for transparency and human intervention in areas where harm from automated decisions could be significant, or in areas where legal and regulatory requirements are implemented by software or algorithms.

Policymakers need to acknowledge that transparency requirements may extend to the processes and algorithms underlying automated decisions. These transparency requirements could come into tension with existing intellectual property rights and the processes and algorithms at the core of certain business' operations.

111. *Privacy, consumer protection, competition law and taxation – new challenges to regulation:* New ICTs could raise serious concerns relating to privacy, consumer protection, competition and taxation. Existing regulatory frameworks may be ill-suited to deal with the new challenges.

112. Comprehensive data collection enabled by the IoT can lead to loss of privacy. Data analytics make it possible to infer sensitive information from non-personal data (e.g. meta-data). The misuse of such insights could infringe core social principles, such as individual autonomy, equality and free speech.

113. Data-driven innovation also raises challenges for competition authorities. These include challenges in: defining a relevant market (the use of data enables the creation of multi-sided markets, while the traditional market definition generally focuses on one side of the market); assessing the degree of market concentration (often relying on analysis of market prices, while many data-driven products are provided for free or in exchange for access to personal data); and, assessing potential consumer detriments due to privacy violation (competition authorities tend to direct specific privacy issues to the privacy protection authorities, which however have no authority over competition issues) (see OECD, 2015b).

114. Data and ICT use across borders can make it difficult for tax authorities to determine where tax-relevant activities are carried out and where value is created. Inherent in this is the difficulty of measuring the monetary value of data, determining who owns data, and being clear on the global interconnectedness of data-driven services.

115. Finally, the convergence of production with ICTs, and the increasing role of software, gives intellectual property rights (IPRs) - in particular copyright - a strategic role in future production. One among a number of IPR concerns relates to application programming interfaces (APIs). APIs are fundamental in that they allow different applications to interact. The control of APIs could therefore lead to anticompetitive behaviour, for instance when the owner of the API can control access to a given system, including access for competitors. Trends towards more closed APIs are therefore raising concerns among actors that rely on open APIs for their innovative services, for instance small companies that supply ICT-rich industrial components that need to interact with components made by larger manufacturers.

Policy considerations 7

Governments need to promote the responsible use of personal data to address privacy concerns. Efforts to promote privacy-enhancing technologies and the empowerment of individuals through greater transparency of data processing, and through data portability, via such initiatives as midata (United Kingdom) and MesInfos (France) should be further considered. Governments also need to increase the effectiveness (i.e. resourcing and technical expertise) of privacy enforcement authorities.

Governments need to assess market concentration and competition barriers through better definition of relevant markets and consideration of potential consumer detriments due to privacy violations. This will also require fostering dialogue between regulatory authorities (in particular in the areas of competition, privacy and consumer protection).

Governments need to encourage improved measurement to help better assess the economic value of data, and to prevent base erosion and profit shifting through aggressive tax planning by firms seeking to reduce taxable income artificially or shift profits to low-tax jurisdictions.

The promotion of open standards in application programming interfaces (APIs) and data formats is important. Adopting such standards would boost interoperability and reuse of data and digital services, while enhancing competition among service providers.

3. Bio-production and industrial biotechnology

3.1 *Summary*

116. Petro-chemistry dramatically changed production in the early twentieth century. The tools exist today to begin a bio-based revolution in production.

117. Everyday chemicals and fuels constitute the largest market for bio-based products. Industrial chemicals are a major part of OECD economies. Industrial biotechnology will affect productivity and could support job creation. Biotechnology also offers unique solutions to dependence on oil and petrochemicals.

118. To date, little policy support has been given for bio-based chemicals. Governments could assist the development of sustainable supply chains for bio-based production. Policymakers could also support industrial biotechnology with demonstrator bio-refineries. These can help to resolve technical and economic questions about production before more costly commercial-scale investments are made. A major challenge for bio-based production is its multi-disciplinarity. Support for research and training is essential.

119. Governments should focus on three goals as regards regulation: reducing barriers to trade in bio-based products; lowering regulatory hurdles that hinder investment; and, establishing a level playing field for bio-based products (such as chemicals and plastics) with respect to fossil-based products and also to bio-based fuels and electricity. Improved regulations on waste matter could also assist the bio-economy, as could policies on public procurement.

Industrial bio-technology is advancing on many fronts

120. Several decades of research in biology have yielded synthetic biology (see Box 7 for definitions) and gene editing technologies. When allied to modern genomics - the information base of all modern life sciences - the tools are in place to begin a bio-based revolution. Bio-based batteries, artificial photosynthesis and micro-organisms that produce biofuels are just some among recent breakthroughs (OECD, 2016b forthcoming).

121. Synthetic biology – the application of engineering concepts to biology - promises radical innovation in sectors ranging from industry to health. For example, in health, plant-derived chemical artemisinin is effective against drug-resistant malaria. But it is scarce and expensive. An early success for synthetic biology has been to produce semi-synthetic artemisinin at industrial scale (National Academy of Sciences, 2015).

122. Everyday chemicals and fuels represent the largest market for bio-based products. In the last few years the technology to produce entirely non-natural chemicals has been proven (Yim *et al*., 2011). This technology is now being commercialised. More recently, thanks to gene editing, even tiny marine plants (diatoms) have been harnessed to produce biofuels (Dabbousi *et al*., 2014). Such a development was technically unthinkable just ten years ago.

Box 7. What are these technologies?

Convergence: is the coming together of different technologies to solve problems that cannot be addressed by a single technology.

Genomics: is a discipline that applies recombinant DNA, DNA sequencing methods, and bioinformatics to sequence, assemble, and analyse the function and structure of genomes. In many ways it is an information technology – the code is not digital but genetic.

Green chemistry: involves designing environmentally benign chemical processes, leading to the manufacture of chemicals with a lesser environmental footprint.

Industrial biotechnology: involves the production of goods from sustainable biomass instead of finite fossil-based reserves. The biomass can be wood, food crops, non-food crops or even domestic waste.

Metabolic engineering: metabolic engineering is the use of genetic engineering to modify the metabolism of an organism. It can involve the optimisation of existing biochemical pathways or the introduction of pathway components, most commonly in bacteria, yeast or plants, with the goal of high-yield production of specific molecules for medicine or biotechnology.

Synthetic biology: aims to design and engineer biologically-based parts, novel devices and systems as well as the redesigning of existing, natural biological systems.

Industrial biotechnology will affect productivity and jobs

123. Industrial chemicals are a major part of OECD economies. In 2013, sales of chemicals accounted for over 7% of EU manufacturing output (Oxford Economics, 2014). Germany and France have 438,000 and 156,600 direct jobs in industrial chemistry respectively. Industrial biotechnology could improve the productivity and competitiveness of the OECD chemicals sector by improving environmental performance, which is now a serious issue. The convergence of industrial biotechnology with green chemistry (see Box 7) could greatly improve the efficiency and productivity of bioprocesses (most biological processes have quite low yields. Green chemistry can improve those yields using low temperature ambient pressure catalysts) (Dusselier *et al*., 2015).

124. The chemicals industry creates many indirect jobs due to its long supply chains. In 2012 the chemicals industry in the United States directly employed over 784,000 workers. But indirect employment among industry suppliers totalled more than 2.7 million.[11] This large multiplier also exists in bio-refining (the industrial-scale conversion of raw materials into finished products). For example, a new bio-refinery currently being constructed in Finland will provide just 200 jobs in the facility itself, but could create 2500 jobs in the supply chain. These jobs involve growing, harvesting and transporting biomass. Work is on-going to analyse job creation in OECD bio-production.

Biotechnology also offers unique solutions to dependence on oil and petrochemicals

125. Biotechnology can provide unique ways to reduce fossil-fuel dependence. For example, by 2050 agriculture will need to feed at least another 2 billion people (UN FAO, 2009). A hugely demanding task is to create food crops that make their own fertilizer, through synthetic biology and, in the near future, gene editing (Keasling, 2015). If achieved, this outcome would help to de-link agriculture from the fossil-fuel based fertilizer industry.

Bio-based products are becoming familiar…

126. Bio-based products are increasingly familiar to the public. And these products span many sectors, not just chemicals (Figure 8).

Figure 8. Bio-based products are becoming widespread and familiar

Source: Courtesy of BIOCOM AG, Germany

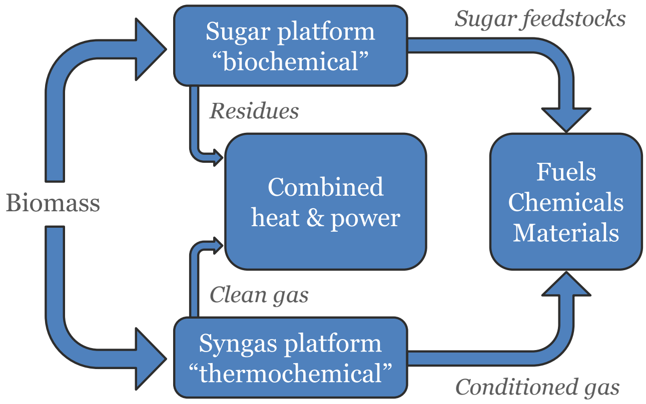
...and bio-based products are starting to become cost-competitive

127. Bio-based materials and fuels currently suffer in competition with the fossil-based industry. Over decades, oil and gas supply chains and production processes have been perfected. The production plants are mature and completely amortised, and the economies of scale achieved mean that fossil-based industries produce many products at low cost. Furthermore, fossil fuel subsidies are vast (IMF, 2013).

128. For bio-based products, none of these conditions exist. Investing in bio-based manufacturing (the most potent symbol of which is the integrated bio-refinery (Box 8) has been a major risk: the early products have not been price-competitive, markets have had to be created by government, and supply chains – particularly the collection of biomass - are far from perfected. However, as figure 8 shows, nascent bio-based manufacturing is bringing new products to market. Indeed, almost one hundred bio-based chemicals are close to commercialisation (E4Tech, 2014).

Box 8. The concept of the integrated bio-refinery

An integrated bio-refinery converts biomass to fuels, chemicals, materials and electricity (Keegan et al., 2013). Truly integrated bio-refineries, which fully convert all the biomass, do not as yet exist, although some approach this level of conversion. At present, bio-refineries are not set up for multiple feedstocks and multiple chemical products. Single-feedstock/single-product bio-refineries are at economic risk owing to changes in feedstock price (especially for food crops). Having multiple feedstocks and products allows for operational changes when economic conditions require.



3.2 Bio-production and industrial biotechnology - main policy considerations

Little policy support has been given to bio-based chemicals

129. To stay competitive, the chemicals industry in OECD countries must innovate. One way to innovate would be to produce chemicals with lower Greenhouse Gas (GHG) emissions (the chemicals sector has the third-highest emissions of any industry, after steel and cement (Saygin *et al*., 2014)). Bio-based production of chemicals could substantially reduce GHG emissions (Hermann *et al*., 2007; 2011; Weiss et al., 2012). But so far little policy support has been given to bio-based chemicals (OECD, 2014c).

Governments could help to create sustainable supply chains for bio-based production

130. Bio-based supply chains are enormously complex. In Europe alone there are some 14 million farm owners (Hetemäki, 2014). Monitoring and controlling the collection of crops and residues is a major task. There are also currently no comprehensive or standard definitions of sustainability (as regards feedstocks), no ideal tools for measuring sustainability, and no international agreement on the indicators to derive the data from which to make measurements (Bosch *et al*., 2015). Furthermore, there are currently no environmental performance standards for bio-based materials. Such standards are indispensable, because most bio-based products are not currently cost-competitive with petrochemicals, while the latter are much more environmentally damaging.

It is likely that as the bio-economy expands, the issue of biomass sustainability will increase in importance.

131. Biomass disputes are already occurring and threaten to create international trade barriers. Disputes could arise between local communities, companies, NGOs, countries and international organizations (Institute Social Innovation, 2012). Global sustainable biomass governance is a patchwork of many voluntary standards and regulations. An international dispute settlement facility could help.

Where industrial biotechnology diverges from other biotechnologies – such as pharmaceuticals - is the need for demonstrator- and commercial-scale bio-refineries

132. Demonstrator bio-refineries operate between pilot- and commercial-scales. Demonstrator bio-refineries are critical for answering technical and economic questions about production before costly investments are made at full-scale. It is hard to know now how many demonstrator plants there are, although the number has grown in the last few years (not all are public: the oil industry is investing in such plants but is not disposed to discussing them in public).

133. Biorefineries and demonstrator facilities are high-risk investments, and the technologies are not proven. Financing through public-private partnerships is needed to de-risk private investments and demonstrate that governments are committed to long-term coherent policies on energy and industrial production.

134. In supporting industrial biotechnology, governments must be aware that demonstrator and pilot plants can be located near to full-scale production facilities. Close proximity to farmers and farmer cooperatives also simplifies biomass transportation. In many cases, farmers also invest in these facilities and are in a good position to be involved in strategic decision making.

Filling gaps in research and training

135. One of the greatest challenges in bio-based production is its multi-disciplinarity. Research and training subsidies will have to create not only the new technologies required, but also a cadre of technical specialists (Delebeque and Philp, 2015). There are some proven ways for governments to tackle this challenge, such as by organising research degrees with a focus on business, not academic, outcomes. To create a non-research workforce, modern apprenticeships would be another mechanism.

Reducing the innovation cycle time of industrial biotechnology

136. A recent estimate suggests that it takes 7.4 years for a synthetic biology company to get a bio-based chemical to market (Lux Research, 2015). A top priority in research should be synthetic biology and metabolic engineering approaches to reducing the innovation cycle time of industrial biotechnology. This would help bring products to market on a timescale that can compete with the fossil industry.

Improving the regulatory environment

137. Governments should focus on three objectives as regards regulations: to boost the use of instruments, in particular standards, so as to reduce barriers to trade in bio-based products; to address regulatory hurdles that hinder investments; and, to establish a level playing field for bio-based products with biofuels and bioenergy (Philp, 2015).

Improvements to waste regulation could also help the bio-economy

138. The legal qualification of some residues or co-products as ‘waste’ hinders many potential bio-refinery initiatives. Governments could ensure that waste regulations are less proscriptive and more flexible, enabling the use of agricultural and forestry residues and domestic wastes in bio-refineries.

Governments could take the lead in market-making through public procurement policies

139. Bio-production has to create supply chains, resolve technical issues in science and engineering and compete with petro-chemistry. Public procurement is one way for governments to create an essential source of demand. Bio-based materials are not always amenable to public procurement as they sometimes

form only part of a product (such as a bio-based screen on a mobile phone). Public purchasing of biofuels is much easier (for instance for public fleets).

4. Nanotechnology – an enabler to the next production revolution

4.1 Summary

140. Nanotechnology is increasingly used in production processes and manufactured products. For instance, nanotechnology can enable the replacement of energy-hungry production processes (such as the fabrication of solar cells in zone-melting processes) with low-cost processes (such as roll-to-roll printing of solar cells in ambient air). Nanotechnology can also underpin cheap single-use products (such as lab-on-a-chip diagnostics).

141. In the short and medium term, nanotechnology will continue to improve existing products and production processes. Entirely new products and processes from nanotechnology-based innovations may arise in the long-term. In both cases, productivity will increase, and demand for skilled workers will rise. Greater understanding will be needed of nanometre-scale phenomena, necessitating investments in basic and applied science.

What is nanotechnology?

142. The term 'nano' describes a length-scale (i.e. $1x10^{-9}$m to $100x10^{-9}$m. A sheet of paper is about 100,000 nanometres thick). The widest definitions of nanotechnology therefore include all phenomena and processes occurring at this length scale, spanning a broad range of processes and features in physics, chemistry, biological systems and various engineering disciplines.

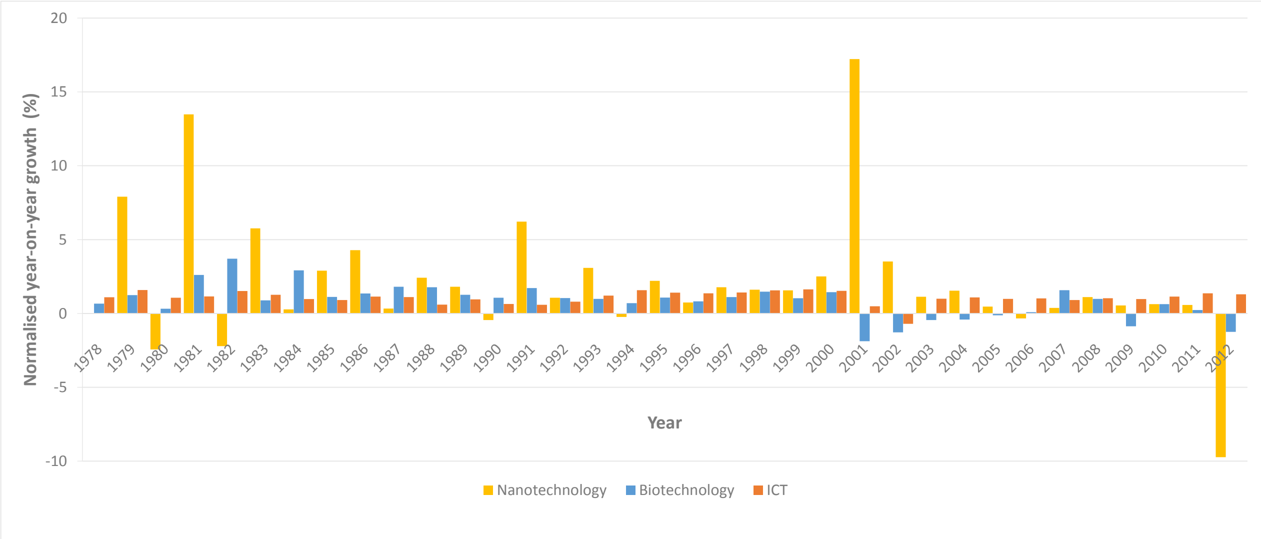
143. The power and versatility of nanotechnology stem from the ability to control matter on a scale where the shape and size of assemblies of individual atoms determine the properties and functions of all materials and systems, including those of living organisms. Nanotechnology is a general purpose technology (GPT) (Helpman 1998, Lipsey 2005). The command of materials on the nanometre-scale can enable innovation in all existing industrial sectors. It can also create new areas of industry. As it develops, nanotechnology will enter a widening range of uses and require complementary technologies and institutions.

Progress in nanotechnology has been hampered by the cost and limitations of the high-accuracy engineering and research environment it demands

144. In the 1980s, science- and technology-foresight studies envisaged rapid advancements from the initial discovery of material-control on the nanometre scale, to the ultimate creation of any complex functional system from its smallest building blocks (Drexler 1986). Figure 9 illustrates the unprecedented hype around nanotechnology opportunities that repeatedly spurred patent growth in nanotechnology several times larger than observed for comparable enabling technologies. Progress in the science and its application, however, has been significantly slower than expected. Progress has been slowed by the high cost of research and development instrumentation, as well as by failures to scale-up from laboratory-scale procedures to industrial manufacture.

145. The difficulty of achieving commercial-scale production was largely due to inadequate understanding of physical and chemical processes at the nanometre-scale, and the inability to control production parameters at that scale. Nanotechnology has increasingly been adopted in process innovations and in the gradual improvement of existing materials

Figure 9 Year-on-year growth of worldwide patent filings in nanotechnology, biotechnology and ICT



Source: OECD patent database. *Note*: Growth rates are normalised to the growth of all patent filings.

146. However, over the last 10 years techniques for large-scale production of nanotechnology-based materials have improved significantly. Many large companies initially adopted nanotechnologies to enable process innovations, and to help reach environmental goals (for instance by reducing the use of organic solvents by working with nanoparticles suspended in water). In addition, advanced nanomaterials are increasingly used in manufacturing processes for high-tech products (for example to polish electronic and optical components).

Nanotechnology is today firmly established as a technological discipline that provides innovative solutions to a number of major challenges

147. Nanotechnology can provide innovative solutions to challenges ranging from the environmental sustainability of industrial processes (for example, through lower use of energy and solvents) to the mitigation of climate change (for example through nanotechnology-based carbon-capture and energy-storage materials) to the affordable provision of preventative medicine (for example, through the creation of invisible sun-blockers) and rapid diagnosis kits (such as through small-scale sensors for lab-on-a-chip applications). A 2014 report found that nanotechnology could contribute to sustainability and resource efficiency in the tyre industry (OECD, 2014d).

148. A number of industrial cases have been studied to highlight the current and future effects that nanotechnology has on industry, with a focus on productivity. Two examples - relating to solar cells and the automotive sector - are described in Box 9.

Box 9. Two examples of current and future effects of nanotechnology in industry

Nanotechnology is set to revolutionise solar cells in four ways:

1. New photoactive materials have been created that outperform incumbent materials in several aspects:

   - ✓ The production cost of solar cells can be significantly decreased by replacing expensive metals (such as platinum) with cheap nano-composite materials (such as flexible sheets of graphite (MIT, 2012)).

   - ✓ The environmental safety of solar cells is improved by replacing toxic materials (such as lead) with innocuous nano-composites (Los Alamos National Laboratory 2013).

   - ✓ The energy efficiency of common solar cells can be increased by greatly reducing the thickness of photoactive material layers (for instance using single-molecule thick sheets of graphene) (MIT 2013).

2. Reducing the size of photoactive materials to the nanometre-scale significantly broadened the range of industrial processes suitable for the production of solar cells, ultimately enabling solar cells manufacturing to move away from an energy-intensive zone-melting processes (for traditional silicon solar cells) to low-cost large-scale thin-film deposition techniques (from liquid and/or gas) and high-throughput printing techniques (e.g. screen-printing, roll-to-roll printing).

3. Thin-film solar cells furthermore enable the creation of flexible and/or spherical solar cells, enhancing collection efficiency compared to flat cells (Lin, 2014).

4. Shrinking all active components of a solar cell (i.e. the photoactive material and both electrodes) can allow the unobtrusive incorporation of near-transparent solar cells into components of buildings. In the long term, nanotechnology-enabled translucent solar cell technology and advanced printing processes will allow buildings to be clad in low-cost solar cells (IEA, 2014).

Rapid advances in solar cell technologies and the boom of the solar cell market have so far only been marginally related to nanotechnology. However, the technology's four-fold impact on the production of solar cells will have effects in the medium and long-term future.

Nanotechnology is reshaping complex automotive manufacturing processes

To increase the fuel efficiency and corrosion-resistance of vehicles, a growing number of metal-based automotive body panels have been replaced with polymer composites. This improvement, however, came at a cost to manufacturers and the environment, because the polymers were not electrically conductive. Not being conductive meant that the new body parts would be excluded from the electrostatic paint line utilised hitherto. Vehicle manufacturers would now have to coat the polymer-based body parts with a conductive primer in a separate step, before the part could be painted with the metallic parts (or they would have to establish a second paint line for the polymer-based parts, often resulting in different properties and optical appearance). The addition of carbon nanofibres (i.e. extremely long, thin and light carbon fibres) to the polymer composite renders the latter electrically conductive, without affecting other relevant properties (Burton 2006). This innovation could reduce manufacturing costs by USD 100 per vehicle (Pelsoci 2005).

4.2 Nanotechnology – main policy considerations

Significant resources are required for R&D in nanotechnology

149. Nanotechnology research is capital intensive, requiring clean-room facilities and advanced microscopy techniques during most steps of the R&D process. R&D in nanotechnology will remain costly and could become more so with advancing specialisation. Specialised equipment, such as combined nano-manipulation and imaging devices, must be used to fully understand processes and properties on the nanometre scale.

Nanotechnology requires increased efforts in international collaboration …

150. The suite of research and engineering tools needed for a comprehensive nanotechnology R&D infrastructure is hard to gather in a single institute (or even region). Nanotechnology research requires international collaboration to achieve its full potential. Publically funded R&D programmes should allow the involvement of academia and industry (large and small companies) from other countries. This can enable targeted solution-driven collaborations between the most suited partners. An example of such an approach is the 'Global Collaboration' initiative under the EU's Horizon 2020 programme (EU, 2016). In 2008, most OECD countries reported that their national nanotechnology policies included "significant co-operation agreements with other countries" (OECD, 2008).

Policymakers should develop multidisciplinary networks…

151. Nanotechnology tends to thrive at the interface of traditional disciplines. This is where discipline-specific research and engineering infrastructures are available – favouring multi-disciplinarity - and the expert knowledge in traditional disciplines is pooled. Examples of such conducive environments include virtual networks, such as Germany has created to support biomedical nanotechnology (Malsch 2005), and research institutes such as the United Kingdom's Interdisciplinary Research Collaborations. Policymakers should seek to support multidisciplinary networks, ideally providing an R&D infrastructure. Such networks should include academia and large and small companies. Public-private-partnerships should be encouraged to foster both scientific excellence and business skills.

…and support innovation and commercialisation in small companies

152. The high cost of nanotechnology R&D is a limitation for many small companies. The cost of equipment use is now often charged under full-economic costing models at universities (for instance, in the United Kingdom the use of a microscope for one day might cost around GBP 5000). Indeed, R&D on nanotechnology is mainly conducted by large companies. Large companies are better placed to assimilate nanotechnology due to their research and development resources, their greater ability to acquire and operate expensive instrumentation, and their capabilities in accessing and using external knowledge (OECD 2010). Policy makers could seek to improve SMEs' access to equipment by: (a) increasing the amount of money SMEs get in research grants; (b) subsidising/waving the service fee; or (c) providing SMEs with vouchers for equipment use. The creation of networks that involve academia, public research laboratories and large and small companies creates an environment in which a research infrastructure can be shared, whilst simultaneously helping start-ups to establish themselves within a current or potential commercial value chain.

153. Regulatory uncertainties regarding risk-assessment and approval of nanotechnology-enabled products severely hamper the commercialisation of nano-technological innovation. This is because products awaiting market entry are sometimes shelved for years before a regulatory decision is made. In some cases, this has caused the closure of promising nanotechnology start-ups, while large companies have terminated R&D projects and innovative products. A 2016 OECD report investigated the treatment of some nanotechnology-enabled products in the waste stream, concluding that more needs to be done to safely integrate nanotechnology in its diverse uses (OECD, 2016c). Policies should support the development of transparent and timely guidelines for assessing the risk of nanotechnology-enabled products, while also striving for international harmonisation. Since 2006, the OECD has led international efforts to harmonise regulatory approaches to the safety of nanotechnology enabled products (OECD, 2011).

5. 3D printing, manufacturing and the environment

5.1 Summary

154. Additive manufacturing, or '3D printing', includes a group of technologies and processes that use a digital file to build a physical three-dimensional object. The physical object is made by successively adding (printing) layers of material until a model is complete (by contrast, the process of machining begins with a piece of material and cuts away unwanted matter. Moulding shapes a liquid material in a single step using a physical mould).

155. 3D printing is growing rapidly and innovations are many. 3D printing could augment manufacturing productivity in a number of ways. But the technology is currently most profitable for small quantities of complex customised products. The next 5 to 10 years will likely see 3D printing supplant the machining of parts. But expansion of 3D printing into other industries depends on the technology's evolution as regards print time, cost, quality, printer size and choice of materials.

156. Diverse claims have been made for the potential environmental benefits of 3D printing. But the OECD's work shows that these claims must be nuanced. The environmental impacts of 3D printing vary widely, from one process to another. To encourage sustainability benefits from 3D printing, policy should facilitate low-energy printing processes and low-impact materials with useful end-of-life characteristics. Governments can take practical steps. These include: targeting financial grants or investments to the commercialisation of relevant research; removing intellectual property barriers to enable 3D printing of repair parts for legacy products (for instance, washing machines that are no longer in production); and, supporting the creation of a voluntary certification system to label 3D printers with different grades of sustainability across multiple characteristics.

3D printing has recently gained widespread attention among manufacturers and the general public

157. 3D printing is expanding rapidly owing to falling printer and materials prices, the rising quality of completed objects, and innovation. Between 2005 and 2011 the number of 3D printers sold doubled (McKinsey, 2012). The global additive manufacturing market is projected to grow at around 20% a year from 2014 to 2020 (Markets and Markets, 2014). And annual printer sales are projected to exceed $10 billion by 2021 (Wohlers, 2014).

158. Recent innovations permit 3D printing with novel materials - such as glass and metals - as well as printing of multi-material objects - such as batteries and drones. DNA printers and printing of body parts and organs from a person's own cells are under development. And bio-printing meat from living cells could eventually become possible (VDI Technologiezentrum GmbH, 2015).

A near-term future has been envisaged in which 3D printing will make micro-scale customised manufacturing economically viable

159. 3D printing permits the marriage of design flexibility and high complexity in printed objects. In general, additive manufacturing technologies become profitable where demand is for small quantities of highly complex and customised products. This might make manufacturing more widely spread geographically.

Positive claims have been made for potential environmental benefits from 3D printing

160. It is sometimes held that: 3D printing could reduce the output of waste in production, as production is additive, rather than subtractive; transport-related pollution and energy consumption could be avoided – as weightless computer code rather than matter is sent from place to place; that environmental

impacts from using some 3D-printed products could be lower than with non-printed equivalents (as is the case with General Electric's 3D-printed jet engine nozzle (Freedman, 2012)); and that material recovery could be increased, encouraging a more circular economy (Ray, 2013; Kilner, 1993; Mayers, 2007). These and other claims are examined in the current work on NPR.

5.2 3D printing and the future of manufacturing

161. 3D printing could augment productivity in a number of ways. For instance, 3D printing of already-assembled mechanisms is possible, which could reduce the number of steps in some production processes. And design processes can be shortened, owing to rapid prototyping (Gibson *et al*., 2015). Objects can also be printed which are otherwise impossible to manufacture (such as metal components contained within other closed and seamless metal components).

162. Currently, most 3D printing is used to produce prototypes, models and tools, with only 15% producing parts in sold goods (Beyer, 2014). 3D-printed goods exist mainly in high-value, small-run niches in sectors such as aerospace, jewellery and medical devices. Almost none of these products are entirely 3D-printed. Rather, they contain 3D-printed components.

The next 5 to 10 years will likely see 3D printing supplant the machining of parts

163. In manufacturing, machining is the main method used for prototyping and producing limited amounts of custom parts. 3D printing is already significantly altering the market for machined plastic and metal parts. For instance, Boeing has already replaced machining with 3D printing for over 20,000 units of 300 distinct parts (Davidson, 2012). However, machining is a small industrial niche, comprising no more than a few percent of total manufacturing sales (accordingly, the environmental impact of 3D printing taking over from conventional machining would be small).

Expansion of 3D printing into other industries depends on the technology's near-future evolution in print time, cost, quality, size and choice of materials

164. The main factor driving or limiting expansion of 3D printing is the cost of switching from mass-manufacturing methods to 3D printing. Costs are expected to decline rapidly in coming years as production volumes grow (MGI, 2013), although it remains difficult to predict precisely how fast this technology will be deployed. Furthermore, the cost of switching is not linear. 3D printing will rapidly penetrate high-cost, low-volume industries such as prototyping, automotive tooling, aerospace and some medical devices. But 3D printing will more slowly penetrate moderate-cost, moderate-volume industries.

5.3 3D printing and the environment

The NPR project has examined two important industrial technologies: machining and injection moulding

165. The environmental impacts of even traditional manufacturing technologies vary greatly and depend on the type of part produced. Consequently, to assess the environmental effects of 3D printing, studies should compare 3D printing to each technology it replaces, for each product type and material. In the absence of such studies, the NPR project has examined two important industrial technologies: machining and injection moulding. These were chosen to represent two ends of a spectrum: single-unit prototyping and mass-manufacturing.

Even considering these restricted cases, the environmental impacts of 3D printing vary widely

166. Life-cycle assessments often show that 3D printing a part in the form of a hollow shell causes lower environmental impacts per part than machining from a block of material. But, by contrast, 3D-

printing causes higher environmental impacts per part than injection moulding in large quantities. However, to further complicate the picture, these results also depend on printer type, frequency of printer utilisation, part orientation, part geometry and other factors. Typically, the environmental impacts of 3D printing primarily reflect energy use. Secondarily they are due to toxicity and the printing materials used. Other impacts come from material waste, and production of the printers themselves. Some experimental systems already have far lower environmental impacts per part than injection moulding—perhaps 70% lower in some circumstances. Industry is not trending towards such systems, but policy could encourage socially desirable choices.

3D printing generally produces parts with lower environmental impacts per part than machining, but there are many exceptions

167. Some part geometries are more efficient to machine than to print, different printers have very different impacts per part, and even a given printer can have very different impacts per part depending on several factors. For plastic parts, two studies show that simply changing printer utilisation causes more variation in efficiency than the difference between 3D printing and machining (Faludi, 2015). Machines which often sit idle have far higher environmental impacts per part than machines producing continuously (whether they are 3D printers or milling machines). Maximising utilisation is therefore a top priority for sustainability in 3D printing. Some 3D printers have higher impacts per part than others due to higher energy use, waste, and material toxicity. Finally, producing hollow-shell part geometries rather than solid-block geometries reduces environmental impacts per part for 3D printing but increases them for machining.

Common misconceptions exist about the environmental effects of 3D printing

168. Eliminating waste and transportation, two of the most frequently cited sustainability benefits of 3D printing, are in fact fallacies. These claims fail to take into account the need for high purity materials that often cannot be recycled and the need for feedstock materials to be transported to the printing site. Many printing methods require such a high level of material purity that they effectively discourage recycling.[12]

3D printing's potential for enhancing environmental sustainability is high

169. 3D printing can encourage less material and energy use through sophisticated design and lean production principles. 3D printing can also enable more sustainable material use because:

- It permits many materials to be shaped in ways previously possible only with plastics;
- It lowers barriers to switching between materials by reducing economies of scale in some processes;
- It can allow fewer chemical ingredients to yield more variation in material properties by varying printing processes; and,
- Reductions in labour costs that 3D printing can bring can permit the use of more expensive materials while still lowering total production cost.

170. 3D-printed parts can also lower the environmental impacts of some products because of how the products can be used, reducing total lifetime impacts even if environmental impacts during manufacturing are high. This can happen in two ways: (i) by printing replacement parts for legacy products that would otherwise be discarded; and (ii) by reducing weight in a vehicle or otherwise improving a product's energy

efficiency. Such energy savings can be quite large, especially in aerospace (G.E.'s lighter 3D-printed parts for a jet engine improved fuel efficiency by 15% (Beyer, 2014)).

5.4 3D printing and sustainability – main policy considerations

171. To encourage sustainability in 3D printing, policy should primarily encourage low-energy printing processes and low-impact materials with useful end-of-life characteristics. Printer design and operation can minimise energy use per printed part by: using chemical processes rather than melting material; using automatic switching to low-power states when idle; and, maximising utilisation (sharing printers among users and, for some printer types, printing more parts simultaneously). Another way in which printers can minimise material impacts is by using compostable biomaterials with high print quality. Printer design and operation can also reduce waste by minimising the use of support material,[13] by producing hollow parts, and by avoiding failed prints. Policy mechanisms to achieve these priorities should include:

- Targeting financial grants or investments (either existing programs or new funds) to commercialising research in these directions;

- Removing intellectual property barriers to enable 3D printing of repair parts for legacy products that lack existing supply chains. For example, a consumer may realise a washing machine is broken and that it only requires a small hinge to be fixed. Theoretically, if the consumer had a 3D printer they could go to their computer, search for the appropriate CAD file and print the new part. The issue is that most CADs are proprietary. One possible solution would be to incentivise rights for third parties to print replacement parts for products, with royalties paid to original product manufacturers as needed.

- Creation of a voluntary certification system to label 3D printers with different grades of sustainability across multiple characteristics, similar to EPEAT[14], Cradle to Cradle (see McDonough and Braungart, 2002), or LEED[15] certifications. Such a voluntary certification system could be combined with preferential purchasing programs by governments and other large institutions.

172. More widespread use of 3D printing, as practiced today, would not automatically be an environmental benefit. But 3D printing technologies already exist that, if more widely adopted, could dramatically shift manufacturing towards more sustainable production. Policies implemented now could have positive effects for decades to come.

6. New materials and the next production revolution

6.1 Summary

173. Recent advances in scientific instrumentation, data science and computation have contributed to a revolution in materials science. This has permitted the development of industrial materials with properties not seen before. The time is ending when materials are developed using trial and error. Increasingly, desired properties will be designed into materials.

174. These developments have numerous implications for industrial processes. Engineers will simultaneously design products and the materials they are made from. A simulation-based approach to materials development will reduce time and costs for companies and yield better products. Successful integration of materials modelling and data sciences into decision support will also shorten the time between materials discovery and their commercial use. New materials will increasingly be a source of competitive advantage for firms.

175. New materials will also raise new policy issues and give new emphases to already-existing policy concerns. For instance, new cybersecurity risks could arise because, in a medium-term future, a computationally-assisted materials "pipeline" could be vulnerable to hackers. Well-designed policies are needed for open data and open science (for instance for sharing simulations of materials structures). Progress on new materials requires close collaboration between industry, universities, research funding agencies and public laboratories. And steps are needed to foster interdisciplinary research and education. Challenges also exist as regards intellectual property rights, particularly concerning the rights to concepts and/or products arising from distributed e-collaborations involving a range of stakeholders, some of which may be consultants and services vendors.

Recent progress in the ability to create and manipulate materials will profoundly affect future production

176. Advances in scientific instrumentation, such as atomic-force microscopes and X-ray synchrotrons, have allowed scientists to study materials in more detail than ever before. Developments in computational simulation tools for materials have also been critical.

177. Today, materials are emerging with entirely novel properties. These include ultra-low density materials (with densities comparable to that of air) and metal which shrinks when heated. Exotic alloys and super-strong lightweight composites, materials that remember their shape, repair themselves or assemble themselves into components, and materials that respond to light and sound are all now realities (*The Economist*, 2015). Manipulating microstructure makes it possible to develop materials with properties that vary from point to point within the material, as desired. And programmable matter that builds itself is a feasible prospect.[16]

The era of trial and error in materials development is coming to an end

178. Progress in computation has allowed modelling and simulation of the structure and properties of materials to inform decisions on how the material might be used in products. Properties such as conductivity, durability, corrosion resistance and elasticity can be intentionally built into new materials. This computation-assisted approach is leading to an increased pace of development of new and improved materials, more rapid insertion of known materials into new products, development of new materials-based technologies (such as ultra-lightweight materials for car bodies), and the ability to make existing products and processes better (for instance, the possibility exists that silicon in integrated circuits could be replaced by materials with superior electrical properties, such as gallium arsenide and perhaps graphene) (MGI,

2014). In the next production revolution, engineers will concurrently design the product and its constituent materials (Teresko, 2008).

New materials matter for productivity and competitiveness

179. A simulation-driven approach to materials development will reduce time and cost as companies perform less repetitive analysis. Simulation will also permit better products, such as stronger complex structures. Successful integration of materials modelling and data sciences into decision support for product development can also shorten the time between materials discovery and their commercial use. In the past, this period could stretch to 20 years or more (MGI, 2014). The Accelerated Insertion of Materials program, run by the United States' Defense Advanced Research Project's Agency (DARPA), has demonstrated such time savings. For instance, in aerospace engine design, concurrent optimization of design and manufacturing processes allowed a rotor disk design 21% lighter and 19% stronger, in half the time of a typical development cycle (MGI, 2014). Large companies, too, will increasingly compete in the development of materials. This is because a proprietary manufacturing process applied to proprietary materials creates long-term competitive differentiation (*The Economist*, 2015).

6.2 New materials and the next production revolution – main policy considerations

New materials will raise new policy issues and give new emphases to long-standing policy concerns

180. Advanced materials raise new policy issues. For instance, new cybersecurity risks could arise because, in a medium-term future, a computationally-assisted materials "pipeline" based on computer simulations could be hackable. Progress in new materials also requires effective policy in areas important for pre-existing reasons, often relating to the science-industry interface. For instance, well-designed policies are needed for open data and open science (for sharing simulations of materials structures, or for sharing experimental data in return for access to modelling tools, for example (Nature, 2013)). Intellectual property rights need to be negotiated in the short- to medium-term suitable for a new-materials innovation ecosystem involving distributed, e-collaborative stakeholders. New kinds of agreements will likely be needed to distinguish community-owned shared data and designs from those of a proprietary character. Progress on new materials also requires close collaboration between industry, universities, research funding agencies and public laboratories.

Interdisciplinary research and education are needed

181. Materials research is inherently interdisciplinary. Beyond traditional materials science and engineering, contributions come from physics, chemistry, chemical engineering, bio-engineering, applied mathematics, computer science, and mechanical engineering, among other fields. In education, students who will become experts in materials synthesis, processing, or manufacture must understand materials modelling and theory, while modellers and theorists must understand the challenges faced by those who make and implement materials solutions (MGI, 2014). These and other policy requirements have been elaborated in the United States' Materials Genome Initiative (MGI). Introduced by President Barack Obama in June 2011, the MGI aims to halve the time, and greatly lower the cost, to discover, develop, manufacture and deploy advanced materials (Box 10).

Box 10. The Materials Genome Initiative

The Materials Genome Initiative (MGI), launched in the United States in 2011, aims to leverage recent breakthroughs in coupling materials modelling, theory and experiments with data sciences to greatly reduce the time and costs to discover and deploy advanced materials. The MGI seeks to connect institutions so as to integrate advanced modelling, experimental capabilities and data. The Initiative will also link networks of stakeholders in academia, government laboratories and industry, to better share the information needed for new material discovery and product development.

The MGI identifies four key challenges to achieving the full potential of new and improved materials:

(1) Delivering a culture shift in materials research, development and deployment, with deeper collaborations between theorists, experimentalists and data scientists, as well as between academics, public laboratories and industry;

(2) Integrating experiments, computation and theory. Materials research spans vast scales of length, from atoms to airplanes, as well as scales of time, from sub-second atomic interactions to the decades of useful life of some manufactured objects. These scales create unique challenges for delivering quantitative and predictive scientific and engineering tools;

(3) Enabling access to easily and reliably searchable digital data, a challenge faced by many other scientific disciplines. Users must be made aware of the tools and data available. A widely accepted governance structure must be designed and implemented. Also, standards must be created to describe data, manage its flow and archival, and assess its quality; and,

(4) Education and training. The next generation of scientists and engineers engaged in materials discovery, development and deployment must be able to collaborate to employ new tools and approaches that integrate experiments, computation, theory and data sciences.

Actions are planned to meet all four challenges, for instance by convening the materials community to identify major scientific and engineering challenges for theory, modelling and simulation for different materials classes and the associated cross-cutting methods and algorithms.

Source : MGI (2014), “Materials Genome Initiative: Strategic Plan”. December 2014, Executive Office of the President, National Science and Technology Council.

7. The diffusion of new production technologies – what can governments do?

7.1 Summary

182. An important way in which framework policies affect the diffusion of technology is through their influence on the process of resource allocation to firms. The efficiency of this process varies considerably across countries. If firms which could lead the next production revolution are unable to attract the resources needed for growth, progress will be stunted. Inefficient resource reallocation can have many causes. These include limited product market competition, rigid labour markets, disincentives for firm exit, barriers to growth for successful firms, and a number of policy conditions, including restrictions on trade.

183. The NPR project is also examining dedicated institutions for technology diffusion, and exploring how they have evolved and may need to change in future. Dedicated technology diffusion institutions include industrial extension programs, technology-oriented business services, applied technology centres and university technology transfer offices. Networks, partnerships and open source collaborations are also increasingly important. Policies have likewise recently placed greater emphasis on demand for new production technologies, with particular attention given to the procurement of technological innovations by government agencies.

184. Governments must give technology diffusion institutions realistic goals and time horizons and avoid mismatch between the institutions' stated aims and their operational realities. For instance, technologies are frequently promoted for their ability to address societal challenges, but institutional funding and evaluation models often prioritize the pursuit of revenues and clients. Policymaking towards the institutions of technology diffusion needs better evidence and a readiness to experiment.

7.2 Framework policies and technology diffusion

A key question is how to ensure that new technologies, ideas and business practices diffuse in OECD economies

185. While ideas are transmitted faster in the digital era,[17] the effects of this on the economy are not straightforward. Indeed, in recent years productivity growth in the United States and other OECD economies has declined. In the United States, for instance, inventories are constant, job tenure is increasing, turnover in S&P 500 firms is flat, and start-up rates are down. While evidence on the role of framework policies in technology diffusion is incomplete, much that is important is known. A key issue is how framework policies affect the process by which firms can attract the resources they need to grow.

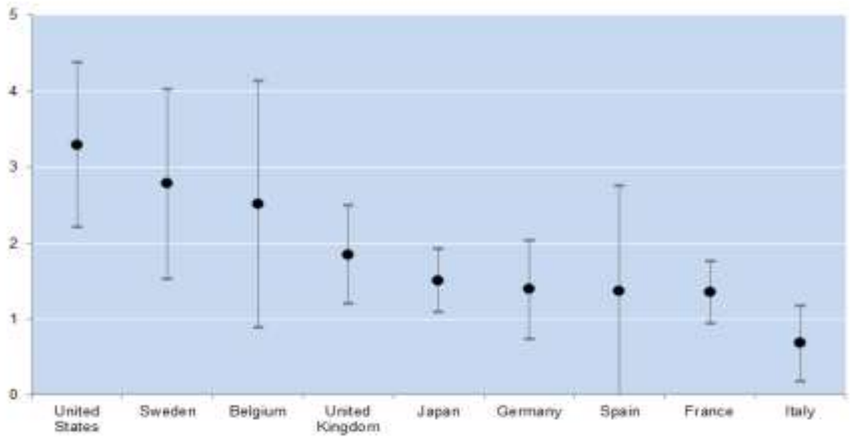
Resources are often trapped in firms which are not able to make best use of them

186. Figure 10 presents data on the extent to which the most innovative firms - proxied by patent stocks - are able to attract financial and human resources. Marked variation exists across countries. For example, in Italy a 10% change in a firm's patent stock increases mean capital investment and employment by less than 1%. In the United States, the equivalent figure is above 3%. If firms which could lead the next production revolution are unable to attract the resources needed for growth, progress will falter.

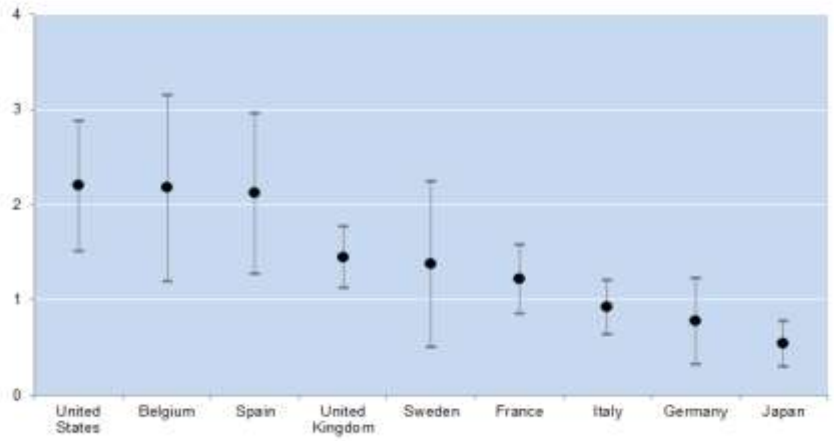
Figure 10. Cross-country differences in resource flows to patenting firms

Change in firm inputs associated with a 10% change in patent stock; selected OECD countries (2003-2010)

A: Capital



B. Employment



Note: The black dot shows the country-specific point estimate while the grey bands denote the 90% confidence interval (note that the confidence intervals vary across countries due to differences in the number of observations).

Source: Andrews, Criscuolo and Menon (2014) based on firm level data from the ORBIS-Patstat Database for the non-farm business sector.

Inefficient resource reallocation can have many causes.

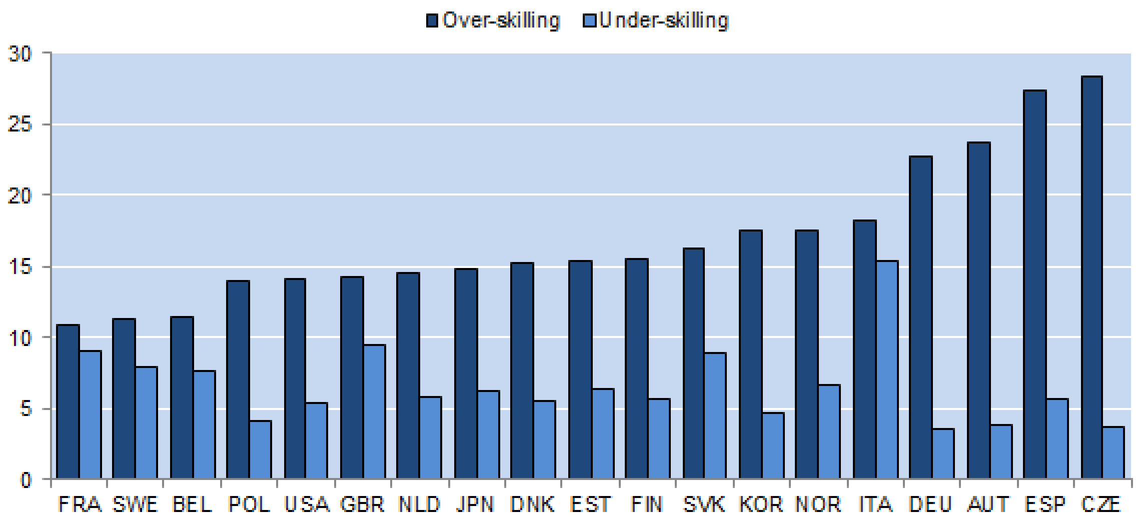
187. As examined in a number of recent OECD studies and reports, the causes of inefficient resource reallocation can include a lack of product competition, rigid labour markets, disincentives for firm exit, barriers to growth for successful firms, as well as policy conditions such as restrictions on trade. For example, the sensitivity of firm-level investment in fixed capital to changes in their patent stock is more than tripled where employment protection legislation is relatively lax (such as in the United States) in comparison with countries where it is stringent (such as Portugal). And the sensitivity of capital investment to a change in the patent stock is almost double in countries where contract enforcement is less costly (such as Norway), relative to countries where it is more costly (such as Italy) (Andrews, Criscuolo and Menon, 2014).

188. Innovation and the use of advanced technology require skills. Around one-quarter of workers report a mismatch between the skills they have and the skills required for their job. A better use of talent could translate in up to 10% higher labour productivity in some economies. Because over-skilling is more prevalent than under-skilling in most OECD economies (Figure 11), the issue is not just one of retraining the workforce. Talent must also be matched with the employment opportunities which allow it to be most productive. In addition to the operation of education and training systems, a variety of policies that affect resource reallocation mechanisms have an impact on the efficiency of skills matching, from employment protection legislation, to policies which affect mobility in housing markets, to the costs of closing a business (McGowan *et al.*, 2015).

Learning from the global frontier is a particular challenge for developing and emerging economies

189. Comin and Mestieri (2013) examined how long it takes technologies to be adopted in developed and developing economies, and how intensely those technologies are used. For 25 technologies, the authors find a convergence in adoption rates across countries, but divergence in the intensity of use. Learning how to use new technologies is still a challenge for companies in many developing economies.

Figure 11. Under-skilled and over-skilled workers



Note: Under- (over-) skilled workers refer to the percentage of workers whose scores are higher than that of the min (max) skills required to do the job, defined as the 10th (90th) percentile of the scores of the well-matched workers in each occupation and country. To control for differences in industry structure across countries, 1-digit industry level mismatch indicators are aggregated using a common set of weights based on industry employment shares for the United States.

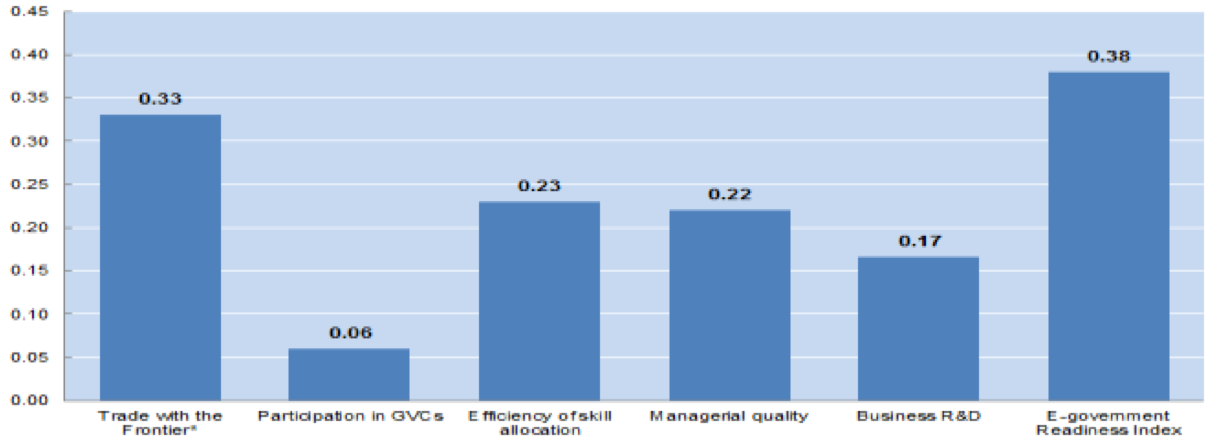
Source: OECD calculations based on the *Survey of Adult Skills* (2012).

Trade also encourages the international diffusion of cutting-edge technologies

190. Trade is a vehicle for technology diffusion and an incentive for technology adoption. Assuming a 2% acceleration in multi-factor productivity (MFP) growth at the frontier, the estimated gain to annual MFP growth would be around a third of a percentage point higher in a country (such as Canada) which trades intensively with the frontier economy, than in one where such trade is relatively weak (such as Austria) (Figure 12). The capacity of governments to develop and implement e-government services also has a particularly large and policy relevant effect.

Figure 12. Learning from the global frontier is shaped by structural factors

Percentage difference in frontier spillover effect between maximum and minimum value of each structural variable, assuming 2% MFP growth at the frontier



Notes: Trade with the global frontier measures the intensity of trade with the productivity leader in each manufacturing industry. GVC Participation is defined as the sum of the share of imported inputs in a country's exports and of its exports used as inputs in other countries exports. (Source: OECD ICIO/TiVA database). The efficiency of skill allocation is measured as the percentage of workers who are either under- or over-skilled (Source: OECD PIAAC database). Managerial quality is proxied by average literacy scores of managers (Source: OECD PIAAC database). Business R&D is defined as the ratio of business R&D expenditure to value added (Source: OECD, Main Science and Technology Indicators). The E-government readiness index is a composite index that measures the capacity of governments to develop and implement e-government services.

Source: McGowan *et al.*, (2015).

7.3 Designing effective institutions for technology diffusion

191. Institutions for technology diffusion are intermediaries, structures and routines that facilitate the adoption and use of knowledge, methods and technical means. A technology diffusion institution may combine a tangible presence (facilities), capabilities (people, expertise, communications), and partnerships (with technology developers and users) alongside informal interactions.

192. Innovation systems invariably contain multiple sources of technology diffusion, such as universities and professional societies. The NPR project's focus is on public or quasi-public institutions, or parts of those institutions, that prioritize technology diffusion roles. Dedicated technology diffusion institutions include industrial extension programs, technology-oriented business services, applied technology centres and university technology transfer offices. Networks, partnerships and open source collaborations are also increasingly important for technology diffusion. Table 1. offers an initial typology of technology diffusion institutions.

The effectiveness of technology diffusion institutions depends in part on firms' absorptive capabilities

193. Firms' absorption capacities and demand for knowledge services are influenced by conditions in innovation and policy systems. This suggests the importance of efforts to foster demand through such mechanisms as innovation vouchers, which encourage users to engage with knowledge or technology suppliers.

Table 1. Initial typology of institutions for technology diffusion

Type	Operational mode (primary)	Example
Dedicated field services	Diagnostics, guidance and mentoring	Manufacturing Extension Partnerships (US)
Technology-oriented business services	Advice linked with finance Capacity development	Industrial Research Assistance Program (Canada) I-Corps (US)
Technology transfer offices	Intellectual property licensing	University TTOs (multiple countries)
Applied technology centres	Contract research	Fraunhofer Institutes (Germany), TNO (Netherlands)
Technology information exchange	Technology community networking	Knowledge Transfer Networks (UK)
Demand-based behavioural change	Knowledge transfer incentives	Innovation vouchers (multiple countries)
Technology partnerships	Collaborative applied research Prototyping and standards	National Network for Manufacturing Innovation (US)
Open source sharing	Open source sharing Virtual networks	Registry of Standard Biological Parts (US)

The conventional rationale for supporting institutions for technology diffusion rests on market failures

194. Enterprises (especially SMEs) often lack information, expertise and skills, resources, strategy and confidence to adopt new technologies. Suppliers and private consultants can experience high transaction costs in trying to diffuse technologies. And finance for scale-up and implementation is not always forthcoming, with the risk that companies will under-invest.

195. In the fast-moving context of new production technologies, the conventional market failure rationales for institutional intervention are likely to become more important, as firms sift through burgeoning amounts of information and attempt to make complex decisions around changing technologies.

Policies to promote diffusion address funding gaps for activities between research and commercialization, and comparable gaps in the capacity for commercialization of research

196. For example, the Innovation Corps (I-Corps) programme was established by the US National Science Foundation (NSF) in 2011 to accelerate commercialization of science-intensive research. Teams of researchers and budding entrepreneurs receive grants to attend training, which encourages ongoing interaction with customers and partners. The program enhances the knowledge of participants and their capacity to start companies around NSF-funded research (Weilerstein, 2014).

New diffusion initiatives are emerging, some of which are still experimental

197. The need for new strategies to promote institutional change, knowledge exchange, capacity development, and demand-led initiatives for technology diffusion has given rise to new initiatives, some of which are nascent or experimental. New production technologies have stimulated partnerships that cross sectoral boundaries and address problems of scaling up between research and production. Alongside established applied technology centres, such as the Fraunhofer Institutes in Germany, there is an increase in partnership-based approaches. An example is the US National Network for Manufacturing Innovation (NNMI). The NNMI uses private non-profit organizations as the hub of a network of company and university organizations to develop standards and prototypes in areas such as 3D printing and digital manufacturing and design.

Digital information technologies are being deployed to facilitate diffusion

198. Analogous to the rise of open sharing of research articles and data is the emergence of libraries promoting sharing of technological building blocks. For example, BioBricks is an open source standard developed at MIT to enable shared use of synthetic biology parts through the Registry of Standard Biological Parts. Such open source mechanisms in biotechnology exist against a backdrop of traditional proprietary biotechnology approaches.

Policies have also placed greater emphasis on demand for new production technologies

199. Attention to the procurement of innovation by government agencies has grown across many countries, often targeted to SMEs. Incentives such as R&D tax credits, regulations and standards are also being used to encourage pre-commercial R&D activities, such as feasibility studies and prototyping. Several countries (including the United Kingdom, Ireland, and the Netherlands) have promoted innovation vouchers. These combine matchmaking with modest financial incentives to increase the readiness of enterprises to interact with sources of technology and knowledge (Bakhshi *et al*., 2013).

Technology diffusion institutions need realistic goals and time horizons

200. Many new technologies are introduced into existing ecosystems where sunk costs have been invested in old ways of doing things. For example, fully automated factories proposed in the 1980s failed in part due to the difficulty of integrating existing supply chains with newly shortened product life cycles. Introducing new ways to integrate and diffuse technology takes time, patience and experimentation. Yet many governments want visible results quickly, without risk.

Misalignment can exist between the stated aims of technology diffusion institutions and their operational realities

201. While some new production technologies are promoted for their ability to address societal challenges, funding and evaluation models in many public technology diffusion institutions prioritize the pursuit of revenues and clients. Furthermore, there is often a focus on disseminating the latest advanced technology, when many enterprises and users do not use current technologies to their fullest extent and lack absorptive capabilities for sophisticated technologies. In such cases, pragmatic approaches to technology diffusion may be needed, coupled with long-term relationships that build capabilities for more advanced strategies.

Policymaking needs better evidence and a readiness to experiment

202. A better understanding of effective organizational designs and practices for technology diffusion is vital. There is more to this than re-designing assessment and evaluation, and fostering knowledge about good practices, although these are important. More fundamentally, existing institutions need to be able to discover new approaches, to embed innovative methods in their own operations and be well integrated into innovation systems. New and perhaps unconventional institutions and strategies for technology diffusion might also need to be considered.

203. Concerns over governmental accountability combined with ongoing public austerity in many economies could mean that current institutions will be reluctant to risk change, slowing the emergence of next generation institutions for technology diffusion.

8. Public acceptance and new technologies – why does this matter and what options are open to government?

8.1 Summary

204. Some of the technologies addressed in this report have raised public concerns of different kinds. Some concerns have to do with risk, such as how nano-technologies might affect human health. Others relate to the control of life processes, which some bio-technologies make possible. The next production revolution could raise societal issues not seen before. For instance, as machine autonomy develops, who will be responsible for the outcomes that machines give rise to, and how will control be exercised?

205. Historically, episodes of public concern about technology have sometimes affected regulation and public investment. Lessons can be learned from these experiences. In particular, holding to realistic expectations about technologies can help maintain trust. Countries can make systems of scientific advice more robust. This can be done by producing and publicising sound and credible scientific evidence on risks, encouraging deliberation with publics, ensuring clear communication about sources of uncertainty, and making processes of appointment and operation more accountable. Science funders can also be attentive to ethical, legal and social issues.

Public attitudes about emerging technologies are hard to gauge, but there is evidence of general optimism

206. In a recent major survey in Europe, at least half of the respondents expected that, 15 years from now, science and technological development will have a positive impact on health and medical care (65%), education and skills (60%), transport and transport infrastructure (59%), energy supply (58%), protection of the environment (57%), the fight against climate change (54%) and housing quality (50%) (EC 2014).

Society's reception of NPR technologies could affect their development and adoption

207. In the past, public concerns have blocked the development and implementation of some new technologies. This has happened even when a technology's technical and economic feasibility has been demonstrated, where there has been a sound rationale for adoption, and where large investments have been made (EC 2013). For example, many countries invested in the construction of nuclear reactors in the 1960s and 1970s. Even in the face of expert opinion avowing safety, political protests often halted their use (Winner 1986).

One result of public concern can be new regulation and approaches to governance

208. Public pressure can feed into regulatory choices that condition the adoption of technology. For instance, in the area of biotechnology, public controversies over genetically modified organisms (GMOs), especially in food crops, have had a major impact on regulation and approvals of new crops in Europe (Watson and Preedy 2016).

While public concerns can constrain technology, they can also lead to increased safety and acceptability

209. Scientific studies and environmental protest in the 1960s and 1970s led to stricter regulation of pesticides and other chemicals (Davis, 2014). There is broad consensus now on the need for such regulations (Rodricks, 2006). Regulation can also enable technology adoption by stipulating the terms of acceptable use: activism in the 1960s about the safety of automobiles led to higher safety requirements and shaped the development of the automobile industry (Packer, 2008).

Biotechnology has been the subject of persistent public conflicts over societal risks

210. In both developed and developing countries, genetically modified crops have raised concerns around health and safety risks, the capacity to contain and reverse their release, and the effects of intellectual property on concentration in the structure of the agro-food industry (Jasanoff 2005). Such concerns have been resolved differently in different countries, with some countries adopting GM crops at a much slower rate than others. Stark regulatory approaches growing out of distinct public attitudes to biotechnology have resulted in disruptions to international trade and have even led to dispute settlement at the WTO (Pollack and Shaffer 2009).

Governments will have to anticipate public concerns around the most recent biotechnological advances, especially gene editing

211. New developments in genetic engineering, particularly gene editing, have sparked intense public debate about the potential benefits and harms of this technology, particularly in the context of human germline engineering (Box 11). Public debate on gene editing is likely to have a major impact on the trajectory of biotechnology (McNutt 2015).

Box 11. Gene editing in society

With so-called “gene editing” techniques, especially those using the CRISPR-Cas9 system (named as by the journal *Science* as the Breakthrough of 2015), scientists are now able to change a DNA sequence at precise locations on a chromosome. Gene editing will make the design and construction of organisms with desired traits easier and cheaper. It raises the possibility, for example, of new methods for the control of pests and diseases as well as improvements in plant and animal breeding. Recently, CRISPR has been used in China to edit genomes of non-viable human embryos. Similar experiments have been approved in the United Kingdom (Callaway 2016).

In March 2015, a group of scientists and ethicists, including Nobel laureates David Baltimore of Caltech and Paul Berg of Stanford, proposed a worldwide moratorium on altering the genome to produce changes that could be passed on to future generations. In December 2015, the National Academies of Science in the United States, along with the Chinese Academy of Sciences and the United Kingdom's Royal Society convened an international summit of experts from around the world to discuss the scientific, ethical and governance issues associated with human gene-editing research (Reardon 2015).

Many unknowns remain about the health and environmental impacts of nanoparticles remain

212. As described earlier in this paper, nanotechnology will bring many benefits. Manufactured nanomaterials are found in more than 1,300 products currently on the market, including medical equipment, fabrics, fuel additives, cosmetics and plastics (Environmental Protection Agency 2016). Regulatory approaches are still evolving, even as nanomaterials enter waste streams along with other commercial products. Recent OECD work has found significant knowledge gaps with respect to the final disposal of nanoparticles (OECD, 2016b).

Government programs to collect and leverage big data have raised significant public concerns and ethical issues

213. The use of big data for national security purposes has recently raised major public concerns, notably in relation to privacy. But other uses of big data have also become the subject of public debate. For instance, health policymakers across the world are seeking to aggregate diverse health data from millions of people to enable comparative effectiveness research (CER) and help produce an innovative big data architecture for research and discovery (Institute of Medicine 2014). A central goal is to integrate population level and personal health data across the public and private sectors to enlarge the evidence base

for clinical care, better monitor quality, and aid the discovery of biomarkers for the development of better diagnostics and drugs (Krumholz 2014).

214. In the United Kingdom, failure to address privacy and access questions triggered a major public controversy among clinical physicians, disease advocacy groups and the larger public, undermining trust in central health authorities (Kirby 2014). These social uncertainties are pressing many governments to develop innovative partnerships and public dialogue with patients, health institutions and other stakeholders to find solutions to questions of privacy, control and justice (Kaye *et al*. 2012).[18]

8.2 Public acceptance and new technologies - main policy considerations

Having realistic expectations about technologies can help maintain trust

215. In areas of emerging technology, "hype" must be avoided. An emphasis on short-term benefits can lead to disappointment (Nuffield Council 2012). For example, stem cell research has involved a pattern of inflated predictions by scientific communities, funding agencies and the media (Kamenova and Caulfield 2015). This has helped cause controversy in California where a USD 3 billion public initiative on stem cell research begun in 2004 delivered scientific advances but failed to yield health benefits.

Science advice must be trustworthy

216. In the late 1990s in the United Kingdom a public controversy arose about how government regulators failed to address uncertainties in their risk assessment and management strategies around BSE, or "mad cow disease". This episode undermined the trust afforded to regulators on the risks of GMOs soon after (Pidgeon, Kasperson and Slovic 2003).

217. Across countries, scientific advice informs policies on emerging technologies in different ways (Jasanoff, 2005). Events such as the BSE outbreak and the Fukushima disaster indicate a need for expert communities and the public to recognise that risk models have limitations and science-based regulatory decisions often carry value judgements (Pfotenhauer *et al*., 2012). Countries must put resources into making systems of expertise more robust by encouraging more exchange with publics, encouraging clear communication about sources of uncertainty, and making processes of appointment and operation more accountable (Jasanoff 2003; OECD, 2015d)

Societal assessment of technology can inform science and technology policy

218. Innovation policy in many OECD countries is now guided by forms of societal technology assessment carried out by a mix of actors, including national ethics committees and other government bodies tasked with taking a broad view of social, health and safety risks. Some of these technology assessments are broadly participatory and involve stakeholder and public input (Durant 1999). These assessments involve formal risk analysis but can also consider longer-term social implications of technologies not easily reduced to immediate health and safety risks.

Box 12. Mechanisms of technology assessment

Processes of societal technology assessment vary across countries, but the following mechanisms have proven most useful:

- The establishment of public advisory bodies. Examples include the Danish Board of Technology Foundation, the Nuffield Council on Bioethics in the United Kingdom, and presidential bioethics committees in the U.S. These groups might be charged with writing reports on particular technologies that gather evidence through research and public testimony and can inform public reasoning.
- The use of scientific academies or regulatory authorities to assess the most technical aspects of emerging technologies
- Public surveys and stakeholder interviews to gauge current opinion.
- Well-designed deliberative exercises involving experts, citizen panels or lay publics
- Hearings meant to inform regulatory agencies

Since the Human Genome Project, science funders in many OECD countries have sought to integrate attention to ethics, legal and social issues

219. The planners of the Human Genome Project (HGP) recognized that mapping and sequencing the human genome would have profound implications for individuals, families and society, and so they allocated over 3% of the budget to the ethical, legal and social implications of research. Since this pioneering approach, efforts have been made in many countries to mainstream social science and humanities work into funding streams. The next generation of these approaches integrate social considerations not at the end of technology pipelines, but in the course of their development, with the aim of supporting innovation rather than constraining it. This includes Europe's Horizon 2020 programme and the U.S. National Nanotechnology Initiative (NNI). Begun in 2003, the NNI coordinates over a billion dollars of research a year. The NNI emphasizes both the need for commercialization and the need to better understand societal impacts and build societal capacity to engage with innovations in nanotechnology (through two dedicated centres).

Public deliberation is important for mutual understanding between scientific communities and the public, and should inform innovation policy

220. Deliberation can take various forms. Citizen panels and town halls have been pioneered in Denmark and elsewhere for a broad range of emerging technologies relevant to the NPR. Deliberation can take place in the context of national advisory processes and public inquiries, which should include dedicated processes for public engagement and the reception and processing of public concerns, so these might feed into the process. The learning spaces mentioned above can facilitate two-way communication so that science addresses problems brought from citizens to scientists. A multitude of these tools have been pioneered in the context of nanotechnology (Guston 2014).

Sweden's nuclear waste program provides a good example of a process that successfully bridged divided expert and public opinion to produce a societally acceptable decision on the future of a technology

221. In response to social concerns about the siting of nuclear waste, Swedish officials conducted and presented a "safety case" as a primary tool in developing a public deliberation on the topic. The process resulted in a publicly approved, licensed facility for nuclear waste disposal. The materials developed by the

Swedish officials conveyed technical arguments in lay language about why the proposed facility was thought to be safe. The materials clearly described what was thought to be the quality of the information available. They also described plans for what would be done to improve understanding, the expected outcome of these efforts, and how previous efforts to improve understanding had performed (as expected or not). At a follow-up, the results of recent experiments were compared with previously predicted results. Over time, the transparency of this process enabled everyone to perceive an increasingly accurate understanding of the facility's performance (Long and Scott 2013).

9. Developing foresight about future production: what should governments do?

9.1 Summary

222. Greater foresight in science and technology is sought by most governments. For instance, a goal of the America Competes Act is the identification of emerging and innovative fields. Better anticipation of trends could clearly assist policy development and the allocation of research funds and other resources. But uncertainty in science and technology is pervasive. Predictions of future technological developments have often been greatly off-target, even when coming from practitioners intimate with the technologies involved.[19] In the context of new production technologies, this section considers foresight studies and how governments should use them. Also examined are procedures for eliciting expert opinion on technology futures, and the use of patent and bibliometric data. Expert elicitation and patent and bibliometric data are often used in the context of foresight processes.

223. Foresight exercises are not new, and are certainly not specific to production technologies. But the great complexity of modern manufacturing and the economic, social, environmental and ethical implications of new technologies underscore the need for foresight processes.

224. Foresight processes have many forms and goals. In addition to a view of the future that foresight develops, process-related benefits also arise (such as strengthened stakeholder networks, including across parts of government which might not normally interact). Formal evaluation of foresight exercises is weak. But some good practices can be identified. In particular, foresight should ideally be institutionalised. While the connection with decision-makers must be strong, the process must also enjoy intellectual autonomy.

225. When assessing the development of a given technology, bibliometric and patent data have often been employed for *ex post* analysis. But these data can also be used as an adjunct to forward-looking studies. In so doing, the limits of the data must be taken into account.

226. Structured elicitation of expert opinion has also been used to examine technology futures in fields from health to energy. Expert elicitation could be applied to issues raised by new production technologies, such as the penetration of robots. Expert elicitation is particularly useful in exploring areas of uncertainty where data are limited. Professional and cognitive biases can affect expert assessments of uncertainty. Protocols to account for these biases must be used.

Foresight is a specific type of prospective analysis aimed at thinking about the future and shaping it

227. Foresight processes aim to systematically and transparently identify and assess social, technological, economic, environmental and policy conditions that shape some aspect of the future. Foresight processes are: (i) action-oriented; (ii) participatory (often involving researchers, business people, policy-makers and representatives of citizen groups); and, (iii) consider multiple futures.

The process foresight often brings benefits in itself

228. Prediction is not the primary role of foresight exercises. In developing roadmaps and examining projections, foresight assists preparation for multiple possible futures. In addition, process benefits arise from doing foresight. Networks of stakeholders are likely to be strengthened, new ones are created, and a future-oriented way of thinking is reinforced. Participatory methods can also re-shape the overall decision-making culture.

The complexity of modern manufacturing makes multidisciplinary policy assessment essential

229. The complexity of contemporary manufacturing means that successful policy needs many types of knowledge. The pieces of knowledge required come from various actors and activities and are rarely available inside a single organisation. It is important therefore to support the generation, diffusion and use of many sorts of knowledge and types of collaboration. The blurring boundaries between manufacturing and services reinforce this conclusion. Foresight exercises can be important for policy in combining diverse sources of knowledge.

Foresight can – and should – take many forms, varying in thematic coverage, geographic scope, focus, methods and time horizons

230. Several foresight exercises have focused on manufacturing and production, including "Making Value for America: Embracing the Future of Manufacturing, Technology, and Work" (2015), "The Future of Manufacturing: A new era of opportunity and challenge for the UK" (2013), "Future of manufacturing in Europe 2015-2020 (FutMan)" (2001-2003), and "Manufacturing Visions – integrating diverse perspectives into pan-European foresight (ManVis)" (2003-2006). Other foresight studies have covered numerous fields including manufacturing.

Foresight processes can have many aims

231. Foresight often aims to build roadmaps to guide technological development efforts. Examples here include "Productive Nanosystems: A Technology Roadmap" (US, 2007), "Nanotechnology for Podlaskie 2020" (Poland, 2012), and a series of Delphi surveys conducted in Korea every 5 years since the early 1990s. But other foresight projects have aimed to build broader strategic visions for manufacturing. Examples include the four foresight projects from the United States, United Kingdom and European Union referred to in the immediately preceding paragraph.

232. The impacts of most foresight exercises have yet to be thoroughly evaluated. This is especially true for recent studies. Yet, as the following paragraphs describe, accumulated evidence on good practices and the necessary conditions for impact suggests a number of benefits, and some key challenges, when conducting foresight.

Foresight can aid thinking about multiple possible futures

233. Governments can easily be trapped by the need to deal with the short-term. Foresight provides space for longer-term thinking. Foresight also explores different possible futures. In uncertain times, thinking in terms of multiple future states is a pre-condition for devising policies to cope with unexpected developments.

Foresight can also foster systems thinking

234. Furthermore, in a complex world, many phenomena cannot be understood in isolation. They must be seen in context, from a number of viewpoints. Foresight involving participatory methods can incorporate necessarily diverse perspectives (see Box 13).

Box 13. The future of manufacturing: a new era of opportunity and challenge for the United Kingdom

The recent British foresight project "The Future of Manufacturing: A new era of opportunity and challenge for the UK", completed in 2013, considers several factors shaping the characteristics of manufacturing to 2050. These include *new business models*, e.g. the 'servitisation' of manufacturing; the *extension of value chains*; but also major *market trends and opportunities*, *'onshoring' of production* back to the United Kingdom, and the increasing share of *foreign ownership*. The likely impacts of five pervasive and six secondary *technologies* are spelt out, along with the features of *future factories, environmental trends* and *skills* requirements. Based on this systemic view of the future of manufacturing, the study presents policy implications. Rather than coming up with suggestions based on simple trend extrapolation, the study stresses the need to: take an integrated view of value creation in manufacturing; follow a more targeted approach to supporting manufacturing based on systemic understanding of STI and industrial policies; and, enhance government capability to evaluate and co-ordinate policy over the long-term.

Foresight can facilitate the mobilisation and alignment of stakeholders

235. Most foresight activities not only explore possible futures, they also seek a common understanding of what a desirable future might be. Such *visions* and – associated to them – operational *roadmaps*, can be instruments for assembling key players around a *shared agenda*. Having such a shared view can reduce uncertainty about the ambitions of partners and competitors, and thus assist long-term investment decisions.

Foresight can support policy co-ordination

236. Foresight usually aims to identify future issues that often cut across established areas of policy interest. By involving participants from different policy domains, policy co-ordination can be fostered both horizontally (i.e. across policy domains, or between parliament and government) and vertically (i.e. between ministries and executive agencies).

And foresight can help to reframe policy issues and spur organisational innovation

237. Government bodies tend to be organised along the lines of rigidly demarcated policy domains. Organisational structures can lag fast-changing scientific and technological fields. In such cases, it can be difficult to find a proper place for cross-cutting research or for new ways of directing research (for example, in shifting from S&T-led research to societal challenges-driven research). Government bodies can also be insular, with the same participants sometimes repeatedly involved in decision-making. Foresight processes have the potential to enlarge and renew the framing of policy issues. In a connected way, foresight can also induce organisational innovations (see Box 14).

Box 14. Foresight and institutional innovation

BMBF Foresight - a strategic instrument of Germany's Federal Ministry of Education and Research (BMBF) - aimed to identify new focal areas in research, defining cross-cutting issues and inter-disciplinary topics that require attention. Two of these novel future fields were described as "Human-Technology Co-operation" and "ProductionConsumption 2.0". These themes obtained high visibility in policy debates and triggered intense discussion on the future of manufacturing in Germany, eventually contributing to shaping the concept of what is now called "Industrie 4.0". One of the fields was subsequently also mirrored in the creation of a new division in BMBF in 2010, called "Demographic Change and Human-Technology Co-operation".

9.2 Foresight studies on future production – main policy considerations

Foresight should be an embedded (institutionalised) practice

238. One-off foresight exercises can be influential. But, ideally, foresight should be institutionalised. Since 1992, the Finnish government, under the Prime Minister’s office, prepares a foresight report for the Finnish Parliament each parliamentary term. These reports have strengthened long-term thinking in Finland, created a dialogue between government and parliament on future issues of national relevance, and provided a strategic framework for policy going beyond election cycles.

239. Foresight activities also take time to affect policies, ways of thinking, policy-making cultures and governance systems. And foresight exercises themselves can be time-consuming. For example, the project on “The Future of Manufacturing: A new era of opportunity and challenge for the UK” lasted for 2 years: it produced 37 background reports, and besides mobilising the major stakeholders it also involved some 300 industry and academic experts, business leaders and other stakeholders from 25 countries.

The links between foresight processes and decision-making should be close…

240. A fundamental condition for achieving impact is having a committed policy client. Foresight should be embedded in the decision-making system. Its timing, relevance to major policy issues, and co-ordination with other policy initiatives are critical. For example, the German BMBF Foresight (2007-2009) sought to underpin German policy on science, technology and innovation, and was closely connected to the German High-tech Strategy. In this way, new focal areas in research and technology were identified, as were cross-cutting and inter-disciplinary topics.

… but foresight exercises must enjoy intellectual autonomy

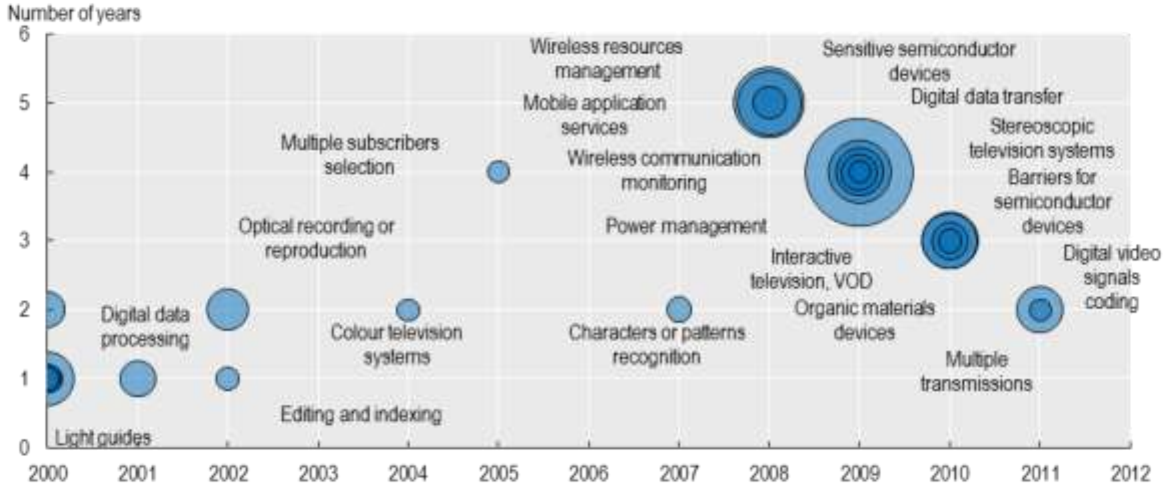
241. It is crucial to find an organisational set-up that eases the inherent contradiction between the need for foresight to be embedded in decision-making, and the need to maintain intellectual autonomy (to generate original ideas and out-of-the-box thinking). Any solution can only be context-specific.

9.3 Using bibliometric and patent data mining to examine technology futures

242. Policy makers have various methods to help guide them in directing public technology support. These often draw on patent and bibliometric data. Areas in which patent data have been used to document the emergence of technologies include biotechnology (Arts *et al*., 2013), telecommunications (Fontana *et al*., 2009; Martinelli, 2012) and paper and electronics (Karvonen and Kässi, 2013).

243. Dernis *et al*. (2015) use data mining to identify technological areas in both scientific publications and patents which suddenly accelerate and then grow at a faster pace than others for some time. The study analyses keywords appearing in the titles of scientific publications and patent classes over the period 1996-2012. Figure 13 shows that at the start of the 2000s, activities burgeoned in the field of digital data processing and editing. However, since 2008 technologies related to wireless communications and improved performance of ICT devices (e.g. power management, data transfer) have accelerated with unprecedented intensity. This work illustrates how scientific topics and technological developments - in the form of patented inventions - emerge, grow and decline. Perhaps most importantly, the use of such data can help to identify emerging technologies at a relatively early stage of development.

Figure 13. Intensity and development in ICT-related technologies, 2000-2012



Source: OECD Science, Technology and Innovation Scoreboard 2015: Innovation for growth and society.

Patent and bibliometric data can be a useful adjunct to other methods, but have limitations which need to be recognised

244. Whether based on patent data or bibliometrics, data-mining exercises have shortcomings. Most importantly, not all inventions are documented in scientific literature or protected at intellectual property offices. Search methods are also likely to be imperfect (there is imprecision in classification systems, ambiguity of terms in keyword searches, etc.). And there may be important sampling biases, since none of the available databases in either domain cover the full population of documents. Nonetheless, despite such shortcomings, data-mining can be a useful adjunct in assessing emerging technological trends.

9.4 Using expert elicitation to assess technology futures

245. To examine emerging technologies it is also common to use either formal simulation models or engineering–economic assessments. In addition, applied decision analysts have tried to generate subjective probability distributions for given outcomes based on information elicited from relevant experts (Morgan 2014). Such expert elicitation can help to explore sources of uncertainty and to answer questions where data are prohibitively expensive or difficult to collect.

246. The great advantage of expert elicitation relative to alternative methods is the ability to quantify uncertainty by drawing on knowledge that is concentrated among experts and unavailable to the public (Bosetti *et al*. 2015). Expert elicitation is particularly valuable where the distribution of possible outcomes can be wide and skewed, and thus where methods which generate estimates of future outcomes based on the "mean" are less useful (for example, expert elicitations were pioneered mainly for decisions relevant to uncertain extreme natural events).

Professional and cognitive biases can affect expert assessments and must be accounted for

247. The principal challenge of expert elicitation is that it relies on individuals who deeply understand a subject, but may have difficulty conceptualising outcomes in terms of probabilities (Verdolini *et al*., 2015). Moreover, a number of professional and cognitive biases can affect expert assessments of uncertainty (see Marquand and Robinson 2008, and Tversky and Kahneman, 1974). Recognition of these biases led to the development of protocols and methodologies for structured expert elicitations.

248. Expert elicitation methods have been used to assess possible technological trajectories in a number of fields. For example, elicitation has been used to assess possible rates of adoption of genetically-modified crops (Tusaka *et al*. 2015). Expert elicitation has often been applied in public health (Butler *et al*. 2015). Perhaps the area where these techniques have been used most frequently is in energy. This reflects the considerable uncertainty about future technological trajectories in energy, and the significant public demand for improved understanding of possible outcomes. Bosetti *et al*. (2015) summarize expert elicitations on (green) technologies. These studies generate new data by asking experts in various ways to estimate future technology costs depending on hypothetical R&D spending.

249. Potentially the most important policy use of expert elicitation to date has been to inform decision making on the optimal energy technology R&D portfolio. For example, in Bosetti *et al*. (2015), the largest percentage increase in R&D is recommended for energy storage, as compared with fossil, solar and other forms of energy generation. Other fields where expert elicitation could potentially be applied relate to issues which bear directly on future production, such as the penetration of robots in different sectors.

10. Enabling upgraded manufacturing in China

10.1 Summary

250. For a number of reasons, the NPR project is examining recent and planned developments in production in China. First, China's weight in global manufacturing has many implications for production elsewhere in the world. Manufacturing is a foundation of China's economy, and China accounted for 20.8% of global manufacturing output in 2013, leading the world for the fourth consecutive year (Chinese Academy of Engineering, 2015). Secondly, China's goal of increasing the knowledge-content of domestic production will expand the range of markets in which China competes and contribute to the development of production technologies in those markets.

251. Manned space flight and deep-sea submersibles, high-speed rail and the world's fastest supercomputer are all examples of China's manufacturing-related achievements. Furthermore, these achievements are associated with progress in research, education and infrastructure (MIIT, 2015a). Li Keqiang, the Chinese Premier, recently stressed that upgrading traditional and new sectors of manufacturing is essential for China's long-term development (Li, 2015). 'Made in China 2025', launched in 2015, is part of a 30-year strategy to strengthen China as a manufacturing power. And, more recently, the 'Internet Plus' initiative aims to digitalize major parts of the economy.

252. But manufacturing in China faces domestic and overseas challenges. Global competition has intensified, labour cost advantages have eroded, and some multinational firms are moving high-end manufacturing back home. Sizeable parts of Chinese manufacturing experience shortcomings in management and digital capability. The private sector's role in some areas of research is also limited, while technological change is raising demand for skilled managers, researchers and technicians. Information security is also a growing concern.

Growth in manufacturing has stalled as China's overall growth has slowed

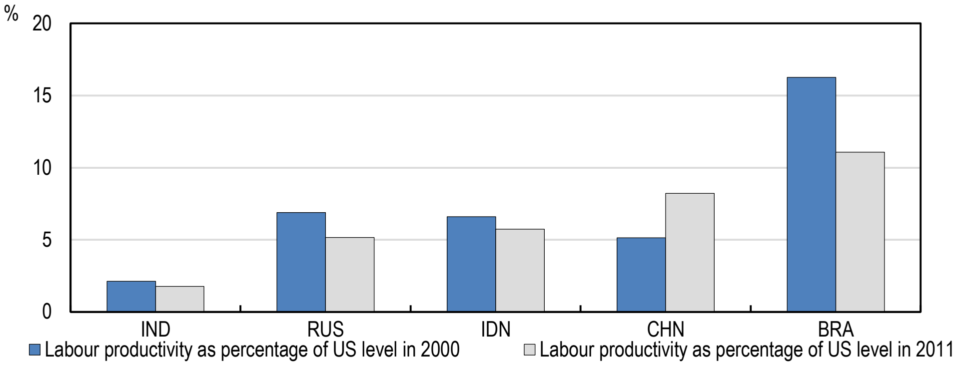
253. January 2016 marked the sixth consecutive month in which the purchasing managers index (PMI) for manufacturing showed contraction (Xinhua, 2016). The same index indicated contraction during seven months in 2015 (National Bureau of Statistics of China, 2016). As the population ages and labour costs surge, the cost advantage of Chinese manufacturing over the United States has fallen to less than 5% (Sirkin, Zinser, & Rose, 2014). While China's labour productivity has risen over the past decade, it is still much lower than in the United States (and other developed countries) (Figure 14). And China still relies heavily on imports for advanced manufacturing. Indeed, in 2013, imported semiconductors exceeded oil as China's largest import item. Environmental concerns have also become more prominent as air, water and soil pollution from manufacturing has worsened.

And Chinese manufacturing faces challenges from abroad

254. Global competition has intensified as advanced manufacturing becomes a strategic priority for many developed countries, as some multinational firms move high-end manufacturing back home, and as low-end manufacturing locates to countries with lower labour costs (MIIT, 2015b).

Figure 14. Labour productivity of BRICS in manufacturing

% of US level

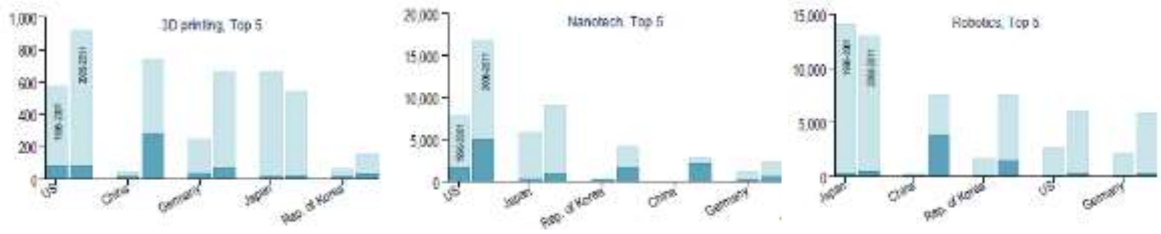


Source: OECD (2015e).

China considers success in the next industrial revolution a feasible opportunity

255. In China, the approach being pursued to achieve success in the next industrial revolution focuses on a deepening integration between information and communication technologies (ICT) and industry. Developments in other key technologies, such as new sources of energy, new materials and bio-technologies, are also important (Development Research Centre of the State Council, 2015). In a number of the relevant technologies, the capability gap between China and global leaders is smaller than ever before (Figure 15).

Figure 15. Top 5 origins in first patent filings, 1995-2001 and 2005-2011



Note: The dark blue bars represent filings from academia and the public sector. *Source*: World Intellectual Property Organisation (2015)

China's industry and government are working proactively to upgrade manufacturing

256. China aims to maintain manufacturing competiveness in traditional fields, such as processing and assembling, by increasing efficiency and quality and reducing costs. But Chinese manufacturers are also making striking progress in technological and product innovation. For instance:

China is now the largest global market for industrial robots (IRs) …

257. Between 2008 and 2013, the total supply of IRs in China increased by about 36% a year on average. In 2013 and 2014 China became the largest international market for IRs, and is expected to have some 428,000 units by 2017 (International Federation of Robotics, 2015). Sales of Chinese-made industrial robots increased 77% in 2014 (Shen, 2015).

… and actively promotes robotics

258. Regions traditionally strong in manufacturing mechanical and electrical products, such as the southeast provinces, have initiated large-scale programmes titled “Robots Replace Humans”. Among them, Guangdong province is promoting robot use in over 1950 companies (Government of Guangdong, 2015). Changying Precision Technology, which reportedly built the first workerless factory in China, has replaced 650 assembly line workers with 60 robots, resulting in a five-fold reduction of manufacturing errors and an increase in production of over 250% (People's Daily, 2015).

3D printing is growing fast in China

259. Sales of 3D printers in China increased from 2 billion RMB to 3.7 billion RMB (about 582 million US dollars) from 2013 to 2014 (Huang, 2015). Sales are predicted to rise by 30% in 2016 (MIIT, NDRC, MOF, 2015). At present, most industrial 3D printers in China are used for R&D in education, the aircraft industry and design, especially for building proto-types (Min, 2015). China’s first 3D printed hip replacement became available to the public in September 2015 (Yang and Wang, 2015). And industrial 3D printing will be used for the C919, China’s first domestically designed commercial aircraft (Ren, 2014).

3D printing is entering the consumer market and Chinese manufactures are active in desktop 3D printing

260. In the consumer market, 3D printing has seen growing applications in product design and personal use. For instance, around 50% of jewellery manufacturers in Guangzhou City use 3D printing in design (Cui and Liu, 2015). Tiertime, once a start-up from China’s Tsinghua University, is now the largest manufacturer of desktop 3D printers in Asia, and 70% of its sales are to overseas markets (Li, 2015).

The internet of things (IoT) and big-data are also flourishing in China

261. In 2014, the IoT market[20] in China was worth over 600 billion RMB (some 94 billion US dollars) (CCID Consulting, 2015). It is estimated that the IoT in manufacturing could add the equivalent of 196 billion US dollars to cumulative GDP over the next 15 years (Accenture, 2015). The IoT in China is creating vast banks of data. In 2015 the market for big data was equivalent to some 1.8 billion US dollars, and is growing rapidly (China Academy of Information and Communication Technology, 2015).

Chinese Internet companies play a leading role in the IoT and big-data

262. Chinese Internet companies, especially the 3 leading players (Baidu, Alibaba and Tencent), not only lead the market for the IoT, cloud computing and big data, they are also extending their influence to manufacturing.[21] In December 2015 Baidu road tested a driverless vehicle (Meng, 2015). And Alibaba is promoting big data applications in sectors ranging from robotics, the IoT and bio-tech, to financing and infrastructure (Alibaba, 2015).

China started early in nanotechnology research

263. By the end of the 11th five year plan (2006-2010), China ranked first in Science Citation Index publications in nanotechnology and second in total citations (MOST, 2012a). In 2010-2013, China ranked fourth in country-share of nanotechnology patents (OECD, 2015f). This scientific prowess has paved the way for applications of nanotechnology in industry.

Nanomaterials, nano-catalysts and nano-printing are being used in industry

264. To make better use of China’s coal resources, nano-catalysts have been applied in large scale industrial coal-based production of ethylene glycol, an important basic chemical material for making

polyester, explosives and solvents (MOST, 2012b). The Dalian Institute of Chemical Physics has achieved direct non-oxidative conversion through nanoscale catalysis (Guo, 2014). Nano-printing technology, combined with metal nano-materials, promises industrial uses in printed electronics, which are more environmentally friendly. A pilot project to print 200,000 RFID tickets has been implemented in the Beijing Metro (Beijing Municipal Science and Technology Commission, 2015).

Bio-industry is of strategic importance in China

265. Bio-industry is considered one of seven emerging industries of strategic importance, given its economic and environmental impacts (State Council, 2010). From 2010 to 2013, China ranked seventh in the global share of biotechnology patents (OECD, 2015g). In 2014, output from China's bio-based industry reached some 497 billion US dollars, or 4.6% of GDP (Feng and Fu, 2015).

Bio-medicine and bio-based materials are developing rapidly

266. Chinese entrepreneurs with an overseas education and business background are setting up companies that develop new bio-medicines, or perform contract research and development for overseas clients. If approved by the U.S Food and Drug Administration, Ibalizumab, developed by WuXi AppTec, would be the first biologic medicine manufactured in China to be launched in the United States (PRNewswire, 2015). Bio-medical engineering in China is seeing the fusion of bio-technology with new materials and ICT to yield new products and services (such as new artificial corneas and gene services). BGI, one of China's leading companies in genetics technologies, is now providing gene diagnostics to the public by combining its strengths in genomics, big data and artificial intelligence (The Southern Daily , 2015).

267. Output from bio-based manufacturing, especially bio-based materials such as PLA, PHA and PBS, could reach the equivalent of 118 billion US dollars in 2015 (State Council, 2012) (PLA, PHA and PBS are bio-based bio-degradable materials that are applied in many fields, such as packaging, food processing, bio-medicine and agriculture). China is especially active in industrial production of and research on PHA (Chen and Wang, 2015a). Synthetic biotechnologies are being developed for manufacturing bio-based materials, and pilot projects for cheaper PHA production are under way (Chen and Wang, 2015b).

China's policy approaches and tools are also evolving

268. As major enabling technologies increasingly pass from the laboratory to industry, direct government investments and incentives are giving way to policies on systemic reform (such as policies to promote the role of market mechanisms, encourage private-sector R&D, support SMEs and start-ups, facilitate technology transfer, strengthen intellectual property protection and develop skills). International co-operation, and policies on open infrastructure (especially large-scale public research infrastructures) and data access, have also been added to the government's toolkit.

Box 15. Chinese government initiatives for the next production revolution

The major Chinese policy initiatives bearing on future production include:

- The Guidelines on National Medium- and Long-term Program for Science and Technology Development (2006-2020) (announced in 2006).
- The Decision on Accelerating the Fostering and Development of Emerging Industries of Strategic Importance (announced in 2010).
- The Twelfth Five-Year Plan for National Economic and Social Development (and other Five-Year Plans in specified sectors) (announced in 2011).
- Made in China 2025 (announced in 2015).
- Internet Plus (announced in 2015).

These overarching policy statements set the directions, priorities and relevant policy frameworks. The upgrading of manufacturing has increased in importance over time, from a single chapter in early initiatives, to being the major subject of 'Made in China 2025'. 'Internet Plus' aims to better integrate the Internet with traditional industries. All of these initiatives are accompanied by a myriad of action plans and related schemes (such as 'Mass Entrepreneurship and Innovation', which aims to make entrepreneurship more widespread).

'Made in China 2025' is part of a 30-year strategy to strengthen China as a manufacturing power

269. 'Made in China 2025' focuses on enhancing innovation, product quality, environmental sustainability, optimizing industrial structure and developing human resources in Chinese manufacturing. 10 key sectors were identified for support: ICT, numerical control tools and robotics, aerospace equipment, ocean engineering equipment and high-tech ships, railway equipment, energy efficient and new energy vehicles, power generation equipment, new materials, biological medicine and medical devices, and agricultural machinery. The core goal of 'Made in China 2025' is upgrading through the greater use of digital technology in industry. As a first step, 46 demonstration projects for so-called 'intelligent manufacturing' have been initiated by the Ministry of Industry and Information Technology (MIIT, 2015d).

270. The following are among the objectives of 'Made in China 2025': by 2025 the ratio of R&D spending to sales in manufacturing should reach 1.68% (Table 2); coverage of broadband is to increase from 50% in 2015 to 82%; energy consumption per unit of added value should be reduced by 34%; and labour productivity is to increase by 7.5% a year to 2020 and thereafter by 6.5% a year to 2025.

Table 2. R&D intensities of manufacturing and high-tech industries in selected countries (%)

	China 2012	US 2009	Japan 2008	Germany 2007	France 2007	UK 2007	Korea 2006
Total manufacturing	1.1	4.0	3.4	2.3	1.7	2.6	1.9
High-tech industries	1.8	19.7	10.5	6.9	5.6	11.4	5.9

Source: MOST (2014)

'Internet Plus' aims to digitalize major sectors of the economy

271. The Internet Plus initiative was announced shortly after 'Made in China 2025' and aims to accelerate the application of digital technologies across the economy. In manufacturing, the initiative has four major goals: the development of intelligent factories; customized manufacturing; synchronization over

the production chain; and, the promotion of manufacturing as a service. Combined with other policies, this initiative is intended, in the words of the Chinese Premier, to bring about a 'new industrial revolution' (Fu, 2015).

Complementary policies address a variety of cross-cutting themes

272. Financial policies increasingly aim to mobilise resources from regional governments and the private sector. An example of a government supported market-based mechanism for industry is a new government Fund of Funds for emerging industries, founded in 2015 with a capitalisation of 40 billion RMB (State Council, 2015).

273. The government is also trying to establish a more streamlined and coordinated national Intellectual Property service and system of enforcement. And support for skills development addresses not only research-related skills, but also skills in management and operations. Support for recruitment of overseas talent is to be strengthened. And far-reaching educational initiatives are underway. For instance, a national programme for teaching robotics in primary and middle schools, under the Ministry of Education, is now being considered for implementation (Ren, 2016).

But many parts of Chinese manufacturing are still lagging

274. Chinese manufacturing is highly polarized. While cutting-edge innovation is evident, most firms lag in terms of management and digital capability. Basic capabilities are often lacking, such as mastery of key processing technologies and the ability to produce necessary materials. The economy-wide impacts of new production technologies are also limited by an industry structure in which resource-intensive sectors, such as steel and cement, are still large.

275. Many domestic companies hesitate to apply the latest technologies because of the scale of the investments required, and uncertainties in technology trends and standards. The private sector's role in some areas of research is also limited. For instance, over 70% of nanotechnology patents, and 50% of robotics patents, are filed by the academic and public sectors (World Intellectual Property Organization, 2015). Chinese companies increasingly consider mergers and acquisitions an option for upgrading.[22]

Labour market impacts also need attention

276. The "Robots Replace Humans" programmes result from a lack of labour and rising wages in eastern China and are not expected to negatively impact the labour market (Bai, 2014). But technological change is raising demand for multi-skilled managers, researchers and technicians (MIIT, 2015e). New labour market policies are also needed as entrepreneurship and self-employment are set to increase.

And information security is a growing concern

277. The average number of detected information security incidents in China and Hong Kong over the 12 months before December 2015 reached 1245, a 417% rise compared to the previous year (PwC, 2015). As ICT becomes critical to key industries, information security is receiving greater government attention. In this connection, in July 2015 the National People's Congress released a draft text of a national cybersecurity law (The National People's Congress, 2015). And in December 2015 China and the United States held a first joint dialogue on cybercrime.

11. Cross-cutting policy considerations

11.1 *Summary*

278. Each chapter of this report identifies possible directions for policy. Many of those policy ideas are technology-specific (these are brought together in the *Executive Summary*). This chapter outlines a number of additional policy considerations. Some policy ideas are raised here because they appear repeatedly across the different technologies and require further comment. Others are included because they have to do with generic policy issues not yet discussed in the paper.

279. Key additional policy ideas outlined in this chapter are that: the range of policy issues which affect future production is extremely broad, which highlights the need for policy co-ordination; future production requires sound science and R&D policies; governments must create a context which fosters business dynamism; helping firms to adopt new technologies is important and can be achieved through well-designed policies; issues of distribution, rather than scarcity, will be a primary concern;

280. Rapid technological change could also challenge the adequacy of skills and training systems to efficiently match demand and supply for new skills. Some new production technologies raise the importance of inter-disciplinary education and research. Greater interaction between education and training institutions is often needed, and this need may grow as the knowledge content of production rises. Ensuring good generic skills throughout the population will be important. NPR may bring changes to labour market policies too. For instance, self-employment could grow, possibly bringing a need for accommodating policies.

281. Policymakers should engage in long-term thinking. More public discussion is needed of the policy implications of the new production technologies. Leaders in business, education and government must be ready to examine policy implications and prepare for developments beyond the next ten years.

282. A long-term perspective on policy also requires reflection on how policy priorities might evolve, for instance as a consequence of technological change itself, or as a consequence of so-called 'mega-trends' such as population ageing, urbanisation and climate change (indeed, all of the technologies in this report can play roles in responding to changing market demand and policy needs linked to mega-trends). Towards the end of this chapter, a number of conjectures are advanced regarding the evolution of policies on the digital economy, synthetic biology, nanotechnology and intellectual property.

The range of relevant policy issues is broad, which highlights the need for policy coordination

283. The range of policy issues relevant to a next production revolution is extremely broad. Evidently, production is affected by many types of policy, from those on skills and training, to policies affecting domestic and international competition, to tax codes that affect investments in machinery and software, to policies which influence the efficiency of judicial systems and the effectiveness of bankruptcy laws, to policies on infrastructure and financial services. In addition, in various chapters this paper has pointed to the roles of a 'meso' level of policy, such as the design of particular institutions and programmes. The breadth of relevant policy issues underscores that some forms of policy coordination may be needed.

Sound science and R&D policies are essential

284. The technologies covered in this report result from science. Synthetic biology, new materials and nanotechnology, among others, have arisen because of advances in scientific knowledge and instrumentation. Many policy choices determine the strength of science and research systems and their impacts on production. Policymakers need to be attentive to such matters as: the procedures for allocating funds for public research; the balance between support for applied and basic research; a variety of

institutional features and incentives which shape open science; the frameworks that provide incentives for firms, public researchers and public research institutes to commercialise research, while protecting the public interest; the development of well-designed public-private partnerships; the implementation of efficient, transparent and simple migration regimes for the highly skilled; the facilitation of linkages and networks among researchers across countries; and, the creation of a judicious evidenced-based mix of support using both supply- and demand-side instruments.

285. Good policy for science and research is also necessary because, despite the many striking technological developments referenced in this paper, the pace of innovation is clearly insufficient in some crucial fields. For instance, today's leading energy generation technologies were mostly developed or demonstrated over a century ago (Webber *et al*, 2013).

Governments must create an environment which fosters business dynamism

286. OECD research over recent years has highlighted the role of new and young firms in net job creation and in nurturing radical innovation. New firms will introduce many of the new production technologies. But Decker *et al*. (2014) show that business dynamism has declined in technology sectors in the early 2000s in the United States. Governments must attend to a number of conditions which affect this dynamism. These conditions have been treated in detail in other OECD analyses (for instance, Calvino, Criscuolo and Menon (2016) and Andrews, Criscuolo and Menon (2014)).

Assisting adoption of the new technologies is important

287. Small firms tend to use key technologies less frequently. For instance, it was observed that in Europe, 36% of surveyed companies with 50 to 249 employees use industrial robots, compared to 74% of companies with 1000 or more employees (Fraunhofer, 2015). Within firms of any size, given technologies might not be fully utilised. It was seen, for example, that adoption of digitally-based precision farming technologies is often partial: only some of the potential applications are practiced (and, again, farm size is a determinant of the probability of using precision farming at all). Chapter 7, on technology diffusion, refers to institutions and policies which facilitate uptake and use. Some of the institutions involved, such as technical extension services, tend to receive low priority in the standard set of innovation support measures. But there is evidence that they can be effective, if well designed. For instance, enhanced access to information through extension services is a factor in the adoption of precision farming (Perpaoli *et al*., 2013). The operation of these institutions will be examined in greater depth in the final NPR publication.

Distribution rather than scarcity will be a primary concern

288. New production technology will make it possible for many to live richer and better lives. But, as discussed in Chapter 1, these technologies could also worsen income inequality. Benefits from new labour-displacing technologies could accrue to a relatively few owners of capital. The intergenerational distributional effects of robot-driven productivity growth could also be damaging, with older cohorts benefitting to the detriment of the young, absent suitable taxes on capital (Sachs and Kotlikoff (2012); Sachs, Benzell and LaGarda (2015)).

289. The distributional effects of new production technologies require policies beyond the domains of science and innovation. An assessment of such policies also exceeds the scope of this report. But the relevant measures could be many: from a basic income guarantee for every adult, to earned income tax credits, and the provision of resources for lifetime learning and job retraining. Tackling an uneven distribution of skills is also a key to lowering wage inequality. Among other reasons, this is because work requiring lower educational attainment is more susceptible to automation (Frey and Osborne, 2013).

290. It should also be recalled that technology-driven growth is also part of the solution to wealth inequality (as contrasted with income inequality). As stressed in Piketty (2014), a rate of growth which exceeds the rate of return to capital might favour a fall in wealth inequality.

291. Depending on how the gains from new technologies are distributed, and how key technologies evolve, future policymakers may need to consider even more fundamental measures, suitable for a context in which work is no longer the main mechanism for determining income.

Education and skills systems will need constant attention

292. Rapid technological change could challenge the adequacy of skills and training systems to match demand and supply for new skills. Various parts of this report have documented that, for some production technologies, current skills supply is considered insufficient. Evidence was also presented that policies to improve the efficiency of skills matching in labour markets also support productivity (McGowan and Andrews, 2015). This theme is rarely absent from discussion of innovation in any OECD country. Any policy novelty with respect to new production technologies may primarily relate to a possible increase in the magnitude or speed of change. But it is as yet unknown whether new generations of production technology will significantly alter past norms as regards skills supply and demand balances (although digital technology could of course play a role in augmenting skills supply, for instance through Massive Open Online Courses).

Some new production technologies raise the importance of inter-disciplinary education and research

293. Parts of this report indicate that advances in engineering and science may require more interdisciplinary education and research. For example, progress in synthetic biology requires interaction among biologists, physicists, synthetic chemists, computer programmers and others. The increasing complexity of some scientific equipment also demands the use of multiple skill types. But some education systems and individual institutions may not respond as well as is needed. Extensive consultation with industrialists in Germany, for instance, led to a conclusion that "Industry 4.0 will create many new cross-functional roles for which workers will need both IT and production knowledge. Many current educational programmes at all levels provide highly siloed training and offer limited interactions among fields." (Lorentz *et al*, 2015).

294. Achieving inter-disciplinarity is not a new challenge. On the supply side, solutions are likely to emerge from individual education and research institutions themselves and from the effects of inter-institutional competition. However, policy might also help. For example, peer review practices bear on the way that public agencies allocate funding for multidisciplinary research. More needs to be known about the practices adopted across research institutions, teams and departments - private and public – which enable inter-disciplinary education and research. Policymakers could seek to replicate, where appropriate, the approaches of institutions that have proven successful in fostering inter-disciplinary research, such as Stanford's Bio-X.[23]

Greater interaction with industry is needed, and this need may grow as the knowledge content of production rises

295. Aspects of postgraduate training may need adjustment. In the United States, current life sciences PhD level education is still focused on training for academic careers (American Society for Microbiology, 2013). However, data published in the National Science Board's (NSB's) 2014 *Science and Engineering Indicators*[24]show that just 29% of newly graduated life science PhDs (2010 data) will find a full-time faculty position in the United States.

Developing a high level of generic skills throughout the population will also be important

296. Generic skills such as literacy, numeracy and problem-solving provide a foundation for the acquisition of technology-specific skills (whatever those technology-specific skills turn out to be in future). Good generic skills help to 'future proof' human capital.

297. Many other policy issues that affect skills systems today will continue to be important, but it is not evident that a next production revolution would *raise* their importance. Such issues include: establishing incentives for institutions to provide high-quality teaching; supporting firm-level training and life-long learning; and, ensuring that any barriers to women's participation in science, technology, engineering and mathematics are removed.

298. Many issues in education of relevance to NPR are addressed in recent and ongoing work of the OECD's Directorate for Education and Skills. For instance, EDU/EDPC/RD(2015)20 – *Future Shocks and Shifts: Challenges for the Global Workforce and Skills Development* – frames many of the major challenges.

NPR may bring changes to labour market policies too

299. New urgency might be given to employment-related policies and institutions if changing production technologies create large labour market shocks. For instance, pre-emptive labour market measures may be needed in the face of large prospective employment shocks. A range of labour market policies that aim to re-employ displaced workers in mid-career might also become more prominent.[25] But technology-driven labour market shocks occur today. The issue, therefore, is whether a new generation of production technologies is likely to change the scale, frequency or character of labour market shocks. Without perfect foresight, governments should plan for worst-case scenarios in which future shocks are large and arrive quickly.

300. *The importance of geography-specific policies may also rise.* The digital economy appears to exacerbate geographic disparities in income, as it amplifies the economic and social effects of initial skills endowments (Moretti, 2012). In many OECD economies, income convergence across subnational regions has either halted, or reversed, over recent decades (Ganong and Shoag, 2015). A number of remedial policies can be considered. A key observation is that investments in skills and technology are particularly important (because investments in infrastructure and transport, to facilitate greater geographic spread of skills and economic benefits, while often beneficial, also have diminishing returns (Filippetti and Peyrache, 2015)). With each new high-tech job many other jobs are created, possibly as many as five (Moretti, 2012).

301. Self-employment could also grow. Growth in self-employment has been marked in some OECD countries in recent years. For instance, the number of people working for themselves in the United Kingdom has increased by around 30% just since 2010 (Dellot, 2014). Further growth in self-employment could result from push and pull factors. On the one hand, digital technologies could lower start-up costs and enable professional autonomy in many occupations. Digital platforms could also reduce information and other transaction costs in product and labour markets, which could facilitate self-employment (for instance, digital platforms can allow customers to link directly with individual producers, with firms losing their advantages as aggregators and intermediaries). On the other hand, new technologies could displace employees who then seek self-employment as the only remaining employment option. Supporting policies – not directly related to production technology - could be needed to accommodate rising self-employment, for instance as regards regulations which affect home-based work.

Policymakers need to engage in long-term thinking

302. More public discussion is needed of the policy implications of the new production technologies. Leaders in business, education and government must be ready to examine policy implications and prepare for developments beyond the next ten years (for instance with respect to progress in machine learning). As a possible model, in Germany, the federal Ministry for Economic Affairs and Energy and the federal Ministry of Education and Research have created a coordinating body bringing together stakeholders to assess long-term strategy for Industry 4.0 (Lorentz *et al*., 2015).

A long-term perspective on policy also requires reflection on how policy priorities might evolve

303. Even best-practice policy today may need to change over time. This could happen because of dynamics inherent to the technologies concerned, or because of wider social or economic trends. Policy makers need to ask ‘are new policy priorities likely to emerge?’. The remainder of this chapter provides informed conjecture about possible policy-related developments in the digital economy, in synthetic biology, nanotechnology and, more broadly, intellectual property.

Big-data, the Internet of Things and the Digital Economy

304. Investment in big-data and big-data analytics in industry is likely to grow. Might this growth alter the importance of some enabling policies?

305. One candidate for growing policy prominence might be cyber-security. Cyber-security risk management is not well understood. Furthermore, it is impossible to eliminate digital security risk without at the same time eliminating the interconnectedness, openness and interoperability on which data-driven innovation relies. The consequences of security breaches will rise as more parts of production systems become digitally connected (because the opportunities for security breaches and their potential harms would both increase). In this same connection, the issue of trust in supply chains – for both hardware and software – could loom larger.

306. More emphasis may be needed on understanding systems-level risk. As production systems become more complex and ICT-mediated, the risk and consequences of system fragility could increase. Greater understanding of complex systems is essential if governments are to protect society from potentially serious disruptions (Nesse, 2014).

Synthetic biology

307. As briefly described in Chapter 3, synthetic biology could become a transformative technology. Entirely novel policies or the overhaul of existing policy frameworks are not called for. But, as outlined in OECD (2014) - *Emerging Policy Issues in Synthetic Biology* - some forward-looking policy issues need to be addressed, in particular:

- DNA synthesis presents biosecurity concerns. Indeed, there is a widely agreed need for a screening process for synthetic DNA manufacture and sale. Aspects that deserve consideration for control are: screening to avoid synthesis of known pathogens or toxin-related DNA; screening to avoid shipment to dubious customers; and, licensing of equipment and substances required for the synthesis of the short chains of nucleotides used in genomics and genetic engineering. Assessing the costs and benefits of such rules, and developing effective (international) enforcement, are significant challenges.

- New CRISPR/Cas9 genome editing technology will make the construction of new microbe strains much more efficient (CRISPR is an acronym for Clustered Regularly Interspaced Short Palindromic Repeats, a new and more precise method for intervening in the genome). This means that new strains will be produced more quickly, and therefore the regulatory process will have to respond more quickly (and ill-intentioned users will also be able to make strains more efficiently).

- The consequences and regulatory implications of so-called 'garage biology' – after a broader diffusion of synthetic biology capabilities among computer-literate non-specialists - are unclear.

- As synthetic biology becomes more widespread, regulatory tensions will likely arise between countries that adopt different regulatory frameworks. The major difference today exists between the United States, with its greater evidence and risk-based approach to regulation, and Europe, where the precautionary principle is the benchmark (i.e. 'stop until proven safe').

Nanotechnology

308. With respect to nanotechnology it might be that the focus on Environmental, Health and Safety (EHS) issues diminishes with time. Over time, more data and analysis will be gathered on EHS risks in different industries and applications, from food production to the treatment (and potential recycling) of end-of-life smart phones. Current uncertainties over how human biology reacts to non-biological nano-particles will lessen. Furthermore, nanotechnology may come to be seen as a solution to some production-related environmental problems. For instance, in making high-performance materials (such as turbine blades), nanotechnology may permit the replacement of some alloys which require proven carcinogenic metals (such as nickel powder) with ceramics.[26] Overall, some current policies on reducing environmental pollution might change their focus from amelioration to 'safe by design' sustainability.

Intellectual Property

309. Two-phases of recent STI-led work on Knowledge-based Capital have explored intellectual property (IP) and its impacts on innovation. The subject is fast-moving, given rapid change in the underlying technologies, the growing role of emerging economies, significant policy developments in a number of countries and calls for further reform.[27]These developments will not be reprised here.

310. It is relevant however that technological change is raising new challenges for the IP system - notably the patent system - and raising questions around some of the system's basic assumptions. One major challenge to the IP system comes from the emerging ability of machines to "create", an ability which until now was restricted to humans. A second challenge stems from the ability to digitalise physical objects. The future of these technologies could be affected by how IP and patent systems adapt. The issues are summarised in Box 16.

Box 16. Technological change and the near future of intellectual property

Artificial Intelligence (AI) is far from being able to invent as humans do. However, certain software can already, or will soon be able to, produce patentable inventions. This is the case notably in chemistry, pharmaceuticals and biotechnology. In these fields many inventions consist in original combinations of existing molecules to form new compounds, or in the identification of new properties of existing molecules. For example, KnIT, a machine learning tool developed by IBM, was successfully run to identify kinases with specific properties among a set of known kinases. Those properties were then tested experimentally. Hence the specific properties of those molecules were discovered by software, and patents were filed for the inventions.

At some point, machines will assume a more prominent role than humans, and the question might arise as to whether a person with ordinary skills in the art but equipped with the right software might have reached the same invention without creativity. In such a case, the inventions in question would not be considered patentable, as they would not embody an "inventive step" (the minimal threshold of non-obviousness required for a patent to be granted).

3D printing will enhance the trends towards digitisation of physical objects. Digitisation of music, images and text from the mid-1990s on has transformed the industries concerned, with a pivotal role played by copyright. Digitisation drastically reduced the cost of copying, creating, accessing and diffusing music. As the Internet became the major marketplace for music in the 2000s, and as few legal places to trade music existed, the lower cost of copying weakened copyright protection (despite measures to stop alleged piracy). As a result, more music was bought online. Recording companies and other intermediaries saw their incomes fall and artists sought complementary income sources (such as ticket sales from live concerts, T-shirts, etc.). At the same time the number of records issued increased and new creations and creators flourished. Might the same happen to digitised physical objects?

Digitising physical things makes their distribution on the Internet possible, along with modification of the source code (when this is open). Digitisation allows households to manufacture goods which are not mass produced, most often based on designs downloaded from the Internet. Creators might post their creations on the Internet, for sharing or for sale to customers. For some manufacturing industries, 3D Printing might have a similar impact to that which the Internet had on the music industry: making innovation easier for all. Some Internet sites already exist offering digital objects, and they are often open source (so the objects can be printed and also modified). In addition, scanners are available which allow many objects to be digitised, after which the code can be placed online. The possibility of copying and modifying objects which are wholly or in part (via some of their components) IP protected might raise new challenges.

3D printing might also create complications in connection with patent eligibility. For instance, if 3D-printed human tissue improves upon natural human tissue, it may be eligible for patenting, even though naturally-occurring human tissue is not. And patented inventions that are described by the process that made them – such as a 3D printer - may face eligibility challenges when the printed object also occurs naturally.[28] 3D printing might also challenge trademarks and copyright (for three-dimensional items like jewelry and sculptures). Infringement could be very difficult to detect as it would often take place at home.

A policy challenge will be how to preserve IP, which is necessary for incentivising certain types of innovation, while not hampering the diffusion of 3D printing and the flourishing of types of innovation which could accompany 3D printing?

Development of the Internet of Things is also likely to force a common understanding of ownership rights regarding the data created by connected devices. A sensor might be manufactured by one company, operate in a system developed by another, and be deployed in an environment (such as a person’s body) owned by a third. Agreement will be needed on who has which rights to the resulting data.

12. Next steps in the NPR project

311. The Secretariat will seek to secure support for a final project conference to be held in the autumn of 2016 in an interested member country. That event would involve presentation and discussion of all the main themes, conclusions and policy ideas from the project's substantive work. Ideally, participation will be had from the academic, business and policy communities.

312. Simultaneously, the Secretariat is working to prepare a publication, some chapters of which are being drafted in collaboration with external experts. Relevant insights from the draft publication would be presented at the final project conference. At present, chapters on the following themes are planned (in addition to an overall synthesis):

- ICT, big-data and production
- Biotechnology and future production
- Nano-technology and future production
- New materials and future production
- 3D printing and its environmental impacts
- Public acceptance and future production
- How should governments use foresight?
- Supporting advanced manufacturing production in the United States
- Diffusing production technologies – what can governments do?
- Connecting manufacturing with research – what can governments do?
- Skills and the next production revolution

313. Resources permitting, the Secretariat wishes to commission additional work on advances in robotics and, most importantly, the productivity effects of synergies among the major digital production technologies.

314. The Committee for Scientific and Technological Policy, which is leading this project, will also draw on relevant ongoing and planned work elsewhere in the Secretariat. For instance, in the area of skills and education, highly relevant new work is planned in the Directorate for Education and Skills on assessing computer abilities to respond to test questions from the PIAAC survey (Programme for International Assessment of Adult Competencies) (Box 17). *Education 2030*, another new project in the Directorate for Education and Skills, will likewise yield valuable relevant insights.

315. The Secretariat has also constituted a small independent expert group to assess and critique the project's findings as they are developed and made ready for publication. These experts would also be invited to take part in a final project conference.

Box 17. Assessing the skills of computers to anticipate future automation and job change

Computer scientists are working on reproducing all human skills. The development of these computer capabilities has far-reaching implications for education, work and productivity. However, policymakers currently have few ways of systematically understanding these implications. To address this need, the OECD is carrying out a project to assess computer capabilities in some of the key skills used in the economy. These assessments will be used to identify the share of jobs vulnerable to automation and the skill requirements of the jobs that will remain. Though the project will not make precise predictions of future job displacement, careful assessments of current technology can show which scenarios are plausible and which are not.

The first stage of work on the project is using the OECD's Survey of Adult Skills (PIAAC) to assess computer capabilities in generic cognitive skills, such as literacy and numeracy. Computer scientists with expertise related to computer capabilities for language, reasoning and problem solving will evaluate the questions on the PIAAC test to determine which questions could be answered using current computer techniques. This assessment will make it possible to compare the capabilities of humans and computers in the PIAAC skill areas.

The focus of the skill comparison will be on cutting-edge computer capabilities that are just now being demonstrated in the scientific literature. This focus on new computer capabilities will make it possible to anticipate new computer applications that are likely to emerge over the next decade but that are not yet visible in economic statistics. This focus on assessing the technology itself provides a way of forecasting likely labour market changes that goes beyond the simple continuation of recent economic trends. PIAAC data on skill use in the workforce will be used to indicate which current occupations are likely to be affected by these new computer applications.

Initial results for the first stage of work suggest that computers now have capabilities that are in the middle of the PIAAC scale for adults. If this initial finding is confirmed, it would imply that there are computers with capabilities in generic cognitive skills that are similar to those possessed by 50-80% of the workforce in OECD countries. The widespread application of such computers could substantially change the skill requirements of many jobs. This initial work will be published in a report at the end of 2016.

A proposed second stage for the project would extend the analysis to two other broad skill areas: physical skills, which are essential in many jobs, and expert skills within particular content areas, which are important for many higher-level jobs. Computer capabilities in these two additional skill areas would be evaluated using questions from other existing tests, such as those used for employee selection or professional certification. The combined results from the first and second stages of the project would make it possible to develop a framework for estimating the likely effects of computers on the productivity and skill demand of industries with different skill profiles. The relative speed of development in the different skill areas will provide new insight about whether current education levels are likely to be too low or too high in relation to future skill demand. If funded, the results of the second stage of work will be published in a report at the end of 2018.

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NOTES

1 The Internet of Things (IoT) is the network of physical objects or "things" with inbuilt electronics, software, sensors and network connectivity that enables these objects to collect and exchange data. The IoT allows objects to be controlled remotely across existing network infrastructure, creating opportunities for more direct integration between the physical world and computer-based systems.

2 Keynes, J.M. (1963), “Economic Possibilities for Our Grandchildren”, in Essays in persuasion (New York: W.W.Norton & Co.1963). “We are being afflicted with a new disease of which some readers may not yet have heard the name, but of which they will hear a great deal in the years to come – namely *technological unemployment*. This means unemployment due to our discovery of means of economizing the use of labor outrunning the pace at which we can find new uses for labor. But this is only a temporary phase of maladjustment”.

3 http://www.ted.com/talks/vijay_kumar_the_future_of_flying_robots

4 http://www.ted.com/talks/robin_murphy_these_robots_come_to_the_rescue_after_a_disaster

5 By contrast, many non-routine cognitive tasks are complemented by new technology (for instance, ICT allows analysts more time to be analytic, and spend less time on mundane data acquisition, organisation and checking). Demand is elastic for many occupations performing non-routine cognitive tasks and their labour supply is inelastic over the short- and medium-run (Autor, 2015).

6 Many jobs were also created for computer, automated teller and office machine repairers (*The Economist*, 2011).

7 However, volume, velocity and variety are in continuous flux. They describe technical properties that change with the state of the art in data storage and processing.

8 These firms also perform better in terms of asset utilisation, return on equity and market value.

9 However, these estimates can hardly be generalised, for a number of reasons. First, the estimated effects of DDI vary by sector and are subject to complementary factors such as the availability of skills and competences, and the availability and quality (i.e. relevance and timeliness) of the data used. More importantly, these studies often suffer from selection biases. For instance, it is unclear whether the firms adopting DDI became more productive due to DDI, or whether they were more productive in the first place. Furthermore, all these studies rarely control for the possibility that some firms may have seen a reduction in productivity due to DDI, and so may have discontinued their investment in it.

10 Cloud computing can be classified into three different service models according to the resources it provides: infrastructure as a service (IaaS) provides users with managed and scalable raw resources such as storage and computing resources; platform as a service (PaaS) provides computational resources (full software stack) via a platform on which applications and services can be developed and hosted; and software as a service (SaaS) offers applications running on a cloud infrastructure. Sometimes clouds are also classified into private, public, and hybrid, according to their ownership and management control.

11 The chemical industry in the United States. http://selectusa.commerce.gov/industry-snapshots/chemical-industry-united-states.html

12 While researchers have created desktop plastic recycling for the materials used in desktop printers, this is unlikely to achieve scale due to the difficulty of sorting materials and the limitation of such systems to thermoplastics. Market forces could favour compostable materials in the long run. Many printable compostable materials already exist today. The most commonly used plastic for home use printing, acrylonitrile butadiene styrene (ABS), is recyclable. However, a recent study showed that emissions of ultrafine particles from printers using ABS and PLA are high and could pose health risks (Stephens, 2013).

[13] Printers of all kinds often use support materials in addition to the actual modelling material to prevent part warping before they are fully formed. Different printing methods may require more or sometimes less support material. The support material can also differ from the model material.

[14] Electronic Product Environmental Assessment Tool is a project of the U.S.-based Green Electronics Council and International Sustainability Development Foundation aimed at assessing the lifecycle of electronic products.

[15] Leadership in Energy and Environmental Design is a North American green building certification system devised by the U.S. Green Building Council that is most widely used in the United States and Canada.

[16] See Professor Hod Lipson at https://www.youtube.com/watch?v=tmPLeQLdfPA

[17] Citigroup-Oxford Martin School (2015) observes that it took 75 years for the telephone to reach 50 million users, 38 years for radio to reach 50 million users, 13 years for TV, 4 years for Internet, 3.5 years for Facebook, and 35 days for Angry Birds.

[18] The OECD Health Committee and the Committee on Digital Economy Policy (CDEP) are currently developing a recommendation on health data and privacy.

[19] One among many such examples came from Robert Metcalfe, the inventor of Ethernet, who in a 1995 *InfoWorld* column affirmed: *"I predict the Internet will soon go spectacularly supernova and in 1996 catastrophically collapse."*

[20] Including chips and components, equipment, software, telecom and networking services.

[21] 6 of the 10 richest Chinese citizens have also made their wealth in Internet-related business (Forbes (2015).

[22] In 2014, Chinese manufacturers concluded 93 outbound M&A deals, with a total value of 6.4 billion US dollars (Deloitte, CMIF, 2015).

[23] See for instance the interview with Carla Shatz, Director of Bio-X, at: http://news.stanford.edu/news/2014/july/biox-success-shatz-072914.html

[24] http://www.nsf.gov/statistics/seind12/

[25] Recent OECD work in this connection is at: www.oecd.org/employment/displaced-workers.htm

[26] http://www.azonano.com/article.aspx?ArticleID=2501

[27] See, for example, the leader article, ‘Time to fix patents’ in *The Economist*, August 8th, 2015.

[28] These examples are taken from: "Intellectual Property Issues Stacking Up for 3-D Printing", October 2, 2014, Douglas R. Nemec and Kristen Voorhees. Skadden, Arps, Slate, Meagher & Flom LLP. Available at: http://www.skadden.com/insights/intellectual-property-issues-stacking-3-d-printing.