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Future Technology Landscapes

Insights, analysis and implications for defence

Tess Hellgren, Maryse Penny, Matt Bassford

CASE STUDY DOCUMENTATION

RAND EUROPE

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Prepared for Dstl

The research described in this report was prepared for the Defence Science and Technology Laboratory (Dstl).

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Preface

In January 2013, RAND Europe was commissioned by the Defence Science and Technology Laboratory (Dstl) to conduct a study on the future landscape of defence technology development. The specific objectives of the study were: to identify where MOD and non-MOD investments in research and technology (R&T) are likely to shape future UK technology capability of relevance to defence; and to explore enablers and barriers for the MOD in maximising the impact of its increasingly limited R&T budget.

This report contains documentation of the five major case studies informing the final project report. The first phase of the project was focused on understanding the wider context of the study and gathering evidence, whereas the second phase focused on analysis of the defence technology landscape and scoping a set of five small-scale case studies. The final phase examined two of these case studies in greater depth to establish a detailed understanding of the technology landscape in these areas and to determine how the MOD can best target its limited investment to leverage other funding.

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Abbreviations

AI	Artificial Intelligence
AM	Additive Manufacturing
AM SIG	Additive Manufacturing Special Interest Group
AR	Augmented Reality
BIS	Department for Business, Innovation and Skills
CAD	Computer-Aided Design
CBRN	Chemical, Biological, Radiological and Nuclear
CIKTN	Creative Industries Knowledge Transfer Network
COTS	Commercial Off-The-Shelf
DCDC	Development, Concepts and Doctrine Centre
DfT	Department for Transport
Dstl	Defence Science and Technology Laboratory
DTEC	Defence Training and Education Capability programme
EADS	European Aeronautic Defence and Space Company
ENISI	Enteric Immunity Simulator
ERDF	European Regional Development Fund
EPSRC	Engineering and Physical Sciences Research Council
GPMG	General Purpose Machine Gun
GPU	Graphics Processing Unit
ICT	Information and Communication Technology
KTN	Knowledge Transfer Network
KTP	Knowledge Transfer Partnership
LoDs	Lines of Development
LVC	Live, Virtual and Constructive training
MMOG	Massively Multiplayer Online Game
MOD	Ministry of Defence
OEMs	Original Equipment Manufacturers
pDSC	pilot Defence Simulation Centre

RCUK	Research Councils UK
REA	Rapid Evidence Assessment
SBRI	Small Business Research Initiative
SDSR	Strategic Defence and Security Review
SE	Synthetic Environments
Semta	Sector Skills Council for Science, Engineering and Manufacturing Technologies
SGS&C	Serious Games Showcase & Challenge
SMEs	Small and Medium-Sized Enterprises
SNE	Synthetic Natural Environment
SSE NTC	Simulation and Synthetic Environments National Technical Committee
T&S	Training and Simulation
TRL	Technology Readiness Level
TSB	Technology Strategy Board
UAV	Unmanned Aerial Vehicle
UTCs	University Technical Colleges
VBS2	Virtual Battlespace 2
VEC	Virtual Engineering Centre

CHAPTER 1 **Introduction**

1.1 The case studies presented in this report support the study aim to maximise the impact of the MOD's increasingly limited resources

This study was commissioned by Dstl to inform its future strategy for technological development. To this end, the study aims to identify the circumstances required for effective development, the key decisions necessary throughout the process and the points at which investment is necessary.

This report contains documentation of the two in-depth case studies and three additional scoping case studies that the study team conducted in order to explore key technology areas with strong potential for MOD in the next 20 years. While the Final Report provides high-level analysis of the recommendations and findings derived from these case studies, this *Case Study Documentation* provides a full account of the evidence base upon which these conclusions were built.

1.2 The three project phases narrowed the study scope down to two case studies

In order to fulfil the study parameters provided by the MOD, we conducted a systematic analysis of the UK defence technology landscape, beginning with a broad overview and working down to two in-depth case studies. Research was conducted in the form of literature review and stakeholder engagement through workshops and key informant interviews.

1.2.1 16 technology areas were narrowed down to two case studies using a systematic process

In the first phase of the project, the team performed a Rapid Evidence Assessment (REA) to scope the broad landscape of future technologies in the UK. The REA focused on answering the overarching question *What are the key trends and enablers in the UK's future defence technology landscape to 2035?* The methodology consisted of a rigorous and systematic search and review of relevant literature on UK defence technologies, which allowed us to extract information on technology trends. As a result of this inductive approach, 16 key technology areas were identified.

The second phase of the project examined five of the 16 technology areas in more depth: additive manufacturing (AM), advanced materials, cybersecurity, small-scale energy storage, and synthetic environments (SE). These five areas were chosen by the project team, in conjunction with the MOD, based on a range of criteria assessing the technologies' potential appeal and feasibility. Short exploratory case studies were conducted in each of these five areas to determine their relevance and impact for the MOD over the next 20 years.

The final project phase examined two of the five case study areas – AM and SE – in more depth. These areas were selected for further exploration by the MOD project sponsor. The in-depth case studies aim to further elucidate the importance of these technology areas for the future of UK defence, emphasising barriers and enablers to adoption, commercial involvement and MOD priorities.

1.2.2 Case study research was conducted through focused literature review and cross-sector stakeholder engagement

For the five short case studies in Phase 2, the research team collected and analysed data based on a focused literature review of recent sources. Data were collected exclusively from open sources, including academic and grey literature, specialist publications and government reports. We designed a template to ensure that case studies were as comparable as possible, including the following categories: overview, priority areas, areas relevant to defence, estimated market size, existing investment, key stakeholders and predicted trends. Cross-cutting findings from this task are included in Chapter 7 of the *Final Report*.[1]

For the two in-depth case studies, the study team combined additional literature review with extensive stakeholder engagement. A total of 32 interviews, 16 for each case study, were conducted with stakeholders across government, academia, business and defence. Two workshops were also held with SE stakeholders from the military and the games sector. An overview of these stakeholder interactions by sector is provided in Table 1-1; full lists of interviewees and workshop participants can be found in Tables 1-2 and 1-3. The project team also engaged with the MOD Strategy Unit and the Doctrine and Concept Development Centre (DCDC) to further explore the range of potential futures for each technology area.

Table 1-1 Breakdown of interactions for the in-depth case studies

Case Study	Government	Academia	Defence	Business	Total
Additive Manufacturing	2	7	4	3	**16**
Synthetic Environments	2	3	5 (+1 wkshp)	6 (+1 wkshp)	**16** **(+2 wkshps)**

[1] Penny, Maryse, Tess Hellgren, Steven Bowns, and Matt Bassford, *Future Technology Landscapes: Insights, Analysis and Implications for Defence – Final Report,* PR-738-MOD, Santa Monica: RAND Corporation, September 2013.

Table 1-2 Interviewees for the AM case study

Name	Organisation	Date
Dr Tony Chapman	EPSRC – Manufacturing Theme	25th Jun 2013
Dr Martin Baumers	University of Nottingham Additive Manufacturing and 3D Printing Research Group – EPSRC Centre for Additive Layer Manufacturing Research Coordinator	27th Jun 2013
James Bradbury	University of Exeter Centre for Additive Layer Manufacturing – Research and Application Engineer	28th Jun 2013
Prof. David Wimpenny	HVM Catapult/MTC, AM SIG Advisory Group – Leader for AM & Net Shape	2nd Jul 2013
Neil Hopkinson	University of Sheffield, Centre for Advanced Additive Manufacturing (AdAM) – Centre Director	2nd Jul 2013
Prof. Russ Harris	Loughborough University – Professor of Medical Engineering and Advanced Manufacturing	2nd Jul 2013
Dr Phil Reeves	Econolyst Ltd – Managing Director	3rd Jul 2013
Dr David Whittaker	AM SIG Working Group – Technology Expert, Materials KTN	8th Jul 2013
Stuart MacLachlan	AM SIG Working Group – Sector Leader Powders, Materials KTN	8th Jul 2013
David Fry	Dstl – Principal Analyst, Land Battlespace Department	10th Jul 2013
Fiona McCue	Dstl – Programme Leader Logistics, Land & Joint Logistics Domain	11th Jul 2013
Prof. Richard Hague	EPSRC National Centre for Innovative Manufacturing in Additive Manufacturing, University of Nottingham – Director, Additive Manufacturing and 3D Printing Research Group	11th Jul 2013
John Hunt	Dstl	12th Jul 2013
Laura Jones	Dstl – Platform Sciences Group, Functional & Non-metallic Materials	12th Jul 2013
Andrew Middleton	Dstl – Exploitation Lead, Dstl Knowledge Innovation & Futures Enterprise	12th Jul 2013
Robin Wilson	TSB – Lead Technologist, High Value Manufacturing	18th Jul 2013
Prof. Ian Hutchings	University of Cambridge Institute for Manufacturing, Ink Jet Research Centre – GKN Professor of Manufacturing Engineering	18th Jul 2013
Dr Graham Martin	University of Cambridge Institute for Manufacturing, Ink Jet Research Centre – Director	18th Jul 2013

Table 1-3 Interviewees for the SE case study

Name	Organisation	Date
Prof. Jeremy Smith	Cranfield University – Head of Simulation and Analytics	1st Jul 2013
Mark Newton	Flight Simulation and Synthetic Trainers PT – Project Manager of DOTC(A)	2nd Jul 2013
Doug Stewart	Flight Simulation and Synthetic Trainers PT – Technology Project Manager	2nd Jul 2013
Dr Gillian Murray	Virtual Engineering Centre, University of Liverpool – Director	4th Jul 2013
Dr Charles Patchett	Virtual Engineering Centre, University of Liverpool – Technical Manager	4th Jul 2013
David Bowman	Virtual Engineering Centre, University of Liverpool	4th Jul 2013
Bharat Patel	Dstl – Senior Capability Advisor, Simulation Training and Evaluation, Policy and Capability Studies Department	5th Jul 2013
Andy Fawkes	Former MOD – Head of Synthetic Environments Co-ordination Office	10th Jul 2013
Mike Raettig	TRL Consulting	11th Jul 2013
Dr Zoe Webster	TSB – Head of Technology	12th Jul 2013
Tom Laws	Dstl – Microbiology, Biomedical Sciences	15th Jul 2013
Richard Leaver	Greybrook Limited – CEO	15th Jul 2013
Dave Harrhy	Dstl	16th Jul 2013
Rob Smith	MBDA – Head of Weapon System Simulation & Experimentation	17th Jul 2013
Zoe Brown	EPSRC – Portfolio Manager, Information and Communication Technologies	18th Jul 2013
Dr Chris Yapp	Independent Consultant in technology and futures thinking – Former Head of public sector innovation at Microsoft	22nd Jul 2013
Sue O'Hare	Former Reading University, The Enterprise Office – Director	25th Jul 2013
George Mallea	Sky Go – Managing Editor	25th Jul 2013
Lars Hoffman	Lars Hoffmann Spil – Learning Games Developer	31st Jul 2013
Michael Poindexter	Serving military troops	6th Aug 2013
Nicona Bryan	Serving military troops	6th Aug 2013
Cody Camp	Serving military troops	6th Aug 2013
Nicolas Aguilar	Serving military troops	6th Aug 2013
Finn Grimwood	Solarflare – Programmer	7th Aug 2013
David Russel	Solarflare – Programmer	7th Aug 2013
Oliver Ray	Solarflare – Programmer	7th Aug 2013
Johnathan Cooper	Solarflare – Programmer	7th Aug 2013

1.3 Structure of the report

This report is structured as follows:

- **CHAPTER 2** and **CHAPTER 3** present the findings for the two in-depth case studies on additive manufacturing and synthetic environments.
- **CHAPTER 4, CHAPTER 5** and **CHAPTER 6** present overviews of the exploratory case studies on advanced materials, cybersecurity and small-scale energy storage.

Each chapter is followed by a list of references cited for that particular technology area.

CHAPTER 2 Additive manufacturing

This chapter presents the data gathered as part of the in-depth case study on additive manufacturing. As this data synthesis provides the evidence base for the case study summary in the Final Report, there are some areas of overlap between the two. The research is based on a combination of literature review and engagement with expert stakeholders across government, academia, business and defence. The list of references specific to this case study can be found at the end of the chapter. The list of key informant interviews that we conducted is elaborated in Chapter 1.

2.1 Additive manufacturing is an emerging technology with great potential

Additive manufacturing (AM) enables rapid conversion of digital designs into physical form by merging thin layers of heated materials into a 3-D form.[2] AM has gone by many names, of which '3-D printing' is one of the most common derivatives today.[3] While the technology was initially used for prototyping, and most of the 50,000 AM machines in existence around the world still serve this purpose, there has been a shift in interest and potential to AM as a route to direct production.[4] Final products now comprise 20 percent of AM output, and projections suggest that this will rise to 50 percent by 2020.[5]

The potential of AM for the future of manufacturing is perceived to be significant – it has been called the 'Third Industrial Revolution', and by some predictions could have the same transformative potential as the Internet.[6] The AM sector has grown in double digits in recent years – by nearly 30 percent in 2011 alone – and could exceed a supply chain value of £80 billion annually by 2020 if current limitations are addressed.[7] Because of this extreme potential, AM has received significant interest and investment. However, experts caution that the media hype about the potential of AM is overestimating the current technology's readiness level.[8] A number of serious challenges exist to the technology's widespread application, and experts expressed a range of different views about the extent to which this potential will be realised.

[2] Sissons and Thompson (2012); Centre for Additive Layer Manufacturing

[3] Other names include advanced manufacturing, rapid prototyping, rapid tooling, rapid technologies, rapid manufacturing, advanced manufacturing, additive fabrication, additive layer manufacturing, direct digital manufacturing, and direct manufacturing. Stratasys (a)

[4] Interviews conducted by RAND Europe (2013)

[5] *The Economist* (2011)

[6] Sissons and Thompson (2012); Campbell et al. (2011), p.9

[7] Hague and Reeves (2013), p.45

[8] Hague and Reeves (2013), p.41

2.2 AM shows great potential for niche applications across many commercial sectors but is still at a low maturity level

2.2.1 AM offers a range of possible benefits

The benefits of AM are manifold, as illustrated in Figure 2-1. Three general manufacturing advantages are in customisation, design freedom and added functionality. Free of moulds and casts, and able to produce very small-scale production runs, AM is ideal for customised products. The properties of the process also provide new opportunities for design freedom, which are further supported by AM's rapid and efficient design-to-product timescales. Furthermore, AM processes enable new levels of complexity, especially for small products, that cannot be achieved with traditional processes. The complex internal structures AM creates can reduce weight, add strength and increase functionality of products.[9] There is also the future potential to combine materials, such as electronics and metals, in new ways by directly printing them together in the same process.

Figure 2-1 Benefits of AM

Design freedom	Elimination of pre-production process (e.g. tooling)
Customisation/personalisation	Distributed/decentralised manufacture
Lightweighting	Complexity of shape and function
Supply chain efficiency	New materials and structures
Small production runs	Reduced need for storage/warehousing

Source: Adapted from HM Govt. (2012); Wohlers (2011) in Scott et al. (2013), p.106; Stratasys (a)

Compared with traditional manufacturing processes, AM reduces timescales and waste products. While the former require long, expensive pre-processing of material blocks which must be prepared and then tooled, AM cuts out these processes entirely. The AM production process also eliminates substantial amounts of waste materials, requiring only 10 percent of the raw material that is otherwise required by conventional 'subtractive' manufacturing methods.[10] Not only does this reduce energy and time requirements, it also lightens metal and plastic parts, which may include non-essential materials when run through conventional manufacturing processes.[11] For example, a European Aeronautic Defence and Space Company (EADS) project on AM's applications to aerospace can produce printed parts that are 60 percent lighter than their machined counterparts without reducing functionality.[12]

Advantages also centre around the technology's ability to reduce costs of entry to the manufacturing process. This has implications for the economic geography of manufacturing as well as for future innovation opportunities. Rather than requiring outsourced production from established manufacturing centres, AM technology enables local manufacturing that can be tailored to personalised specifications, even in one-off or very small production batches.[13] AM also improves the efficiency of design-to-product timescales, lowering the risks of new innovations by reducing the time and resources needed for multiple rounds of developmental testing.[14]

[9] Manyika et al. (2013), p.106
[10] *The Economist* (2011); Kirkley (2012)
[11] *The Economist* (2011)
[12] *The Economist* (2011)
[13] Sissons and Thompson (2012)
[14] *The Economist* (2011)

2.2.2 AM encompasses several standardised techniques

Within the scope of AM, seven classifications of production techniques have been standardised internationally. Table 2-1 delineates these processes. Each technique presents different trade-offs: electron beams, for example, speed up the process but create a rougher surface finish compared to lasers.[15] For defence and security, powder bed fusion and directed energy deposition are the techniques with the most potential for widespread application. While directed-energy deposition is less mature, the technique has the potential be scaled up to items of large size.[16] In the future, inkjet printing techniques may overcome some of the barriers of current techniques, such as the physical limitations on laser speed that slow down the process and hence drive up costs.[17]

Table 2-1 AM Classifications

Process	Description	Materials	Market
Vat Photopolymerisation	First process, commercialised in 1986, using photo-curing polymers (photolithography)	Photopolymers	Prototyping
Material Jetting	Building material layers with an inkjet print head, using wax or photopolymers	Polymers, Waxes	Prototyping, Casting Patterns
Binder Jetting	Similar to material jetting, printing polymer binder across powdered material layers for metals, polymers and ceramics	Polymers, Metals, Foundry Sand	Prototyping, Casting Molds, Direct Part Production
Material Extrusion	Building material layers through material extrusion from a nozzle, commonly used in DIY home kits	Polymers	Prototyping
Powder Bed Fusion	Selective fusion of powder bed regions using thermal energy (CO_2 lasers for polymers, fibre lasers and electron beams for metals)	Polymers, Metals	Prototyping, Direct Part Production
Sheet Lamination	Stacking and joining pre-cut sheets of paper, plastic or metal	Paper, Metals	Prototyping, Direct Part Production
Directed-Energy Deposition	Melting materials with focused thermal energy to fuse them as they are deposited	Metals	Repair, Direct Part Production

Source: RAND analysis of Farmer et al. (2011) and Scott et al. (2012), p.2

Across these techniques, AM is used to address the needs of multiple industries in four broad markets: prototyping, tooling, direct part manufacturing, and maintenance and repair.[18] Table 2-2 provides a description of these areas.

[15] Excell and Nathan (2010)
[16] Interviews conducted by RAND Europe (2013)
[17] Interviews conducted by RAND Europe (2013)
[18] Scott et al. (2012), p.ii

Table 2-2 Overview of AM market application

Markets	Description of AM application
Prototyping	Used as visual aids and in the design process, allowing companies to print, evaluate and revise
Tooling	Produces castings for tooling moulds
Direct part manufacturing	Used as manufacturing process to create usable finished products
Maintenance and repair	Provides a metallurgical bond in weakened area, providing a stronger bond with less associated residual stress

Source: Adapted from Scott et al. (2012), pp.3–4

2.2.3 The medical, aerospace and consumer goods sectors are leaders in AM application

While AM is an emerging technology, it is already widely applied across disparate sectors, from medical implants to personalised football boots to solid-state batteries.[19] A detailed breakdown of industrial sectors where AM is already commercially applied is shown in Figure 2-2. Some sector-specific applications of AM are summarised in Figure 2-3.

Figure 2-2 Current commercial or near-to-market application of AM relative to sector

Process	Material	Aerospace (airframe)	Aerospace (power)	Aerospace (cabin)	Auto (road)	Auto (sport)	Medical (orthopaedic)	Medical (prosthetic/orthotic)	Medical (dental implants)	Medical (surgical guides)	Medical (hearing aids)	Energy (generation)	Energy (storage)	Creative industries (artefacts)	Consumer goods (jewellery)	Consumer goods (toys & games)	Consumer goods (home/fashion)	Defence (weapons)	Defence (PPE/armour)	Defence (logistics & support)	Electronics (packaging)	Electronics (sensing)	Prototyping	Tooling and casting
Powder bed fusion	Metal	Y	Y	Y	Y	Y	Y	N	Y	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	N	Y	Y	Y
	Polymer	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
	Ceramic	N	Y	N	N	N	Y	N	Y	N	N	N	Y	Y	N	N	N	N	Y	N	N	Y	Y	Y
Directed-energy deposition	Metal (powder feed)	Y	Y	N	Y	Y	N	N	N	N	N	Y	N	N	N	N	N	N	Y	Y	N	N	Y	Y
	Metal (wire feed)	Y	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	Y	Y	N	N	Y	Y
Material jetting	Photopolymer	N	N	N	N	Y	N	Y	N	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y	Y	Y	Y
	Wax	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y
Binder jetting	Metal	N	N	N	Y	Y	N	N	Y	N	N	N	Y	Y	Y	N	N	N	N	N	N	Y	Y	Y
	Polymer	N	N	Y	Y	N	Y	Y	N	Y	N	N	Y	Y	N	N	N	N	N	N	Y	N	Y	N
	Ceramic	N	Y	N	N	Y	Y	N	Y	N	N	N	Y	Y	N	Y	N	N	N	N	N	Y	Y	Y
Material extrusion	Polymer	N	N	Y	Y	N	Y	Y	N	Y	N	N	N	Y	N	N	N	N	N	Y	Y	Y	Y	Y
Vat Photo-polymer-isation	Photopolymer	N	N	N	N	N	N	Y	N	Y	Y	N	N	Y	Y	N	Y	N	N	N	Y	Y	Y	Y
Sheet lamination	Hybrids	Y	Y	Y	N	Y	N	Y	N	N	Y	N	Y	N	N	N	N	N	Y	N	Y	Y	Y	N
	Metallic	Y	Y	Y	N	Y	N	N	N	N	N	Y	Y	N	N	N	N	Y	N	N	Y	N	Y	Y
	Ceramic	N	Y	N	N	N	Y	N	Y	N	N	N	Y	N	N	N	N	N	N	N	N	N	Y	N

Source: AM SIG (2012), p.9

[19] *The Economist* (2011)

Figure 2-3 Selected applications of AM by sector

Sector/Type of Application	Prototyping	Manufacturing	Custom	References
Auto	- Light-weight parts such as fixtures and design prototypes (BMW)	- Interior parts in luxury cars (Audi) and wheel caps (Toyota)	- A customisable gear shifter (BMW) - 300 Bugatti Veyron dashboards	Stratasys (c); Sculpteo, '3D Printing…'; Auto Express (2013); Shapeways (2013b); Shapeways (2013a)
Aerospace/Space	- 'Smart wings' for UAVs with functional electronics - Control surfaces, cooling systems, reduced-weight landing gear and bracket components (trials by Airbus)	- Ducts and similar parts for F-18 fighter jets (Boeing) - Air ducts for cooling and other 'non-critical' parts for Boeing 787 Dreamliners - Titanium parts in satellites (Airbus) - Gatewing X100 unmanned aircraft fuselage (Materialise) - Titanium strips bonded onto the leading edge of fan blades (GE jet engines) - Metal brackets to connect cabin structures to planes' primary structure (Airbus et al.)		Optomec (2013); Excell and Nathan (2010); Rosen (2007); Materialise (d); Freedman (2011); *Manufacturing Engineering* (2011)
Medical	- Pre-surgical models, e.g. ones of valvular and ventricular septal defects and cardiovascular and dental models (Materialise, Protaico) - Surgical guides in orthopaedic surgeries (Materialise)	- Standing aids for people with disabilities (Altimate Medical) - Bezels and other parts for pill-dispensing systems (ScriptPro)	- Hearing aid shells (Siemens, Phonak, Widex - Dental aligners (clear braces) (Align Technology) - Cranial implants, hip replacements, dental crowns - Custom assistive devices such as the Wilmington Robotic Exoskeleton (WREX) for patients with physical impairments (Stratasys 3D Printers)	Desktop Engineering (2013); Stratasys (e); Stratasys (d); Park (2013); Stratasys (b); Stratasys (g); Rosen (2007); Scott et al. (2012), p.iii; Stratasys (f)
Formula 1	- A car body of a Formula 1 prototype including sophisticated cooling channels (Materialise)	- A lightweight battery holder for an electric racing car - Hydraulic components for Formula 1 cars		Materialise (b); EOS, website; Cooper et al. (2012)
Others	- Desktop printers of 3-D models - Product demonstrations and prototypes across industries	- Robotic arms able to achieve high acceleration (Intrion)	- High-value customised pens (Materialise)	Cubic Technologies, website; World Future Society (2012); Materialise (c); Materialise (a)

Source: RAND Europe analysis of references

AM use in UK industry is led by the medical, aerospace and consumer goods sectors. The **medical** sector is the largest adopter of AM, with applications including products such as cranial implants, hip replacements and dental crowns. Hearing aid production is the largest-volume use of AM. For the medical sector, the main driver is cost, as additive processes offer cheaper alternatives to expensive conventional production.[20] For instance, AM is used globally to make 64,000 dental aligner moulds a day, reducing costs associated with time and labour by cutting down the design time from days to minutes.[21]

Aerospace has also been among the most prevalent users of AM techniques, with Boeing using laser-sintered cooling ducting on its F-18 a decade ago. Today, Boeing is flying approximately 20,000 laser-sintered parts in both commercial and defence aircraft, including 32 parts on its 787 Dreamliners.[22] Airbus is currently trialling a range of additional applications, such as reduced-weight landing gear, brackets, cooling systems and control surfaces.[23] AM's ability to reduce material waste is a major driver for this sector, in which 90 percent of the initial material for titanium aircraft parts may be lost under traditional machining processing.[24] Lightness of materials is another driver, empowered by AM's ability to create parts with latticed interiors. Airbus is currently capitalizing on this lightness to make brackets that weigh only 20–50 percent of their traditionally manufactured counterparts.[25] These benefits have led Mike Vander-Wel, director of Boeing's manufacturing technology strategy group, to call AM 'the ultimate manufacturing method' for the aerospace sector.[26] However, experts express some uncertainty whether aerospace will ramp up AM application, as many parts are coming up against significant barriers of certification and quality assurance.[27]

Consumer goods are another area of major application, at both the high and low levels. Fast-moving consumer goods are seeing projected growth, with AM used for products from phone cases to lampshades.[28] Use of 3-D production for low-end goods is a major area of development, and from 2007–2011 the sale of personal 3-D printers grew annually by 200–400 percent.[29]

Finally, a number of other commercial sectors use AM technologies. There are many applications for the **creative industries**, where AM use is driven by the low production volume of customised products.[30] The weight of AM produced parts could also benefit the **automotive** industry. Although this sector has been slower to apply the technology, printed parts are already being used in low-production, luxury vehicles by companies like BMW and Bentley.[31] **Motorsport** is also demonstrating interest in incorporating the technology.[32]

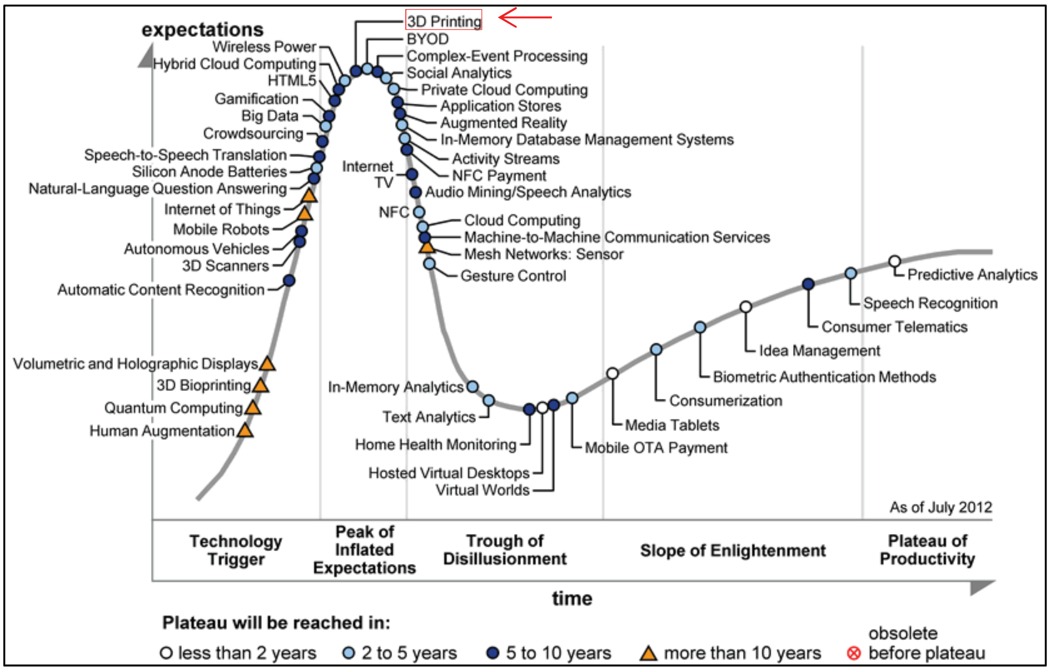
[20] Excell and Nathan (2010)
[21] Hague and Reeves (2013), p.44
[22] InterPRO, website
[23] Excell and Nathan (2010)
[24] Houses of Parliament (2012), p.2
[25] InterPRO, website
[26] InterPRO, website
[27] Interviews conducted by RAND Europe (2013)
[28] Interviews conducted by RAND Europe (2013)
[29] Manyika et al. (2013), p.105
[30] Interviews conducted by RAND Europe (2013)
[31] Freedman (2012)
[32] Interviews conducted by RAND Europe (2013)

2.2.4 Expert forecasts for additive manufacturing vary and include the development of novel applications

Despite high media expectations, the future potential of AM is uncertain

While the media focus on AM is undeniable, expert perspectives on the future potential of AM vary greatly. Some see the area as potentially exceeding all expectations, while others are more reticent in considering the barriers to application that must be overcome.[33] A study by the Centre for Business Relationships, Accountability, Sustainability and Society found that the public hype about AM tends to give an exaggerated perspective on current and future potential, based largely on selective and anecdotal evidence.[34] In Gartner, Inc.'s 2012 Hype Cycle for emerging technologies, shown in Figure 2-4, 3-D printing is at the climax of public excitement – the so-called 'peak of inflated expectations' that comes before the 'trough of disillusionment'.[35] According to this trajectory, while AM may have strong future potential, it is likely that expectations will fall before rising again in more proportionate measure with the technology's development.

Figure 2-4 Gartner's 2012 Emerging Technologies Hype Cycle



Source: Gartner (2012)

This disconnect is also partially linked to the different definitions and terminologies encompassed in the field, which equate 3-D printing and AM when these techniques differ considerably. While AM is applied to high-value manufacturing, 3-D printing produces low-value goods that are more limited in their size, complexity, resolution, materials and final part integrity.[36] In our interviews, expert stakeholders repeatedly pointed out that the terms describing these techniques correspond to very different outputs and involve very different barriers, enablers and processes.[37] Looking ahead, experts point out that there will be substantial divergence in trends for these high- and low-level AM processes. While it is

[33] Interviews conducted by RAND Europe (2013)
[34] Smith (2012), p.1
[35] Gartner (2012) in LeHong and Fenn (2012)
[36] Hague and Reeves (2013), p.40
[37] Interviews conducted by RAND Europe (2013)

possible that home 3-D printing systems will be widely available to consumers in the next five years, potentially at costs similar to current inkjet printers, this development is divorced from the needs of high-value manufacturers. And despite the publicity of the low-end consumer market, experts point to high-value manufacturing as the area of greatest impact for the future of AM.[38]

Giving the emerging nature of the technology, concrete trends are difficult to predict for the next 15–20 years, although the area is projected to grow radically, creating new realms of opportunity and capability. Experts pointed out that AM has grown dramatically in the past 20 years, beyond most researchers' wildest expectations.[39] AM could be particularly game-changing as it is a 'general-purpose technology' that is pervasive, widespread and long-lasting.[40] It is also a highly interdisciplinary technology, with relevant areas ranging from chemistry to physics. Its impact may be multiplied as other complementary technologies evolve in these various domains – for example, in materials development.

AM is unlikely to replace conventional manufacturing in the next 20 years

In terms of revolutionary potential, experts predict that it is unlikely AM will ever fully replace conventional manufacturing, as it is not necessarily the most cost effective or suitable technique for all manufactured items. Ongoing work to increase the avenues of AM application should focus on the gaps that are poorly served by conventional methods – its future development, while possibly substantial, seems likely to focus on niche applications in the most relevant sectors. In 10 years, for example, AM may be much more widespread in the fast-moving consumer goods sector, used in applications such as packaging. It is also likely to grow in the aerospace sector, both civilian and defence, especially as metal parts can be replaced by lighter-weight plastic polymers.[41] In the next 20 years, the technology's adoption will also become more widespread as industries gain more confidence in the additive process. A wider range of materials should begin to be seen as market demand increases.[42] AM may also serve to supplement conventional methods directly, through its use in producing casts and moulds for traditional processes.[43]

After the next decade, there is the potential for developments to slow as physical limits are reached. Experts noted that this true particularly for laser-based systems, which face constraints in the speeds that are possible given the physics of materials and their transition from solid to liquid state. Given these constraints, techniques such as inkjetting may provide a strong alternative. This technique uses a 3-D version of 2-D printing processes, which have already seen an 800 percent increase in speed over the past five years. While only polymer jetting has reached a higher technology readiness level (TRL), 3-D jetting processes have the future potential to overcome both the speed and scale issues of laser-based processes.[44]

Novel applications may emerge

Experts also expect to see novel applications, many of which are already in the early stages of development. Potential areas include multi-materials, multi-functionality, compacting functionality, printing electronics into product structures, and printing systems as opposed

[38] Interviews conducted by RAND Europe (2013)
[39] Interviews conducted by RAND Europe (2013)
[40] Manyika et al. (2013), pp.23–25
[41] Interviews conducted by RAND Europe (2013)
[42] Interviews conducted by RAND Europe (2013)
[43] Interviews conducted by RAND Europe (2013)
[44] Interviews conducted by RAND Europe (2013)

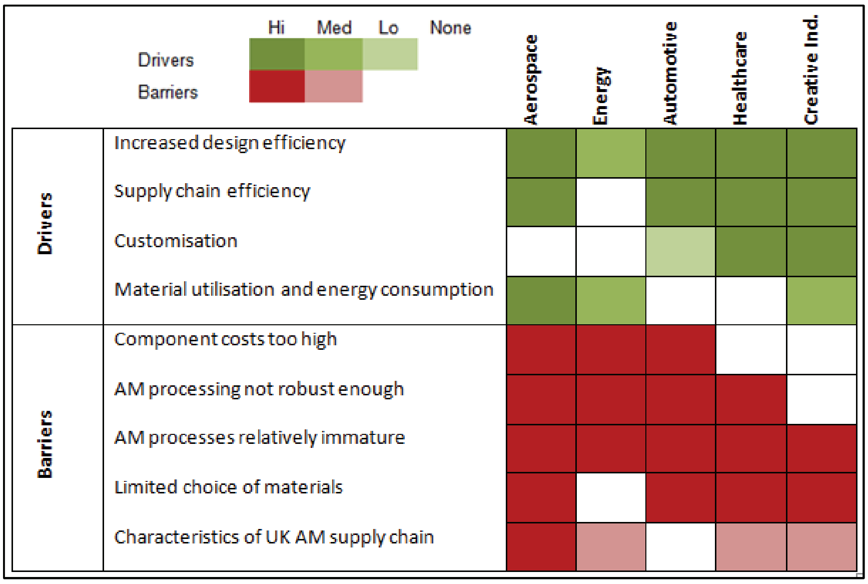
to individual components.[45] Recent years have the seen the emergence of such innovative areas as lightweight and complex structures, and conformal electronics.[46] Beyond 2025, there is also the possibility that AM will be used to 'bioprint' live organs.[47] Experts also stressed that there is a need for more focused investment in response to expressed market needs, which will empower incremental technology evolution to move forward, driven by R&D expenditure. As AM offers high degrees of flexibility, it is likely that unforeseen applications of the technology will emerge.[48]

2.3 The future trajectory of AM depends on the evolving balance of drivers and barriers

2.3.1 Drivers for AM integration vary depending on sector needs

Priority areas depend on the sector, particularly as machines and techniques vary greatly to address a range of unique applications. The TSB's Additive Manufacturing Special Interest Group has identified four primary drivers in the UK for additive manufacturing: design freedom, supply chain efficiencies, customisation of products, and material utilisation.[49] These priority areas all contribute to accelerating the manufacturing process, reducing costs, and supporting innovation. Figure 2-5 shows the importance of these AM drivers for five major industrial users, along with corresponding barriers in each sector.

Figure 2-5 Drivers and barriers for UK additive manufacturing



Source: AM SIG (2012), pp.10, 12

2.3.2 A wide range of barriers poses challenges to cost, quality and integration potential

The AM sector faces multiple challenges to development, as summarised in Figure 2-6. Overwhelmingly, experts point to **cost effectiveness** as a major priority for ensuring the future adoption and expansion of AM technologies. With the exception of some medical

[45] Interviews conducted by RAND Europe (2013)
[46] Scott et al. (2012), p.iii
[47] Manyika et al. (2013), p.105
[48] Interviews conducted by RAND Europe (2013)
[49] AM SIG (2012), p.11

applications, conventional manufacturing techniques are currently much more cost effective than additive alternatives. One expert estimated AM costs currently at £4,000/kg – costs would need to be reduced to one-eighth of this figure (£500/kg) to make the technology commercially attractive in a widespread sense. There are numerous factors contributing to high costs, including limited options for materials and suppliers. Costs also accrue due to scientific limitations of the process. The speed of lasers, for example, is limited by the physical properties of materials. Due to restricted production speeds, additive machines depreciate much more quickly relevant to production output than do conventional alternatives. This depreciation cost is passed down to the price of component parts produced, making the entire endeavour too expensive for many industries to justify.[50]

Figure 2-6 Barriers to AM

Cost effectiveness	Physical properties
Upscaling to production	Materials
Reliability and quality	Fragmented supply chains
Pre- and post-production	Intellectual property
Standardisation	Computer-aided design (CAD)

Source: RAND Europe analysis

Upscaling to production from prototyping is another priority in AM development. At present, it is estimated that over 20 percent of AM outputs are final products rather than prototypes; this figure is predicted to rise to 50 percent by 2020.[51] In order to expand this production to a mass scale, it will be necessary to reduce costs that are directly related to the speed of manufacturing.[52] The TSB has identified the scale of AM outputs as a priority research area, offering funding for collaborative industry solutions to address mass production.[53]

Reliability and quality of printed products is another barrier to AM adoption. One academic expert quoted the reliability of AM production at only 70 percent, with 20 percent of parts failing before completion and an additional 10 percent completing manufacture with fatal internal flaws.[54] This latter point is a serious issue for AM's integration into industry, as companies need to be able to verify the quality of their manufactured products.[55] Similarly, current AM processes lack accuracy in executing designs. Precision and repeatability pose a particular problem for use in sectors such as aerospace and defence, where reliability is a key requirement and validation processes have long timescales.[56] Individual AM machines may also react differently to different conditions, and environmental factors such as temperature must be carefully monitored.[57] More research is required to address inconsistencies in quality, as even AM experts do not fully understand how and why inconsistencies occur in the production process.[58] Further study should also be dedicated to understanding how

[50] Interviews conducted by RAND Europe (2013)
[51] *The Economist* (2011)
[52] Digital Manufacturing Report (2012)
[53] TSB (2012), p.3
[54] Interviews conducted by RAND Europe (2013)
[55] Interviews conducted by RAND Europe (2013)
[56] Interviews conducted by RAND Europe (2013)
[57] Excell and Nathan (2010)
[58] Interviews conducted by RAND Europe (2013)

factors including material choice, part shape, temperature and cooling time impact on the quality of the process.[59]

Pre- and post-production challenges vary by type of AM classification and may pose barriers to the cost and efficiency of the process.[60] The TSB has highlighted this issue in a recently sponsored competition dealing with the 'high nuisance, low-value' aspects of the AM process, including build preparation, data generation, heat treatment, inspection, finishing and validation.[61] Barriers in **computer-aided design** (CAD) will also need to be addressed, as current software techniques are unable to support the full design complexity enabled by AM processes.[62] CAD systems are also complex to use, and will require improved accessibility of user interfaces if the technology is to expand.

The **physical properties** of current AM processes pose limitations in other areas, such as speed of the printing process.[63] There is related concern over the actual knowledge of the technology processes, given the relatively short existence of AM. While the microstructure properties of traditional manufacturing techniques, such as conventional metal forming, are well understood, there is more uncertainty over the full extent of the scientific processes involved in additive techniques.[64] More research is needed into the fundamental science behind AM, in order to better understand material properties and physical constraints.[65]

The nature of AM techniques places limits on the **size** of outputs produced. While ideal for creating small, complex products, AM is unable to produce large items, such as aircraft wings. Processes such as inkjet printing are working to overcome this size threshold.[66]

Large scale application of AM will require improvements in the **standardisation** of machines as well as input materials. The current lack of industry standards results in inconsistent outputs when the same design is processed through comparable devices. The absence of an established supply chain also means that input materials may vary in quality.[67] For the UK to develop a strong competency in AM technology, it will be necessary to consolidate and mainstream the presently fragmented supply chain.[68]

Finding the right **materials** is a challenge for AM, as there are currently only a very small number of usable plastic and metal compounds. The science of the process is a limiting factor here, as compounds must have the correct physical properties to melt and solidify in the correct timeframe. As AM-specific materials are still in relatively low demand, they are typically available from niche suppliers, and correspondingly cost 50–100 times as much as comparable materials for conventional manufacturing.[69]

Fragmented **supply chains** restrict the integration and effective use of AM. On the materials side, the limited number of usable materials corresponds to a limited number of material suppliers. Until there is greater market demand, this trend is likely to persist.[70] In terms of machine components, there is a lack of standardisation between suppliers. This landscape

[59] Freedman (2012)
[60] Digital Manufacturing Report (2012)
[61] TSB (2012), p.3
[62] Excell and Nathan (2010)
[63] Interviews conducted by RAND Europe (2013)
[64] Interviews conducted by RAND Europe (2013)
[65] Interviews conducted by RAND Europe (2013)
[66] Interviews conducted by RAND Europe (2013)
[67] Digital Manufacturing Report (2012)
[68] TSB (2012), p.3
[69] Freedman (2012)
[70] Interviews conducted by RAND Europe (2013)

means that many suppliers offer materials and machines that supplement each other, but are incompatible with competitors' models. This proliferation of niche monopolies within the AM landscape is a challenge for industry users as it limits their options and their ability to choose from a competitive market.[71] As AM develops, this landscape will change as consolidation occurs and certain processes and materials either grow in popularity or are pushed out by better performing alternatives.

Finally, **intellectual property** (IP) can be an impediment to open research. IP remains mostly confidential, as industry has a degree of unwillingness to share sensitive information that might compromise firms' competitive advantage.[72] Time-dependent developments in IP are opening up new opportunities for innovation in the coming years. Experts consistently noted that many critical patents are due to expire soon, providing new enablers for ground-breaking research. However, others pointed out that new patents are constantly being issued, and that the advantage for innovation is likely to remain with the large suppliers who hold these rights.[73] In the future, there will need to be proactive thinking on how to resolve the tension between openness, encouraging wider innovation, and returns on investment, providing incentives for business to dedicate themselves to developing evolved techniques.[74]

2.3.3 Overcoming barriers to feasibility is a key priority step in unlocking the potential of AM

The future trajectory of AM depends largely on the overcoming of key barriers, such as high costs and the challenges involved in printing multi-material products. Overcoming barriers to the feasible application of AM was the major priority stressed by experts, although they expressed that it is unclear which barriers are most likely to be overcome, and at what speed. Addressing the range of challenges will require significant investment. The 2013 TSB competition to tackle AM's 'dirty secrets', for example, is offering targeted funding to overcome barriers to AM's market growth and commercial uptake.[75]

Despite the number of challenges, timelines for commercialisation are shrinking and opportunities are abundant. Developing faster and more robust technologies, such as inkjet printing, may overcome the physical restrictions of current processes, enabling products that are larger and made faster.[76] Finding ways to upscale production rates would also lead to a dramatic drop in costs. Opening up the supply chain would further empower industries and lower costs by increasing the supplier options available.[77]

Experts also widely emphasised the need to invest in the so-called 'valley of death', the transition from research to application that poses a significant hurdle in general technology development. More targeted investment in mechanisms of transition from research to application would encourage main stakeholders (from both research and industry) to devote more resources to the technologies.[78] The Catapult Manufacturing Technology

[71] Interviews conducted by RAND Europe (2013)
[72] Interviews conducted by RAND Europe (2013)
[73] Interviews conducted by RAND Europe (2013)
[74] Sissons and Thompson (2012), p.3
[75] TSB (2012), p.3
[76] Interviews conducted by RAND Europe (2013)
[77] Interviews conducted by RAND Europe (2013)
[78] Interviews conducted by RAND Europe (2013)

Centre in Coventry, for example, aims to work with a range of large and small companies to overcome this barrier.[79]

2.4 AM stakeholders are fragmented across government, academia and business

2.4.1 Government provides centralised funding, particularly through the EPSRC and TSB

Support of AM development complements the government's attitude towards the manufacturing sector as a crucial component of the UK economy.[80] Over the past 20 years, the manufacturing sector has halved its share of the UK economy, from 20 to 10 percentage points. The UK government has made it a priority to 'rebalance' back towards manufacturing.[81] As part of this effort, AM may be able to call upon support from vested interests such as the Sector Skills Council for Science, Engineering and Manufacturing Techniques (Semta), which aims to support manufacturing and engineering organisations of every size access funding and training and develop supply chain capability.[82]

Government has an important role in encouraging AM developments in the UK, particularly at the early TRL stages and through the transition from research to commercialisation. Experts widely spoke of government's important role in providing seed funding for new ideas and early-TRL investment, empowering potential breakthroughs that are too new to qualify for more application-specific funding. [83]

The Engineering and Physical Sciences Research Council (EPSRC) is the largest government funder of AM technologies, providing focused funding to centres throughout the UK to investigate bounded facets of additive technology. EPSRC funding ranges from TRL 1–3. While it cannot fund business directly, it could play an increasingly important role in encouraging universities to cooperate with relevant industrial partners. One expert also pointed out that 70 percent of EPSRC funding goes to a dozen well-defined AM programmes with very specific research areas. By focusing on circumscribed areas within AM, EPSRC may be limiting important innovation in novel, potentially break-through areas.[84]

Complementing the EPSRC, the TSB funds research linked to commercialisation in the later TRL stages, from 4–7. In addition to providing funding – such as the £7m call for collaborative research launched with EPSRC in December 2012 – the TSB runs a number of Knowledge Transfer Networks (KTNs) that aim to facilitate relationships and networks within a given technology area.[85] Within this structure, Special Interest Groups are dedicated to technology areas – like AM – that do not fit neatly into the KTN structure.[86]

2.4.2 UK universities conduct focused research on AM in niche areas, particularly through funded centres

In the academic realm, there are a number of focused centres that work on different materials, processes and applications in AM. Funding for academic efforts comes in two

[79] HM Government (2012)
[80] HM Government (2012)
[81] Houses of Parliament (2012), p.3
[82] Semta, website
[83] Interviews conducted by RAND Europe (2013)
[84] Interviews conducted by RAND Europe (2013)
[85] TSB (2012), p.2
[86] Interviews conducted by RAND Europe (2013)

main forms: managed and standard. Managed funding occurs when an external entity, such as the EPSRC, specifies research requirements in a call for tender and researchers respond to this call. In standard funding, on the other hand, the initiative rests with researchers, who put forward investigator-led proposals to compete for general project funding (often in smaller amounts than managed funds).[87] One university noted that while 70 percent of its AM research is done in cooperation with industry, funding is mostly from research grants and government sources.[88]

Much of the UK's targeted research in AM occurs in EPSRC-funded centres, of which there are 16 in total. EPSRC centres receive initial grants of £6m, to be invested in projects over five years, at which point renewal is possible.[89] Our interviews revealed that academic experts tend to move between universities, often with entire teams, in order to locate themselves within a programme covering their niche areas of research. For example, several AM researchers shifted their base from Loughborough to Nottingham University in order to take advantage of Nottingham's departmental strengths in multi-functional and multi-materials production (a technique that is able to deposit different materials in a single process). Similarly, other academic centres also possess their own areas of research emphasis.[90]

2.4.3 A range of industries is interested in leading or adopting AM integration

Industry is strongly represented in research efforts. Of the 81 organisations performing research in AM since 2007, 57 were companies and 24 universities.[91] The AM industry is currently rather fragmented, with different companies catering to varying niche markets with specialised products.[92] Involved sectors are those who identify and wish to pursue AM for its direct commercial opportunities. Stakeholders like the medical and aerospace industry have an active interest in AM mainly because they see it as an opportunity for better cost competitiveness. One expert noted that with the rise in publicity around 3-D printing, CEOs from a variety of sectors are increasingly being proactive in exploring the possibilities that AM might offer their business.[93] Experts noted that original equipment manufacturers (OEMs) are driving many industry developments because they bring adequate funding and infrastructure to help develop the business stream.[94]

In broadening industry involvement in AM development, there is a need to facilitate small- and medium-sized enterprises (SMEs) and raise awareness of the technology more widely. Experts noted that the niche expertise and innovation potential of SMEs is important to cultivate through targeted initiatives and collaborative support.[95] For small companies, access to long-term venture capital is important. 'Incubator' facilities can also be beneficial in providing the high levels of initial capital expenditure needed to support innovative ideas.[96] Educating more companies about the potential of AM is also an important priority.[97] In helping bridge the gap between research and application, companies such as

[87] Interviews conducted by RAND Europe (2013)
[88] Interviews conducted by RAND Europe (2013)
[89] Interviews conducted by RAND Europe (2013)
[90] Interviews conducted by RAND Europe (2013)
[91] AM SIG (2012), p.17
[92] Interviews conducted by RAND Europe (2013)
[93] Interviews conducted by RAND Europe (2013)
[94] Interviews conducted by RAND Europe (2013)
[95] Interviews conducted by RAND Europe (2013)
[96] HM Government (2012)
[97] Excell and Nathan (2010)

Econolyst play an important role in liaising with a wide range of companies to assess suitability and opportunities for investment in AM adoption.[98]

2.4.4 Connecting stakeholders is an important priority

Coordinating efforts between universities and small and large businesses is a challenge, as is integrating diverse elements of the manufacturing sector.[99] University-hosted research institutes provide one structured opportunity for collaboration between academic and industry partners. The EPSRC Centre for Innovative Manufacturing in Additive Manufacturing, for example, prioritises commercialisation technologies, and is currently engaged in industrial research collaborations with a number of companies including Diginova and ALSAM.[100] At the University of Exeter, the Centre for Additive Layer Manufacturing has engaged with over 300 global businesses in its first 18 months of operation, focusing on providing support and partnership for SMEs across industrial sectors.[101]

The need for more collaborative efforts across government, academia and industry was a major priority expressed by multiple experts. Experts involved in collaboratively funded programmes (such as EPSRC efforts) expressed that such participation was accompanied by strong networking opportunities. However, when the funding was ended, the corresponding networks also tended to be lost. Expanding and preserving these connections will be important in furthering dialogue around the technologies.[102]

Informal networks are particularly valuable

While the broader UK AM community interacts regularly in a number of ways, including through structured exchanges such as conferences (both national and international), interviewees emphasised the importance of informal networks within the field. Experts stressed that AM developments rely on intense networking and active information sharing. Informal personal connections were mentioned as especially important in helping overcome confidence issues from the industry perspective, as many companies are hesitant to invest in AM due to its unfamiliarity.[103] In moving collaboration forward, this issue of trust was highlighted as extremely important – it is a priority to foster communication among stakeholders, and to help establish confidence in the technology and its potential.[104]

Within industry, collaboration across sectors is also important in sharing expertise around common barriers. In response to CAD barriers, for example, EADS is currently exploring software used in creative imaging (such as computer gaming) and in medical visualisation systems.[105] The TSB could play a particularly useful role in facilitating the creation and maintenance of these relationships. The MTC-TSB projects are an excellent example of this type of productive collaboration, bringing together a range of partners from such disparate sectors as medical devices, motorsport and aerospace to address common challenges related to AM adoption.[106]

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[98] Reeves, '3D Printing in aerospace & automotive'
[99] HM Government (2012)
[100] EPSRC Centre for Innovative Manufacturing, website
[101] Hopperton (2012)
[102] Interviews conducted by RAND Europe 2013
[103] Interviews conducted by RAND Europe (2013)
[104] Interviews conducted by RAND Europe (2013)
[105] Excell and Nathan (2010)
[106] Interviews conducted by RAND Europe (2013)

2.5 The UK is a leader in AM research, but struggles with commercialisation and skills shortages

2.5.1 Internationally, the UK has a strong research base but lags behind in commercialisation and patents

The UK is very well-placed to engage with AM's projected growth on a global scale, and is helping lead the technology's development as the largest centre for AM research and development in Europe.[107] Both industry and academia have been involved in this area for the past 10–11 years, placing the UK at the forefront of AM development.[108] Certain sectors are particularly well situated to engage with AM advances, such as the UK's strong design industry, which will benefit from the design flexibility enabled by AM.[109] UK competence in AM applications is also particularly strong in the aerospace sector and in prototyping more widely.[110]

The UK is a global leader in AM research, with strong academic output. Its relevant research base is very strong, with three of the world's top ten engineering and technology universities. It also has a 14 percent global share of the most cited papers in engineering and technology.[111] In contrast to the US, the UK has benefitted from government support of basic research, which offers opportunities for unforeseen findings and applications. This places the UK in a strong position regarding next generation technologies.[112]

Experts expressed strong consensus in identifying the UK's weakness in the commercialisation of AM technologies. There are major gaps in the UK supply chain due to a lack of in-country production, with Reninshaw the only machine supplier in the UK. Consequently, the 'highest bidders' for commercial deals are usually out of the UK. Global production leaders are the US and Germany, with France, Japan and China also emerging as players.[113]

Compared internationally, UK researchers also have low rates of patenting, particularly in typically patentable areas such as physical sciences (including computing) and engineering. According to the Derwent Innovations Index, of the 3,200 AM-related patents issued globally since 1971, the US leads with a quarter of all patents. As Figure 2-7 shows, the UK has a particularly low share at only 2 percent, below the numbers for five other countries as well as 'world' and 'European' patents.[114] As most IP has thus been owned outside the UK, it is especially crucial to improve links throughout the UK value chain by diversifying and strengthening its platform manufacturing capacity.[115]

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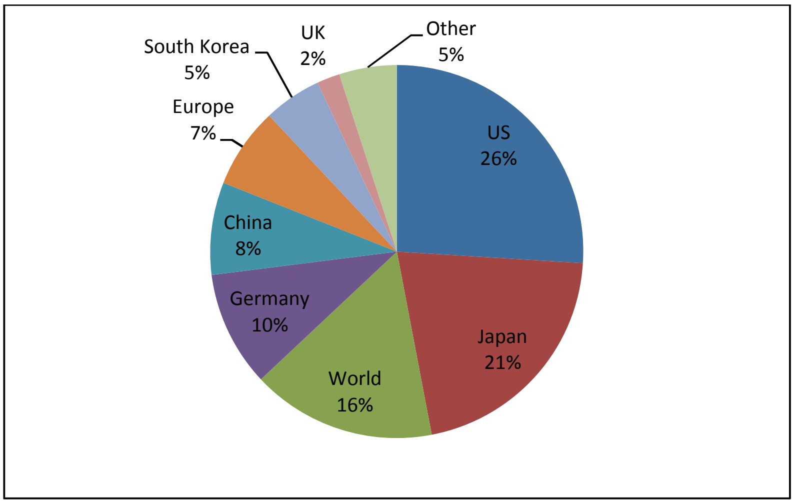
[107] Thornton (2012)
[108] AM SIG (2012), p.17
[109] Sissons and Thompson (2012), pp.10–11
[110] AM SIG (2012), p.20
[111] Houses of Parliament (2012), p.1
[112] Interviews conducted by RAND Europe (2013)
[113] Interviews conducted by RAND Europe (2013)
[114] Dstl (2012)
[115] Interviews conducted by RAND Europe (2013)

Figure 2-7 Global share of patents issued regarding AM



Source: Adapted from Dstl (2012)

2.5.2 UK manufacturing and engineering are facing a shortage of skills and expertise

In the UK manufacturing sector in general, there is a serious skills shortage, due to a combination of an ageing workforce and negative public perceptions of manufacturing.[116] The manufacturing sector is facing the challenge of an ageing workforce, with the need to recruit 82,000 people simply to cover retirements up to 2016. This skills dearth is particularly true for positions requiring a prerequisite of advanced apprenticeships.[117] In the related engineering sector, there is similarly a skills challenge in finding high-quality mid-career engineers who will be ready for leadership roles, which may have been partially influenced by a skills drain towards city banking jobs in the 1990s.[118] Engineering diplomas for 14–19 year olds were downgraded by the UK government in 2011, further discouraging participants.[119] Under-representation of youths and women in advanced manufacturing and engineering is particularly pronounced, with 16–24 year olds making up only 7 percent of the workforce compared to 11 percent for all sectors, and women comprising only 20 percent compared to 49 percent overall.[120]

In addition to general sector-wide skills concerns, the AM community also faces the challenge of a lack of focused expertise. The recruitment of strong PhD students is a major challenge for the technology's development.[121] Experts spoke widely of the need to support more educated professionals with high-level, relevant knowledge at the doctorate level. One expert mentioned the future formation of a Centre for Doctoral Training in AM, which would provide focused training for PhD candidates. There is also a dearth of specialised technicians and operators, who need familiarity with CAD software operation and design in order to properly oversee AM production.[122]

[116] Houses of Parliament (2012), p.4
[117] HM Government (2012)
[118] HM Government (2012)
[119] Houses of Parliament (2012), p.4
[120] Semta (2013b)
[121] HM Government (2012)
[122] Interviews conducted by RAND Europe (2013)

2.5.3 A number of training and educational initiatives are underway

A number of targeted initiatives are underway to encourage skills in the manufacturing and engineering areas, led by organisations such as Semta and the National Apprenticeship Service. To encourage the development of these skills, there is an intended expansion in University Technical Colleges (UTCs), which provide semi-vocational training for 14–19 year olds that includes advanced manufacturing. There are currently two of these government-funded academies, with 22 more set to open by 2014.[123] Since March 2012, over 400 places have also been made available in a new programme supporting high apprenticeships in advanced manufacturing and engineering.[124] Additionally, the EPSRC awards industry-oriented EngD doctorates at its 19 Industrial Doctorate centres, which are beginning to pursue collaborative projects with the other Catapult and EPSRC Centres.[125]

There is some evidence that these efforts to improve the skills base are having positive effects. In the past two years, new apprentice candidates in engineering and advanced manufacturing have increased in number by over 85 percent. Growth has been particularly strong in the West and East Midlands, North East and Yorkshire & Humber regions. In 2011–2012, the sector benefitted from 31,070 new starters, a consistent increase from 22,300 in 2010–2011 and 16,760 in 2009–2010.[126]

General education about AM is also spreading

For the AM community, expanding education at a more basic stage is also a priority.[127] Recent initiatives have sought to provide schoolchildren with 3-D printers in the classroom to encourage early stage exposure and interest in the technology.[128] Design software could also become more user-friendly to encourage widespread engagement and further innovation.[129] At a general level, a collaborative effort between Siemens, the Cabinet Office, the Department of Education and BIS has established an education and careers portal to encourage schoolchildren aged 11–14 to engage with opportunities in the engineering and manufacturing fields.[130]

Alongside these various targeted efforts, general raising of public awareness and interest was voiced by experts as another area that could increase skills and engagement. Despite the difference between the perceptions and realities of 3-D Printing and AM, experts point out that the 'hobby' of home-based 3-D printing is helping the industry as a whole by raising awareness and catalysing interest from new companies. Information in the public domain helps educate potential stakeholders about the technology's potential and generate interest and investment in AM.[131] Awareness raising is also supplemented by public events like the 3D Printshow, held in London, which aims to provide a 'fully interactive technology event that's inspiring, entertaining and educational', including features such as a 3-D printed hospital, a 3-D printed art gallery, and a working consumer home.[132]

[123] Houses of Parliament (2012), p.4
[124] Houses of Parliament (2012), p.4
[125] Houses of Parliament (2012), p.4
[126] Semta (2013b)
[127] Interviews conducted by RAND Europe (2013)
[128] HM Government (2012)
[129] Interviews conducted by RAND Europe (2013)
[130] Semta (2013a)
[131] Interviews conducted by RAND Europe (2013)
[132] 3D Printshow, website

2.6 Supported by widespread investment, the AM global market has the potential to see exponential growth

2.6.1 Current UK funding comes from a variety of sources, with government supporting early stage TRL and industry contributing the majority of investment

As suggested by the varied stakeholder landscape, UK investment in AM comes from sources across government, research, industry and academia. Most of this investment has focused on research and development, followed by technology transfer. In the 2007–2016 period, £95.6m will have been invested in collaborative or university projects, of which £80m will have been allocated to research and £15.6m to technology transfer initiatives.[133] Industry has contributed the largest single share of funding, with £25m invested over the 2007–2016 period.[134] Research institute funding has come from both the TSB, who has committed approximately £13m from 2007–2016, and Research Councils UK (RCUK).[135] The EPSRC Centre for Innovative Manufacturing in Additive Manufacturing, for example, is supported by £5.9m of funding to investigate the full course of AM, from initial design to end manufacture.[136] A range of government funding mechanisms is summarised in Table 2-3. European support for AM has also been significant, with the EU Framework Programmes and the European Regional Development Fund (ERDF) each investing £13m over the same 2007–2016 period.[137]

Table 2-3 Government funding mechanisms for AM

Funding mechanisms	Description	Sectors involved
High-Value Manufacturing Catapult	Launched in 2011, consists of 7 centres. Emphasises collaboration between industrial investors and small companies to apply technology	Industry, academia
EPSRC Centres for Innovative Manufacturing	12 centres work on exploratory research at low TRL	Academia, industry
Advanced Manufacturing Supply Chain Initiative	Announced in 2012, £125m fund to support companies' UK supply chains and international competitiveness	Industry
R&D tax credit scheme	Offers tax relief/credits to encourage companies to invest in R&D, with enhanced offers to small companies	Industry
Foresight Future of Manufacturing Project	To be published in autumn 2013, investigates UK's manufacturing potential to 2050	Industry

Source: Adapted from Houses of Parliament (2012), pp.3–4

In accordance with the fiscal evidence, experts emphasised that the majority of overall investment in AM comes from industry. However, this research is largely reactive, responding to customers' concerns and identified market gaps.[138] To continue AM developments, UK industry may need to take greater responsibility for later-stage research in the coming years.[139] Support for industry-led research is evidenced by the recent £7m in project funding offered by the TSB and RCUK towards collaborative, business-led

[133] AM SIG (2012), p.17
[134] AM SIG (2012), p.17
[135] AM SIG (2012), p.17
[136] *The Manufacturer* (2012)
[137] AM SIG (2012), p.17
[138] Interviews conducted by RAND Europe (2013)
[139] AM SIG (2012), p.18

proposals for industrial research into AM.[140] To date, UK industry research spending remains concentrated, with six companies comprising half of the total spend.[141] Table 2-4 summarises the key sector contributors to AM research, led strongly by aerospace. As the table demonstrates, current industry investment is especially valuable for the public funds leveraged through these initiatives.

Table 2-4 Key UK industry sectors contributing to AM research

Sector	Direct investment in additive manufacturing R&D, 2007-2016	Public funds leveraged for additional additive manufacturing R&D, 2007-2016
Aerospace	£13m	£20.5m
Automotive	£3.5m	£6.5m
Medical	£3m	£11.5m
Creative Industries	£2.5m	£7.5m

Source: AM SIG (2012), p.9

2.6.2 Future growth in the global AM market could be extreme, with high-value manufacturing playing a strong role

The current global market for AM is small, but its future growth trajectory is potentially extreme. The AM industry was valued at only £1.2 billion in 2011, but the sector has seen consistent double-digit growth in recent years.[142] Annual revenues from AM products and services have also grown dramatically in the past two decades, rising ten-fold from £64m in 1993 to £640m in 2007.[143]

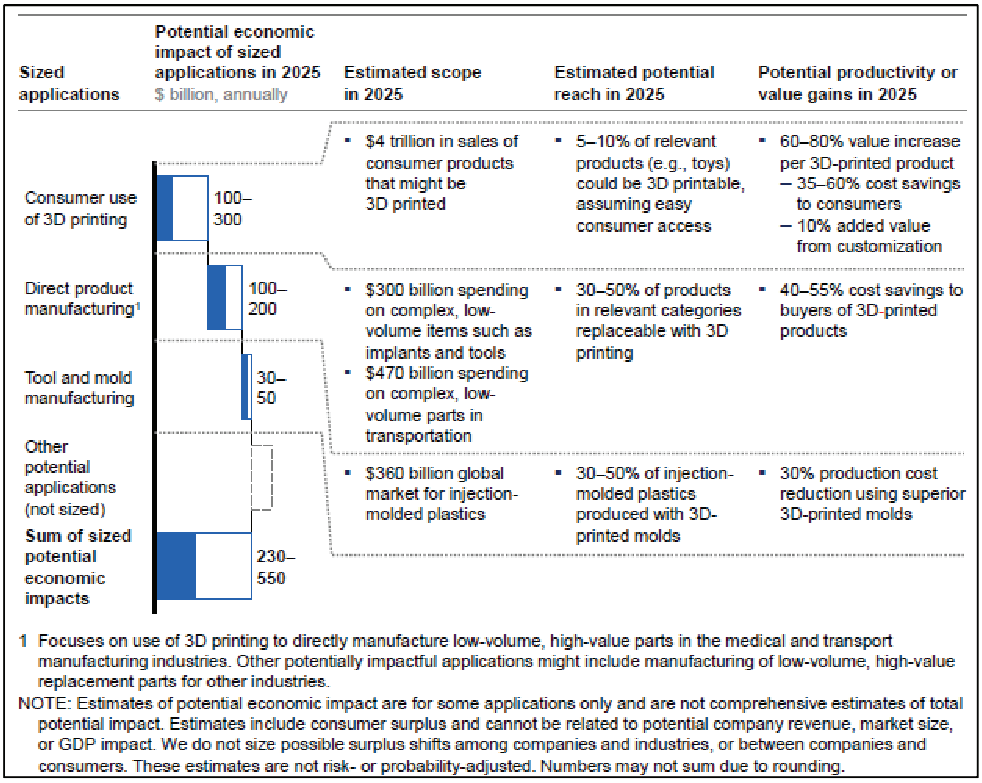
It remains to be seen whether the perceived potential of AM is realised by 2035, as forecasts for the technology's future vary widely. By 2020, if AM continues organic growth based on current technologies, the sector is forecasted to reach annual revenues of £4.8 billion.[144] However, based on potential future applications, analysts predict that the technology has reached less than 8 percent market penetration. If barriers to entry for these new applications are addressed, the projected value of additive manufacturing by 2020 may exceed £64 billion annually.[145]

By 2025, McKinsey estimates that AM will range in global economic impact from £150–350 billion ($230–550 billion) annually, with the largest impact coming from consumer uses followed by high-value manufacturing (see Figure 2-8).[146] McKinsey predicts that AM use in complex, low-volume, high-value production – such as current applications in the medical and aerospace sectors – could generate £60–130 billion ($100–200 billion) in yearly impact by 2025, comprising 30–50 percent of the overall market for these items. Their forecasts suggest that products could decrease 40–55 percent in cost due to the benefits of AM processes in reducing waste and pre-/post-production expenses.[147] While McKinsey predicts the vast majority of products will still be created through conventional manufacturing by 2025, AM can also support traditional techniques such as injection

[140] TSB (2012), p.2
[141] AM SIG (2012), p.19
[142] AM SIG (2012), p.4
[143] Wohlers Associates (2010)
[144] AM SIG (2012), p.4
[145] AM SIG (2012), pp.4–5; Thornton (2012)
[146] Manyika et al. (2013), p.105
[147] Manyika et al. (2013), p.111

moulding; the printing of tools and moulds could generate £20–30 billion ($30–50 billion) in economic impact by 2025.[148]

Figure 2-8 Breakdown of AM impact by 2025



Source: Manyika et al. (2013)

Looking ahead, widespread application of AM has potentially significant consequences for new divisions and decentralisation of labour in the manufacturing sector.[149] However, implications on this global scale will depend upon the future route the technology takes. Considering that manufacturing GDP is valued at over £7trillion, involving 12 percent (320m) of the global workforce, the dispersed impact of AM growth could have significant labour impacts.[150]

Whatever the future market penetration, it is also clear that AM is not a 'one-size-fits-all' solution. Of the more than 230 products and businesses Econolyst has assessed for AM application over the past seven years, 80 percent were unsuitable for this technology for a number of reasons. Challenges to application included issues such as surface finish, mechanical limitations, part accuracy and the consistency of product quality.[151]

[148] Manyika et al. (2013), p.111
[149] King (2013), p.38
[150] Manyika et al. (2013), p. 5
[151] Reeves (2012)

2.7 Defence is currently assessing the potential of AM, particularly regarding operational logistics and specialised applications

2.7.1 Emerging forms of AM may suit many defence needs, including specialised applications and in-theatre production

From a defence perspective, AM is an area of substantial but undetermined future potential. The MOD is currently engaged in a number of studies and scoping exercises to determine the feasibility of applying this technology, and to assess the degree to which AM could be a 'game-changer' for certain defence operations.[152] The relevance of AM for defence mirrors its commercial priorities of customised/localised production, reduced cost, high specifications and enhanced opportunities for innovation. In addition to the general benefits of reducing design-to-production timescales and lowering expenditure for producing/replacing equipment, the defence application of these benefits is favourable in a number of specific contexts, summarised in Figure 2-9.[153]

Figure 2-9 Defence-specific benefits of AM

In-theatre production	Specialised applications (e.g. stealth materials, sensors)
Aircraft, particularly UAVs	Lightening soldiers' carrying loads
Improving energy use	Reducing logistics repairs burden
Modifying equipment design phase	Space premium mission

Source: RAND Europe analysis of interviews, 2013

In a general sense, AM application is being considered in three major domains, relating to soldiers, vehicles, and bases. The MOD is interested in how AM can provide solutions such as improving energy use, lightening soldiers' carrying loads, reducing the logistic repairs burden and modifying the equipment design phase.[154] AM also has the potential to replace physical with digital inventories on space premium missions, such as submarines.[155]

There is also the potential for defence to benefit from various **specialised applications** of AM by capitalising on the technology's ability to produce complicated, intricate structures with new material properties. Embedded sensors, able to gauge the wear and stress on a structure, could be useful in monitoring the need for upgrades and new parts. Opportunities also exist in such applications as temperature resistant devices, armour plating for military vehicles, explosive materials, stealth products, acoustic absorbency, and even biomedical monitoring applications to ensure soldiers are receiving the nutrients they need.[156]

Defence **aircraft**, particularly unmanned aerial vehicles (UAVs), are another major area of potential for AM processes. The benefits here are shared with those of the aerospace sector, namely lightweight materials and reduction of waste in part production. However, defence has the added advantage of lower certification requirements. Particularly with the proliferation of unmanned aerial vehicles, safety concerns are less of a risk. This reduces the barrier of extensive qualification requirements, although aspects such as airworthiness must still be guaranteed. Improving the weight-to-power ratio of UAVs is thus one particular area where AM parts may be employed in the future. This potential makes it important for

[152] Interviews conducted by RAND Europe (2013)
[153] Interviews conducted by RAND Europe (2013)
[154] Interviews conducted by RAND Europe (2013)
[155] Wohlers (2011) in Scott et al. (2012), p.15
[156] Interviews conducted by RAND Europe (2013)

defence to engage with the aerospace industry and stay apprised of advances made in this sector.[157]

AM's ability to produce selected equipment in small batches, with localised processes, can be especially valuable for **in-theatre production** where immediate, customised production would be a major tactical asset.[158] This in-theatre production could valuably reduce the frequency and length of supply chains, diminishing costs by reducing the need for fuel and convoys. It would also present a tactical benefit by lowering the risk of troop and equipment vulnerabilities during the convoy process.[159] On-site production would reduce storage requirements and reduce the cost and time lag of resupplying equipment.[160] In-theatre production could also be useful from a medical perspective, for example in providing temporary implants for wounded soldiers to support them through emergency evacuation.[161]

However, the implementation of in-theatre production is very complex and has not yet been tested. Concerns about the suitability of AM machines in varying conditions – such as in dusty or high-temperature environments – are yet to be answered.[162] Supplying raw materials and addressing post-production processes would also need to be addressed. Current research is scoping the potential for AM in this area, focusing on its impact on logistics and operations to assess what barriers and enablers exist. Certain techniques may also be more favourable to in-theatre use.[163] Experts pointed to feed deposition modelling using plastic filaments in making spare parts and also the relatively versatile powder bed fusion process.[164]

AM also poses new security risks

Finally, along with the many defence benefits brought by AM, the technology may introduce certain defence and security risks by expanding the ability to design and produce weapons. Additive processes make weapons easier for both individuals and states to produce, and the localised nature of production removes dependency on developed countries for manufacture. Weapons will also be more easily disguised at the manufacturing stage, with implications ranging from advanced IEDs to improved counterfeiting techniques.[165]

2.7.2 The MOD is assessing opportunities to engage with the broader AM community

In the broader landscape of AM stakeholders, experts emphasised that the MOD is currently assessing the extent to which AM can be used within a defence context. The approach is now oriented on scoping the terrain and establishing future avenues of research and development.[166] Dstl already engages in technology watch activities and consistent horizon scanning in order to stay apprised of AM developments in the commercial landscape. In assessing the feasibility of AM, the MOD has also looked to industries with similar constraints to learn from their examples – for instance, one expert noted that the oil

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157 Interviews conducted by RAND Europe (2013)
158 Scott et al. (2012), pp.15–16
159 Interviews conducted by RAND Europe (2013)
160 Interviews conducted by RAND Europe (2013)
161 Interviews conducted by RAND Europe (2013)
162 Interviews conducted by RAND Europe (2013)
163 Interviews conducted by RAND Europe (2013)
164 Interviews conducted by RAND Europe (2013)
165 Campbell et al. (2011), p.13
166 Interviews conducted by RAND Europe (2013)

industry is watched to see how remote stations maintain self-sufficiency. It is expected that Dstl will continue to encourage industry research into AM technologies, and will increase MOD funding of these efforts if the current initiatives present promising results.[167]

Looking ahead, there is scope for collaboration with both industry and, to a limited extent, academia. In terms of engaging with industry, the MOD typically looks to its prime suppliers as a trusted source with a wide range of technological capacity. For example, industry partners are consulted to help the MOD identify and address supply chain issues.[168] In the future, participation in structured collaborations – such as the cross-sector MTC-TSB projects mentioned in Section 2.4.4 – could provide a space for the MOD to liaise with non-defence partners towards common goals.[169] While experts spoke less about the potential to engage with universities, one considered that academic expertise might be utilised to support logistical concerns. Specifically, university expertise could be useful in calculating algorithms for the correct shelf supply of spare parts if AM processes were introduced in theatre.[170]

At the same time, experts noted a number of barriers to defence engagement with the wider technology stakeholder community. In addition to concerns over classified and sensitive information, defence often is driven by very different factors than its potential commercial partners. In terms of R&D investment, for example, universities have comparatively slower timescales, while industry is typically driven by competitive advantage rather than capability concerns.[171] Defence may also have requirements for specialised applications, such as stealth coating, that are not typically served by commercial providers.[172] Finding ways to mediate these disconnects will be important in empowering future collaborations with the AM realm.

2.7.3 Significant barriers need to be reduced to give the MOD the confidence and incentive to adopt AM more widely

In some ways, AM is highly suited to defence production which is often high value, low volume, and involves complex designs. At the same time, a number of defence-specific barriers exist. Lack of precision and reliability in current AM processes remains a particularly prohibitive barrier for defence, in which validated accuracy and repeatability of products is highly important.[173] Experts also noted that substantial testing and evaluation of AM methods would need to occur before the process is trusted by the defence establishment and allowed to become more widespread.[174] One expert noted that defence is committed to proven materials, meaning that the new materials required for AM would need to be vigorously tested to empower confidence in their integration.[175]

The MOD also needs to consider how the integration of AM may displace the logistics burden by requiring manufacturing components and materials, rather than completed spare parts, to be brought into theatre. For instance, AM machines currently have high energy requirements, which could be problematic in theatre – one expert pointed out that fuel

[167] Interviews conducted by RAND Europe (2013)
[168] Interviews conducted by RAND Europe (2013)
[169] Interviews conducted by RAND Europe (2013)
[170] Interviews conducted by RAND Europe (2013)
[171] Interviews conducted by RAND Europe (2013)
[172] Interviews conducted by RAND Europe (2013)
[173] Interviews conducted by RAND Europe (2013)
[174] Interviews conducted by RAND Europe (2013)
[175] Interviews conducted by RAND Europe (2013)

shipped to operational theatres is 40 times more expensive. Dstl is currently conducting a study to focus more specifically on the logistics aspects of AM for land forces.[176]

Further integration of AM will also impact on the ways in which the MOD engages with suppliers and manufacturers. It will be important to explore the contractual consequences of shifting from conventional to AM methods, for example to transfer designs and establish quality for AM versions of current parts. The MOD will also need to consider legal implications of reproducing conventional parts through AM, particularly around ownership of IP rights. Some other Ministries of Defence worldwide have already completed this evaluation and adapted their contractual agreements accordingly.[177]

In forecasting AM's defence potential, experts again provided a range of projections. The next five years are likely to focus heavily on testing the quality and feasibility of limited AM application, with one expert suggesting early use would focus on mass-produced non-critical items like bolts and brackets.[178] Within five years, another expert predicted that AM should be mature enough for the MOD to employ it in one 'pilot area', with its use spreading to other areas if and when capability grows and costs fall.[179] Initial impact for military forces is thus likely to be limited until AM is more developed and its use is more widespread – and it is shown that AM methods are better suited for certain applications than traditional manufacturing. In the longer term, niche applications such as stealth coating, self-lubricating metals, and use of recycled materials could occur in the next 15 years, with AM processes potentially rising in prominence after 2030 if proven effective.[180]

[176] Interviews conducted by RAND Europe (2013)
[177] Interviews conducted by RAND Europe (2013)
[178] Interviews conducted by RAND Europe (2013)
[179] Interviews conducted by RAND Europe (2013)
[180] Interviews conducted by RAND Europe (2013)

References

3D Printshow. As of 28 August 2013: http://3dprintshow.com/london2013/about-london-2013/

Additive Manufacturing Special Interest Group (AM SIG) for the Technology Strategy Board, *Shaping Our National Competency in Additive Manufacturing*, September 2012.

Auto Express, '3D printing: the future of the car industry?', 4 July 2013. As of 28 August 2013: http://www.autoexpress.co.uk/car-news/consumer-news/64799/3d-printing-future-car-industry

Campbell, Thomas, Christopher Williams, Olga Ivanova and Banning Garrett, *Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing*, Strategic Foresight Report, Atlantic Council, Washington, October 2011.

Centre for Additive Layer Manufacturing, 'What is additive layer manufacturing?', University of Exeter. As of 28 August 2013: http://emps.exeter.ac.uk/engineering/research/calm/whatis/

Cooper, David E., Mark Stanford, Kevin A. Kibble and Gregory John Gibbons, 'Additive manufacturing for product improvement at Red Bull Technology', *Materials & Design* 41, 2012, pp.226–30.

Cubic Technologies, 'SD300 3D Printer'. As of 28 August 2013: http://www.cubictechnologies.com/SD300.htm

Department for Business, Innovation and Skills (BIS), *International Comparative Performance of the UK Research Base – 2011,* 2011.

Desktop Engineering, 'Additive Manufacturing: A Body of Work', 1 April 2013. As of 28 August 2013: http://www.deskeng.com/articles/aabjpe.htm

Digital Manufacturing Report, 'Additive Manufacturing's Dirty Secrets Exposed', Tabor Communications, Inc., 21 November 2012. As of 28 August 2013: http://www.digitalmanufacturingreport.com/dmr/2012-11-21/additive_manufacturing%E2%80%99s_dirty_secrets_exposed.html

Dstl, 'Additive Manufacturing', Dstl Science & Technology Foresight Briefing Paper, Dstl/PUB64249 Issue 1.1, December 2012.

The Economist, 'The printed world', 10 February 2011.

EOS, 'The Challenge of Lightweight Construction'. As of 28 August 2013: https://www.eos.info/additive_manufacturing/for_your_engineering/challenge_lightweight_construction

EPSRC Centre for Innovative Manufacturing, website. As of 28 August 2013: http://www.3dp-research.com/Home

Excell, Jon and Stuart Nathan, 'The rise of additive manufacturing', *The Engineer*, 24 May 2010. As of 28 August 2013: http://www.theengineer.co.uk/in-depth/the-big-story/the-rise-of-additive-manufacturing/1002560.article

Farmer, Benjamin, Andrew Hawkins and Jonathan Meyer, *Forecasting Advances in Design, Fabrication & Manufacture,* EADS Innovation Works, Report IW-202154, 3 February 2011.

Freedman, David, 'Layer by Layer', MIT Technology Review, January/February 2012. As of 28 August 2013: http://m.technologyreview.com/featuredstory/426391/layer-by-layer/

Gartner, 'Gartner's 2012 Hype Cycle for Emerging Technologies', August 2012.

Hague, Richard and Phil Reeves, 'Additive Manufacturing and 3D Printing', *Ingenia* 55, June 2013, pp.39–45.

HM Government, '3D printing comes to Parliament', 13 September 2012. As of 28 August 2013: http://www.parliament.uk/mps-lords-and-offices/offices/bicameral/post/post-news/advanced-manufacturing/

Hopperton, Laura, 'UK additive manufacturing research leads the field', *Eureka*, 13 September 2012. As of 28 August 2013: http://www.eurekamagazine.co.uk/design-engineering-features/technology/uk-additive-manufacturing-research-leads-the-field/44790/

Houses of Parliament, 'Advanced Manufacturing', Parliamentary Office of Science and Technology, No. 420, September 2012.

InterPRO, 'Aerospace and Defense 3D Printing'. As of 28 August 2013: http://www.interpromodels.com/industries/defense-and-aerospace-3d-printing/

King, Matt, 'Of Labour, Unions and 3D Printing', ArbitrageMagazine.com, May 2013, pp.35–38.

LeHong, Hung and Jackie Fenn, 'Key Trends to Watch in Gartner 2012 Emerging Technologies Hype Cycle', *Forbes*, 18 September 2012. As of 28 August 2013: http://www.forbes.com/sites/gartnergroup/2012/09/18/key-trends-to-watch-in-gartner-2012-emerging-technologies-hype-cycle-2/

The Manufacturer, 'Additive manufacturing: What does it add up to?', 27 August 2012. As of 8 May 2013: http://www.themanufacturer.com/articles/additive-manufacturing-what-does-it-do/

Manyika, James, Michael Chui, Jacque Bughin, Richard Dobbs, Peter Bisson and Alex Marrs, *Disruptive technologies: Advances that will transform life, business and the global economy,* McKinsey Global Institute, May 2013.

Manufacturing Engineering, 'Making Products By Using Additive Manufacturing', April 2011. As of 28 August 2013: http://www.sme.org/MEMagazine/Article.aspx?id=68650&taxid=1426

Materialise (a), 'Intrion robots are up to speed with Materialise's additive manufacturing'. As of 28 August 2013: http://manufacturing.materialise.com/cases/intrion-robots-are-speed-materialises-additive-manufacturing-0

Materialise (b), 'The 3D Printed Pen is Mightier than the Sword'. As of 28 August 2013: http://manufacturing.materialise.com/cases/3d-printed-pen-mightier-sword

Materialise (c), 'The Arieon by Formula Group T: The World's First 3D Printed Race Car'. As of 28 August 2013:

http://manufacturing.materialise.com/cases/areion-formula-group-t-worlds-first-3d-printed-race-car

Materialise (d), 'The Gatewing X100: prototypes take flight with manufactured end-use parts'. As of 28 August 2013: http://manufacturing.materialise.com/cases/gatewing-x100-prototypes-take-flight-manufactured-end-use-parts-1

Optomec, '3D Printing is Merged with Printed Electronics', 23 March 2013. As of 28 August 2013: http://www.optomec.com/site/latest_news/news95

Park, Rachel, '3D Printed Surgical Guides Make Their Malaysian Debut,' 20 June 2013. As of 28 August 2013: http://3dprintingindustry.com/2013/06/20/3d-printed-surgical-guides-make-their-malaysian-debut/

Reeves, Phil, '3D printing & China – Umbrellas, Ninja scooters & Illicit VPNs', blog, Econolyst, 9 June 2013. As of 28 August 2013: http://www.econolyst.co.uk/blog/?p=248

Reeves, Phil, 'Putting 3D Printing into your value stream: opportunities for new business models', presentation, 3D Printshow London 2012, Econolyst, 19 October 2012.

Reeves, Phil, '3D Printing in aerospace & automotive', Econolyst, presentation.

Rosen, D.W., 'Computer-Aided Design for Additive Manufacturing of Cellular Structures', *Computer-Aided Design & Applications* 4:5, 2007, pp.585–94.

Scott, Justin, Nayanee Gupta, Christopher Weber, Sherrica Newsome, Terry Wohlers and Tim Caffrey, *Additive Manufacturing: Status and Opportunities*, IDA Science and Technology Policy Institute, March 2012.

Sculpteo, '3D Printing for the Car Industry – an Audi Example'. As of 28 August 2013: http://blog.sculpteo.com/2012/04/04/3d-printing-for-the-car-industry-the-audi-example/

Semta (2013a), 'You're hired: Huge increase in engineering and manufacturing apprentices', 29 January 2013. As of 28 August 2013: http://semta.org.uk/media/press-releases/youre-hired-huge-increase-in-engineering-and-manufacturing-apprentices

Semta (2013b), 'Siemens tackles skills gap with UK's first engineering education and careers portal for schools', 28 February 2013. As of 28 August 2013: http://semta.org.uk/media/press-releases/siemens-tackles-skills-gap-with-uks-first-engineering-education-and-careers

Semta. As of 28 August 2013: http://semta.org.uk/

Shapeways (2013a), 'The Bugatti Veyron's 3D printed dashboard', 8 January 2013. As of 28 August 2013: http://www.shapeways.com/blog/archives/archives/164-The-Bugatti-Veyrons-3D-printed-dashboard.html

Shapeways (2013b), '3D printed customizable Gear Shifter for BMW', 10 June 2013. As of 28 August 2013: http://www.shapeways.com/blog/archives/477-3d-printed-customizable-gear-shifter-for-bmw.html

Sissons, Andrew and Spencer Thompson, *Three Dimensional Policy: Why Britain needs a policy framework for 3D printing,* Big Innovation Centre, October 2012.

Smith, Alastair, *Opportunities for, and potential contribution of, social science research relating to the nature and development of Additive Manufacturing,* The Centre for Business Relationships, Accountability, Sustainability and Society, Cardiff, 2012.

Stratasys (a), 'Additive Manufacturing 101: How the Future of Product Development and Manufacturing is Changing'. As of 28 August 2013: http://www.stratasys.com/resources/webinars/additive-manufacturing-101.aspx

Stratasys (b), 'Altimate Medical'. As of 28 August 2013: http://www.stratasys.com/resources/case-studies/medical/altimate-medical

Stratasys (c), 'Automotive Case Studies.' As of 28 August 2013: http://www.stratasys.com/resources/case-studies/automotive/bmw

Stratasys (d), 'Dental Case Studies: 3D printing builds more smiles', As of 28 August 2013: http://biomedical.materialise.com/webinars-2012-heartprint-effective-physical-models-bench-testing-communication-and-surgical-planning

Stratasys (e), 'Medical Case Studies: 3D printing helps save lives'. As of 28 August 2013: http://www.stratasys.com/resources/case-studies/medical/casa-di-cura

Stratasys (f), 'Nemours'. As of 28 August 2013: www.stratasys.com/resources/case-studies/medical/nemours

Stratasys (g), 'Script Pro'. As of 28 August 2013: http://www.stratasys.com/resources/case-studies/medical/script-pro

Technology Strategy Board (TSB), 'Inspiring new design freedoms in additive manufacturing/3D printing', competition for collaboration R&D funding, December 2012. As of 28 August 2013: https://www.innovateuk.org/competition-display-page/-/asset_publisher/RqEt2AKmEBhi/content/inspiring-new-design-freedoms-in-additive-manufacturing-3d-printing

Thornton, Phil, 'How additive manufacturing can boost the UK economy', Economic and Social Research Council, 17 December 2012. As of 28 August 2013: http://www.esrc.ac.uk/impacts-and-findings/features-casestudies/features/24501/how-additive-manufacturing-can-boost-the-uk-economy.aspx

Wohlers Associates, *Wohlers Report 2012*, 2012.

Wohlers Associates, 'Annual Revenues from Additive Manufacturing Products and Services Worldwide', *Wohlers Report 2010*, 2010. As of 28 August 2013: http://wohlersassociates.com/growth2010.htm

World Future Society, 'Investing in the Future of 3D Printing', 12 July 2012. As of 28 August 2013: http://www.wfs.org/blogs/james-lee/investing-future-3d-printing

CHAPTER 3 Synthetic environments

This chapter presents the data gathered as part of the in-depth case study on synthetic environments. As this data synthesis provides the evidence base for the case study summary in the Final Report, there are some areas of overlap between the two. The research is based on a combination of literature review and engagement with expert stakeholders across government, academia, business and defence. The list of references specific to this case study can be found at the end of the chapter. The list of key informant interviews and workshops that we conducted is elaborated in Chapter 1.

3.1 Synthetic environments combines virtual and human elements to provide a simulated experience

Applied widely across both the commercial and defence spheres, synthetic environments (SE) combines the human element with simulation technology, the latter encompassing 'the imitation of the operation of a real-world process or system over time'.[181] As defined in a think piece by the UK Department of Transport:

> *Synthetic environments (SE) refers to a set of technologies that seek to join up advanced models and simulations in order to facilitate experimentation, concept exploration and product development. They enable existing computational models, virtual environments and simulations, people, objects and equipment to interact in a virtual world.*[182]

SE may represent either natural or artificial environments, and is capable of modelling complex relationships and interactions between various actors and components of a given system.[183]

SE is a multidisciplinary technology area, involving subjects from visual design to maths and engineering.[184] Improvements in SE, such as simulation and virtual reality technologies, are informed by the integration of multiple technology areas, including information, communication and visualisation technologies.[185] Developments in SE technologies are particularly driven by advances in areas such as the games industry, where competitive market pressures are motivating an increasingly immersive and realistic simulation experience.

Simulation technology is widely leveraged to reduce the cost, timescales and risk of product testing and training programmes, both in commercial and defence contexts. By providing virtual conditions replicating real-life constraints, it is possible to rapidly test new

[181] Fawkes (2013)
[182] Neffendorf et al. (2007)
[183] University of Manchester Aerospace Research Institute, informational brochure.
[184] Interviews conducted by RAND Europe (2013)
[185] University of Manchester Aerospace Research Institute, website

technologies in a controlled environment.[186] SE technologies also save time and money when applied to training processes that test real-life skills. Software can create virtual environments whose realistic conditions serve the needs of a range of participants.[187] Customised synthetic environments provide an immersive real-time environment in which participants can realistically engage with operational networks and develop more effective decisionmaking.[188] Simulation also can empower testing and training in hypothetical scenarios that might otherwise be impossible to experience, due to scale or impracticality.

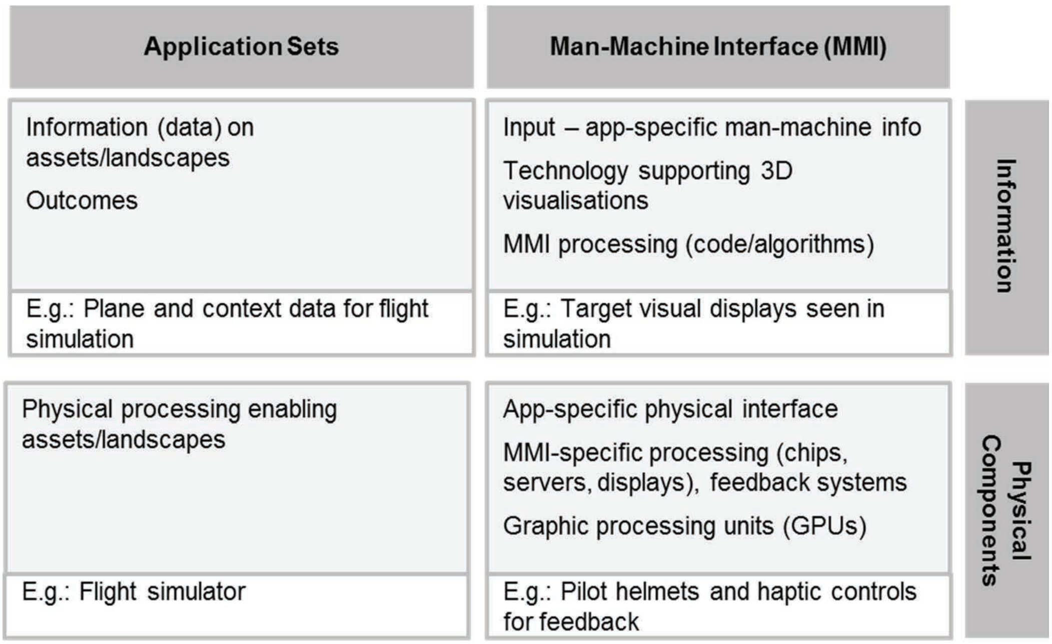
3.1.1 SE is characterised by shared components

All synthetic environments contain three key components:[189]

1. **Data:** inputs to the system, informing elements such as landscapes and scenarios.
2. **Processes**: the hardware and software enabling use by assets (individuals or groups).
3. **Applications**: the intended outcome achieved by employing SE.

Within these broad classifications, a number of technological capabilities are employed to empower both the means and the ends of the process. Figure 3-1 summarises these technologies within the broader components of the SE system.

Figure 3-1 Components of SE systems



Source: RAND Europe analysis and expert workshop

3.1.2 SE has a range of uses across a wide variety of sectors

SE technologies are employed for a number of purposes in a range of disparate sectors, a summary of which is captured in Figure 3-2. Key applications include training, education, support to acquisition, and operational analysis. For many industries, simulation technologies are used before the manufacturing process to empower design, testing and evaluation.[190] Simulation also supports performance evaluation in supply chain

[186] Cornford (2012), p.68
[187] University of Manchester Aerospace Research Institute, website
[188] University of Manchester Aerospace Research Institute, website; TSB (2009), p.26
[189] Interviews conducted by RAND Europe (2013)
[190] Interviews conducted by RAND Europe (2013)

management by helping optimise conditions, analyse decisions, evaluate diagnostics and minimise risks.[191] This is especially useful for large companies with complex supply chains involving hundreds of components, who are faced with more data than they can productively assess through other analytical means.[192] Supply chain simulation can facilitate a more streamlined supply chain in a range of sectors, from automotive to energy.[193] Pre-packaged simulation tools are also emerging, such as the StrIVE package of pre-configured software, relevant engineering and implementation services, and a training programme.[194]

Uses of SE in the medical field provide a snapshot of the technology's varied application. Simulation technologies have been incorporated in medical teaching, employing such interface devices as haptic gloves that provide tactile feedback that mirrors the feel of real surgeries.[195] In the case of the Enteric Immunity Simulator (ENISI), a simulator has been used to study potential immunity responses to gastrointestinal bacteria.[196] SE technologies have also benefitted from other technological advances, as in the case of new simulators that replicate precise anatomical models using advances in sensor miniaturisation, additive manufacturing and 3-D graphics cards.[197]

In other sectors, SE and virtual reality are also gaining traction in training and education. For instance, for many commercial airline pilots, simulation is used to such an extent that their first live flight may be on a commercial flight with passengers aboard.[198] Universities are also increasingly exploiting the possibilities offered by these technologies to widen their reach through online classes and seminars.[199]

Over the past decade, the simulation and modelling domain has been led by commercial rather than defence developments.[200] Technologies relating to SE are used in a wide range of mainstream applications, from navigation systems to video review for sporting events. For the 2013 Tour de France, for instance, Pro-Form introduced a new stationery bike that offers a simulated experience, complete with Google Maps course imagery and realistic mechanical adjustments to model the slope, wind resistance and gear shifts of an actual ride.[201] Real-time simulators are used in industrial applications from statistical power grid protection tests to space robot integration.[202] SE is also used in the aerospace sector, for example in air traffic management and in prototyping processes.[203] Additionally, simulation supplements the use of modelling in the transport sector, particularly when systems are highly complex and interactive. The clearest example of transport simulation in the UK is the use of microsimulation packages for road network traffic operations.[204]

[191] GoldSim Technology Group LLC (2007)
[192] GoldSim Technology Group LLC (2007)
[193] Interviews conducted by RAND Europe (2013)
[194] Simudyne, website
[195] Issenberg, et al. (2001), p.16
[196] Wendelsdorf et al. (2011), p.1
[197] Lampotang et al. (2012)
[198] Interviews conducted by RAND Europe (2013)
[199] Interviews conducted by RAND Europe (2013)
[200] ITEC, website
[201] Pro-Form, website
[202] Dufour, et al. (2010)
[203] University of Manchester Aerospace Research Institute, informational brochure
[204] Neffendorf, et al. (2007), p.ii

Figure 3-2 Selected applications of SE by sector

Sector/Type of Application	Training	Design	Operations	References
Auto		- Rapid Automotive Performance Simulator to test vehicle systems in a virtual environment - Virtual design of cars including a simulation of sights, sounds and smells	- Virtualised Traffic to simulate traffic flows	Southwest Research Institute, website; Thompson (2013); Van den Berg et al.
Aerospace/ Space	- Flight simulators for commercial, military and civil aviation pilots	- Weather simulations on computerised meteorological systems	- Advanced simulation and visualisation technologies to help build next-generation air traffic management systems	Royal Aeronautical Society, website; CAE, website; Golding (2000); VT MAK, website; Burduea (2000)
Medical	- Haptic Gloves to model user interactions - Enteric Immunity Simulator of gastrointestinal immune mechanisms - Surgery training and rehearsal	- National Capital Area Medical Simulation Centre for immersive instruction in medicine with sophisticated simulations of body parts and a virtual reality theatre	- A neurosurgery simulator and an anatomy viewer	Burduea (2000); Wendeldorf (2011); National Capital Area Medical Simulation Center, website; Ohbuchi et al. (1996)
Energy/ Nuclear		- Construction planning related to nuclear power plant design and construction at Penn State University's SEA Lab	- Distributed synthetic environment power plant design and processes simulations in power plants	The Synthetic Environment Applications Library, website; Ansaldo Energia, website; Bruzzone and Petuhova (2011)
Military	- LVC Training Environments - Virtual Interactive Combat Environment - Close Combat Tactical Trainer for vehicles found in close combat units	- Conceptualisation, design and testing of new equipment	- Integrated simulation solutions for soldiers - Simulations of Military Operations on Urbanised Terrain - War games	Federal Business Opportunities, website; Dynamic Animation Systems, Inc., website; US Army PEO STRI, website; RAND Europe interviews, 2013; Pugliese (2013); Sabol (2008)
Others	- Large-area terrain representations of any location on the globe from vector and elevation source data	- Pro-Form stationery bikes simulating riding experience from Tour de France - The 3-D modelling program SketchUp - 3-D virtual reality and model building for plant engineering in COMOS Walkinside - 3-D urban planning in PlastiCity - 'Serious games' like Urban Decision Room - Virtual prototyping of complex machinery and vehicles to replace hardware prototypes - Designing market and supply chain in the PC industry	- Supply chain design and management based on modelling and simulation - Cloud supply chain management in the pharmaceutical industry - Simulations of emergency situations such as the Simulation of Large Scale Catastrophic Events, and Drillsim, a Multi-Agent Simulator for Crisis Response - AR mobile apps for sport fans - Movie special effects - Video and computer games - Communications, such as avatar VTC - Real time sporting review systems	Presagis, website; Proform, website; Sketchup, website; Siemens, website; Delft University of Technology, website; Maplesoft, website; Chaturvedi and Mehta; Cal-Tek, website; *Financial Times* (2012); Dartmouth College, website; Donald Bren School of Information and Computer Sciences, website; Laird (2013); RAND Europe interviews, 2013

Source: RAND Europe analysis of references

3.2 Important developments have taken place in visualisation, interaction and processing technologies, enabled by progress in IT

Synthetic environments advances are occurring in the areas of visualisation, interaction and processing technology, as summarised in Table 3-1.

Table 3-1 Priority areas of development for SE technology

Priority areas for simulation technologies	Examples
Visualisation	- 3-D visualisation / autostereoscopy - Augmented reality (AR)
Interaction	- Multiplayer capacity - Motion controls through advanced sensor technology - Improved user-environment interface - Interoperability
Processing technology	- Microprocessors - Graphic processing units (GPUs)

Source: RAND Europe analysis

3.2.1 Visual improvements encompass 3-D and augmented reality

New immersive and virtual reality technologies are improving the realism of the simulated experience, for example through 3-D and augmented reality (AR) capabilities. New advances in autostereoscopic technology combine elements of micro-optics and LCD to enable 3-D images without the use of assistive eyewear.[205] In the games sector, this technology is beginning to appear in consoles like the portable, glasses-free Nintendo 3DS.[206] First-person shooter games are also developing graphics capabilities that are 3-D and close to reality in order to heighten the player experience.[207] Augmented reality (AR) technology is developing new aspects of realism in simulated environments, and has the capacity to layer information and visualisations on real-world images, providing an additional level to inform decisionmaking in training programmes.[208] AR is already finding applications in new consumer technologies, such as Google Glass. This innovative product uses display technology (among other features) built into spectacle frames to layer data, such as translations or transcriptions, onto an individual's field of vision via a prism screen.[209]

3.2.2 Interoperability and interface are improving to provide more interaction and connectivity

Interaction is improving in a number of ways. Network interoperability – the ability for an SE to connect to other systems during use – is enabling more advanced connectivity, for example in distributed simulations that involve multiple machines.[210] The participant-environment interface is also improving through multiplayer and motion-sensor technologies. Massively multiplayer online games (MMOGs) have the capacity to sustain simultaneous play by hundreds or thousands of players around the world.[211] This technology enables players to interact through competition and cooperation on a global

[205] Adolph (2011), p.16
[206] Streib (2010)
[207] Adolph (2011), p.16
[208] Deloitte (2012), p.45
[209] Rivington (2013)
[210] Interviews conducted by RAND Europe (2013)
[211] Adolph (2011), p.5

scale – the game Counter-Strike, for example, has been played online by more than 90,000 gamers simultaneously.[212] This level of gaming requires technology advances in real-time synchronisation and multi-user voice chat, which challenge servers and networks to accommodate this increased demand.[213]

In terms of interface, motion-based gaming is also growing, with Nintendo's Wii followed by new devices from both Microsoft and PlayStation. Microsoft's Kinect, for example, tracks players' movements with a 3-D camera that allows players to control an on-screen avatar.[214] Motion-sensing technologies optimise the natural user interface through a combination of cameras, microphones, gyroscopes and accelerators that capture and transmit users' movements to the virtual imagery. Similar types of sensor technology are already being exported from the games industry to inform user interfaces in contexts such as vehicles and home appliances, creating devices capable of reacting to voices, gestures and facial expressions.[215]

3.2.3 Mobile technology is on the rise

The increasing use of mobile technologies such as smartphones and tablets also has a transversal impact on a range of sectors. For instance, broadcasting companies have targeted these platforms to diversify their reach to customers. Most TV channels in the UK now offer an online video on-demand service, with individual accounts where this service is by subscription only.[216] Video games are increasing use of mobile devices as well – FIFA players, for instance, are able to manage their teams on their smartphones, complementing their console-based experience. Similarly, Playstation Vitas act as direct extensions of fixed consoles and sync with each other as players progress through the game on either platform.[217]

3.2.4 Computing technology has enabled advances in other areas

These various advances in visual simulations are enabled by improvements in computing technology. Experts confirmed that new innovations in software development will be important in enabling the continuing evolution of SE.[218] Graphics processing units (GPUs) are the technological component behind realistic visual effects, such as light and smoke, 3-D capacity, and high-resolution imagery.[219] Maintaining and enhancing GPU effectiveness to heighten the simulation experience of synthetic environments is an ongoing priority. This is evidenced by the frequent release dates of new GPU chips: as of May 2013, for instance, the company AMD had released 81 mobile and 56 desktop GPU chips since January 2011.[220] Similarly, development in processing capacities were instrumental in enabling the progress in artificial intelligence seen over the last years.[221] Finally, significant changes in the accessibility, reliance and bandwidth of broadband networks have enabled a pervasive change throughout society, fundamentally affecting how individuals work, play and access information.[222]

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[212] Adolph (2011), p.7
[213] Adolph (2011), p.7
[214] Streib (2010)
[215] Adolph (2011), p.15
[216] *The Economist* (2013), p.15
[217] Interviews conducted by RAND Europe (2013)
[218] Interviews conducted by RAND Europe (2013)
[219] Adolph (2011), p.17; Deloitte (2012), p.45
[220] TechPowerUp (2013)
[221] Interviews conducted by RAND Europe (2013)
[222] Interviews conducted by RAND Europe (2013)

3.2.5 Future development will make best use of IT innovation and will continue to benefit from favourable wider societal trends

Experts predict that the non-defence technology landscape will change dramatically for SE over the next 20 years.[223] Potentially revolutionary developments will come in areas such as increased bandwidth, ray-tracing and 3-D visuals.[224] Across the many uses of SE, there is a continued push towards increasing realism and interactive potential, blurring the boundaries between 'real' and 'simulated' experiences. In the future, rendering speeds will be improved by advances in data storage and processing. This will assist with the detail and realism of the experience. Current rendering speeds are such that in a high-speed simulation, often the icons momentarily glitch (e.g. an aircraft 'judders' across the screen) while the data is processed. With improved rendering speeds, the simulation will appear more seamless.[225] As these processing and display capabilities improve, future constraints may arise around the capacity of the human brain to absorb and respond to the various streams of information with which it is simultaneously presented.[226]

A continued increase in integration is expected, especially leveraging the potential of mobile platforms as they become more powerful. The realism of virtual reality and artificial intelligence is also predicted to be refined as processing capacities develop. On a social level, it is likely that the use of serious gaming and other trends associated with gamification will continue to spread, as the percentage of adult gamers increases.[227] This trend can be seen, for example, in the Serious Games Institute that is hosted by Coventry University and works on furthering research in serious games, augmented reality and virtual worlds.[228]

3.3 Key SE actors are found transversally across the technology landscape

The UK stakeholder network for SE technologies is not clearly defined at a national level, but its actors are found across government, academia and business, including SMEs. While there is no university department dedicated to virtual reality, there are research centres focusing on SE aspects as part of wider computer science departments. Similarly, SE-relevant funding provided by the EPSRC is found within the wider information and communications technology (ICT) funding cluster. As SE is closely linked with computing technologies, clearly bounding the landscape and actors is challenging. However, this section presents the high-level agencies and organisations engaging in SE.

3.3.1 Government funding is led by the TSB

The Technology Strategy Board (TSB) is the leading government stakeholder outside defence, supporting a number of SE-related projects that are distributed across several research areas.[229] Due to the digital content of SE, this technology relates primarily to the TSB's ICT research cluster, where it overlaps with subjects such as advanced software engineering and the evolving digital–human interface. The TSB is also involved in supporting sector-specific interests in SE from areas such as transport, energy and materials. In aerospace, for example, the TSB has funded a 'Next Generation Composite Wing' project using SE to facilitate a rapid wing design process. Other SE-relevant projects

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223 Interviews conducted by RAND Europe (2013)
224 Interviews conducted by RAND Europe (2013)
225 Interviews conducted by RAND Europe (2013)
226 Interviews conducted by RAND Europe (2013)
227 Gamification Corp., website
228 Serious Games Institute, website
229 Interviews conducted by RAND Europe (2013)

include a Knowledge Transfer Partnership (KTP) with the energy sector to model building energy performance, a project using augmented reality to provide an interactive historical simulation, and a project supporting a 3-D mobile gaming engine driven by audio rather than visual feedback.[230] Initiatives like Programme SMART also investigate technology applications in both the defence and civilian sectors, aiming to test and prove concepts, markets and developments.[231]

The EPSRC is also investing in fundamental research that contributes to SE with grants spread across a wide range of universities across the UK. Most of the EPSRC's SE initiatives fall under its ICT theme, within which there are a number of relevant research areas. The graphics and visualisation area considers the various visual aspects of SE, including virtual reality and AR, while research on displays deals with how this visual information is presented. Image and vision computing research further supports SE visualisation, covering both 2-D and 3-D images. Work on human–computer interaction addresses the man–machine interface, while artificial intelligence (AI) technologies research focuses on areas such as intelligent systems and machine agents. The software engineering area provides research that underpins many of the enabling processes involved in SE.[232]

3.3.2 Universities are engaged in SE research through focused centres

SE research is also occurring at universities across the UK. At the University of Manchester, for example, SE and simulation work is being done in a range of areas, from the man–machine interface to agent-based computation modelling to information management and data-mining.[233] Many universities host focused research centres that bring together academia, industry and government funding for a range of research and training purposes. Cranfield University's Simulation and Synthetic Environment Laboratory, for example, was founded with investment from the MOD, but has since received support from industrial sponsors.[234] The Virtual Engineering Centre (VEC), led by the University of Liverpool and funded by a number of partner companies, also bridges academia and industry by providing a facility in which companies can utilise immersive simulation technologies to support product development and testing.[235] This is particularly valuable for SMEs that are unable to invest in state-of-the-art simulation facilities themselves. The VEC also works to break down barriers between manufacturers and foster integration, raising suppliers' awareness about their interdependency.[236]

3.3.3 Industry stakeholders are found across sectors, led by IT and the games industry

SE benefits from strong industry stakeholders in the variety of sectors previously discussed. In the case of larger companies, there are two groups: firstly, there are IT-focused companies acting as drivers or windows for the development and diffusion of SE technologies, such as Google, Apple, Electronic Arts or Ubisoft; secondly, there are large companies that use SE technologies to improve their internal processes. For instance, Bentley has been an early adopter of virtual reality and modelling to design its new vehicles as SE enables it to adopt a through-life approach and integrate manufacturing and maintenance issues as early as possible. SE is interesting for businesses in this way as it enables them to de-risk projects as well as to streamline their operations. A multinational

[230] Interviews conducted by RAND Europe (2013)
[231] Interviews conducted by RAND Europe (2013)
[232] EPSRC, website
[233] University of Manchester Aerospace Research Institute, informational brochure.
[234] Cranfield University, website
[235] Cunningham (2012), pp.17–18
[236] Interviews conducted by RAND Europe (2013)

defence prime has also adopted a top-down emphasis on moving towards simulation-based offerings, which has facilitated integration at a European level.[237]

At the other end of the spectrum, the SE technology landscape is characterised by the presence of a large number of SMEs. For instance, a large proportion of apps available to buy on Apple's Appstore are made by small businesses with a frequent release of products to spread the risk.[238] There are also a number of smaller companies that develop one specific aspect of SE only, whether in terms of man–machine interface, software or hardware. These products include the DCS series now used for military training, which was initially developed by a small Russian company as a desktop trainer before spinning out with both commercial and military applications.[239] A number of experts also referred to 'bedroom programmers', individuals who develop code themselves with great potential for very targeted issues. These individuals either engage with companies or provide the code as open source, depending on their original motivations.[240]

3.3.4 Collaboration between stakeholders is occurring through both formal and informal means

Given the fragmented landscape of SE stakeholders, and the number of small companies involved, collaboration is an especially important priority in moving the technology forward. Experts emphasised the need to address the gap between academia and industry in promoting advances and integration of SE.[241] The TSB is an important stakeholder in both sponsoring and participating in collaborations. One of its main goals is to support the acceleration of research to product development by fostering collaboration between partners that might not otherwise work together. In addition to its funding mechanisms, the TSB offers networking opportunities, such as the 'Collaboration Nation' events that bring together small companies to share their research on technology feasibility. KTPs also offer support for joint research undertaken by industry and university partners. The TSB also participates in collaborative exercises itself, consulting widely with industry partners to develop priorities for programmes and investment.[242]

In addition to the collaborative research centres hosted by universities, the Simulation and Synthetic Environments National Technical Committee (SSE NTC) is a good example of a cross-sector effort bringing together government, academia and industry to share technologies and knowledge across both civilian and defence domains. This group aims to support SE stakeholders through the complete technology life cycle, working to foster communication, provide guidance and share best practice.[243] It also represents stakeholder interests in advising government and industry policy.[244]

In terms of defence cooperation with industry, most interaction occurs with prime suppliers, such as Lockheed Martin and BAE Systems. One expert noted that while defence–commercial industry collaboration does occur around exchanges of best practice, individual companies are often interested in slightly different aspects of SE, which means that priorities are not productively aligned. Additionally, while there are numerous SMEs with whom the MOD might engage, there is a two-way barrier to market access between

[237] Interviews conducted by RAND Europe (2013)
[238] Interviews conducted by RAND Europe (2013)
[239] Royal Aeronautical Society (2011)
[240] Interviews conducted by RAND Europe (2013)
[241] Interviews conducted by RAND Europe (2013)
[242] Interviews conducted by RAND Europe (2013)
[243] Simulation and Synthetic Environments NTC, website
[244] Simulation and Synthetic Environments NTC, website

these smaller companies and the MOD. Firstly, smaller companies do not have the financial reserves to cope with the MOD's typically long procurement processes. Secondly, small companies are often unable to meet the requirements of certification and clearance that are required to work with the MOD.

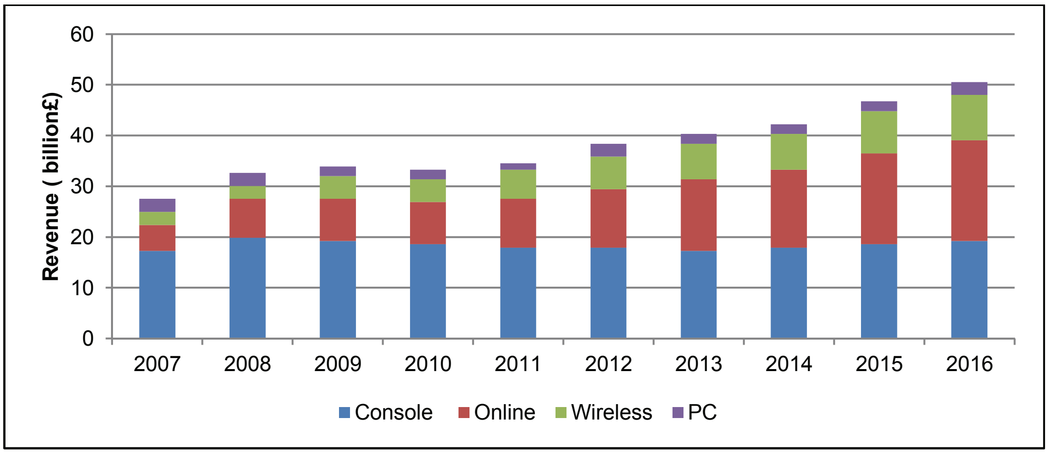
3.4 The UK has a strong SE market, but suffers from skills shortages

3.4.1 The market size of SE-enabled sectors is expected to grow continuously

As the SE market area typically is not a measured sector, we have chosen to analyse the UK video games and interactive entertainment industry, as it is a major driver of SE innovation and technology. The UK games industry is the largest in Europe and one of the largest globally, contributing approximately £1 billion to UK GDP every year.[245] Interactive entertainment is now used by 1 in 3 people in the UK, and the value of the boxed video games retail market was £2.52 billion in 2011.[246]

In the next few years, the interactive entertainment industry is forecasted to see strong growth, both globally and in the UK. PwC estimates that the global video games market will grow from £27.5 billion in 2007 to £50.6 billion in 2016, as shown in Figure 3-3.[247] Recent growth has also been seen in the UK: in 2012, the games sector contributed £947m to UK GDP, a £35m increase from 2010.[248] Following a three-year decline in employment numbers, both employment and investment in UK video games also increased last year, with 118 more studios operating in 2012 than in 2011.[249]

Figure 3-3 Global consumer spending on video games, by platform type, 2007–2016



Source: PwC (2013)

The UK is a leading country in European research and application of SE technologies, although it falls behind the US in terms of product development and skills. The UK is also leading country specifically in the gaming side of SE, although not enough resources have been allocated to fully exploit this potential. Looking ahead, the UK has the potential to build on developments such as the StrIVE package to be a global leader in supporting supply chain simulation.[250]

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[245] TIGA (2013)
[246] The Association for UK Interactive Entertainment (UKIE), website
[247] PwC (2013), p.19
[248] *The Guardian*, 2013
[249] *BBC News*, 2013
[250] Interviews conducted by RAND Europe (2013)

In terms of the defence market, recent analysis by Frost & Sullivan in their *Global Military Training and Simulation Market Assessment* finds that £23.6 billion was spent on global military training and simulation in 2012. This figure is projected to rise to £29.4 billion by 2021. The analysis suggests that simulated training will continue to grow at a rapid pace to provide useful and affordable training solutions.[251] According to Frost & Sullivan predictions, global demand for training and simulation (T&S) will grow steadily from 2012–2021 at a CAGR of 2.51 percent. Frost & Sullivan predicts that this sector will provide up to £263.08 billion in revenue opportunities for industry.[252]

Within the overall growth in SE application for military training, the Frost & Sullivan report predicts that the largest opportunities will occur in the air sector, driven by the acquisition of new systems and platforms with greater complexity. Demand in the land sector is smaller, due to global personnel reductions and platforms that are comparatively less expensive and complex. However, urban mission training and embedded training (within transit vehicles) are likely to grow. There is also scope for SE to aid decisionmaking for C4ISTAR assets. The naval sector is predicted to maintain long-term stability, with training opportunities emerging for unmanned underwater systems.[253]

3.4.2 There is a shortage of niche skills in the key sectors of IT and the games industry

As the SE technology area is closely linked with IT developments, issues linked to skills and facilities overlap between the two. For instance, interviewees mentioned a generational shift away from widespread programming skills.[254] As software becomes increasingly complex and games more widely available, individuals currently joining the workforce have been less incentivised to develop their own programmes than were the previous generation. As a result, many skilled graduates are now lacking in certain areas of what used to be more basic expertise. This is a particular problem in SE as companies that implement or deploy SE always use a combination of commercial off-the-shelf (COTS) and bespoke technologies developed by in-house programmers. These skills also need to be regularly updated due to the high speed of changes within COTS technologies.[255]

SE-specific skills can also be quite niche as they focus on the integration of several disciplines into a virtual environment. As a result, those with such skills tend to represent a small proportion of individuals in any given organisation. According to a 2010 RAND Europe report, the SE skills base is small in the military fixed wing and related sectors: of the 29,000 technical staff working exclusively or primarily on military fixed wing activities, SE has fewer than 300 individuals across the entire skill base.[256] SE was also identified as a low-density skill among MOD key suppliers in the areas of operational analysis, military-specific simulation and modelling.[257] As a low-density skill, SE is important to monitor since it is critical to the current and future fixed wing fleet, and because there is a risk that highly specialised knowledge will be lost in the next 5–10 years due to the small skills population.[258]

Regarding facilities, interviewees stressed the importance of networks in enabling them to develop their own internal SE. This was the case, for instance, for MBDA, which invested

[251] Frost & Sullivan, website
[252] Leboulanger and Kimla (2013)
[253] Leboulanger and Kimla (2013)
[254] Interviews conducted by RAND Europe (2013)
[255] Interviews conducted by RAND Europe (2013)
[256] Bassford et al. (2010), p.26
[257] Bassford et al. (2010), p.49
[258] Bassford et al. (2010), p.47

significantly in SE to facilitate distributed communication between the company's sites in different European countries.[259]

3.4.3 Government funding often prioritises SMEs, and aims for collaboration

As with market size, information on government and research institute funding for simulation technologies is challenging to isolate. Recognising that small companies face larger funding barriers in supporting innovation, the TSB offers a number of targeted funding mechanisms to support technology development in SMEs.[260] Feasibility studies offer small amounts of seed funding for early stage, lower-TRL research from small companies, offering the possibility of greater funding if the research proves promising. The Launch Pad initiative is also geared towards small companies, with up to 50 percent of research funding provided by the TSB with the remainder supported by an additional investor within 12 months. One expert also noted the importance of government investment in general SE research, as commercial stakeholders are driven by profitability concerns in niche areas rather than in the general progress of the field.[261]

The EPSRC also funds research on SE through relevant areas of its ICT programme. A breakdown of total projects and investment in these relevant research areas in 2011 is provided in Table 3-2, with the most substantial funding dedicated to interface and AI research.[262] Research in these areas often resonates with different types of stakeholders. For example, the most visible users of AI research tend to be large companies, while graphics and visualisation have links with both large and small businesses, with high importance in the creative industries sector.[263]

Table 3-2 EPSRC funding for select ICT research areas, 2011

Research area	Number of EPSRC grants	Value of grants
Artificial intelligence technologies	150	£37.3m
Displays	20	£4.4m
Graphics and visualisation	37	£7.4m
Human–computer interaction	174	£66.1m
Image and vision computing	76	£21m
Software engineering	68	£18.7m

Source: EPSRC, website

Additional government investment occurs in conjunction with funding from other partners – industry, academia and research institutes – to support targeted projects. For example, the UK government invested £8.7m of a £17.4m project, led by an Airbus consortium, to apply computer simulation to aircraft testing.[264] The Creative Industries Knowledge Transfer Network (CIKTN), which partially encompasses the games sector, also works to build on these cross-sector links between the TSB, EPSRC, private investment and the European Commission.[265] The CIKTN catalysed £23.89m of new proposals and projects in 2011 alone.[266]

[259] Interviews conducted by RAND Europe (2013)
[260] Interviews conducted by RAND Europe (2013)
[261] Interviews conducted by RAND Europe (2013)
[262] EPSRC, website
[263] EPSRC, website
[264] Publicservice.co.uk, 2007
[265] The Creative Industries Knowledge Transfer Network (2011), p.9
[266] The Creative Industries Knowledge Transfer Network (2011), p.6

3.4.4 More support is needed for the games sector, which is characterised by high R&D investment and many SMEs

In addition to public funding, simulation developments are supported by R&D priorities in the games sector, which is characterised by high R&D investment: UK game developers spend an average of 20 percent of turnover on R&D.[267] However, as part of the UK creative industries, games developers struggle from lack of funding in realising their economic potential. This challenge was captured in a 2011 BIS and DCMS report, which identified particular funding barriers for creative content businesses.[268] This situation is evidenced by the high failure rate for games SMEs – by 2012, 21 percent of UK games start-ups established in 2010 had shut down.[269]

TIGA, the industry body for the video games sector, has raised concerns about support for the UK games sector in a number of areas. In addition to a lack of public awareness about high-level games production in the UK, TIGA has noted a shortage of highly skilled games producers, with more specialists needed from backgrounds ranging from computer science and physics to art and maths.[270] In 2011, a TIGA report also showed that many UK games producers were moving abroad, to countries such as Canada, where favourable tax subsidies exist.[271] To help address these challenges and support the industry, the UK government has plans to provide a tax break of up to 25 percent for small video games developers, although the policy is pending EC review.[272]

3.5 The MOD is already engaged in using SE, focusing primarily on training and acquisition

3.5.1 A number of SE initiatives and applications are already underway

Defence is already actively engaged with SE technologies in a number of ways. In the defence stakeholder landscape, Dstl plays a major role in supporting SE integration, providing technical direction to research programmes and advising the MOD about training simulation capabilities. It is already engaged in some focused collaboration with external stakeholders, particularly through the Synthetic Environments Tower of Excellence. Launched a decade ago, this initiative aims to build capacity across the defence stakeholder community by bringing together 40 companies, government departments and universities with interests in SE R&D.[273]

The MOD also has several additional structured programmes in place to support integration of SE technologies. The Defence Training and Education Capability (DTEC) programme arose from the 2010 *Strategic Defence and Security Review* (SDSR) requirement that the MOD increase productive utilisation of SE in training.[274] This programme is evaluating a number of MOD activities with the goal of reducing barriers to SE integration, such as cultural hesitance and acquisition processes.[275] In supporting relevant research initiatives, the Athena research repository acts as a central database to store scientific and technical research reports sponsored by the MOD.[276] More widely, the MOD works closely

[267] TIGA (2013)
[268] Creative Industries Council (2012), p.3
[269] *BBC News*, 2013
[270] *BBC News,* 2011
[271] Lee, 2011
[272] Williams (2013)
[273] Interviews conducted by RAND Europe (2013)
[274] UK MOD (2013b); UK MOD (2010)
[275] UK MOD (2013b)
[276] LTPA, website

with the TSB on these issues, particularly through mechanisms like the Small Business Research Initiative (SBRI), which helps it better define its requirements to engage a broader range of partners.[277]

The MOD integrates and leverages SE for a wide range of purposes. SE plays an important role in training programmes, where it offers realistic simulated experiences in a cost-effective manner. SE is also used throughout the acquisition life cycle, from enabling design processes to supporting testing and evaluation methods. Training and acquisition are currently the most important areas of SE integration, and are explored at greater length in the following sections. However, SE can also be integrated more broadly in a number of other domains to supplement and streamline existing processes, from wider defence education initiatives to supply chain management.[278] It also plays a role in supporting defence operations, particularly in areas such as command and control.

3.5.2 LVC training is the primary defence application of SE

UK military training and education involved 257,160 military/civilian individuals in 2011, encompassing a range of roles from pilots to maintenance.[279] With the reduced tempo of modern military operations, and the lack of spaces in which to conduct live training at a realistic scale, simulation technologies fill an important niche in allowing soldiers to gain and maintain the appropriate operational experience.[280]

Live, virtual and constructive (LVC) training can be used at all stages of the training process: providing initial learning, preventing skills fade and delivering post-mission recuperations.[281] Live training involves a real person operating in a real-world platform, while virtual training refers to a real person operating in a virtual platform, such a role-player station or simulator. Constructive training takes the simulation one step further, with a computer-generated force that is under role-player control or fully autonomous. The boundaries between these types of training are increasingly being blurred, particularly as blended training may often be most effective – for example, providing supplementary onboard simulation during live aircraft training missions.[282] A breakdown of LVC training is provided in Table 3-3.

Table 3-3: Examples of LVC applications in defence

Type of simulation	Description	Examples
Live	Real operators, real equipment	- Fire drills - Operational tests - Initial production runs with soft tooling
Virtual	Real operators, simulated systems	- Aircraft trainers - Built-in training - Tactical trainers for naval and close combat
Constructive	Simulated operators, simulated equipment	- Wargames - Missile fly-out simulation - Flow diagrams - Computer-aided design/manufacturing (CAD/CAM)

Source: Adapted from Loper, p.16

[277] Interviews conducted by RAND Europe (2013)
[278] Interviews conducted by RAND Europe (2013)
[279] Fawkes and Cunningham (2013)
[280] Dobson (2008)
[281] Kirby et al. (2011), p.3
[282] Kirby et al. (2011), p.3

A number of SE-supported training facilities are in use. The pilot Defence Simulation Centre (pDSC) at Boscombe Down, for example, is run by the MOD and QinetiQ. This centre aims to 'support technical trials and evaluation creating an archive of information and reusable hardware', and acts a centralised support entity for the MOD's SE capabilities. The centre's repository facilities include the DTEC Synthetic Natural Environment (SNE) catalogue and repository on geospatial data, as well as the UK register of current simulation interoperability enumerations.[283] The MOD's simulation facility at Abbey Wood also relies on SE for a number of purposes. Focusing on F-35 aircraft, the centre uses simulation to test potential systems integration of different weapons and various mechanical components. It also utilises simulation technologies, such as visual displays within helmets, to train F-35 pilots. These types of training facilities are also set to expand: as recently as July 2013, the MOD announced a new £226m investment in a specialist training school that will include two full flight simulators and a cockpit simulator for both pilots and engineers.[284]

3.5.3 SE supports the full defence acquisition cycle, from conceptualisation to testing

SE is valuable for defence testing and training capabilities, both by decreasing cost and risk and by modelling hypothetical situations. SE enables equipment to be tested in a controlled environment, decreasing the expense and risk of real-life demonstrations. The rise in simulation has a direct impact on the frequency of real trials for new military systems. While 50 years ago new systems might require 100 real trials, the use of SE has diminished this to five or six real trials per system.[285]

In supporting the testing and development of defence equipment and systems, SE can provide benefits in the five major phases of concept, assessment, demonstration/manufacture, in-service and disposal. In the concept phase, SE can support abstract theorisation about impacts through all six Lines of Development (LoDs). Through assessment and demonstration/manufacture, SE allows de-risking and trialling to occur. During the in-service phase, it can serve to test upgrades. SE is also useful in modelling disposal scenarios, such as in the UK's recent case study on disposal options for a nuclear-powered submarine.[286]

The Virtual Engineering Centre (VEC) near Warrington is one example of a testing facility that enables simulation of aircraft and UAV models, incorporating real-life elements such as noise, filters and lag time to test the accuracy of flight technologies in a wide range of possible situations.[287] This type of testing has significant time-saving potential, as evidenced by the CFMS Core Programme that enables the reduction of aircraft design timelines from 350 to only 36 days.[288] Simulation technology also enables cost-effective training programmes that realistically test skills and decisionmaking. The MOD's Chemical, Biological, Radiological and Nuclear (CBRN) centre of excellence in Winterbourne Gunner, for example, simulates a range of realistic CBRN scenarios of varying intensities to which troops must respond.[289]

[283] LTPA, 'Defence Simulation Centre'
[284] UK MOD (2013a)
[285] Interviews conducted by RAND Europe (2013)
[286] Jackson, 'Effective Use of Synthetic Environments to Support the Acquisition Life Cycle'
[287] Cunningham (2012), pp.17–18
[288] Publicservice.co.uk, 2007
[289] Argon Electronics, website

3.5.4 SE enables the simulation of hypothetical situations that are otherwise impossible to model

Simulation technology also provides a realistic, immersive experience of potential scenarios that are impossible to model in a real-life context. Simulated environments can avoid real-life constraints that would otherwise pose a barrier to equipment testing; for example, BAE has created a computerised simulation facility for testing UAV platforms, which are currently banned from flying in UK airspace.[290] Virtual environments also enable large-scale training programmes that would otherwise be unfeasible, and can model future technologies that have not yet been developed. Earlier this year, nearly 200 soldiers participated in the UK's largest virtual simulation exercise to date, a scenario intended to present new challenges of future battlefields and weaponry.[291]

In addition to operational training and testing, simulation technologies offer a range of related possibilities to defence. For example, simulation can play a valuable role in modelling the spread of disease by showing potential interactions between bacteria and host. These findings can be applied to important defence uses, such as developing countermeasures against biological warfare agents or predicting emergency response requirements for toxic cloud movements.

3.6 The MOD's use of SE is driven by cost concerns, with significant potential to benefit from strategic COTS integration

3.6.1 Cost is the primary driver for a greater use of virtual environments

Cost presents the major driver for SE in defence training. Experts emphasised that the MOD's priorities in the SE realm are shaped by tight budgets.[292] Indeed, maximising value from SE was directly mandated for the MOD in item 9.2 of the 2010 *Strategic Defence and Security Review*.[293] For example, flight training in the Eurofighter Typhoon costs approximately £70,000 per hour, making live training unfeasible for the duration of pilots' training process.[294] Simulators cost an average of 10 percent of the cost of operating the actual systems that are being simulated, making a strong case for capitalising on SE capabilities.[295] The rise in simulation is directly related to a strong reduction in costly live training, with one company indicating that if it used to conduct about 100 live tests by programme 50 years ago, it now conducts only five or six.[296]

SE training can be adapted in a cost-effective manner to different scales (individuals, teams and joint/collective forces) and intensity levels (generic versus specialised skillsets).[297] Simulation can also be used by soldiers to refresh skills during mission transit periods, taking advantage of formerly wasted hours.[298] Simulating operations just before entering in-theatre combat can also be a useful tool for cost-effective troop preparation.[299] One expert noted that it is useful to integrate SE training early when introducing new models, in order to give users more time to get used to the new system. When a new aircraft enters service, pilots typically require around three years to familiarise themselves with the new system – if

[290] Cornford (2012), p.69
[291] Stoker (2013)
[292] Interviews conducted by RAND Europe (2013)
[293] Kirby et al. (2011), p.2 ; UK MOD (2010)
[294] Kirby et al. (2011), p.2
[295] Kirby et al. (2011), p.2
[296] Interviews conducted by RAND Europe (2013)
[297] Kirby et al. (2011), p.6
[298] Kirby et al. (2011), p.3
[299] Interviews conducted by RAND Europe (2013)

realistic simulation begins before the aircraft is finished, however, it can give pilots a head start in learning about the new operating environment.[300]

SE also enables training between remote entities, with the potential to allow different military branches to conduct joint training operations. One expert extended this relevance to multinational training exercises, for which simulated training can link various international troops while avoiding complicated financial and logistical challenges.[301] The military is increasingly interconnected in modern defence operations, making it important for SE to support these linkages by providing collective training opportunities.[302]

At the same time, the use of SE is not a one-size-fits-all solution for training. It is important to balance the mixture of live, virtual and constructive training in order to maximise effectiveness and minimise costs.[303] It is also difficult to evaluate the actual cost effectiveness of training exercises.[304] Additionally, within the MOD, there remains an ingrained culture that 'live will never be replaced'. However, the operational use of simulation is growing in familiarity and trust.[305]

A range of other SE benefits also exists

There are also a range of other drivers to increasing defence use of virtual environments. These include avoiding space or noise restrictions, reducing timescales and adapting a through-life approach to equipment acquisition that involves the MOD in the early definition of requirements. SE can also help de-risk the acquisition process and promote greater integration of the supply chain.[306] Additionally, SE enables mobile access to training, increasing opportunities for soldiers to engage.[307]

3.6.2 COTS technologies provide opportunities for integration

To maximise SE investments, there is a desire to ensure that the technologies are cost effective and provide multiple enterprise benefits.[308] The integration of COTS technologies is thus an important opportunity in the realm of SE. COTS technologies offer cost-effective and deployable opportunities for defence from sectors such as computer graphics, gaming technologies and mobile devices.[309] In identifying COTS potential, the MOD is looking for technologies that are cost effective, immersive, flexible and offer 100 percent serviceability.[310] Presently, COTS technologies are mainly used on the periphery of the MOD's activities where useful, while most of the core systems and software for SE are made in-house.[311] The MOD is currently seeing improvements in the ability to define defence training requirements, and a corresponding ability to tailor SE solutions to meet those needs.[312] Looking ahead, defence needs to stay informed and take full advantage of opportunities to integrate COTS technologies at lower cost. For example, one expert

[300] Interviews conducted by RAND Europe (2013)
[301] Interviews conducted by RAND Europe (2013)
[302] Dobson (2008)
[303] Frank et al. (2000)
[304] Fawkes and Cunningham (2013)
[305] Fawkes and Cunningham (2013)
[306] Interviews conducted by RAND Europe (2013)
[307] Robinson (2011a)
[308] Interviews conducted by RAND Europe (2013)
[309] ITEC, website
[310] Fawkes and Cunningham (2013)
[311] Interviews conducted by RAND Europe (2013)
[312] Interviews conducted by RAND Europe (2013)

pointed to the Microsoft Flight Simulator as a less expensive option for the MOD to train pilots to fly in formation.[313]

The MOD is engaged in targeted initiatives to gauge COTS potential

In order to selectively benefit from relevant commercial developments, the MOD is already engaging in a number of initiatives. The defence SE domain maintains continuous dialogue with elements of the commercial sphere to ensure that when the MOD is in a position to procure, a mature specification and shared understanding exists.[314] The MOD also engages in general horizon scanning and technology scoping, consulting relevant resources and literature to stay apprised of broader developments in the SE sphere.[315] Dstl has a COTS special interest group that produces an annual roadmap predicting the technology development. This roadmap uses a traffic lighting system and forecasts on a 6–18 month timescale.[316] One expert also noted that for defence, many COTS options are accessed through informal interactions, either at technology conferences or through contact with existing suppliers/partners.[317]

The gaming sector has particular opportunities for spin-ins to defence

Among COTS advances, the games industry is one sector that provides particular potential for future collaboration. Since 2006, the Serious Games Showcase & Challenge (SGS&C) has worked to promote awareness and integration of gaming technology as a training medium.[318] Experts confirmed that despite initial scepticism from the defence community, there is valuable scope for application of SE technologies developed by the commercial games industry.[319] In adapting advances from games technologies, The MOD may need to 'tone down' some of the entertainment-specific aspects of commercial systems (such as detailed graphics) in order to adapt the technologies to defence operations in a realistic way.[320] However, gaming techniques can be well adapted to simulate scenarios such as urban warfare environments, allowing trainee players to control the actions of modelled assets in real time.[321]

A particularly powerful example of defence use of COTS technology from the games industry is Virtual Battlespace 2 (VBS2), a battlefield simulation system developed by Bohemia Interactive Simulations as a gaming technology and adopted by the MOD for use in defence. This integration was particularly successful because the MOD was able to identify the potential and engage directly with Bohemia to adapt the programme to defence specifications. VBS2 is now used more widely through Europe because the MOD was able to use the programme successfully and encourage other partners to do so as well.[322] VBS2 enables a range of individual and collective training scenarios, simulating events from convoy drills to vehicle checkpoints in a hostile village, as shown in Figure 3-4.[323] It can also be adapted to individual user requirements by allowing custom upload of new scenarios, terrain data, and interfaces to particular equipment simulators.[324] VBS2 has also

[313] Interviews conducted by RAND Europe (2013)
[314] Interviews conducted by RAND Europe (2013)
[315] Interviews conducted by RAND Europe (2013)
[316] Interviews conducted by RAND Europe (2013)
[317] Interviews conducted by RAND Europe (2013)
[318] Gritton (2013)
[319] Interviews conducted by RAND Europe (2013)
[320] Interviews conducted by RAND Europe (2013)
[321] Thales Training & Simulation (2002)
[322] Interviews conducted by RAND Europe (2013)
[323] Bohemia Interactive, website
[324] Bohemia Interactive, website

inspired further simulation, such as the general-purpose machine gun (GPMG) simulator currently under development for Dstl, which provides both visual and tactile feedback. This portable system will be able to simulate a number of environmental conditions as well as realistic scenarios, such as anti-piracy and port-based missions.[325]

Figure 3-4 Snapshot image of VBS2 technology

Source: Bohemia Interactive

3.7 The MOD faces a number of barriers to SE integration

3.7.1 Simulations can only reproduce what they have been programmed to display

A virtual environment reproduces the data with which it has been programmed, within parameters that have been determined in advance. As a result, only a set number of scenarios can be run. In a flying training setting for instance, this may mean that the panel of the most frequent training issues will be covered as part of the curriculum, including some known and programmable emergency scenarios. However, such training cannot fully prepare a pilot for the uncertainties linked to live flying or operations.

Similarly, it is currently not possible to reproduce the multidimensional subtleties found in human interactions. The MOD is exploring research into narrative simulations to incorporate more nuanced elements of human behaviour into training exercises. This area presents a key market gap for the gaming industry to better account for the 'human factor', which is very difficult to programme convincingly. Part of this incorporation needs to account for factors such as culture and religion in order to increase the realism of training exercises. There is also ongoing research on incorporating 'patterns of life' into constructive training simulations, integrating baselines of sociocultural contexts and human behaviour to maximise the utility and realism of the synthetic experience.[326] The use of narrative in simulations is also intended to capture the real-life relationships and power dynamics inherent in operational contexts. Research has been done into interactive branching simulations in which trainees' choices lead to varying storylines with distinct consequences.[327] In the US, for example, efforts are underway to combine academic

[325] Naval-technology.com (2013)
[326] Schatz et al. (2012)
[327] Iuppa et al. (2004)

research, military training strategies and behavioural models to create an immersive simulator for Marines to engage in increasingly immersive training scenarios.[328]

3.7.2 Cost and acquisition timelines are the most significant barriers to SE

The most significant barriers to SE integration in the defence context are cost and acquisition timelines.[329] Testing requirements and compatibility with legacy equipment also pose problems.[330] Another barrier for MOD adoption is the short technology life cycle for SE, in which state-of-the-art devices may require replacement in as little as 6–9 months. For example, graphics cards are central to the simulation process and can change in terms of technical capacity and specification over a matter of months. This rapid turnover presents major challenges in planning for future iterations and accounting for new technologies in overall systems design.[331]

Long acquisition cycles pose a particular challenge to the MOD's work with other SE stakeholders. It is difficult for the MOD to interact with the SE landscape and leverage innovation successfully due to the SE sectors' high level of fragmentation and small size of actors. SE is dominated by SMEs, who typically find it difficult to plug into the MOD's lengthy procurement processes.[332] Looking ahead, the MOD may need to adapt procurement processes to better link in to a sector dominated by fast-moving innovation.[333]

There are also impacts of an increasing use of SE and virtual learning that have not yet been fully apprehended. For instance, as a larger proportion of training is done virtually and the number of real flying hours decreases, the amount of wear and tear on aircraft also diminishes. While this may reduce maintenance costs, it will also have the consequence of providing fewer opportunities for aircraft maintenance staff to develop or maintain their skills.[334] Similarly, it is still unclear whether simulated training is fully equivalent to live training or whether the use of SE can also lead to some negative training effects.[335] For example, SE training may not be able to adequately simulate the fear of death or injury that real training is able to instill.[336]

3.7.3 The defence culture and environment pose additional barriers to the integration of SE and COTS technologies

In the case of the defence skills base, experts noted that knowledge transfer and continuity of expertise are crucial. More skilled workers are always in demand, but various factors are currently discouraging graduate recruitment. Barriers include a lack of competitive salaries and promotion opportunities – while the defence model of promotion tends to work in 3–5 year cycles, this type of technological expertise takes longer to develop and sustain. Experts also emphasised that defence needs to offer more support for SE-relevant skills in areas such as computer programming.[337] Additionally, thoughtful integration of SE may require the MOD to rethink a cultural bias towards live training.[338]

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[328] Schatz et al. (2012)
[329] Interviews conducted by RAND Europe (2013)
[330] Interviews conducted by RAND Europe (2013)
[331] Interviews conducted by RAND Europe (2013)
[332] Interviews conducted by RAND Europe (2013)
[333] Kirby et al. (2011), p.9
[334] Interviews conducted by RAND Europe (2013)
[335] Interviews conducted by RAND Europe (2013)
[336] Robinson, (2011b)
[337] Interviews conducted by RAND Europe (2013)
[338] Kirby et al. (2011), p.9

In addition to the aforementioned benefits of COTS technologies, there are also number of barriers to adapting these solutions to defence needs. In utilising COTS equipment, it is a challenge to find technology that fits the full requirements of the MOD's recognised training gaps.[339] The sensitivity of security issues is another barrier to defence integration of commercial advances, as the balance between off-the-shelf benefits and classified systems must be handled carefully.[340] Additionally, although much SE development is largely driven by the commercial sector, the components of military requirements sometimes have a level of specification that COTS technologies are unable to meet.[341]

In attempting to foster interactions with the commercial SE community, defence also faces disconnects in driving priorities. While consumer-oriented companies want to expand market opportunities by maintaining quality and driving down costs, defence often cares less about this level of cost reduction and more about improvements in quality to meet evolving specifications.[342] On the other hand, sometimes COTS offers high quality in areas unnecessary to the MOD. For example, the emphasis on incredible detail of visual imagery in some games technology can be counterproductive for MOD use, where such fidelity slows down simulation systems.[343]

Given this commercial motivation, there is also the challenge that civilian technologies are often siloed to work only with certain distributors' systems, rather than being standardised. For example, one expert was involved with a simulator prototype for counter-IED training that wanted to find a commercial platform – however, it was highly difficult to find any programme that would be compatible between different end-user machines (such as PCs and Macs).[344] In order to overcome this type of barrier, the MOD might follow the example of companies such as Sky Go, which works closely with mobile and tablet manufacturers to ensure the compatibility of their interface with users' hardware.[345]

3.8 SE presents significant potential for the MOD if enabling factors are pursued

In current climate of reduced R&D, defence use of SE is guided largely by cost constraints. For example, one expert pointed out that even simulated tests are sometimes being replaced by spreadsheet modelling. Looking forward, the MOD plans to invest in training and potentially create a new defence simulation centre. One expert pointed out that while SE developments within defence are rather incremental, a major sea change in defence integration may occur if a low-cost, robust network could be established that offered both high specifications and smaller costs/infrastructure.

3.8.1 Of priority areas, standardisation will be a key enabler for defence adoption

In determining the future incorporation of SE by defence, a number of broad areas will need to be addressed, as summarised in Table 3-4.[346] Across these domains of defence concern, improving the **flexibility and agility** of simulated systems will be important to adapt technologies to varying requirements, such as the need for different training/playing

[339] Dobson (2008)
[340] Interviews conducted by RAND Europe (2013)
[341] Interviews conducted by RAND Europe (2013)
[342] Interviews conducted by RAND Europe (2013)
[343] Interviews conducted by RAND Europe (2013)
[344] Interviews conducted by RAND Europe (2013)
[345] Interviews conducted by RAND Europe (2013)
[346] Interviews conducted by RAND Europe (2013)

environments (ranging from snow to harsh terrain).[347] The **time management** of simulated training is also important to develop, in order to ensure that the synthetic experience mirrors challenges (such as the lack of time for analysis and planning) that occur in real operations.[348] **Integration** of technology and processes was stressed by experts as another priority area. As various SE elements are being developed independently, there is an increasing demand for **complementarity**.[349] **Interoperability** between simulations also needs to improve, as individual simulations may vary in aspects such as resolution and security level. Interoperability is a particular challenge as individual SE technologies often develop at different rates, making continued compatibility difficult to ensure.[350]

Table 3-4 Defence priorities in SE integration

Priority areas	Description
Live, virtual and constructive simulations	Includes augmented reality, virtual reality and human representation; controlled by operators
Synthetic, natural and physical environments	Based on 3-D models; IR plays a role
Interoperability	Combines live and virtual; based on NATO standards
User-to-synthetic environment interface	Linked to data collection; visualisation output is also important
Developing military use of ICT	Transfers commercial ICT developments to the defence sector; complicated by communication issues

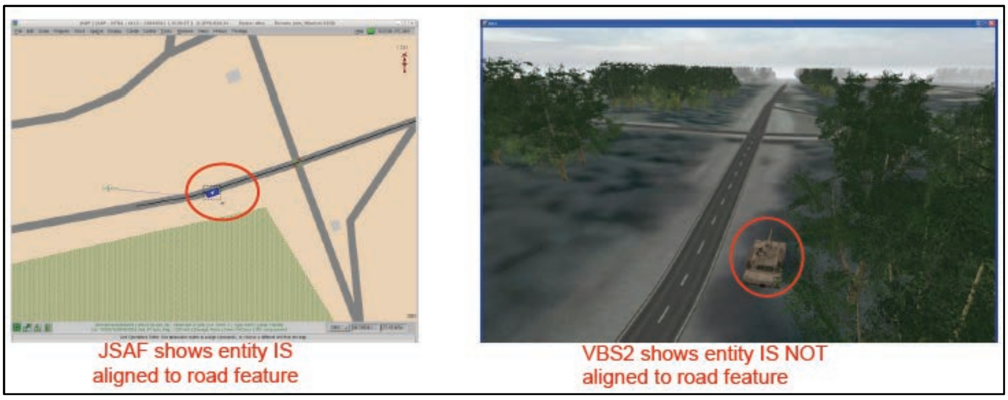
Source: RAND Europe analysis

Experts also consistently expressed the need for the MOD to move away from bespoke design of equipment and towards **standardisation** and generalisation. Standardisation would address a number of challenge areas, such as communications, interoperability, costs and reusability.[351] An example of this would be the increasing use of standardised common data sets. An SE based on a common data set would allow users to see and interact with identical features within a simulation regardless of whether they were flying overhead at high speed (e.g. flight simulator) or on foot patrol (e.g. tactical trainer). The SE would be able to tap into the appropriate level of granularity depending on the demands of the user. This would move away from the problem of stove-piped simulations that depend on the use of bespoke data. Associated to this shift, a challenge will be configuration and version control as datasets require continuous updating.

Geospatial data sets are one such area in need of standardisation, as illustrated by the inconsistencies shown in Figure 3-5. Terrain data systems for training operations are very expensive and time consuming to provide. They may also vary significantly in fidelity requirements depending on whether they are used in simulations or in operational support. Efforts should be taken to encourage convergence and consistency in the data sources and their representation to improve interoperability.[352]

[347] Interviews conducted by RAND Europe (2013)
[348] Interviews conducted by RAND Europe (2013)
[349] Interviews conducted by RAND Europe (2013)
[350] Interviews conducted by RAND Europe (2013)
[351] UK MOD (2013c); UK MOD (2013d)
[352] Hieb and Maxwell (2012)

Figure 3-5 Example of inconsistent geospatial visualisations



Source: Hieb and Maxwell (2012)

To support the standardisation and integration of SE systems, the MOD's 2002 *Open Systems Strategy* makes a number of recommendations. Widely accepted, consensus-based standards are important to enable generalisable production. Related to this, modular design and key interfaces should be standardised such that components can be easily connected within and between existing systems. Validating systems' openness through focused testing is also recommended as a priority to ensure that performance requirements are met.[353] These requirements would be strong enablers of SE technologies by improving the cost effectiveness and compatibility of different systems.

The MOD is already taking a number of steps to meet standardisation recommendations. The Directorate of Analysis Experimentation and Simulation is currently seeking to address issues of compatibility, aiming to establish re-usable, shared databases for the MOD.[354] As elaborated in the *DTEC Modelling & Simulation (M&S) Standards Profile (DMSP)*, DTEC is meant to serve as a 'defence-wide enterprise system', offering common, interoperable components based on cutting-edge COTS technologies and maximising integration of 'plug & play' systems.[355]

3.8.2 New applications of SE could include the integration of mobile solutions

Another area of relevance to the MOD is how to integrate mobile technologies into its architecture and how to make best use of them both for training and in theatre. The use of mobile applications may be relevant to defence to improve situational awareness or mission rehearsal. Although the MOD has shown some reluctance towards these uses for the technology, our engagement with other sectors indicated that the MOD's concerns are similar to others. For instance, Sky Go's business model relies on secure access to the services it offers, as fraudulent access to the data would infringe on the rights the company has negotiated with producing studios.[356] Greater mobile integration will require addressing these types of security concerns to be addressed.

[353] UK MOD (2013d)
[354] Dobson (2008)
[355] UK MOD (2013c), p.1
[356] Interviews conducted by RAND Europe (2013)

References

Adolph, Martin, *Trends in Video Games and Gaming,* ITU-T Technology Watch Report, September 2011.

Ansaldo Energia, 'Ansaldo Energia Power Generation Solutions'. As of 28 August 2013: http://www.ansaldoenergia.it/easyNews/NewsLeggi.asp?NewsID=5

Argon Electronics, 'MoD CBRN centre of excellence invests in Argon simulation technology'. As of 28 August 2013: http://www.argonelectronics.com/case-studies/mod-cbrn-centre-excellence-invests-argon-simulation-technology/

Association for UK Interactive Entertainment (UKIE). As of 28 August 2013: http://ukie.info

Barollo, Juri, 'Interview three: ITEC 2013 Advisor', ITEC. As of 28 August 2013: http://www.itec.co.uk/page.cfm/link=87

Bassford, Matt, Hans Pung, Nigel Edgington, Tony Starkey, Kristin Weed, Mark Area, James Kallimani, Gordon Lee and Obaid Younossi, *Sustaining Key Skills in the UK Military Aircraft Industry,* RAND Corporation, Santa Monica, 2010.

BBC News, 'Games industry employment increases in UK', 18 March 2013. As of 8 May 2013: http://www.bbc.co.uk/news/technology-21828869

BBC News, 'UK video games and special effects firms "need support"', 1 February 2011. As of 28 August 2013: http://www.bbc.co.uk/news/technology-12326688

Bohemia Interactive, 'VBS2 overview'. As of 28 August 2013: http://products.bisimulations.com/products/vbs2/overview

Bruzzone, A.G. and J. Petuhova, 'Research Experience The UNITE Mobility – Latvia-Italy', Riga Technical University, presentation, 20 May 2011. As of 16 August 2013: http://www.itl.rtu.lv/mik/unite/Julija_Petuhova.pdf

Burduea, G.C., 'Haptics issues in virtual environments', *Computer Graphics International*, 2000, pp.295–302.

CAE, 'Flight Training Systems'. As of 28 August 2013: http://www.cae.com/defence-and-security/simulation-products-solutions/flight-training-systems/

Cal-Tek, 'Solutions – Research & Development'. As of 28 August 2013: http://www.cal-tek.eu/RD/

Chaturvedi, Alok R., and Shailendra Raj Mehta, 'Synthetic Environment for Analysis and Simulation: A Case Study of Market and Supply-Chain Co-design in the PC Industry', Purdue e-Business Research Center.

Cornford, Rupert, 'Making it virtual', *Insider*, April 2012.

Cranfield University, 'Simulation and Synthetic Environment Laboratory (SSEL)'. As of 28 August 2013: http://www.cranfield.ac.uk/cds/operational%20and%20decision%20analysis/ssel.html

Creative Industries Council, *Access to Finance Working Group Report*, December 2012.

The Creative Industries KTN, *Impact Statement 2011,* 2011.

Cunningham, Justin, 'A sense of realism', *Eureka*, 17 April 2012, pp.17–18. As of 28 August 2013: http://www.eurekamagazine.co.uk/design-engineering-features/technology/how-the-virtual-world-is-being-increasingly-exploited-for-engineering-advantage/41706/

Dartmouth College, 'Synthetic Environment for Emergency Response Simulation'. As of 28 August 2013: http://www.ists.dartmouth.edu/projects/archives/synth.html

Delft University of Technology, 'The Urban Decision Room'. As of 28 August 2013: http://www.bk.tudelft.nl/?id=15286&L=1

Deloitte, *Tech Trends 2012: Elevate IT for digital business,* 2012.

Dobson, Mike, 'A synthetic solution?', Education and Training, *Defence Management Journal* 41, May 2008. As of 28 August 2013: http://www.defencemanagement.com/article.asp?id=342&content_name=Education percent20and percent20Training&article=10115

Donald Bren School of Information and Computer Sciences, 'DrillSim: Multi-Agent Simulator for Crisis Response'. As of 28 August 2013: http://www.ics.uci.edu/~projects/drillsim/

Dufour, Christian, Cacilda Andrade and Jean Belanger, 'Real-Time Simulation Technologies in Education: a Link to Modern Engineering Methods and Practices', Proceedings of the 11th International Conference on Engineering and Technology Education, INTERTECH 2010 Ilhéus, Bahia, Brazil, March 7–10, 2010.

Dynamic Animation Systems, Inc., 'The Virtual Interactive Combat Environment'. As of 16 August 2013: http://www.d-a-s.com/VICE

The Economist, 'The travel channels', 20 July 2013, p.55.

EPSRC, 'Research Areas Related to Information and Communication Technologies (ICT)'. As of 28 August 2013: http://www.epsrc.ac.uk/research/ourportfolio/themes/ict/Pages/researchareas.aspx

Fawkes, Andy, 'Training and Simulation for Decision Makers', presentation, IQPC International Armoured Vehicles Conference, Farnborough, 7 February 2013.

Fawkes, Andy and Rory Cunningham, 'The Live/Synthetic Balance: Operational and Policy Perspectives', SMI Joint Forces Simulation and Training Conference, Farnborough, 04-05 February 2013.

Federal Business Opportunities, 'Synthetic Environment (SE) Core Common Virtual Environment (CVE) Management Program', 21 October 2010. As of 28 August 2013: https://www.fbo.gov/?s=opportunity&mode=form&tab=core&id=314cda5d9287918a09d465a30378cccd&_cview=1

Financial Times, 'Pfizer moves supply chain to cloud', 11 September 2012. As of 28 August 2013: http://www.ft.com/intl/cms/s/0/1608e5d6-fc59-11e1-ac0f-00144feabdc0.html#axzz2ahyZpz27

Frank, Geoffrey, Robert Helms II and David Woor, 'Determining the right mix of live, virtual and construtcive training', Research Triangle Institute, 2000.

Frost & Sullivan, 'Global Military Training and Simulation Market Geared to Address New Realities with Novel Solutions', Press release, 7 May 2013. As of 28 August 2013: http://www.frost.com/prod/servlet/press-release.pag?docid=277970556

Gamification Corp. As of 15 August 2013: http://www.gamification.co

GoldSim Technology Group LLC, *Dynamic Simulation and Supply-Chain Management*, White Paper, 2007.

Gritton, Ken, 'Serious Games Showcase and Challenge Goes Global', I/ITSEC Newsletter 12:1, March 2013, p.2.

The Guardian, 'UK games industry is growing says trade body,' 18 March 2013. As of 28 August 2013: http://www.guardian.co.uk/technology/2013/mar/18/uk-games-industry-growth/print

Hieb, Michael, and Daniel Maxwell, 'Converging Simulation and C2: Improving Foundation Data Consistency and Affordability', Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC), 2012.

I/ITSEC, '2012 Conference Statistics'. As of 28 August 2013: http://www.iitsec.org/about/Pages/HighlightsFromLastIITSEC.aspx

ITEC, 'ITEC 2013 to draw together the military training and simulation community', 20 May 2013. As of 28 August 2013: http://www.itec.co.uk/page.cfm/Action=Press/libID=1/listID=1/libEntryID=67

Issenberg, S. Barry, Michael Gordon, David Gordon, Robert Safford and Ian Hart, 'Simulation and new learning technologies', *Medical Teacher* 23:1, 2001, pp.16–23.

Iuppa, Nicholas, Gershon Welman and Andrew Gordon, 'Bridging Hollywood Storytelling Techniques to Branching Storylines for Training Applications', 3rd Narrative and Interactive Learning Environments, Edinburgh, Scotland, 2004.

Jackson, Peter, 'Effective Use of Synthetic Environments to Support the Acquisition Life Cycle', Thales Training and Simulation Ltd., UK.

Kirby, Barry, Graham Fletcher and Helen Dudfield, 'Live Virtual Constructive Training Blend Optimisation Study', NATO, RTO-MSG-MP-087, 2011.

Laird, Sam, 'Augmented Reality Tickets Give Sports Fans a Boost', *Mashable*, 24 April 2013. As of 28 August 2013: http://mashable.com/2013/04/23/augmented-reality-sports-tickets/

Lampotang, Samsun, Frank J. Bova, David E. Lizdas, Didier A. Rajon, William A. Friedman, Albert R. Robinson III, Isaac Luria, Wilhelm K. Schwab and Nikolaus Gravenstein, 'A Subset of Mixed Simulations: Augmented Physical Simulations with Virtual Underlays', Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC), 2012.

Leboulanger, Alix, and Dominik Kimla, *Military Training & Simulation Market Spreads its Wings*, Frost & Sullivan, 22 January 2013. As of 28 August 2013: http://www.slideshare.net/FrostandSullivan/fs-mi-trainingsimulation2013

Lee, Dave, 'UK "must act to solve games industry brain drain"', *BBC News*, 5 October 2011. As of 28 August 2013: http://www.bbc.co.uk/news/technology-15188385

Loper, Margaret, *Distributed Simulation Fundamentals,* presentation, Georgia Tech Research Institute.

LTPA, 'Defence Simulation Centre'. As of 28 August 2013: http://www.ltpa.co.uk/capabilities/dsc/index.asp

Maplesoft, 'Virtual Prototyping'. As of 28 August 2013: http://www.maplesoft.com/solutions/engineering/AppAreas/virtualpro.aspx

Montrucchio, Cristiano, 'Interview One: ITEC Conference Chairman', Head of Avionic Systems at Alenia Aermacchi, ITEC. As of 28 August 2013: http://www.itec.co.uk/page.cfm/link=78

National Capital Area Medical Simulation Center. As of 28 August 2013: http://simcen.usuhs.edu/Pages/default.aspx

Naval-technology.com, 'UK Dstl contracts NSC for ship-mounted general purpose machine gun simulator', 17 May 2013. As of 28 August 2013: http://www.naval-technology.com/news/newsuk-dstl-contracts-nsc-for-ship-mounted-general-purpose-machine-gun-simulator

Neffendorf, H., S. Armstrong, S. Price, A. Parkes and A. Dumbuya, *Synthetic Environments in Transport*, Katalysis Ltd, QinetiQ Ltd, and TRL Ltd, Report for the Department for Transport, November 2007.

Ohbuchi, R, T. Miyazawa, M. Aono, A. Koide, M. Kimura and R. Yoshida, 'Integrated medical-image system for cancer research and treatment', *IBM Journal of research and Development* 40:2, 1996, pp.185–210.

Presagis, 'SEGen Server'. As of 28 August 2013: http://www.presagis.com/products_services/products/modeling-simulation/content_creation/segen_server/

PricewaterhouseCoopers (PwC), *The UK film, TV and Video Games industries today: Powering Ahead*, January 2013.

Pro-Form, '2013 TDF Centennial'. As of 28 August 2013: http://www.proform.com/webapp/wcs/stores/servlet/Product_-1_14201_16002_29511_221569

Pro-Form, 'Tour de France', product site. As of 28 August 2013: http://www.proform.com/webapp/wcs/stores/servlet/Product_-1_14201_16002_29511_191319

Publicservice.co.uk, 'Funding for simulation technology', 13 February 2007. As of 28 August 2013: http://www.publicservice.co.uk/news_story.asp?id=2365

Pugliese, David, 'CAE Introduces Next Generation Synthetic Environment for Training and Simulation,' *Ottawa Citizen,* 3 December 2013. As of 28 August 2013: http://blogs.ottawacitizen.com/2012/12/03/cae-introduces-next-generation-synthetic-environment-for-training-and-simulation/

Rivington, James, 'Google Glass: What you need to know', *TechRadar*, 25 April 2013. As of 28 August 2013: http://www.techradar.com/us/news/video/google-glass-what-you-need-to-know-1078114

Robinson, Tim (2011a), 'Flight sims in 2011', Aerospace Insight Blog, 18 February 2011. As of 28 August 2013: http://media.aerosociety.com/aerospace-insight/2011/02/18/flight-sims-in-2011/3718/

Robinson, Tim (2011b), 'Virtual air power?', Aerospace Insight Blog, 13 May 2011. As of 28 August 2013: http://media.aerosociety.com/aerospace-insight/2011/05/13/virtual-air-power/4121/

Royal Aeronautical Society, 'Flight sims in 2011', 28 February 2011. As of 28 August 2013: http://media.aerosociety.com/aerospace-insight/2011/02/18/flight-sims-in-2011/3718/

Royal Aeronautical Society, 'The impact of flight simulation in aerospace,' Royal Aeronatuical Society Flight Simulation Group. As of 28 August 2013: http://aerosociety.com/Assets/Docs/Publications/DiscussionPapers/The_impact_of_flight_simulation_in_aerospace.pdf

Sabol, Louise, 'Digital Development: Visalizing Projects in Synthetic Environments', *Real Estate Review* 36:4, February 2008.

Schatz, Sae, J.T. Folsom-Kovarik, Kathleen Bartlett, Robert Wray and David Solina, 'Archetypal Patterns of Life for Military Training Simulations', Paper No. 12193, Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC), 2012.

Sea Simulation Systems, 'DECK*sim*', informational brochure.

Serious Games Institute, Coventry University. As of 28 August 2013: http://www.seriousgamesinstitute.co.uk/

Siemens, 'Comos Walkinside'. As of 28 August 2013: http://www.automation.siemens.com/mcms/plant-engineering-software/en/comos-walkinside/pages/default.aspx

Simudyne, 'Engineering Reality'. As of 28 August 2013: http://www.simudyne.com/simudyne/

Simulation and Synthetic Environments NTC, 'What we do'. As of 28 August 2013: https://connect.innovateuk.org/web/simulation-and-synthetic-environments-ntc/what-we-do

Sketchup. As of 28 August 2013: http://www.sketchup.com/

Southwest Research Institute, 'Rapid Automotive Performance Simulator (RAPTOR)'. As of 28 August 2013: http://www.swri.org/4org/d03/vehsys/advveh/raptor/

Stoker, Liam, 'Video feature: Urban Warrior 5 – the UK's new military simulation', 6 February 2013. As of 28 August 2013: http://www.army-technology.com/features/featureurban-warrior-5-uk-new-military-simulation

Streib, Lauren, 'The 12 Coolest New Videogames', *The Daily Beast*, 16 June 2010. As of 28 August 2013: http://www.thedailybeast.com/articles/2010/06/16/video-games-12-coolest-products-at-e3-expo.html

The Synthetic Environment Applications Library. As of 28 August 2013: http://www.engr.psu.edu/ae/cic/facilities/sea_lab.aspx

Technology Strategy Board (TSB), *Creative Industries Strategy 2009–2012,* Swindon, 2009.

TechPowerUp, 'GPU Database', 9 May 2013. As of 28 August 2013: http://www.techpowerup.com/gpudb/

Thales Training & Simulation, 'Synthetic Environment Supporting MOUT & Special Operations', informational brochure, November 2002.

Thompson, Rufus, 'Jaguar Land rover leads UK universities to develop virtual simulation tech', 11 June 2013. As of 28 August 2013: http://www.cardesignnews.com/site/home/display/store4/item281282/

TIGA, 'UK video games industry', 2013. As of 28 August 2013: http://www.tiga.org/about-us-and-uk-games/uk-video-games-industry

UK Ministry of Defence (UK MOD) (2013a), '£226 million training facilities announced for new RAF transport planes', 4 March 2013. As of 28 August 2013: https://www.gov.uk/government/news/300-million-training-facilities-announced-for-new-raf-transport-planes

UK Ministy of Defence (UK MOD) (2013b), 'The defence training and education capability programme', 18 June 2013. As of 28 August 2013: https://www.gov.uk/the-defence-training-and-education-capability-programme

UK Ministry of Defence (UK MOD) (2013c), *DTEC Modelling & Simulation (M&S) Standards Profile (DMSP),* 25 January 2013.

UK Ministry of Defence (UK MOD) (2013d), *System of Systems Approach (SOSA) open systems strategy*, 18 January 2013.

UK Ministry of Defence (UK MOD), *Securing Britain in an Age of Uncertainty: The Strategic Defence and Security Review,* London, October 2010.

University of Manchester Aerospace Research Institute, 'Synthetic Environments and Systems Simulation', informational brochure.

University of Manchester Aerospace Research Institute, 'Synthetic environments and systems simulation'. As of 28 August 2013: http://www.umari.manchester.ac.uk/research/areas/synthetic-environments/

US Army PEO STRI, 'Close Combat Tactical Trainer (CCTT)'. As of 28 August 2013: http://www.peostri.army.mil/PRODUCTS/CCTT/

Van den Berg et al., 'Virtualized Traffic: Reconstructing Traffic Flows from Discrete Spatio-Temporal Data'. As of 28 August 2013: http://gamma.cs.unc.edu/TRAFFIC_RECON/traffic_recon.pdf

VT MAK, 'Air Traffic Management'. As of 28 August 2013: http://www.mak.com/industries/air-traffic-management.html

Wendelsdorf, Katherine, 'Enteric Immunity Simulator, A Tool for Insilico Study of Gut Immunopathologies', 2011 IEEE International Conference on Bioinformatics and Biomedicine (BIBM), November 2011, pp.462–69.

Wendelsdorf, Katherine, Josep Bassaganya-Riera, Keith Bisset, Stephen Eubank, Raquel Hontecillas and Madhav Marathe, 'Enteric Immunity Simulator: A Tool for *In Silico* Study of Gut Immunopathologies', Virginia Bioinformatics Institute, Virginia Polytechnic Institute and University, Blacksburg, Virginia.

Williams, Christopher, 'EU threatens British video games growth', *The Telegraph,* 21 April 2013. As of 28 August 2013: http://www.telegraph.co.uk/technology/video-games/10006361/EU-threatens-British-video-games-growth.html

CHAPTER 4 **Advanced materials**

This chapter presents the data gathered as part of the small-scale case study on advanced materials. The list of references specific to this case study can be found at the end of the chapter.

4.1 Advanced materials encompass a diverse landscape of materials, technologies and applications

Advanced materials make up a multidimensional landscape in which materials, technologies and applications are intertwined in a variety of sectors. This is due to the inherently interdisciplinary nature of materials science, within which fundamental research is coupled with engineering, and base knowledge is intimately related with technology.[357] As defined in the *Advanced Material Strategy 2008–2011*, advanced materials are found in high-value-added products and processes, and include the following items: lightweight materials and structures, such as composites and hybrids; materials able to withstand aggressive environments; electronic and optical materials; smart and multifunctional materials, devices and structures; surface engineering and coating technologies; bioresorbable, bioactive and biocompatible materials; natural and bio-based materials; joining technologies; materials for portable power sources, such as batteries and fuel cells; and materials with reduced environmental impact through life.[358]

Advanced materials can be categorised by either sector or by function of application. A taxonomy by sector of application would include biosciences, medicines and healthcare; energy generation and supply; transport; low-impact buildings; high-value manufacturing; creative industries; and electronics, photonics and electrical systems. Categorising by function across each of these sectors would produce the four classifications offered by the *Advanced Materials Strategy 2008–2011*: structural, functional, multifunctional and biomaterials. Examples of these categories would include lightweight materials (structural), photovoltaic superconductors (functional), textiles (multidimensional), and plant-based materials (biomaterials). Figure 4-1 summarises the key advanced materials and the different dimensions through which they can be categorised.[359]

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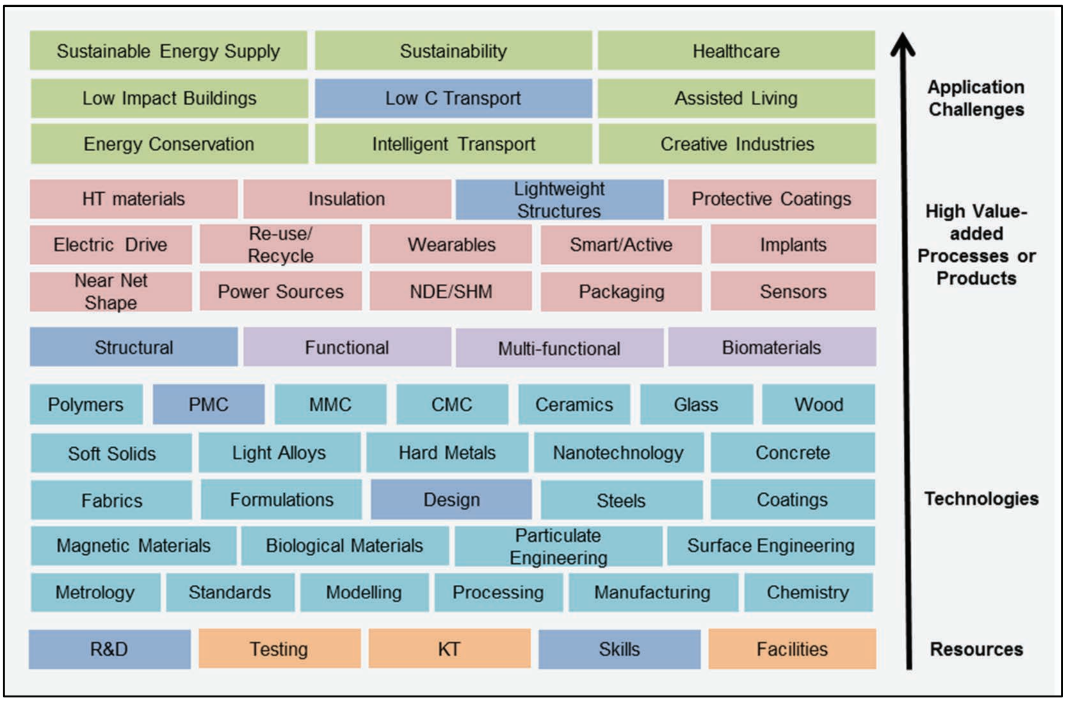
[357] European Science Foundation (2011), p.7. Advanced materials and nanotechnologies are often treated together but we have decided not to include nanotechnologies to limit the scope of this specific case study. Initial analysis suggested that the scope covered by nanotechnologies was as wide as that of advanced materials, with qualitatively distinct development issues and applications

[358] TSB (2008), pp.7, 10, 19

[359] TSB (2008), p.19

Figure 4-1 The advanced materials landscape



Source: TSB (2008)

4.2 Priority areas traverse energy, sustainability and high value markets

Advanced materials have only recently been identified as a group to facilitate high-level investment and prioritisation. However, as an enabling technology, they are part of different strategies and receive significant levels of investment at all stages of technological development. The TSB outlined the following three priority areas for investment in advanced materials in its *Enabling Technologies Strategy 2012–2015*:

- Materials for energy: materials for cheaper and more efficient energy storage and management; materials for energy transmission/distribution that minimise energy, power and thermal loss; and materials for high-durability energy generation at small and large scales.
- Materials for sustainability: lightweight materials; materials with reduced through-life environmental impact; nanotechnology-enabled materials and functionality; substitution approaches to reduce the use of less sustainable materials; development of new materials technologies and processes to support a circular economy; materials for infrastructure and asset protection and traceability; materials for sustainability of other world resources; and water purification.
- Materials for high-value markets: integration of new materials, coatings and electronics; materials to survive in aggressive environments with extremes of temperature, corrosion, erosion or stress; and bio-based materials.[360]

The TSB also identified certain enabling advanced materials that are cross-cutting and apply to all high-value manufacturing: smart, hybrid and multiple materials; intelligent systems and embedded electronics; and advanced coatings.[361] These three areas would

[360] TSB (2012), p.10
[361] TSB (2012), p.10

equally benefit from priority development and are reflected in TSB partnerships and initiatives, for instance in the Materials KTNs[362]

Other actors in the advanced materials landscape have also identified complementary priority areas, which are usually informed by their own areas of expertise and key activities. A non-exhaustive list of these areas is summarised in Table 4-1, which also includes the areas of existing strength in UK advanced materials capability.

Table 4-1 UK strengths and challenges in advanced materials

Existing strengths in UK capability	Areas in priority need of development
- High-performance metals - Biomaterials - Materials for renewable and nuclear energy - Plastic electronics - Composites - Low-temperature superconducting (LTS) applications	- Lightweight materials - Sophisticated imaging and microscopy - Metrology and materials processing - Fabrication and characterisation equipment required for both the development and manufacturing of advanced materials - High-temperature superconducting (HTS) conductor manufacture - Engineering and manufacturing of HTS applications

Source: RAND analysis of Willetts (2013) and Melhem (2011)

4.3 Advanced materials can be used to improve the materials and functionality of defence equipment

The 2006 *Defence Technology Strategy* outlined advanced materials as a key cross-cutting technology area, as it underpins many aspects of the design, development and manufacture of military platforms and equipment.[363] The Strategy outlined the following key drivers and areas of interest: low observable materials; platform structural materials; smart materials and active structures; multifunctional materials and structures; structural modelling, design and through-life support; smart/interactive textiles; materials for protection, especially ceramics and steels; and the modelling of structural and dynamic issues of composite materials.[364]

Defence applications of these technology areas can be found across many defence equipment types. Lighter and stronger materials can be applied, for example, to military aircraft, missiles, ground vehicles and munitions.[365] Advanced materials can also be used to improve the performance of reduced radar visibility, coatings for jet engine performance, and armour for military vehicles.[366] For some of these applications, especially regarding aircraft structures, there are strong ties with civilian developments and applications. The civilian sector has been integrating new materials in commercial aircraft for many years, and the Boeing 787 Dreamliner will be an essentially all-composite airliner.[367]

4.4 Advanced materials have a large estimated market size

The cross-cutting position of advanced materials as an enabling technology area is reflected in its large estimated market size. However, this integration makes it difficult to isolate the value of advanced materials from the wider materials sector. The TSB has estimated that

[362] TSB, website
[363] UK MOD (2006), p.27
[364] UK MOD (2006), p.27
[365] Hermann (2008), p.380
[366] Hermann (2008), p.380
[367] Hermann (2008), p.380

UK businesses involved in producing, processing, fabricating and recycling materials have an annual turnover of around £197 billion.[368] Earlier figures from 2008 suggested that these businesses contribute about 15 percent of UK GDP, with a gross value-added (GVA) of around £60 billion.[369] These companies also form an important element in the supply chain of many high-value manufacturing businesses.[370] Additionally, advanced materials are large contributors to exports of finished and semi-finished goods, reported in 2010 to represent £60 billion for the UK alone.[371]

4.5 Investment in advanced materials is often directed towards specific centres or materials of interest

Investment in advanced materials is made at all stages of technology development, from research focusing on individual materials to initiatives examining manufacturing processes or integration with other technologies. Due to the uncertain nature of early stage technological development, investment into materials research and application-driven integration is often high risk.[372] Where investment does occur, it is fragmented and often collaborative between academia, industry and government.

Government funding tends to be directed towards specific centres or sectors within the advanced materials landscape. Liverpool University was recently granted £33m to establish the first ‘materials innovation factory’ in Europe.[373] Advanced materials are also included in the ‘eight great technologies’ awarded UK government funding, and will receive £45m for new equipment and facilities in specific areas of UK strength, such as high-performance alloys, telecommunications, low-energy electronics, and advanced composites.[374] The TSB has also committed roughly £20m annually towards high-risk, early stage technology priorities, including advanced materials.[375]

Certain materials have gained more hype and targeted investment, such as graphene. Multiple UK research institutes are working to develop this highly anticipated material for commercialisation and integration in society. The Cambridge Graphene Centre has received over £12m of government and EPSRC funding and over £13m from industry partners, while similar institutes in Manchester and Lancaster have received around £11m in funding from the European Research Council.[376] A project on graphene and similar layered materials is one of the first ‘Future Emerging Technology’ programmes funded by the European Commission, which is committing €1 billion (£820m) towards the application and commercialisation of these materials.[377]

4.6 Stakeholders are found across government, business and the wider research community

The UK materials sector is both large and diverse, with stakeholders across business, government and the research community. This range of actors is summarised in Figure 4-2.

[368] TSB, website
[369] TSB (2008), p.6
[370] TSB (2008), p.6
[371] Quarshie (2010)
[372] Materials Innovation and Growth Team (2006), p.29
[373] Maino (2013)
[374] BIS (2013)
[375] TSB (2012)
[376] University of Cambridge (2012)
[377] University of Cambridge (2013a)

UK stakeholders span the full life cycle of advanced materials research, from extraction, primary production and process development through to product design, testing, application, and end-of-use disposal.[378] Certain materials areas also benefit from significant cross-over with upstream stakeholders in the chemistry sector.[379] Due to the range of relevant technologies and market applications for advanced materials, this sector tends to be highly fragmented in the UK. The Advanced Materials KTN and other industry networks thus play an important role in establishing a coherent business sector.[380]

Figure 4-2 UK stakeholder landscape for advanced materials

Source: Adapted from TSB (2008), p.8

4.7 Future trends vary widely by material area

Due to the vast scope of the advanced materials sector, we have been unable to find strong predictions for future developments in this field. Forecasted growth will vary widely by individual material area, and may also depend on the progress of other relevant technologies. In their 2006 *Strategy for Materials*, the Materials Innovation and Growth Team identified five key areas in which the UK should invest to support the materials community: transferring knowledge; raising awareness; accelerating innovation; improving skills and knowledge; and building a better business environment.[381] Although dated, we expected these recommendations to remain valid and help to determine the future of advanced materials in the UK context.

[378] TSB (2008), p.8
[379] TSB (2008), p.8
[380] TSB (2008), p.8
[381] Materials Innovation and Growth Team (2006), p.30

References

Department for Business, Innovation and Skills (BIS), '£600 million investment in the eight great technologies', press release, 24 January 2013. As of 28 August 2013: https://www.gov.uk/government/news/600-million-investment-in-the-eight-great-technologies

European Science Foundation, *Materials for Key Enabling Technologies*, ed. H. Richter, Strasbourg, June 2011.

Hermann, Robert J., 'National security challenges and competition: US defense and space R&D in a strategic context', *Technology in Society* 30, 2008, pp.371–81.

Maino, Richard, 'Europe's first new materials centre to be in UK,' *London Press Service,* 5 February 2013. As of 8 May 2013: http://londonpressservice.org.uk/lps/tradeindustry/item/443940.html

Materials Innovation and Growth Team, *A Strategy for Materials,* Department of Trade and Industry, March 2006.

Materials Knowledge Transfer Network (KTN), 'Priority areas', 2013. As of 8 May 2013: https://connect.innovateuk.org/web/materialsktn/priority-areas

Melhem, Ziad, *Superconducting Materials and Applications: A UK Challenge and an Opportunity*, Materials UK Preliminary Review, June 2011.

Quarshie, Robert, 'Challenges and Opportunities for Advanced Materials in Europe,' Materials KTN, presentation at EU KET Open Day for Advanced Materials, 25 October 2010.

Technology Strategy Board (TSB), *Enabling Technologies Strategy 2012–2015,* Swindon: November 2012.

Technology Strategy Board (TSB), *Advanced Materials Strategy 2008–2011,* Swindon, 2008.

Technology Strategy Board (TSB), 'Advanced materials'. As of 28 August 2013: http://www.innovateuk.org/ourstrategy/our-focus-areas/advancedmaterials.ashx

UK Ministry of Defence (UK MOD), *Defence Technology Strategy*, London, October 2006.

University of Cambridge (2013a), 'Europe pledges one billion euros on graphene as platform for emerging technologies', 28 January 2013. As of 28 August 2013: http://www.cam.ac.uk/research/news/europe-pledges-one-billion-euros-on-graphene-as-platform-for-emerging-technologies

University of Cambridge (2013b), 'Graphene: Taking the wonder-stuff from dream to reality,' 24 January 2013. As of 28 August 2013: http://www.cam.ac.uk/research/news/graphene-taking-the-wonder-stuff-from-dream-to-reality

University of Cambridge, 'Changing our material future, layer by layer,' 20 December 2012. As of 28 August 2013: http://www.cam.ac.uk/research/news/changing-our-material-future-layer-by-layer

Willetts, David, *Eight Great Technologies*, Policy Exchange, London, 2013.

CHAPTER 5 Cybersecurity

This chapter presents the data gathered as part of the small-scale case study on cybersecurity. The list of references specific to this case study can be found at the end of the chapter.

5.1 Cybersecurity is a rapidly expanding area of importance, with 3 billion online users expected by 2016

Cyberspace is rapidly expanding its scope and impact as more people gain online access and more activities occur through or are enabled by Internet connectivity. Some 2 billion people worldwide are already online, and another billion are expected to join by 2016.[382] In 2010, £5.1trillion changed hands in online commerce, and there are currently more than 5 billion online devices worldwide.[383] The UK is an international leader in the cyber domain, with a strong digital sector and Internet economy. As the cyber-enabled realm continues to grow, investment focuses on providing effective online activities needed to maintain and expand the UK's economic opportunities.

Just as cyberspace facilitates economic growth by fostering communication and knowledge exchange, it also creates new opportunities for criminal breaches. The openness and speed of online systems pose particular challenges in managing cyber-enabled threats.[384] Cyber criminals are improving their ability to adapt to security research findings and new Internet platforms, such as social network sites and cloud services.[385] They are also building more dangerous and extensive attacks with which to breach secure systems, ranging from advanced malware to increasingly sophisticated denial-of-service attacks.[386]

To enable the continued growth of the UK's Internet economy, optimising cybersecurity technologies is of the utmost importance. Ranked against other G20 countries, the UK is first in its ability to withstand cyber-attacks and sustain a strong digital economy.[387] The UK government identified cyber-attacks as one of the four top-priority national risks from 2010–2015.[388] Cybercrime is estimated to cost the UK £18–27 billion a year, and there were 44m cyber-attacks in 2011 alone.[389]

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[382] HM Government (2011), p.11; NAO (2013), p.4
[383] HM Government (2011), p.11
[384] HM Government (2011), p.7
[385] Sophos (2013), p.2
[386] Sophos (2013), p.2
[387] NAO (2013), p.4
[388] HM Government (2010), pp.11, 29
[389] NAO (2013), p. 4

5.2 Cybersecurity priorities centre on the need to stay 'one step ahead' of criminals

Cybersecurity technologies are driven by the need to stay 'one step ahead' of criminals, combining proactive and reactive technologies to manage and pre-empt threats as effectively as possible. Table 5-1 provides an overview of three broad areas where protection is needed: preventing unauthorised access, securing network perimeters and managing the 'human' element.

Table 5-1 Priority themes for cybersecurity

Priorities	Technology areas	Examples of security solutions	
Preventing unauthorised access	**Anti-malware**	Anti-spam	Anti-virus
	Application security	Application security	Application code security
	Encryption	Patch management Digital signatures	Encryption/PKI/digital certificates Storage security
	Identity access management	Authentication Biometrics Digital rights management	Identity and access management Single sign on/security tokens
	Secure transactions	Physical/virtual authentication and identification	
Securing network perimeters	**Mobile**	End point security Mobile security/mobile devices management	Remote access VPN
	Perimeter/ infrastructure	Cloud security Content monitoring/filtering Converged security Data leakage prevention Email/IM security Firewalls Internet security/network security Intrusion prevention/ detection	Penetration testing/risk and vulnerability assessment Secure disposal Security EM Unified threat management Virtualisation security VOIP security Wireless
Managing the 'human' element	**Human factors/ governance/ compliance**	Audit Governance risk and compliance Information risk management Insider threat/social engineering	Legislation and standards PCI-DSS Security policy Security training/awareness/ education/recruitment
	Outsourcing/ managed services	Managed security services	Security web services/security as a service

Source: RAND Europe analysis, categories adapted from InfoSecurity Conference materials

As cyber criminals employ increasingly sophisticated methods to access secure systems and databases, there has been a rise in security solutions, ranging from stricter authentication to targeted software. The rise in encryption technologies to guard data access and integrity is one reflection of this trend.[390] Organisations' investment in encryption technologies has almost doubled over the past eight years, from 10 percent to 18 percent of overall IT security spending.[391] Data protection in general is also a heightened priority, rising from 23 percent to 30 percent of IT security spending over the same period.[392] Other developments

[390] Lyne (2012)
[391] Thales (2012), p.31
[392] Thales (2012), p.30

include adapting current solutions to advanced persistent threats (APTs), 'the next generation of Internet crimeware', and integrating security services with overarching network security to detect and respond to new forms of attack.[393]

The expansion of network bases introduces system vulnerabilities by increasing the perimeter that must be protected. Networks that are accessible from multiple access points – such as over mobile devices, through VPN and via cloud services – must contend with new challenges to the maintenance of secure systems. Network perimeters are made especially vulnerable by the 'bring your own device' (BYOD) system of integrating personal devices into corporate networks.[394] Companies faced with an expanding network infrastructure should adopt solutions such as device-specific protections, harmonisation of network access into a single security framework and centralised management oversight.[395]

Perhaps the least controllable priority area for cybersecurity is the human element of expanding Internet usage. Simple computer or network 'hygiene' could prevent 80 percent of typical cyber-attacks.[396] Organisations are also vulnerable from uncertain compliance when they rely on network users to sustain conscientious behaviour, such as managing passwords and installing security updates. This end-user variable can be managed by developing protective software systems where decisionmaking is machine-driven, rather than user-driven, and by regularly verifying operating systems and security licences.[397] The introduction of new security technologies must also be accompanied by appropriate rules and regulations that educate network users to employ cyber protection tools.[398]

5.3 Defence priorities are similar to those of the civil sector

Cybersecurity priorities for defence mirror those outlined for the civilian sector, although they are driven by national security rather than privacy or profitability concerns. This coherence means that the MOD has a vested interest in capitalising on commercial advances in cyber protection while maintaining independent assessment of security products to ensure defence thresholds of protection are met.

The MOD has already taken measures to secure its networks and equipment to its requisite thresholds, having opened a Global Operations and Security Control Centre at Corsham to spearhead cyber defence concerns for the armed forces.[399] The military has also established two Joint Cyber Units dedicated to enhancing cybersecurity in the defence context, including attention to information security threats.[400]

The MOD also faces specific organisational challenges in protecting the process as well as the content of its networks.[401] Lack of continuity in defence positions, for example two-year rotations, introduces higher levels of vulnerability by increasing the number and turnover of network users. Sustaining top cyber analysts is also a challenge in the current fiscal climate. In 2012, the Intelligence and Security Committee drew attention to GCHQ's failure to retain IT specialists in the face of private sector competitors.[402]

393 Lyne (2012)
394 Lyne (2012)
395 Lyne (2012)
396 NAO (2013), p.4
397 TSB (2012), p.22; IASME, website
398 TSB (2011)
399 HM Government (2011), p.27
400 HM Government (2011), pp.26–27
401 Interview by RAND research team, 17 April 2013
402 NAO (2013), p.26

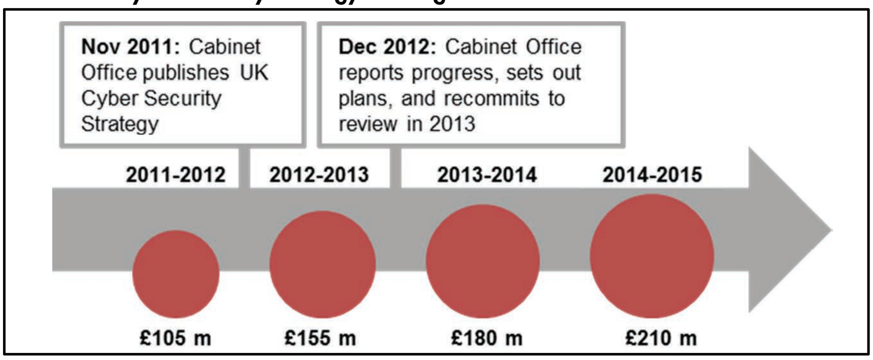
5.4 The UK cyber-based economy is among the strongest globally

The UK Internet economy and e-commerce sector are among the strongest worldwide. The UK's Internet-based economy was valued at £121 billion in 2010, comprising a greater share of national GDP (8 percent) than in any other G20 country.[403] Network usage is directly related to wider economic benefits, with every £1 spent on Internet connectivity corresponding to £5 of wider revenue for the UK Internet ecosystem.[404] The proportion of UK business-to-consumer e-commerce sector to GDP is also three times the global average.[405] Additionally, cyber technologies are part of the UK information and communications technology (ICT) sector, which contributed £66m in GVA in 2010 encompassing revenues of £137 billion from over 116,000 companies.[406]

5.5 UK investment in cybersecurity is driven by the *UK Cyber Security Strategy*

The *UK Cyber Security Strategy* (CSS), published in 2011, is the main government policy establishing an integrated national response to cybersecurity threats.[407] The CSS also sets out a £650m government investment in cybersecurity from 2011–2015. As Figure 5-1 shows, annual funding is set to steadily increase to £210m in 2014–2015. Within this structure, the role and funding of each relevant department is carefully delineated, as shown in Figure 5-2.

Figure 5-1 The UK Cyber Security Strategy funding timeline



Source: Adapted from NAO (2013), p.4

403 NAO (2013), p.4

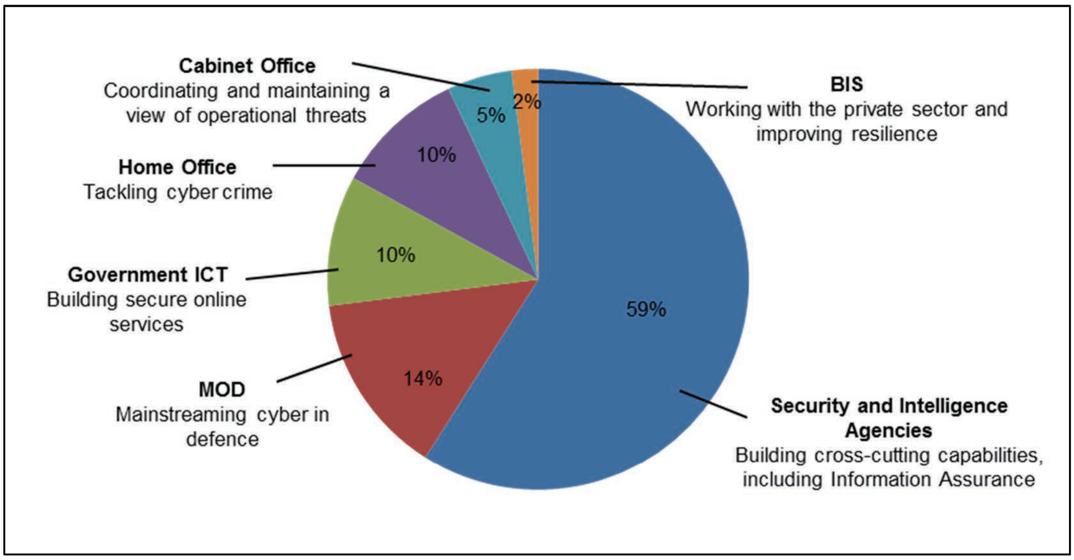
404 The 'Internet ecosystem' is a subset of the total Internet economy. See A.T. Kearney (2012), p.3

405 A.T. Kearney (2012), pp.3, 11

406 TSB (2012), p.20

407 HM Government (2011)

Figure 5-2 Funding for the National Cyber Security Programme by department, 2011–2015



Source: HM Government (2011), p.25

Cybersecurity also benefits from targeted funding from both RCUK and the TSB in coordination with the priorities outlined by the CSS. RCUK spends over £50m on a broad range of cybersecurity issues, and has invested £10m in new projects for each of the past three years.[408] The Centre for Secure Information Technologies (CSIT) is the single largest of these investments, receiving total funding of £30m over five years to develop information security infrastructures.[409] The TSB is also investing in ICT, for example as part of a recent £20m-per-year initiative to fund higher-risk, early stage innovation across four main priority areas.[410]

Despite significant investment from government and the private sector, some cyber experts have criticised the UK for committing too little too late to cybersecurity.[411] Assessing the need for cybersecurity investment is challenging because accurate information on cyber threats is unreliable, particularly due to a lack of reporting from companies who fear publicising attacks will hurt their reputation.[412] When details of 77m Sony customers were captured in 2011, for example, the company's share price fell by 5 percent.[413]

5.6 Cybersecurity stakeholders are spread across the public and private sectors

Due to the enabling nature of information technologies, cybersecurity is deeply cross-cutting, with key actors across government, business, academia and the broader research community. As already shown in Figure 5-2, various government departments are involved under the remit of the CSS.[414] The CSS also stresses the centrality of private sector infrastructure and investment in the cybersecurity agenda, emphasising that the innovation and expertise to address cyber threats will be driven by business rather than government.[415]

[408] Research Councils UK (RCUK), p.10
[409] RCUK, p.11
[410] TSB (2012), p.3
[411] Shah (2013); Gilbert (2013)
[412] NAO (2013), p.25
[413] NAO (2013), p.25
[414] NAO (2013), p.14
[415] HM Government (2011), p.22

In the research community, the EPSRC leads cybersecurity research efforts from the RCUK, helping initiatives such as the Academic Research Institutes that bring together leading academics, industry experts, and international researchers to address cyber challenges.[416] Government-sponsored Academic Centres of Excellence (ACEs) in Cyber Security Research have existed since 2012.[417] A global cybersecurity centre is also due to open at Oxford University, receiving £1m in government funding over the next two years.[418]

A number of cyber initiatives bring together public and private sector expertise. The Cyber Information Sharing Partnership, formed in January 2013, is an example of government and business working together to share knowledge and best practice. While initially limited to large companies within the Critical National Infrastructure, a second phase intends to expand this remit to involve SMEs.[419] The top-secret 'Fusion Cell' is another collaborative effort that coordinates cyber defence, staffed by government intelligence services and representatives from 160 of the UK's largest companies across finance, pharmaceuticals, energy, telecommunications and defence.[420]

5.7 Future trends are highly uncertain

There are very little data on predicted trends in the cyber area due to the proactive/reactive nature of developments and the innovation rate of the sector as a whole. It is challenging for cybersecurity technologies to remain 'one step ahead' of attackers by adapting to new platforms, such as cloud services, as well as to new threats. Attacks will likely continue to target weaknesses in systems and processes, from software code failings to supply chain issues. New detection methods will be necessary to counter attacks such as 'Man-in-the-Browser' malware that takes complete control of Internet browsers, requiring an adaptation of typical anti-malware solutions.[421] The rise in virtual cyber environments is also introducing vulnerabilities that will need to be addressed.[422] The relative dearth of ICT and cybersecurity professionals in the UK, which has not kept pace with Internet expansion, may also pose a problem as greater expertise is demanded to counter a rapidly evolving threat landscape.[423]

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416 EPSRC (2013)
417 EPSRC (2013)
418 Hamacher (2013)
419 Shah (2012)
420 Hutton (2013)
421 WatchGuard (2012), p.1
422 WatchGuard (2012), p.1
423 NAO (2013), p.26

References

A.T. Kearney, *The Internet Economy in the United Kingdom*, 2012.

Engineering and Physical Sciences Research Council (EPSRC), 'UK's second cyber research institute launched', press release, 21 March 2013. As of 28 August 2013: http://www.epsrc.ac.uk/newsevents/news/2013/Pages/secondcyberresearchinstitute.aspx

Gilbert, David, 'UK's Cyber Security Strategy Seriously Under Funded', *International Business Times*, 22 March 2013. As of 28 August 2013: http://www.ibtimes.co.uk/articles/449334/20130322/uk-cyber-security-under-funded-kaspersky-expert.htm

Hamacher, Andrea, 'UK to host global cybersecurity centre', 10 April 2013. As of 28 August 2013: https://connect.innovateuk.org/web/ictktn/article-view/-/blogs/uk-to-host-global-cybersecurity-centre

HM Government, *UK Cyber Security Strategy: Protecting and promoting the UK in a digital world*, November 2011.

HM Government, *A Strong Britain in an Age of Uncertainty: The National Security Strategy*, October 2010.

Hutton, Robert, 'U.K. Sets Up Cybersecurity Center to Coordinate Computer Defense', Bloomberg, 26 March 2013. As of 28 August 2013: http://www.bloomberg.com/news/print/2013-03-27/u-k-sets-up-cybersecurity-center-to-coordinate-computer-defense.html

IASME Consortium, '10 steps to Cyber Security – Guidance for SMEs'. As of 28 August 2013: http://www.iasme.co.uk/index.php/10steps

Lyne, James, 'Eight Trends Changing Network Security', Sophos, Boston and Oxford, 2012. As of 28 August 2013: http://www.sophos.com/en-us/security-news-trends/security-trends/network-security-top-trends.aspx

National Audit Office, *The UK cyber security strategy: Landscape review*, 5 February 2013.

Research Councils UK, *Global Uncertainties Strategic Plan 2011–16*.

SecurityInfoWatch, 'Study: Encryption and key management increasingly viewed as strategic issues', SIW Staff Reports, 25 February 2013. As of 28 August 2013: http://www.securityinfowatch.com/news/10884364/study-encryption-and-key-management-increasingly-viewed-as-strategic-issues?page=2

Shah, Sooraj, 'UK's investment in cyber security is "embarrassing", say experts', *Computing*, 8 April 2013. As of 28 August 2013: http://www.computing.co.uk/ctg/news/2259866/uks-investment-in-cyber-security-is-embarrassing-say-experts

Shah, Sooraj, 'One year on: The UK Cyber Security Strategy', *Computing*, 3 December 2012. As of 28 August 2013: http://www.computing.co.uk/ctg/news/2229166/one-year-on-the-uk-cyber-security-strategy

Sophos, *Security Threat Report 2013*, 2013. As of 28 August 2013: http://www.sophos.com/en-us/security-news-trends/reports/security-threat-report.aspx

Technology Strategy Board (TSB), *Enabling Technologies Strategy 2012–2015,* Swindon: November 2012.

Technology Strategy Board (TSB), *Future Internet Report*, UK Future Internet Strategy Group, Swindon, May 2011.

Thales, *2012 Global Encryption Trends Study*, Thales e-Security and Ponemon Institute Research Report, February 2013.

WatchGuard, 'WatchGuard's 2013 Security Predictions', 2012. As of 28 August 2013: http://www.watchguard.com/docs/brochure/wg_2013_security_predictions.pdf

CHAPTER 6 Small-scale energy storage

This chapter presents the data gathered as part of the small-scale case study on small-scale energy storage. The list of references specific to this case study can be found at the end of the chapter.

6.1 Small-scale energy storage offers a range of options for mobile power

Mobile and small-scale energy storage aims to provide energy quickly, efficiently and without emissions. These energy storage options typically present trade-offs between a number of characteristics, including: amount of power generation; speed of power discharge; time between charges; length of charge time; cycle life (number of charges before replacement); size; and weight. Table 6-1 shows a selection of storage technologies, demonstrating the range of power and selected applications of different energy types.

Table 6-1 Range of energy storage applications, with mid- to small-scale shaded

	<1uW	1W	1-75W	75W–75kW	>75kW
Applications	Sensors, lab-on-a-chip and Smart card	Pacemakers, mobile phones and GPS	Laptop, tablets, UAVs, military comms, power tools and IC vehicles	EV, hybrid vehicles, submersibles and aircraft	Renewables storage (wind turbines, solar panels) and grid buffering
	MOBILE				**STATIC**
Example storage techs	Thin film	Polymer and Li-Ion	Li-ion, Ni-Cd and Pb-acid	Li-Ion, ZEBRA and Li-S	Pumped hydro, Li-ion, Flow Cell and Heat

Source: TSB NanoKTN (2012)

For the purposes of our analysis, we are most interested in the mid- to small-capacity range of storage. This area encompasses two major markets: portable electronic devices (such as laptops, mobile phones and GPS) and transportation (such as hybrid and electric vehicles).[424] While a range of energy storage solutions are being developed, our scope focuses on the most commonly employed battery and fuel cell technologies.[425] Battery technologies offer the benefit of providing self-contained energy sources without requiring

[424] TSB (2012)

[425] Other small-scale energy storage solutions include, for example, supercapacitors. In recent years this storage technology has gained traction, and the world market is expected to exceed £1.3 billion by 2015. This technology has the advantages of a long life cycle and high power efficiency. Its current drawback to widespread application is its relatively low energy output. If this area were to see significant developments, it could present a favourable option for energy storage applications. See European Science Foundation (2011), pp.17–18

refuelling. Fuel cells also offer significant potential as an energy storage technology, and fuel cell vehicles have been shown to cost less than comparable battery-electric or plug-in hybrid vehicles.[426] Over 10,000 portable fuel cell units were shipped globally in 2008 alone, and 150 hydrogen refuelling systems already exist.[427]

6.2 Priority areas focus on improving the energy content, timescales and physical properties of storage technologies

Energy storage technologies encompass a number of priority areas, as outlined in Table 6-2. Common challenges include three major lines of development: energy content, timescales and physical properties.

Table 6-2 Qualitative SWOT analysis of UK versus RoW for energy storage technologies

Technology area	Market demand	UK Strength
Cell chemistry development	High – dominated by US, China, Korea, Taiwan	Strong – University
Cell manufacture	Limited prototyping facilities in UK	Weak
Thin film and micro battery manufacture	Future demand	Could be strong
Pack design and manufacture (devices)	Some activity for mobile phones	??
Pack design and manufacture (auto)	High demand in UK and globally	Very strong consultancy
Battery management system	High demand for auto	Strong
Recharging systems	Demand increasing	New players emerging in UK
Battery testing facilities	Increasing	One major UK facility, some small industrial
Recycling	Increasing	Limited
Re-use of Li batteries	Increasing	Not at present
Life cycle analysis	Increasing	Strategic consultancy strength supported by funding from the TSB, Committee on Climate Change

Source: TSB NanoKTN (2012)

Energy content is a particular priority for mobile and small-scale energy storage, for which the size and weight of storage technologies are restricted. The challenge here is two-fold: to increase energy density and to increase the overall energy levels that can be achieved and sustained by the storage device. The development of lithium-sulphur and -oxygen batteries, for example, may offer up to 10 times the energy density of current lithium-ion options.[428]

The timescales over which energy storage options can sustain and discharge power make up another axis of development. Depending on their application, small-scale energy storage technologies may be required to discharge power for timescales ranging from seconds to

[426] Energy Generation and Supply KTN, website
[427] Energy Generation and Supply KTN, website
[428] European Science Foundation (2011), p.17

hours.[429] Fuel cells present advantages here, with limited charging time enabling long running periods.[430] For batteries, both of these elements can be improved. Increasing the number of recharge cycles sustained by a single battery is also important to optimise performance.[431] For example, while new developments in lithium-sulphur batteries offer lower costs and higher energy densities, this technology typically has a comparatively short life cycle: 80 charge-discharge cycles compared to the conventional lithium-ion duration of 500.[432] Research is underway on new composite solutions to improve this capacity to over 250 charge-discharge cycles.[433]

Finally, the physical properties of energy storage technologies not only impact characteristics of energy content and timescale, but also introduce concerns about size, weight and disposability. It is an ongoing challenge to improve energy storage solutions, lightening them for mobile and portable devices while also achieving the requisite levels of energy. The potential toxicity or recyclability of storage technologies is another concern, particularly for situations where proper disposal is not easily guaranteed.

6.3 Mobile and small-scale energy storage offers both high- and low-power solutions for defence equipment and logistics

Mobile and small-scale energy storage is highly relevant to defence for its ability to provide lightweight, self-contained power without requiring external replenishment. Defence benefits from energy storage technologies in a similar way to the commercial sector, but often with higher specifications at either end of the spectrum. For example, while an extended field mission may require energy storage with long-term duration and low power discharge, high-power equipment may need short-term but intense bursts of energy release. Small-scale energy storage technologies can be particularly beneficial for three aspects of in-theatre operations: logistical constraints; modern soldier requirements; and vehicular and UAV application.

In a logistical sense, in-theatre conditions often mean that the need to refuel or recharge power sources leads to vulnerable troop movements. Advances in energy storage technologies enable deployed units to avoid such movements for longer periods of time.[434] Improvements in weight reduction allow more power units to be carried by troops, while increases in the duration of power discharge reduce the need for troops to travel to refresh power sources when located in dangerous areas.[435] In addition to these tactical concerns, energy storage advances decrease expenditure on refuelling expeditions and the risk of relying on uncertain commercial power grids.[436]

Small-scale energy storage technologies are also highly suited to modern soldiers' requirements for more power for portable electronic devices. The rise in technological components used by modern troops, from GPS to tablets, has introduced new challenges and constraints, including additional weight, requirements in energy release and length between charging times. In 2012, it was estimated that UK patrol troops carry an average of

[429] Energy Research Partnership (2010), p.31
[430] Energy Generation and Supply KTN, website
[431] TSB (2012)
[432] Zhang (2013)
[433] Zhang (2013)
[434] Keller (2013)
[435] Seah and Tang (2011)
[436] Pike Research (2011a)

8kg in batteries.[437] Reduced weight also decreases the burden of spent batteries in cases where on-the-go disposal would compromise troops' position.[438]

New energy storage technologies are also highly relevant for military UAV and vehicle demands. UAVs particularly benefit from advances in energy storage technologies, as miniaturised, low-weight power increases their energy capacity. They call for advanced batteries with high power density, in order to avoid a loss of efficiency from the power source's added weight.[439] Recent use of lithium sulphur batteries in a UAV demonstration achieved a flight time of 2 hours, with an energy output of 350Wh/Kg – a 50 percent increase on energy output on top-end lithium ion batteries.[440] This emphasis on high energy output is the primary strength of fuel cells, which have a higher energy density than typical military batteries. Fuel cells are also favourable for in-theatre vehicles' stealth priorities, which include low noise levels and low heat signatures.[441]

6.4 Small-scale technologies are a small proportion of the energy storage sector, but their value is growing rapidly

Although energy storage technologies comprise a small part of the current UK energy industry, their market size is growing rapidly at a global level. Most of this market expansion will be generated by increasing demand from electronics and electric vehicles. Overall, UK energy industries were valued at £60 billion in 2010, comprising 4 percent of GDP and directly employing 173,000 people.[442] Data on market size of mobile and small-scale energy technologies is limited at a UK level, but global figures show a strong predicted increase in both battery and fuel cell technologies. The global lithium-ion battery market was valued at £7.6 billion in 2010 and is expected to expand to £34.6 billion by 2020, primarily reflecting increased demand from the civil sector.[443] The predicted growth in fuel cells mirrors this trend, with military market size alone expected to rise from £5.8m in 2011 to £770m in 2017.[444]

6.5 Energy investment tends to focus on larger-scale solutions, although early stage technology funding is occurring

In order to capitalise on the energy sector's substantial growth opportunities, investment in low-carbon technologies has been identified as a major priority for the UK economy. Globally, the International Energy Agency (IEA) estimates that at least £173trillion of investment in energy will be needed by 2050.[445] The UK's Department of Energy and Climate Change (DECC) has allocated £24m to its science research for 2011–2012.[446] Energy storage was also identified as one of the UK's 'eight great technologies', receiving a

[437] OXIS Energy (2012)
[438] Seah and Tang (2011), p.73
[439] Seah and Tang (2011), p.74
[440] SION Power Corporation and QinetiQ
[441] Pike Research (2011a)
[442] TSB (2012)
[443] Zhang (2013)
[444] Pike Research (2011b)
[445] DECC (2012), p.5
[446] DECC (2012), p.7

£30m investment.[447] However, this investment primarily focuses on grid-level storage solutions, rather than the small- to mid-capacity range.[448]

UK funding has particularly targeted the accelerated commercialisation of new energy technologies, and small-scale and mobile energy storage has not been a top priority area. The DECC and BIS have committed £200m from 2011–2015 specifically to projects supporting R&D into low-carbon technologies.[449] However, battery and fuel cell technologies are not among the areas to which this funding is allocated.[450]

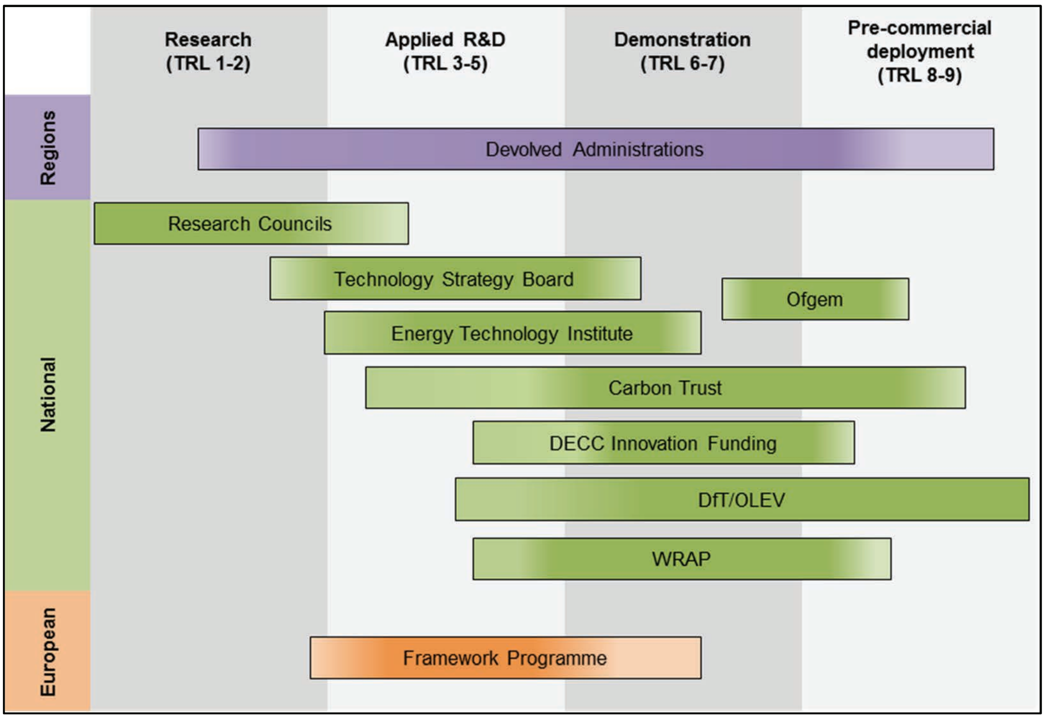
When investment is occurring, it tends to support early stage technology companies over the life cycle of energy storage innovation, aiming to develop technologies through to commercialisation. The TSB and DECC have partnered to invest over £40m in fuel cell and hydrogen projects worth up to £90m, supporting business R&D at multiple stages: materials innovation, technology development, vehicle integration, technology demonstrators and whole system integration.[451] This support has enabled the expansion of research programmes as well as the formation of strategic partnerships that will lead to further funding and development.[452]

6.6 Stakeholders are involved across the full TRL range

Numerous stakeholders are involved in R&D into energy storage technologies. An overview of these actors and their stage of technological involvement is given in Figure 6-1. Most stakeholders are involved in the middle range of technological development, engaging with applied research and development (TRL 4–5) and especially the demonstration (TRL 6–7) of technologies.

[447] BIS (2013)
[448] BIS (2013)
[449] BIS and DECC (2013)
[450] BIS and DECC (2013)
[451] TSB (2012)
[452] TSB (2012)

Figure 6-1: UK energy technology funding landscape



Source: DECC (2012), p.22

Major energy actors can be divided into three main categories: government, research institutes and the private sector. Various government departments fund energy research to fit a range of applications, from transport to residential concerns. In addition to the DECC, the Devolved Administrations and the Office of Gas and Electricity Markets (Ofgem) provide funding for energy initiatives. The Office of Low Emission Vehicles (OLEV) also provides over £400m to support R&D for ultra-low emission vehicles (ULEV).[453] Research and innovation organisations provide most funding for early stage technology development. The TSB and the Research Councils – particularly the EPSRC and NERC – fund a number of emerging technology projects. Academia also supports the discovery and early development of potential energy technologies. Finally, private sector actors are involved throughout the life cycle of technology development. These actors may also benefit from government funding or partnership, as in the cases of the Energy Technologies Institute (ETI), Carbon Trust and WRAP.[454]

There are also a number of cross-cutting energy initiatives conducted by organisations from the full range of stakeholder areas. For instance, the Low Carbon Innovation Group facilitates knowledge exchange and communication between major public sector-backed organisations, with a main focus on low-carbon technology development. Its core membership includes government (BIS, DECC, Scottish Enterprise and the Scottish government), research (the TSB and EPSRC) and the private sector (the Carbon Trust and ETI).[455]

[453] OLEV, website

[454] WRAP, website; Carbon Trust, website; ETI, website

[455] Low Carbon Innovation Co-ordination Group, website

6.7 Future advances will be shaped by energy developments more generally

Looking ahead, research into small-scale energy technologies is likely to continue seeking longer lifespans as well as higher energy density and release. These concerns are directly relevant to defence needs for long-lasting, high-output energy. New polymer lithium-sulphur batteries, for example, are being developed to better fit the military context; these can perform at 5 times the level of lithium-ion batteries, and a goal has been set to further reduce the batteries' weight by 20 percent.[456] Improvements to fuel cells will also be necessary, particularly to meet military performance and production demands. A recent report from Pike Research predicts that soldier-portable and -wearable applications (replacing current battery technologies) will represent over 50 percent of the military fuel cell market by 2017, followed in size by fuel cell application in military sensor equipment.[457]

Given the status of energy storage as an enabling technology, developments in this domain will be largely shaped by advances across the energy sector more generally.[458] Future development would benefit from a coherent strategy for energy analysis and innovation as well cross-sector programmes targeting energy storage technologies. Demonstration of energy storage technologies should also be increased to provide visibility for energy storage as a priority area of research and investment.[459]

[456] OXIS Energy (2012)
[457] Pike Research (2011b)
[458] Energy Research Partnership (2011), p.5
[459] Energy Research Partnership (2011), p.5

References

Carbon Trust. As of 28 August 2013: http://www.carbontrust.com/

Department for Business, Innovation and Skills (BIS), '£600 million investment in the eight great technologies', press release, 24 January 2013. As of 28 August 2013: https://www.gov.uk/government/news/600-million-investment-in-the-eight-great-technologies

Department for Business, Innovation and Skills and Department of Energy and Climate Change (BIS and DECC), 'Innovation funding for low carbon technologies: opportunities for bidders', 8 May 2013. As of 28 August 2013: https://www.gov.uk/innovation-funding-for-low-carbon-technologies-opportunities-for-bidders

Department of Energy and Climate Change, *DECC science and innovation strategy 2012*, April 2012.

Energy Generation and Supply KTN, 'Fuel Cells and Hydrogen Official Group'. As of 28 August 2013: https://connect.innovateuk.org/web/fuel-cells-and-hydrogen/who-we-are

Energy Research Partnership, *The future role for energy storage in the UK: Main Report,* Energy Research Partnership Technology Report, London, June 2011.

Energy Research Partnership, *Energy innovation milestones to 2050*, Energy Research Partnership report, London, March 2010.

Energy Technologies Institute (ETI). As of 28 August 2013: http://www.eti.co.uk/

European Science Foundation, *Materials for Key Enabling Technologies*, ed. H. Richter, Strasbourg, June 2011.

Keller, John, 'Navy to field-test hydrogen fuel cell- and solar-powered military renewable energy system', Military and Aerospace Electronics, 1 March 2013. As of 28 August 2013: http://www.militaryaerospace.com/articles/2013/03/Navy-renewable-energy.html

Low Carbon Innovation Co-ordination Group, 'About the LCICG'. As of 28 August 2013: http://www.lowcarboninnovation.co.uk/about_the_lcicg/

Office for Low Emission Vehicles, website. As of 28 August 2013: https://www.gov.uk/government/organisations/office-for-low-emission-vehicles

OXIS Energy, 'Soldiers lose weight', 31 October 2012. As of 28 August 2013: http://www.oxisenergy.com/downloads/OXIS_MoD.pdf

Pike Research (2011a), 'Fuel Cells for Military Applications', 2011. As of 28 August 2013: http://www.navigantresearch.com/research/fuel-cells-for-military-applications

Pike Research (2011b), 'Military Fuel Cell Market to Reach $1.2 billion by 2017', press release, 15 August 2011. As of 28 August 2013: http://www.navigantresearch.com/newsroom/military-fuel-cell-market-to-reach-1-2-billion-by-2017

Seah, Calvin and Gareth Tang, 'The Defence Energy and Power Conundrum', *Pointer*, Journal of the Singapore Armed Forces, 22 December 2011.

SION Power Corporation and QinetiQ, 'UAV Flight Time Increased By 80 Percent Using New High Energy Battery System'. As of 8 May 2013:

http://sionpower.com/pdf/articles/QinetiQ%20and%20SION%20Zephyr%20Flight%2011-21-06%20News%20Relea.pdf

Technology Strategy Board (TSB), *Energy Supply Strategy 2012–2015,* Swindon: October 2012.

Technology Strategy Board NanoKTN, *Mobile and Small-scale Energy Storage – Towards a New UK Industry,* Industry Consultation Report, October 2012.

WRAP. As of 28 August 2013: http://www.wrap.org.uk/

Zhang, Can, 'Building a better battery', Cambridge University, 7 March 2013. As of 28 August 2013: http://www.cam.ac.uk/research/news/building-a-better-battery