Expert paper

Responsible Research & Innovation in Nanoelectronics and ICT

Roger De Keersmaecker

Executive Advisor for imec, the R&D and innovation hub in nanoelectronics and digital technologies in Leuven, Belgium.

RESPONSIBLE INNOVATION COMPASS

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Author(s)	Em. Prof. Dr Roger De Keersmaecker
Role	Expert Advisory Board member to the COMPASS project
Email	info@innovation-compass.eu
Project Coordinator	a.Prof. Dr André Martinuzzi Institute for Managing Sustainability Vienna University of Economics and Business (WU Vienna) Welthandelsplatz 1, A-1020 Vienna/Austria http://www.sustainability.eu/

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Content

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1. Setting the scene

This paper first covers the intimately connected domains of (i) nanoelectronics and (ii) its applications in the field of Information and Communication Technology (hereafter abbreviated as "ICT"), not with the aim of providing an exhaustive review but, rather, to clarify these technology domains to a sufficient extent to underpin the subsequently discussed issues related to Responsible Research and Innovation (hereafter abbreviated as "RRI").

In the realm of the COMPASS project, nanoelectronics is considered part of the domain of nanotechnology. This position can be contested e.g. at the ontological level, since nanoelectronics and nanotechnology are both constituting domains of the key enabling technologies (KETs) as defined by the EC.[1] On the other hand, according to one of its definitions "nanotechnology R&D is directed towards the understanding and control of matter at dimensions of roughly 1 to 100 nanometres".[2] State-of-the-art nanoelectronics devices typically involve structures with at least one dimension < 100 nm which means that - from the size point-of-view - nanoelectronics can be considered as a branch of nanotechnology. It is to be noted that although the multiple benefits of nanotechnology for economic growth and competitiveness have been stressed in policy discourses, some scholars have consistently framed nanotechnology as more risky than beneficial. Putting nanoelectronics under the general "umbrella" of nanotechnology then poses the risk of an increased negative public response to nanoelectronics.

Apart from this section 1 ("Setting the scene") and section 8 ("A few concluding reflections"), I address the following topics, In line with the editorial guidance from the COMPASS consortium:

- In section 2, "Current and emerging topics in nanoelectronics and ICT", including the European strategy for a digitalised future (in 2.3) and the impacts of ICTs (in 2.4);
- in section 3, "Current and emerging RRI issues in nanoelectronics and ICT"; 3.1 elaborates on the RRI concept; 3.2 lists the Societal Challenges; in 3.3 the constituting elements of RRI (from the policy point-of-view) are discussed; in 3.4 alternative frameworks for RRI are briefly reviewed;
- in the following two sections, I discuss the regulations (section 4) and the incentives (section 5) influencing research and innovation in nanoelectronics and ICT;
- in section 6, I review the collaboration culture between the players in the nanoelectronics and ICT sectors;
- in section 7, I look at RRI from the point-of-view of SMEs.

As this paper is largely based on a critical literature review of the respective topics and not on field work or experimental research, my approach is *descriptive*, not *normative*, especially in relation to aspects of RRI. As to technology evolution, "hard" determinists such as e.g. Kevin Kelly[3] assume that there is a "bias", a built-in momentum, in the nature of technology that tilts it in a certain direction and drives the development of society, its social structure and cultural values. However, I take a position based on "soft determinism" according to which technology is the enabling force of society's evolution, but in interaction with socio-political forces, i.e. we have a chance to make decisions regarding the outcomes of a situation.

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2. Current and emerging topics in nanoelectronics and ICT

In view of the 'research and innovation' (R&I) focus of this paper, I will concentrate on state-of-the-art technology and emerging topics in nanoelectronics and ICT. It is to be noted that "ICT" nowadays is an inseparable hybrid (of computing and communicating devices), which is the consequence of the technological convergence of computation and communication which took off about 3 decades ago.

2.1. Overview of nanoelectronics developments

One of the remarkable technological achievements of the last 50 years is the integrated circuit (IC) of which the capabilities have grown at an exponential rate. According to Moore's Law,[a] electronic devices have become smaller, faster and more power-efficient. Using advanced lithography tools geometric scaling is applied to transistor dimensions, allowing to double the transistor count per unit area every two years.[4,5] This allows to systematically increase transistor densities and enhance circuit performance. The International Technology Roadmap for Semiconductors (ITRS) has been instrumental in laying out the directions of research in a range of technology areas, with a time horizon of 15 years.[6] Based on the most recent findings and needs, this outlook is updated every two years. Starting in 2016, the ITRS 2.0 and the IEEE Rebooting Computing Initiative jointly launched the International Roadmap for Devices and Systems (IRDS),[7] with a broad scope from base technology through systems and architectures.

Intel has announced that it will ship the first processors built using its "10 nm"b chip technology sometime in 2017 and "7 nm" and "5 nm" technologies are being forecasted. In order to continue this trend, trade-offs will have to be taken into account, but the trend will definitely continue for some time. Meanwhile, the functionality of circuits can be extended via other pathways than the scaling of devices and, moreover, at some point nanoelectronics devices will morph into different structures:

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[a] "Moore's Law" is the observation that the number of transistors in a dense integrated circuit (IC) doubles approximately every two years. The observation is named after Gordon Moore, the co-founder of Fairchild Semiconductor and Intel, who in 1965 projected the increase of transistor count per IC to double every year and in 1975 revised the forecast to doubling every two years. Moore's law is not a physical or natural law but a prediction which, however, proved accurate for many decades, and has been used in the semiconductor industry to guide long-term planning and to set targets for research and development. The insight became the 'golden rule' of the electronics industry, as it meant that computing would dramatically increase in performance and decrease in relative cost, at an exponential pace. The principles of device (MOSFET) scaling are outlined in a seminal paper published in 1974 by Robert H. Dennard et al.: it states, roughly, that as the transistor gets smaller and applied voltage is scaled accordingly, it switches faster and power density stays constant, so that the power use stays in proportion with area. "Dennard scaling" relates to Moore's law as scaling reduces the delay time per circuit at the same rate. Since around 2005–2007 Dennard scaling appears to have broken down (resulting in saturating device speed) but this has been confused with the end of "Moore's law": while transistor dimensional scaling faces limitations from physics, other means of continued increase of devices per cm^2 have been proposed (e.g. using 3D structures).

[b] Today, the correlation between the name of the technology "node" and the dimension of any transistor feature is rather complex. But logic cells (transistor combinations to perform standard logic functions) built in the "10 nm" technology can still be less than 50% the size of those built in the preceding "14 nm" technology.

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1. More than Moore (MtM) – It is already possible to extend the functionality of logic and memory silicon circuits by integration with other technologies. This has been referred to as “More than Moore” - as the focus is then not solely on the scaling of devices (according to Moore’s Law), but on scaling the full system by hybrid assembly. In this way, it is possible to create high value micro/nanoelectronics systems with vast application potential. The CMOS imager which can be found in any current cell phone camera is an example of such hybrid integration. The co-integration can be performed directly on a silicon chip (creating a “system-on-chip”) or by stacking various technologies (creating a “system-on-package”).[8]

2. New technology options are being considered – Current state-of-the-art “FinFET”[c] transistors are being replaced by lateral nanowires which in turn will be replaced by vertical nanowires. Also two-dimensional integration is being replaced by three-dimensional (3D) structures, vertically integrating successive layers of devices. This trend is combined with 3D heterogeneous integration (DRAM, logic, optical I/O a.s.o.). In terms of novel materials a drastic change would be the replacement of silicon by carbon. Carbon NanoTubes (CNTs) - discovered about 20 years ago – have attributes that make them appealing as miniaturised electronic components. Based on high expectations in various domains, the EC launched the “Graphene” FET Flagship[d] project in 2013.[9]

   For the more distant future, an alternative for the silicon transistor as elementary information carrier is the subject of intense research. Molecular electronics and magnetic components are two categories being considered as “beyond CMOS” devices.[10]

3. System and architecture innovations are being introduced – Another aspect is that classically, devices/circuits have been co-developed together with the technology; today, the co-design occurs one level up, i.e. between the complete system and the technology.

   New architectures are being researched that exploit the properties of the novel “beyond-CMOS” devices; neuromorphic (brain-inspired) networks are currently receiving considerable attention.

Also, with the advent of the Internet of Things (IoT), I want to address specific applications for which data gathering and analysis, data security and the transmission network are important elements. As the application adds a third layer to the Technology-System combination, (i) hardware will have to be dedicated to the specific function; and (ii) hardware and software will be co-optimised.

[c] The term FinFET (fin field-effect transistor) was coined by U. of California researchers to describe an advanced nonplanar type of transistor, with as distinguishing characteristic that the conducting channel is wrapped by a thin silicon "fin".

[d] According to the EC website, “*Flagships are visionary, science-driven, large-scale research initiatives addressing grand Scientific and Technological (S&T) challenges. They are long-term initiatives bringing together excellent research teams across various disciplines, sharing a unifying goal and an ambitious research roadmap on how to achieve it*.”

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2.2. Overview of ICT developments

At the outset of this section I want to refer to the distinction between the *technologies* and the *applications* enabled by these technologies. Example: the technologies enabling digital communication networks are: (1) client/server computing; (2) packet switching; (3) TCP/IP and connectivity. Each of these technical components is important and continues to be developed – but analysing the underlying *foundational* technical features (both hardware and software) are beyond the scope of this paper. I will focus on some selected 'technologies' (in fact: applications) enabled by the foundational technologies.[e]

Various consulting companies annually interview company executives, study roadmaps and present their review of technology trends. One of such periodic efforts is the "Gartner hype cycle"[f] which typically provides insights from more than 2,000 technologies and compresses that list into a succinct set of emerging technologies that are seen to be going through the 'hype cycle' and eventually will enter on the market. Even the compressed list typically contains a few dozen 'must-follow' emerging technologies which cannot be individually discussed here. Rather I will extract a few overarching trends from the 2016 hype cycle and then discuss in somewhat more detail a few selected technologies illustrating those trends.

The three distinct technology trends that are expected to lead to rapidly accelerating digital innovations are the following:[11]

1. *Transparently immersive experiences* – Technology will continue to become more human-centric to the point where it will introduce transparency between people, businesses and things. This relationship will become much more entwined as the evolution of technology becomes more adaptive, contextual and fluid within the workplace, at home, and interacting with businesses and other people. Critical technologies to be considered include thought-provoking futuristic technologies: brain-computer Interface and human augmentation, but also more 'mundane' technologies such as the connected home, augmented reality and virtual reality.

2. *The perceptual smart machine age* – Machine intelligence is not new, but until now this involved (very) specific machine intelligence, i.e. a machine which is extremely good in doing one simple task. General-purpose machine intelligence (or artificial general intelligence) is something different: it will be the most disruptive class of technologies in the next decade due to radical computational power, near-endless amounts of data, and impressive advances in deep neural networks that will allow to harness data in order to adapt to new situations and solve problems that no one has encountered previously. Typical technologies in this theme are: smart dust, machine

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[e] Various models are being used to analyse the digital transformation. IDC's stepped model sees a "third (computing) platform" at the heart of the digital transformation, consisting of mobility; the cloud; big data/analytics; and social business. These in turn enable a range of "Innovation Accelerators" (such as robotics, 3D printing, IoT, a.s.o.), resulting in turn in continuous industry transformation. See http://www.idc.com/prodserv/3rd-platform/

[f] The technological "hype cycle" is a graphical representation (developed by Gartner) for representing the maturity, adoption and social application of specific technologies. The conceptual presentation of the maturity of emerging technologies goes through several phases, including the "peak of inflated expectations" (hence the name 'hype cycle'), the "trough of disillusionment" and finally the "plateau of productivity". The model has been criticised but is used as an indication for the state of development of technological fields contributing to investment decisions by companies.

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learning, autonomous vehicles, virtual personal assistants (autonomous smart agents), smart workspace, smart robots, commercial drones, conversational user interfaces and natural-language question answering.

3. *The platform revolution* – Thanks to emerging technologies, new organisational forms are appearing of which the platform organisation seems very promising. The shift from technical infrastructure to ecosystem-enabling platforms is laying the foundations for entirely new business models that are forming the bridge between humans and technology. Organisations redefine their strategy to create platform-based business models, and exploit internal and external algorithms in order to generate value: Uber, AirBnB and Alibaba are examples of this new type of organisations. Examples of emerging technologies that are drivers behind the platform revolution are: blockchain, IoT platforms, and Software-Defined Anything (SDx).

In the remainder of this section, I will look at some selected technologies that are expected to have the most profound impact in the coming years: the Internet of Things; autonomous vehicles; blockchain; artificial intelligence; and 5G mobile networks.

Internet of Things – The "Internet of Things" (IoT), sometimes also called "Internet of Everything" (IoE), is about to become ubiquitous. One of the key characteristics of IoT is that it is merging the digital and the physical world: it will indeed be all around us and reside into the background of our lives. According to S. Vandebroek, three technologies will make the IoT possible:[12] (1) smart everyday objects; (2) information-centric networks; and (3) automated real-time insights. Electronics play a central role in each of these three pillars: (1) smart everyday objects that sense data everywhere will be created by printed hybrid logic and sensor circuits using organic inks and "inks" containing microchips; (2) information-centric networks that increase the internet's versatility, reduce its traffic congestion, and improve security, will require novel hardware and software; and (3) the creation of automated real-time insights at the "edge" of the IoT network will require deep-learning chips and novel machine-intelligence software. By connecting billions of every-day devices to the internet, the IoT will open up opportunities for companies and consumers: it will enable information gathering and management of the connected devices thus increasing efficiency and providing new classes of service (e.g. remote health monitoring; assisted living; wearables; pay-as-you-use services, ...). The IoT is also enabling other developments such as: connected cars, the smart home, smart cities and the Industrial IoT (the Smart Factory or Industry 4.0).

Autonomous vehicles – 90% of all vehicle innovation comes from electronics and software,[13] addressing passenger comfort (navigation, entertainment), power supply/efficiency and driver support (cruise control, lane departure warning, parking assistance).[14] But taking the "human factor" out of driving has recently become a high priority: every year there are 1.3 million road fatalities worldwide and 94% of accidents are driver-related. Large-scale proliferation of self-driving fully-connected cars will only materialise if they are secure and reliable. Current consumer confidence in these new technologies is rather low and therefore automotive quality and security are essential. Key functions needed to enable autonomous driving like V2X (vehicle-to-environment or

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vehicle-to-vehicle) communication, car radar, and ethernet local area network (LAN) technology become available today but will continue to evolve in performance as well as in integration level for the sensing, computing and acting functions to be implemented. Advanced mixed-signal RFCMOS technology enables the integration of high-performance wireless functionality, together with digital signal processing at low power and low cost.

Blockchain – Whereas the purpose of most traditional protocols used by internet applications is *information* exchange, blockchain enables protocols for *value* exchange (financial transactions such as bitcoin; but also digital assets, proof of ownership, authenticity of luxury goods, smart contracts).[15] The data are recorded independently, not in one place but distributed across a multitude of computers around the world; records are condensed (into 'blocks') and interlinked (into 'chains') using complex algorithms. This new technology facilitates a shared understanding of value attached to specific data and thus allows transactions to be carried out. In itself, blockchain is a distributed database that acts as an open, shared and trusted public ledger that nobody can tamper with and that everyone can inspect. Protocols built on blockchain (such as bitcoin) specify how participants in a network can maintain and update the ledger using cryptography and through general consensus. The combination of transparency, strict rules and constant oversight that can potentially characterise a blockchain-based network provides sufficient conditions for its users to trust the transactions conducted on it, without the need for a central institution. As such the technology offers the potential for lower transaction costs as it removes the necessity of trustworthy intermediates to conduct the value transfers. It could disrupt markets and public institutions of which the business model is the provision of trust behind transactions.

Artificial Intelligence – A huge milestone was reached in March 2016 when AlphaGo, a program developed by Google's DeepMind unit, defeated legendary "Go" player Lee Se-dol at the ancient Chinese board game, which has long been considered one of the great challenges faced by artificial intelligence (AI) in view of the high level of intuition and evaluation required by Go. DeepMind's AlphaGo program is the most advanced AI effort yet, using a complex system of deep neural networks and machine learning. As opposed to other AI systems, DeepMind is not pre-programmed for a specific task: using "deep learning" on a convolutional neural network, it learns from experience, using raw pixels as data input. More 'serious' applications e.g. in health care have been announced: DeepMind would be applied to the analysis of anonymised eye scans, searching for early signs of diseases leading to blindness and in August 2016, a research programme was announced with the aim of developing an algorithm that can automatically differentiate between healthy and cancerous tissues in head and neck areas. According to Marc Benioff, we are on the cusp of a major convergence: big data, machine learning, and increased computing power will soon make AI ubiquitous.[16] He projects that AI will become like electrical current: invisible and augmenting almost every part of our lives.

5G mobile network – As the world becomes increasingly connected, we need a network that will support emerging technologies like self-driving cars, virtual reality and the IoT.[17] Using advanced ICT infrastructure and encoding, 5G will be able to carry more data, at higher speeds and will also be able to move around obstacles, providing greater coverage. The Next Generation Mobile Networks Alliance (NGMN) is aiming to get 5G to 20 Gbps

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speeds and 1 ms latency. If it reaches this, download speeds will be 40 times faster than for today's 4G network. A 5G network is set to provide up to a million connections per square kilometre. This will be fundamental when it comes to creating "Smart Cities", as it will connect millions of IoT devices, from traffic lights to wearables. 5G is going to change the way we live, work and play. Its high data throughput and low latency will allow the mobile viewing experience – including virtual touch – of virtual and augmented reality to go mainstream. But 5G is not just about exciting new media experience opportunities – it will also help to improve the world around us: remote communities will have access to fast broadband, and bandwidth for residents in urban environments will not be limited. The reduced latency in a 5G network will ensure that self-driving cars will respond instantaneously to commands (e.g. to brake). Dangerous and hazardous tasks could be executed from a safe distance through drones and precise machine-to-machine communication. Equipment maintenance and training will also be facilitated through virtual reality (VR) over 5G.

2.3. The European Strategy for a Digitalised Future

In order to boost Europe's productivity which has been lagging with respect to the U.S., the ubiquitous adoption of ICT throughout the European economy – and the resulting transformative change it can bring – is generally seen as a powerful instrument[18] and the strategy for the Digital Single Market (DSM) in Europe – launched by the EC on 6 May 2015 – is one of the top priorities of the Commission Juncker.[19] By bringing down 'digital barriers' within Europe it has been estimated that the DSM would contribute an additional €415 billion to Europe's aggregated GDP. In its communication, the EC saw the DSM based on Europe's actions in 3 major areas: (i) better access for consumers and businesses to digital goods and services across Europe; (ii) creating the right conditions and a "level playing field" for digital networks and innovative services (from both traditional and new players) to flourish; and (iii) maximising the growth potential of the digital economy. The EC pointed out that issues of data, skills and common standards need to be addressed. These are essential for all industrial sectors to be able to integrate new technologies, such as big data or cloud computing, and manage the transition to a "smart industrial system". At a larger scale, this would allow European citizens to fully benefit from interoperable e-services, from e-government to e-health, and develop their digital skills to boost their chances on the job market. For many observers, the 'acid test' of Europe's DSM strategy will be its impact on economic growth and job creation. In 2010 the EC launched "Europe 2020",[20] the European Union's ten-year strategy for jobs and growth, with a vision for a social market economy that would (i) be aiming at helping Europe come out of the economic crisis; but (ii) also involve social innovation, as the goal was to create the conditions for growth that would be 'smart' (i.e. based on knowledge and innovation), 'sustainable' (i.e. more resource-efficient) and 'inclusive' (i.e. delivering social and territorial cohesion).

It is generally acknowledged that in order to fully benefit from the "digital inside" in products; from digital transformation in processes and from disruptive changes in business models through the use of new platforms, the support of a strong Europe-wide digital industry is essential.[21] This is thought to be facilitated through: (i) coverage of the full value and innovation chain in Europe's digital industry; (ii) a smart specialisation network across Europe's regions; and (iii) alignment of policies and resources across Europe (see also section 6. below).

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As to R&I, ICT-related activities are supported in the framework programme "Horizon 2020" – implementing the Innovation Union – covering the full innovation chain from basic research to market uptake, i.e. in the 3 pillars Excellent Science; Leadership in Enabling and Industrial Technologies; and Societal Challenges (involving multidisciplinary application-driven R&I).[22,23]

2.4. Impact of ICTs

We live in an unprecedented era of hyperconnectivity[g] that is redefining our societies, cultures, living spaces and communications.[24] All around us, the world has become dependent on electronic systems. From data collection and search engines to e-commerce and social networking, the internet has become the "ubiquitous cloud" that is connecting every aspect of our daily lives. Today, our mobile devices support social media and web browsing, multimedia entertainment and various forms of connectivity that allow instant access to thousands of applications and internet-based services. Tomorrow, these devices will support augmented reality, seamless voice control, 3D holographic screens and powerful predictive analytics. All of these advances offer possibilities that enrich the lives of people around the world while generating growth and opportunities across the global economy.

The World Economic Forum (WEF) has recently published the report of a survey[25] intended (i) to capture some of the "deep shifts" occurring in society as a result of the exponential rate of technological change we are experiencing; and (ii) to encourage everyone to consider the impact of these shifts and to prepare for the changes ahead. The survey results were also analysed to see what percentage of respondents expected the shift or "tipping point" (equivalent to 80% of respondents) to occur and by when. A total of 21 technologies were studied and 11 of these had a tipping point by 2025 or before. Both positive and negative anticipated impacts of each shift were listed. A discussion of the results is beyond the scope of this paper, but two emerging capabilities are clear: (i) digital connectivity of everyone to everything, everywhere and at any time; and (ii) a set of mechanisms and/or tools for analysing and using the data associated with nearly all aspects of daily life. This will result in innumerable services by and between individuals and organisations of all types (companies, non-profit organisations and governments).

The WEF report (ref. 25) has also identified some impacts which cut across many facets of society and the online economy. It discusses a few key areas: (i) the transformation of jobs and the nature of work; (ii) security as a competitive differentiator and mechanism of trust for users and partners; (iii) protected privacy and ensured trust as a shared responsibility; (iv) data and information as 'the new currency', its emancipatory potential and the impact on the economy; (v) shifting relationships between the individual and organisations & communities; (vi) shift from ownership to access in a collaborative economy.

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[g] The term "hyperconnectivity" was coined by Canadian social scientists Anabel Quan-Haase and Barry Wellman (in 2001), arising from their studies of person-to-person and person-to-machine communication in networked organisations and networked societies; see https://en.wikipedia.org/wiki/Hyperconnectivity. For persons, the term refers to the state of "being connected anywhere any time on any device". It is interesting to note that in response to calls for improving the work-life balance, France is the first country in the world where a law entered into effect as of 1 January 2017, allowing workers to remain "off-line" after working hours.

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The WEF also regularly publishes the results of its “Global Risks Perception Survey”. In the 2017 survey,[26] respondents have rated AI and robotics as the emerging technology with the greatest potential for negative consequences over the next decade. What happens e.g. when the AI “ecosystem” begins to listen in on private conversations and decide independently what is best for us? Maynard distinguishes between risk from technology for which technology in turn can provide solutions (e.g. a health or environment risk); and risk “as a threat to something we value” – depending on what is important to individuals, communities and organisations (self-worth, culture, sense of security). Maynard considers the latter a richer way of thinking about possible impacts from emerging technologies as it inspires us to look for “new technologies that make our world a better place, not just a different one”.[27]

2.4.1. Impact for companies

The tectonic shift which we are observing is made possible by the fundamental building blocks of the digital world: semiconductors and the ICTs based upon them. They enable and amplify the megatrends that (i) help the companies to achieve greater flexibility at lower cost; and (ii) these companies in turn seize the opportunities of providing their customers with disruptive products and services.

One important way in which ICTs are affecting the business environment is by reducing the importance of distance: companies have more freedom in locating certain economic activities in other labour or capital markets while still monitoring and integrating their value chain using ICT tools. The potential downside or threat from digital disruption for companies is first and foremost at the strategic level: a lack of suitable response to the challenge of a technological change can dramatically increase a company’s vulnerability.[h]

2.4.2. Impact for society

Opportunities and threats perspired from the examples mentioned in the overview of ICT developments above (section 2.2). Let us e.g. consider the blockchain technology again: it allows assets to be shared which will lead to new business models and create opportunities for social self-organisation in the sharing economy. However, as it is unregulated and not overseen by any central bank, it means there will be less control over monetary policy for governments.

In recent years, the impact of ICT on the nature and future of work has caused an animated debate. The rapid technological change influences the number and quality of jobs, the nature of work, the income inequality and the polarisation of the labour market. Technology has been blamed to cause wage stagnation and to “hollow-out” the middle-skill and middle-wage positions which often consist of routine tasks that are increasingly threatened by automation and computerisation. While these jobs are declining, there is a growing demand for non-routine jobs requiring analytical, interpersonal and creative skills to address non-standard problems.[28] Some economists, on the other hand, have suggested that technology’s role in wage inequality is overstated, and point to policies of encouraging labour-reducing innovation.

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[h] A notorious case is that of Eastman Kodak which struggled with decline as digital photography destroyed its film-based business model. Despite massive efforts spanning two decades, Kodak was unable to convert its strategy in digital photography into either market leadership or profitability.

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Frey and Osborne suggest boldly that – with the availability of big data and suitable algorithms to analyse these – also a wide range of non-routine cognitive tasks are at risk of being computerised.[29]

The multitude of online platforms allow people to interact nearly continuously. They also have expanded the civic space by providing citizens and organisations with (i) new opportunities to make their voices heard, express their grievances and demand their right; and (ii) innovative ways to hold decision-makers accountable. At the same time, ICTs benefit individuals or groups seeking to leverage technology for spreading hate or misinformation, and present challenges for law enforcement and other authorities. Digital life is becoming inextricably linked with a person's physical life allowing us to connect in multiple ways and disseminate or collect information anywhere any time. But technological tools are also being used to increase surveillance and control over citizens, whether because of legitimate security concerns or – in regions where freedom of speech is under threat – in an attempt to eradicate criticism and opposition.

It is important that we recognise the public responsibilities of "superpowers" such as Google, Facebook and Twitter that have been dubbed POPS (for 'privately owned public spaces'). They do more than merely enable our global public "agora".[30] The algorithm of Facebook's news feed determines the selection of news viewed by hundreds of millions of people every day, which represents extraordinary power. Research suggests that misinformation is as likely to go viral as accurate information, so if the main criterion for the algorithm is "*what your friends have liked*" this is not helpful in combatting "fake news". Until recently the internet companies have been reluctant to face up to this responsibility as they preferred to present themselves as neutral intermediaries. Fortunately, this is beginning to change in the wake of recent notorious cases of fake news. This led Facebook's CEO Mark Zuckerberg to write a remarkable post in which he said: "We're a new kind of platform for public discourse — and that means we have a new kind of responsibility to build a space where people can be informed." It remains to be seen to what extent Facebook will be willing to modify its algorithm in order to filter out fake news. But it becomes clear that the emerging platforms and online intermediaries (such as Facebook, but also Uber, Airbnb a.o.) – although emblematic for the collaborative economy – will need some form of regulatory environment.

2.4.3. Impact for individuals

Innovation studies have mainly been interested in how the diffusion of new technologies affects economic performance: growth, competitiveness and employment. Recently, innovation studies have started to study the nature and determinants of human well-being and a.o. the effects of ICTs. In spite of the large variety of mechanisms linking ICT use to well-being, one study groups the effects in four categories – affecting the working and social life and each with a mix of benefits and risks:[31] (i) time saving; (ii) emerging activities; (iii) access to information; and (iv) communication and interaction tools.

One of the emerging activities I would like to emphasise is (new formats of) learning, as retraining and upgrading professional skills is important in a society based on rapidly advancing technologies. This results in life-long learning which is supported by complementing

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class-room education with online education via the internet (massive open online courses or MOOCs; virtual class-rooms etc.).

I already referred to people's growing digital presence linked as an extension of their physical life, multiplying their interactions in (virtual) space and in time. In 2012 the EC envisioned and implemented the remarkable "Onlife Initiative"[32] which involved a multidisciplinary team of 12 experts (i) exploring the key question "What does it mean to be human in a hyperconnected era?" and (ii) addressing gatekeepers and policy makers in the private and political sector. The outcome of the project was "The Onlife Manifesto". The team concluded that the hyperconnectivity in all aspects of human life affects radically the human condition and has identified 4 'tectonic' shifts: (i) the blurring of the reality/virtuality boundary; (ii) the blurring of the human/artefact/nature distinction; (iii) the reversal from information scarcity to Information abundance; (iv) the shift from primacy of 'entities' to that of 'interactions'. One of the most innovative thoughts of the Manifesto is that our information age can also be seen as the "attention age". In contrast to the infinite mass of information, attention is a very limited good and this leads the team to conclude that the contest of the working world and of the economy for human attention is a serious threat. The team's position regarding the claim of the human as a political actor is clear. Less clear is the demand for a more balanced distribution of power and responsibility among public authorities, corporate agents and citizens.[33]

The authors of a thought-provoking paper[34] on the "hybridisation" processes characterising human entanglements with emerging technologies suggest that we move beyond the politics of internet governance and focus on the "constitutional" nature of the resulting transformations against a background of basic rules that bind a state to its citizens – and vice versa – that have undergone only minor modifications. Six technological settings are identified that challenge our existing constitutional features: (i) the "digitalisation" of our body; (ii) the "collectivisation" of our memory; (iii) the extension of our senses and action radius through the internet-of-everything; (iv) the amplification of our physical observation capacity (cameras and drones, but also remote care); (v) the extension of our physical contacts and connections through our cyber profiles; and (vi) the emerging "political space" and technologically mediated citizenship. The authors remark that constitutional legal thinking has traditionally taken for granted the boundary between nature and society, knowledge and norms and (citing Jasanoff) the "tacit understanding that humanness is held constant by nature (biology)".[i] The authors call on all stakeholders to (i) consider the constitutional dimensions introduced by ICTs; (ii) consider the values embodied by our technologies and make them a site for transparent access and choice; and (iii) favour human integrity and agency while preserving it from impoverished human relations.

Other authors have – along the same line of thought – pointed out that transformations to the law are called for in relation to our expanding digital culture and the "smart" technologies that rapidly reconstruct our world, with perhaps one salient functionality: the prediction and pre-emption of our day-to-day activities, preferences, health, spending capacity, credit risk and – even – criminal intent. Hildebrandt states that we are in transit between an "information society" and a "data society" with far-reaching consequences.[35] The pervasive employment of

[i] S. Jasanoff, "Rewriting Life, Rewriting Rights" (2011), see https://ael.eui.eu/wp-content/uploads/sites/28/2013/04/02-Tallacchini-Rewriting-Life-Reframing-Rights.pdf

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machine learning technologies that inform data-driven agency threatens our privacy, identity, and autonomy. She argues that smart technologies undermine and reconfigure the ends of law in a constitutional democracy. However, she calls on lawyers, computer scientists and civil society not to reject smart technologies and explains how further engaging these technologies may help to "reinvent" the effective protection of the rule of law.[j]

Online privacy is one of the aspects of our "digital identity" that causes growing concern: we feel it is under constant pressure of being undermined while on the other hand privacy is essential to reinforce user trust of online services. The Internet Society states that promoting strong, technology-neutral data-privacy laws, privacy-by-design principles and ethical data collection and handling principles are key elements of an approach to protecting and fostering online privacy.[36] Some authors take a rather lenient position on privacy reminding us that neither "privacy" nor "property" can have absolute value in an ecosystem based on platforms. In a business environment where we want personalised service, we have to allow transparency and give up some privacy. Kelly (ref. 3) lists 25 types of devices and systems in the U.S. that routinely track some kind of personal information, from high-way traffic cameras to the postal mail being scanned and digitised. Not all of these bit streams are related to personal service, but rather with safety or government interaction. Kelly reassures us that at this moment, the 25 bit streams are not integrated and correlated – although that is technically possible and might happen in the future. Another concern in the "Big Data" era that we are entering is the extent and efficiency of stripping out or encrypting personally identifiable information, which might be vulnerable to "re-identification" making the data trivially associated with an individual.

Implants and human augmentation are technologies that appeal to the imagination. As we are becoming more 'connected' to devices, at some point these devices will no longer be solely worn on the body. In fact, pacemakers and cochlear implants have been widely accepted and mark the beginning of this trend. Four companies are currently working on mechanical devices that can permanently replace the human heart, two of which have regulatory approval for clinical trials.[37] But at some point, devices will also be implanted for other functions such as communication, location and behaviour monitoring, advanced health monitoring or support. The WEF report mentioned above (ref. 25) indicates 2023 as the 'tipping point' for the first implantable communication device becoming commercially available. Human brain – computer interfaces are already used for therapeutic purposes, one example being deep brain stimulation used to relieve the symptoms of Parkinson's disease. Cases have been reported where people who have suffered spinal injuries are able to control physical functions using devices that capture their brain signals. While these can be considered essential medical interventions to relieve suffering or restore functions,[38] other "non-essential" 'digital' interventions for human enhancements (such as brain modification to increase memory or

[j] The EC recently proposed policy and legal solutions to unleash Europe's data economy, as part of its DSM strategy; see http://europa.eu/rapid/press-release_IP-17-5_en.htm?locale=en . The package aims at addressing "unjustified restrictions to the free movement of data across borders as well as several legal uncertainties". Related public consultations have been opened.

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reasoning capacity) as a preview of a “trans-human”[k] era have stirred controversy and ethical debate.

2.4.4. Concluding reflections on the impact of ICT

There is no doubt that the emerging technologies will inevitably transform the world in many ways – some desirable and others not. The extent to which the benefits are maximised and the risks mitigated will depend on the quality of governance – the rules, norms, standards, incentives, institutions and other mechanisms that shape the deployment of each particular technology. Too often the debate takes place at the extremes of possible responses: among those who focus on the potential gains and others who emphasize the potential dangers. The real challenge lies in navigating between these two poles: building understanding and awareness of the trade-offs and tensions we face, and making informed decisions about how to proceed. This task becomes more pressing as technological change deepens and accelerates.

Transformative technologies and innovation resulting in a growing dematerialisation and demonetisation have inspired some analysts to paint a utopian future of abundance, where 8.5 billion people on earth (projected by 2030; UN 2015 estimate) have a “first-world” standard of living – with access to sufficient food, clean water, shelter, energy, education, health and freedom. But the fear exists that the precarious “pre-abundance” period will still be characterised by a “digital divide” – an uneven distribution of knowledge, access and services – leading perhaps to turmoil and animosity.

3. Current and emerging RRI issues in nanoelectronics and ICT

3.1. What is the origin of RRI?

The connection between innovation and economic growth is solidly embedded in European policy discourse. This equally holds for expectations from innovations in nanoelectronics and ICT. In section 2.4, I have broadened the scope and elaborated on the broader impact of nanoelectronics and ICT on society-at-large. In a recently published comprehensive overview of innovation,[39] its nature and complexity are analysed and the many initiatives taken by Europe at all levels to promote innovation and growth are examined. It rests on the overarching conviction that Europe will want to remain an innovator *in and for the world*.

The relationship between ‘science’ and ‘society’ has gradually shifted in EU policy narratives[40,41] towards “science *with* and *for* society” and in Horizon 2020, RRI appears not only in focused projects but also as a cross-cutting ambition.[l] The EC defines RRI as “... an

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[k] “Transhumanism is a class of philosophies of life that seek the continuation and acceleration of the evolution of intelligent life beyond its currently human form and human limitations by means of science and technology, guided by life-promoting principles and values” (Max More, 1990).

[l] Through a study of documents issued by the various EU institutions, S. de Saille (ref. 41) gives a fascinating account of the history of the science-society relationship in Europe and of the extent, range and nature of RRI. In her concluding thoughts, the author notes that *“... the translation of RRI from academic theory to innovative*

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approach that *anticipates and assesses potential implications and societal expectations* with regard to research and innovation, with the aim to foster the design of inclusive and *sustainable* research and innovation."[42]

More explicitly stated, RRI wants to be the expression of the ongoing process of aligning Research and Innovation with the values, needs and expectations of society.[43] It requires "(...) *stakeholders to become mutually responsive and ascertain that research and innovation outcomes underpin grand challenges of our time, for which they share responsibility."* Stilgoe et al. have defined responsible innovation as "(...) *taking care of the future through collective stewardship of science and innovation in the present*".[44]

Its conciseness makes the definition of Stilgoe attractive, but it raises questions about exactly how RRI should be implemented. According to von Schomberg,[45] "*RRI should be understood as a strategy of stakeholders to become mutually responsive (...) and anticipate research and innovation outcomes underpinning the Grand Challenges of our time, for which they share responsibility."* More specifically as a definition for RRI, he proposes: "*A transparent, interactive process by which societal actors ... become mutually responsive aiming at (i) ethical acceptability, (ii) sustainability and (iii) societal desirability of the innovation process and its marketable products*." It should be noted that this largely exceeds the requirement that R&I effectively addresses the grand (societal) challenges (SC): the societal actors need to address the SC while aiming at (i) ethical acceptability, (ii) sustainability and (iii) societal desirability of the innovation process and its marketable products. On its website, the UK Engineering and Physical Sciences Research Council (EPSRC) in the same spirit states that "Responsible Innovation is a process that seeks to promote creativity and opportunities for science and innovation *that are socially desirable and undertaken in the public interest*."[46]

RRI implies some form of responsibility which needs clarification. In Iatridis and Schroeder[47] three components of responsibility are mentioned: legal obligations, contractual obligations and moral obligations. It is also noted that moral responsibility in a work context is the most difficult to define. Moreover, invoking responsibility immediately begs the follow-on questions: "Responsible for what?" and "to whom?". Interesting as these questions may be, it is beyond the scope of this paper to further elaborate on the responsibility aspect.

At this point, I would like to add a few remarks on the linkage between Research and Innovation, which is far from obvious. The origins of the linear model of innovation (basic research – applied research – development – production) have been studied and the model criticised.[48] Whereas – partly due to its simplicity – the linear model is widely applied, it still has its opponents. Innovation is a complex process that as a tool to progress has been shown to have many different sources. In this light, a single framework for research and innovation may prove problematic: the mission of research is to advance objective knowledge about nature,[m] whereas (technological) innovation is concerned with application. The role of technology itself has changed: in the past it related to conquering *nature*; in our times, it often

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European policy framework produces several tensions which will need to be addressed in order for RRI to become truly responsible to the needs, ambitions, and values of European society."

[m] "*Gravitation cannot be held responsible for people falling in love*" (A. Einstein, quoted in ref.49). While this quote does not translate well in all languages, its meaning is clear: fundamental laws of nature are there to be studied and understood, but cannot account for whatever consequences they may lead to.

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interacts directly with human relations and society. Add to this the ubiquity of modern technology and the magnitude of its impact: nanoscience generates an enabling nanotechnology with countless applications. Linking both Research and Innovation to the notion 'responsible' is an indication that doubt about scientific progress is not confined to its technological application, but is increasingly raised at the stage of research.[49]

Jerome Karle[n] observed already in 2000[50] that public officials in the U.S. "(...) wish to alter somewhat the pattern of funding for science.(...) It is becoming increasingly apparent that those public officials who control public funds, will be reluctant to fund research programs that they consider unrelated to national needs." He continues by stating that "the major developments in science and technology generally derive from curiosity-driven research and these developments have had over time great impact on the national interest, enriching the country with whole new industries and making contributions to the health, welfare, comfort and security of society." In the concluding section of his paper, he states rather bluntly "There is no question that science and society will continue to co-evolve. The nature of this evolution will certainly be affected by the extent to which governments set funding priorities. Societies whose governments recognize the dependence of the development of successful novel technologies on broadly supported basic research are more likely to be healthier and economically prosperous in the future than those that do not."

3.2. Societal Challenges

The "Horizon 2020" (H2020) program for R&I reflects Europe's policy priorities and addresses major concerns shared by citizens in Europe and elsewhere.[51]

The foundational idea is that a challenge-based approach will (i) bring together resources and knowledge from different fields, technologies and disciplines, including social sciences and the humanities (SSH); and (ii) cover activities from research to market with a new focus on innovation-related activities, such as piloting, demonstration, test-beds, and support for public procurement and market uptake.

Challenges in 7 priority areas have been identified, where targeted investment in R&I are expected to have a real impact benefitting the citizens:

1. Health, demographic change and wellbeing;
2. Food security, sustainable agriculture and forestry, marine and maritime and inland water research, and the bio-economy;
3. Secure, clean and efficient energy;
4. Smart, green and integrated transport;
5. Climate action, environment, resource efficiency and raw materials;
6. Europe in a changing world – inclusive, innovative and reflective societies;
7. Secure societies – protecting freedom and security of Europe and its citizens.

[n] 1985 Nobel laureate in chemistry.

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It should be noted that these are 'priority areas' and not specific challenges; these have been described in more detail in other reports from the EC.[52]

It is comforting to see that already in 2008, a select group of international experts identified the grand challenges for engineering and – among other initiatives – two Global Grand Challenges Summits were convened (in 2013 and 2015) jointly by the US National Academy of Engineering, the UK Royal Academy of Engineering and the Chinese Academy of Engineering; a follow-on summit is planned for 2017. In a joint publication,[53] the presidents of the 3 academies note that "adoption of the Grand Challenges is more akin to a movement than a project. People in movements are drawn to needs and ideas that they adopt, nurture and introduce to others."

3.3. What are the constituting elements of RRI?

In 2012 the EC DG Research published a brief leaflet[54] laying out six 'keys' of RRI: (1) inclusive engagement; (2) ethics (defined as shared values reflecting fundamental rights); (3) gender equality; (4) science education; (5) open access to the results of publicly-funded research (publications and data); and (6) new governance models (with the aim of designing science with and for society). Later the 'keys' or 'action lines' were reduced to the first 5, where the 6th key (related to governance) became an overarching action aiming at the uptake of the RRI approach by stakeholders and institutions, ensuring "good governance" through the promotion of institutional change.[55] In my view, S. de Saille correctly remarks (ref. 41) that the six keys are not necessarily specific to RRI, but *"... are broadly the result of legal changes in the governance of the EU, and to an evolution in the understanding of the rights of the citizens to have a say in how they are governed*."

In the remainder of this paragraph, I will review the six keys or dimensions of RRI - with reference to nanoelectronics and ICT wherever possible. But the framework for ensuring RRI has not been unambiguously established. Therefore, I will briefly discuss other RRI governance models in section 3.4,

3.3.1. Public engagement

In the description of the successive H2020 work programmes for ICT, the EC has emphasised the importance of new mechanisms of communicating the outcome of EC-funded research projects and improving the public level of understanding and societal uptake through two-way public engagement activities.

Boucher et al. have reported on three case studies (open IoT, civil drones and wearable sensors) for which they used "ethics dialogues", involving in-depth interviews and focus group methodologies.[56]

It should be noted that only recently have people begun to think *systematically* about how to promote better public discourse and decision-making about what is sometimes controversial

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science.[o] Scientists would like to rely on evidence, to gain insight on how to most effectively communicate what they know and do. But the '*science on how to communicate science*' across different issues, social settings and audiences has not led to concrete recommendations.[57] It e.g. becomes increasingly clear that the 'deficit model' (assuming that by "filling up people" with science knowledge they will become increasingly rational decision-makers) does not work. A very recent draft report by the U.S. National Academies of Science ("Communicating science effectively: a research agenda" – see ref. 57) makes a number of recommendations in this respect. In Europe, some recent focused projects – such as the PE2020 project – have studied innovations in public engagement in depth.[58]

3.3.2. Ethics

Clearly the pervasive use of state-of-the-art ICT makes interactions in modern society more complex and thus harder to understand, which impedes interventions to avoid harm. Therefore ethics aspects have been addressed early-on in the design of information systems. For similar reasons ethics is one of the RRI keys that have been most reported on, also by the EC.[59,60] Santucci (ref. 59) gives a comprehensive overview of some important ICT domains and the relevant ethics issues.

The ETICA project (Ethical Issues of Emerging ICT Applications) (7FP, 2009-2011) was one of the leading projects that (i) identified ethical issues of emerging ICT technologies and their potential application areas; and (ii) developed recommendations on how to engage with the ethics of emerging ICT in a proactive and acceptable manner. Stahl has published a comprehensive overview of the rationale of and the findings from the ETICA project.[61] The author argues that there is a mismatch between the ethical issues one can reasonably predict and the ways used to address them. He lists recommendations which the various stakeholders should adhere to in order to be proactive and allow innovation to be socially responsible. He also remarks that (i) some objects of responsibility may be context-dependent; and (ii) that responsibility is not a predefined structure but may require review – together with stakeholders – in the course of the technology development process.

Usually three levels are considered in terms of ethical behaviour: (1) "*Are we behaving ethically within the organisation?*" – At the European level, ALLEA (the federation of 53 national academies of science and humanities) adopted the "European Code of Conduct for Research Integrity"[62] addressing proper conduct and principled practice as a canon for self-regulation with clear recommendations.[63,p] (2) "Are we *doing things right*?" (at company level) – Do we minimise harm to society or the environment through our processes (e.g. do we avoid eliminating jobs)? Example: Iameco Computers is an Irish company devoted a.o. to developing a sustainable, ecological, high-performance computer, free from the harmful chemicals and

[o] Scientists have been confronted for years with disregard for and inappropriate use of scientific evidence. The recently increased interest in science communication coincides with the selection by the Oxford English Dictionary of "post-truth" as the 2016 word of the year, defined as "*relating to or denoting circumstances in which objective facts are less influential in shaping public opinion than appeals to emotion and personal belief*".

[p] The European Association of Research and Technology Organisations (EARTO) has recently provided comments to the ESF-ALLEA Code of Conduct, stating that most RTOs already follow ethical norms based on universal principles as laid out in the Code of Conduct, but would like to see it adapted to the specificities of all research actors, i.e. not limited to science, but also encompassing applied research, technology and innovation.

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heavy metals built into most computers.[64] Are we behaving correctly within our government relations? Example: are we dutifully paying taxes? do we respect the rule of law and regulations? (3) "Are we *doing the 'right' things*? – Are our products 'socially desirable'? Are they of high priority? Example: do we contribute to efforts towards closing the global digital divide between developing and developed countries?

The ETICA project is perhaps one of the most extensive applications of future-oriented thinking to the ethical issues raised by ICT: it identified 11 major categories of ICTs expected to reach a significant level of development in the next 10-15 years (including ambient intelligence, artificial intelligence, cloud computing, robotics and virtual reality). It has been recognised that future-oriented ethical analysis should inform technology design, so that negative consequences can be anticipated and minimised.[65] Markus and Mentzer mention several applications of futures thinking to ICT ethics, e.g. a study of the privacy issues raised by the use of sensors and tracking devices; and a design-oriented study of video-surveillance technology.

The Menlo Report[66] is the result of a series of workshops in the U.S. which thoroughly summarizes a set of basic principles to guide the identification and resolution of ethical problems arising within the broad context of ICT, involving networks, hardware and software technology. It does not recommend particular enforcement mechanisms, but rather aims at improving consistency in ethical analyses and self-regulation for both individuals and organisations. The companion to the Report[67] details the principles and applications more granularly and illustrates their implementation in real case studies.

The World Summit on the Information Society (WSIS) is a broad platform of the "ICT for development community" for work on strengthening ethical development and avoiding unethical consequences. In a discussion paper for the 2013 WSIS meeting,[68] the global ethics network Globethics.net calls for value-based decisions and actions for the development of information, communication and knowledge. The paper makes recommendations in nine "P" core topics of the information and knowledge society.[q] In the paper Globethics.net also presents a call-for-action to the International Telecommunications Union regarding the governance of an ethical information society and encourages the implementation of that call as a contribution to the upcoming 2017 WSIS meeting in Geneva.

3.3.3. Gender

Working towards gender equality is an essential part of European R&I policy. The EC DG Research & Innovation periodically publishes a report providing indicators addressing the situation of women in all scientific disciplines. In the latest report "She Figures 2015"[69] the data also shed light on differences in the experiences of women and men working in research – such as relative pay, working conditions and success in obtaining research funds.

The gender gap in the work environment directly relates to the situation in education (see also section 3.3.4 below). Specific figures for gender differences in ICT are hard to find, but I assume that a first-level idea can be obtained from figures for STEM (science, technology,

[q] Principles, participation, people, profession, privacy, piracy, protection, power, and policy.

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engineering and mathematics). In Belgium, 4 out of 10 students in the 3rd level of secondary education (i.e. ages 16-18) choose the STEM option. But very few girls choose STEM options in technical and vocational secondary education. They are also underrepresented in most STEM disciplines in higher education (HE) (except in those with a focus on biology): although girls account for over half of new entrants in HE, three quarters of STEM students are male.[70] These phenomena can be observed throughout Europe, albeit in varying degrees.

Several reports have provided analyses and made recommendations to close the gender gap in STEM.[71,72] One phenomenon observed is the “leaky pipeline” which consists of the situation whereby the further a woman advances in her scientific studies and profession, the higher the likelihood she will drop out.
This is due to a number of conditions: marginalisation, funding gaps, family-unfriendly work environments, lack of female peers and mentors and a lack of professional recognition.

3.3.4. Education

The EC published the report of an expert group on science education,[73] offering a vision for “science for society”. It argues that we must provide the space for open, inclusive and informed discussions on the research and technology decisions that will impact citizens' lives. The report is aimed primarily at science education policy makers. It identifies the main issues involved in helping citizens to access the scientific debate; provides guidance on how industry can contribute to science education; and proposes a new framework for all types of science education from formal to non-formal and informal approaches.

When turning to the formal education of young people, it is critical to address the declining interest in STEM across Europe. Numerous efforts have been made to engage pupils, including: increasing the students’ interest by enlivening STEM classes; giving students a better understanding of the relevance of STEM through informal education; engaging students in awareness-raising activities around STEM jobs a.s.o.[74]

The international survey ROSE (Relevance of Science Education) analyses the views and attitudes to science of pupils towards the end of secondary school. The survey views positive attitudes towards science and technology as important learning goals, as interests influence later career choices.[75] Moreover, attitudes to science acquired in school might determine a person’s relationship to science and technology in adult life. The ROSE results seem to indicate several differences between the attitudes of boys and girls. Boys tended to be interested in the technical, mechanical, electrical, spectacular aspects of science; conversely, girls tended to show more interest in health and medicine, the human body, ethics, aesthetics and paranormal issues. Based on these findings, the ROSE research team suggests that the gender differences in interests and motivation be taken into account when teaching science in schools.

Sjoberg and Schreiner (ref. 75) also point out that many groups of stakeholders are involved with science education: (1) science teachers; (2) researchers in the field of science education; (3) research scientists; and (4) national and international organisations producing policy reports (such as UNESCO, EC, OECD). In practice, it is thought that educators lack cohesive understanding of STEM education and could benefit from a conceptual framework that

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emerges from recent education literature, providing a rationale for teaching STEM concepts in an integrated way, i.e. delivered in project, problem, and design-based approaches.[76]

In 2001, Marc Prensky introduced the term "digital natives",[77] referring to the students that are native speakers of the digital language of computers, video games, the internet and – today also – social media which are an integral part of their life. The way "digital natives" behave is characterised by (i) a transverse and complex approach to knowledge gathering; (ii) networks as an organisation and "way of thinking"; and (iii) collective intelligence. Education must prepare the citizens of our digital society, which poses not only technological, but also pedagogical and political questions.[78] It could be assumed that today's students – growing up as "digital natives" – are intuitively perceptive online. A report recently released by Stanford U.[79] finds the opposite to be true, i.e. that many students are having a hard time judging the credibility of online news and information. The Stanford researchers therefore urge teachers to create curricula focused on developing students' civil reasoning skills.

3.3.5. Open access

In its 2012 communication,[80] the EC set out measures to ensure that the results of Europe's publicly-funded research would be fully accessible for researchers, businesses and citizens and invited the European Parliament and the Council to show their support for the initiative. The European Competitiveness Council in its meeting of May 2016,[81] agreed to promote the mainstreaming of open access to scientific publications as the default by 2020. The Council encourages optimal reuse of research data from publicly-funded research projects, whilst recognising the need for different access regimes (because of IPR, personal data protection and confidentiality, security concerns, as well as economic competitiveness interests), stating as the underlying principle for the reuse of research data: "*As open as possible, as closed as necessary*".

Upon publication of the 2012 EC communication, the European Association of Research and Technology Organisations (EARTO) issued a report commenting on the plea for open access of publicly-funded research. Recently, EARTO has issued a position paper[82] stating that the open innovation model – widely used by RTOs – risks to be in conflict with the "open science" model if this is associated with "free-of-charge access for all". EARTO states that in a balanced approach to "open science", the emphasis should be on the availability and wide dissemination of technology rather than on the absence of pricing.

The Open Digital Science project[83] explored whether radically different scientific practices enabled by digital technologies are emerging, what they consist of, and how they are changing the relation of science and society. In particular, the study resulting from the project analysed and stimulated openness of scientific knowledge, by and for everyone to access, acquire, and benefit from.

3.3.6. Governance

Governance aims at reaching futures that are acceptable and desirable; the path forward is to some extent open to collective choice as the outcomes of R&I often are at the same time beneficial and taxing to society. Governance arrangements have to be (i) robust and adaptable

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to the development of R&I; (ii) familiar enough to align with existing practices in R&I; and (iii) allow for a shared responsibility and accountability among a large group of actors.

At this point, I would like to inject a caveat, realising that our innovation system sits at the intersection of two massive social enterprises: the system of knowledge production and the market system. The multitude of actors in innovation, their heterogeneity and dispersion and the organisational complexity of their interactions are daunting.[84] The "invisible hand" of the market organises a large portion of the interactions among these actors. But there is also a web of incentives and constraints designed by the "visible hand" of public and private organisations, resulting in laws, rules, standards, practices and patterns of behaviour. Efforts to adapt our innovation policy will need to take into account – or at least be aware of – these governing institutions, mechanisms and networks as a whole.

Balmer et al. reflect on a modus operandi for productive interdisciplinary collaborations between natural and social scientists.[85] They propose five 'rules of thumb' which offer a general guide based on practice rather than on theory.

Making abstraction of the complexity of the interactions mentioned above, RRI can be seen as a "critical accompaniment of technological development".[86] A responsible approach to ICT R&I requires a mix of pragmatic and theoretical thinking attitudes. For example, what we mean by privacy or how to enable trust is deeply impacted by the deployment of ICTs and requires both thoughtfulness and concrete actions. Such a proactive approach to RRI based on a critical accompaniment of technological development can be structured on 3 levels:

1. at the macroscopic level, by observing the evolution of the information society and building anticipatory perspectives of a responsibility-driven society development versus the market-driven development (e.g. involving the pervasive deployment of IoT);
2. at the meso-level, by grouping ICT-related research projects and associated SSH research to assess RRI developments at the level of specific ICT domains;
3. at the micro-level, by helping single ICT-related research projects to self-assess the implementation of the RRI concepts and approach in their specific R&I activities.

The H2020 project "RRI-ICT Forum" is one of the projects aiming at analysing, supporting and promoting the contribution of SSH to the RRI approach in ICT R&I. It has published a booklet providing good RRI practices and practical examples of their applications in different projects and ICT domains (such as smart cities, Internet of Things, e-agriculture, e-health, robotics and e-infrastructure).[87]

The recently completed "RRI-Tools" project has thematically categorised desirable RRI outcomes and identified the process requirements which the R&I activities have to meet.[88]

In 2012 the EC launched an initiative for Collective Awareness Platforms for Sustainability and Social Innovation (CAPS), in which the internet doubles as a forum for free production and exchange of knowledge. Resolving societal challenges requires more than sufficient political will, but will emerge from virtuous circles involving all stakeholders leveraging the networked intelligence of all involved for the public good.[89]

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In relation to governance, I would like to mention 'science diplomacy', an emerging term for an all but new issue: the interaction between science and diplomacy and the many challenges and opportunities arising from it. The use of science cooperation to improve international relations (*science for diplomacy*), facilitating international science cooperation (*diplomacy for science*) and informing foreign policy objectives with scientific advice (*science in diplomacy*) have a decisive role to play in solving global and societal challenges and setting the future ahead.[90]

3.4. Alternative frameworks for responsible research/science and innovation

As described in section 3.3, the EC has identified 6 key components of RRI that should be seen as "policy agendas", each with the potential to contribute to realising RRI processes and outcomes. Below I will briefly mention a few alternative frameworks for implementing RRI.

3.4.1. Four integrated dimensions (Stilgoe et al., 2013)

There are few agreed structures that rule emerging technologies which therefore require a move from old governance models to more decentralised and open-ended governance. Stilgoe et al. have articulated and explored 4 integrated dimensions of responsible innovation (ref. 44):

1. Anticipation: prompting researchers and organisations to ask "*What if...?*" questions; involving systematic thinking aimed at increasing 'resilience';
2. Reflexivity: rethinking prevailing conceptions about the moral division-of-labour; challenging scientific 'amorality';
3. Inclusion: adding new voices in the governance of science and innovation, leading to debate with 'mini-publics'
4. Responsiveness: responding to new knowledge as it emerges and to emerging perspectives, views and norms.

3.4.2. Four political rationalities (Glerup and Horst, 2014)

Based on the notion of 'political rationality' and considering (i) whether the object of 'steering' is *outcome* versus *process* based; and (ii) whether regulation is internal versus external, Glerup and Horst identify the following rationalities, represented in a 2 x 2 matrix:[91]

1. demarcation rationality (process oriented; internal regulation), aiming at excluding the social from the scientific production (which has an internal commitment to truth);
2. reflexivity rationality (outcome oriented; internal regulation), pointing towards science's responsibility to let itself be guided by society and its problems (providing 'truthful' and socially relevant science);

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3. contribution rationality (outcome oriented; external regulation), emphasising that responsible science and innovation should answer the public call for innovation and democracy;
4. integration rationality (process oriented; external regulation), advocating that science should be co-constructed with societal actors, based on "a dialogue before the fact", aiming at knowledge that is aligned with society's norms and values.

While each rationality is distinct, all of them address an 'interface' between science and society, which means that scientists cannot avoid a relationship with society. Within the realm of each of the 4 rationalities a way of securing the responsibility of science (and innovation) can be identified.
The reason why the rationalities are 'political' is that it is open for contestation as to how they should be defined and debated: this directly relates to the governance of science (see section 3.3.6), to the way in which it is regulated and practiced.

The identification of the 4 rationalities serves as a map of contemporary ideas on science and innovation governance which in turn can be used as a reference point for directions. But Glerup and Horst conclude their analysis with the sobering remark that their map "*does not make us any wiser about the relationship between what scientists actually do in their laboratories and the normative and political statements about proper conduct of science*".

3.4.3. Process dimensions (RRI-Tools, 2016)

The booklet "A practical guide to Responsible Research and Innovation", published by the RRI-Tools project (see ref. 88), addresses the various stakeholders involved in RRI. It lists 4 process dimensions which R&I practitioners need to implement in order to achieve the desired RRI outcomes. The process should be:

a. diverse and inclusive
b. anticipative and reflective
c. open and transparent
d. responsive and adaptive to change.

It appears that these process dimensions result from an aggregation of (i) an 'activated' version of the 6 policy dimensions as proposed by the EC (see section 3.3); and (ii) the 4 integrated dimensions as proposed by Stilgoe et al. (see section 3.4.1).

3.4.4. Concluding considerations

The various frameworks for RRI all face some conceptual problems:[92] (i) a certain fuzziness surrounds RRI, as the concept may have different interpretations in different national contexts and a different focus or importance in different technical areas; (ii) the various approaches of RRI (top-down or bottom-up; fixed or open-ended; general or case-sensitive) raise 'workability' concerns; (iii) RRI is conflict-prone, as it sits at the intersection of a multitude of social 'enterprises' with often very diverging interests.

The guiding principles proposed by Balmer et al. (see ref. 85 and also section 3.3.6 on Governance) for interactions between natural and social scientists deserve attention. They are deceivingly simple, but require that both sides make a considerable investment in the

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relationship, which should be based on: active and open-minded exchanges; a fair amount of professional risk-taking; open discussion of unshared goals; and "neighbourliness".

At this point, I would like to call attention to the strategy of "Creating Shared Value",[r] which aims at pursuing financial success for companies in a way that also yields societal benefits. The reason why corporations are developing a growing interest in the model, is that (i) the legitimacy of business has been called into question, and companies seek to regain the public's trust; and (ii) many of society's problems are so far-reaching that solutions need the expertise and scalable business models of the private sector. But aligning innovation and product development with the expectations of society requires businesses to initiate "collective impact" efforts that involve all stakeholders in their ecosystem.[93] Five elements are needed for a collective-impact effort to achieve its aim of large-scale societal change: (i) a common agenda; (ii) a shared measurement system; (iii) mutually reinforced activities; (iv) constant communication; and (v) a dedicated "backbone" support (from one or more independent organisations) to guide vision and strategy and ensure that all parties remain aligned and informed.

4. Regulations influencing R&I in nanoelectronics and ICT

Within the scope of this paper, I want to address regulations only as far as they relate to responsible practices in the research and manufacturing environment of nanoelectronics devices and systems. This means that other aspects will not be addressed, such as: (i) environmental issues (local and global) covering the full value chain from mining of critical raw materials to disposal of electronic waste; (ii) social issues and regulations (local and global) related with the production and usage of ICT systems (e.g. job quality); (iii) general safety and health issues (e.g. radiation levels from wireless devices; medical devices for monitoring and therapy). A report by Martinuzzi et al. contains a discussion of some of these ICT-related issues.[94] The FP7 project "SATORI" has also performed an ethics assessment of emerging technologies with focus on the KETs, including a.o. micro/nanoelectronics and nanotechnologies.[95]

The IOSH[s] has published an authoritative guide on general health and safety practices in a research environment, mainly addressing higher education institutes and research councils.[96] As mentioned in the introduction (section 1.), nanoelectronics is considered as part of the domain of nanotechnology.[t] Therefore, with respect to the more specific domain of nanoelectronics research, the general Code of Conduct (CoC) for Responsible Nanosciences and Nanotechnologies Research, developed by the EC in 2008, is applicable.[97] But the CoC was the subject of continued discussion. In its final report in 2012, the NanoCode project

[r] In the landmark paper "Creating Shared Value" (HBR 2011), Michael Porter and Mark Kramer argued that companies can move beyond CSR and gain competitive advantage by including social and environmental considerations in their strategies.

[s] IOSH (Institution of Occupational Safety and Health) is the chartered body for health and safety professionals, with over 40,000 members in 80 countries.

[t] This is based on the observation that it relies on a multitude of semiconductor processes that result in the patterning of macroscopic objects (viz. silicon wafers) at the nanoscale level (between 1 and 100 nm).

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recommended that the principles and guidelines of the code be extended to all new technologies and to science as a whole, as the recommendations of the CoC were in line with the ideas of RRI which started to develop around the same time.[98]

Several publications suggest that 'nanomaterials' should not be exclusively defined in terms of size (e.g. 1-100 nm); other considerations should also be taken into account, such as: (i) specific new effects that the material may exhibit below a size threshold; (ii) whether the nanomaterial is free or embedded. In an embedded form (such as in electronic devices) the material may pose low risk because of minimal consumer exposure and environmental release. However, some semiconductor fabrication steps involve nanoparticles, as e.g. present in slurries used for Chemical Mechanical Planarisation (CMP). Risk mitigation and determination of safety measures is then usually performed according to standard ISO/TS 12901[u] which provides guidance on occupational health and safety measures relating to engineered nanomaterials. Although nanomaterials in electronic devices – as mentioned earlier – are embedded in large-scale structures and thus pose no problem to the end user, fab workers can be occasionally exposed to nanomaterials, e.g. during maintenance of the processing equipment, or nanomaterials can be released into the environment. As long as the environmental and toxicological properties of engineered nanomaterials are not sufficiently known, the 'precautionary principle' is applied in handling the materials. The 'NanoStreeM' project[v] is defining strategies for safety assessment in IC manufacturing.

The manufacturing or use of bulk chemical substances is controlled by the EU legislation known as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), enacted in 2007 and intended to ban harmful substances or chemicals in products sold in the EU.[w] REACH requires companies to identify or register chemical substances that are manufactured in or imported into the EU with the European Chemicals Agency (ECHA) for safe handling. The substances are then evaluated by independent groups or authors to determine if they are harmful to human health and reproduction or to the environment. REACH also addresses what is known as '(chemical) substances of very high concern' (SVHC). The SVHCs are added to the candidate list of harmful chemicals, with suitable alternatives identified, if possible. Strictly speaking the REACH legislation does not apply to research organisations – as they are not directly bringing any product into the market – but (i) they adhere to strict ESH procedures in their research facilities; and (ii) they take REACH legislation into account, as their commercial partners will be bound by it once the fabrication process moves from the research to the manufacturing environment.

Recently there has been some debate resulting from friction between regulatory constraints and innovation. The semiconductor process sequence for a state-of-the-art IC consists of hundreds of steps in which new materials are regularly introduced. There is often a long lead time (up to 15 years) between the research stage and volume manufacturing using a new fabrication process. If the regulation process results in the ban of a specific chemical

[u] ISO Standard "Nanotechnologies -- Occupational risk management applied to engineered nanomaterials" -- Part 1 (2012): "Principles and approaches"; Part 2 (2014): "Use of the control banding approach".
[v] http://www.nanostreem.eu/
[w] The REACH legislation does not take into account any size of particles. More specific requirements for nanomaterials have proven necessary, therefore the EC is considering modifying some of the technical provisions in the REACH Annexes.

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substance, considerable development time may be lost which ultimately will impact the innovation and competitiveness of the European industry. Therefore, the European semiconductor industry has been arguing for chemical regulation certainty with exemptions/allowances for continued use of semiconductor materials – also considering the stringent practices of risk containment already enforced in the semiconductor industry.

5. Incentives influencing R&I in nanoelectronics and ICT

The available or anticipated market has been and still is a strong incentive for companies to keep developing technologies with scaled features, allowing in turn the development of more performing systems which in turn support the development of richer applications. The $340 billion global semiconductor market (2017, estimated) provides essential components for the much larger electronics devices and systems industries, including e.g. the automotive, entertainment, and medical devices industries. The rapidly increasing capability of IC systems supports rapid growth in functionality which translates into a feature-driven market. That is, electronics customers, in general, replace their electronic systems well before they are no longer useful, because the newer devices offer a compelling increase in capability (see ref. 10, p. 1723).

In order to prepare for access to the market with new technologies-systems-applications, semiconductor companies will allocate an important part of their budget to R&D. Global R&D spending of semiconductor companies in 2015 amounted to $56.4 billion,[99] which represents approximately 16% in R&D-to-sales ratio. At the same time, companies weigh critical "make-or-buy" decisions for the innovative technologies and many believe that purchasing in-progress research from research organisations (or other companies) provides a better return than relying on in-house research.

Authorities (at regional, national and EC level) have traditionally stimulated R&D in various ways. The data published by Eurostat[100] indicate that the European average R&D intensity of 2.03 % of GDP (2014) is still far removed from its 2020 target of 3 %. The justification for public subsidies to stimulate research at private firms is that the generation of new knowledge generates positive externalities. The problem for firms is that the new knowledge cannot be fully protected by intellectual property rights and, therefore, firms tend to under-produce such knowledge. At this point, governments will come in and make R&D support available. R&D support can be in the form of direct (competitive) grants, tax benefits, reduction of social security contributions for R&D personnel, support for training a.s.o. As an example of tax benefits, I refer to the French R&D tax credit scheme, called "Crédit d'Impôt Recherche" (CIR). As per the announcement in 2008, research tax credit rates have been increased to 30% up to a limit of 100 million euros of R&D expenditures. In 2013, the state contributed a total of €5.6 billion in support through the CIR scheme.[101]

In 2013 the Electronics Leaders Group released its strategy document towards doubling the economic value of semiconductor components produced in Europe by 2020-25 (see also

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section 6).[102] The ambitious action plan was based on an anticipated investment of €100 billion by semiconductor companies, support of €10 billion in public/private R&D over 7 years of the H2020 time frame, €5 billion of which distributed through the ENIAC/ECSEL JTIs as follows: €1.2 billion from the EC; €1.2 billion from Member States and > €2.4 billion from private companies.

An investment plan in the form of an "Important Project of Common European Interest" (IPCEI) in electronics has also been prepared as part of the EC's bold strategy. Getting an investment labelled as an IPCEI would trigger a special regulatory process that allows large-scale public/private investments in (pilot) production.[103] It is estimated that up to 20 % of the total cost can be covered by (local) state support, which is normally not allowed under EU state aid rules, but which is deemed important in order to create a global level playing field.

National funding is also available through the EUREKA projects: (i) PENTA, with a budget of €1.5 billion over 5 years; (ii) EUROSTARS (aimed at R&D performing SMEs; co-funded by the EC), with a budget of €1.15 billion over 7 years.[104]

As in recent years their R&D costs were increasing rapidly while revenues were only modestly growing, semiconductor companies have turned systematically to outsourced research according to the "open innovation" model,[105] also realising that the differentiating element is less in the technology, but rather in the customised systems developed in-house using that technology.

6. Collaboration cultures between the players in nanoelectronics and ICT

With respect to the development of semiconductor processing technology, international collaboration has been going on since about 20 years. As the IC industry evolved, the various technological steps, performed by specialised machines built by a variety of equipment suppliers, became increasingly complex. In order for the semiconductor industry to advance at the rate projected by Moore's law, the need was felt for coordination of equipment development and of the research on the corresponding process steps. A technology roadmap was thought to be useful as it would give an idea when a certain capability would be needed, allowing equipment suppliers and research teams to develop the various tools and process steps in time for assembly into the next process generation – tuned by the IC companies according to their device and system needs. This led to the ITRS (see also section 2.1), consisting of a set of documents which (i) are produced by a group of semiconductor industry experts; and (ii) represent their best opinion on the directions of research into various areas of technology, with time-lines up to 15 years into the future.

On the European scene, Public-Private Partnerships (PPPs) are an emerging constellation of actors for innovation purposes addressing the grand societal challenges which requires redefining the borders between science and society. Research funding agencies (at regional, national and European level) will often play an active role in defining the R&I roadmap and making sure technical, economic and social issues are addressed. The European Joint

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Technological Initiatives (JTIs) in ICT are an excellent example of PPPs as "spaces for concertation".[106]

As mentioned in section 2.3, a strong Europe-wide digital industry is essential in order to reap the benefits of the transformative shift from a digitised industry. In 2013 the Electronics Leaders Group (ELG) brought together the leaders of Europe's 10 largest semiconductor and design companies, equipment and materials suppliers and of the three largest research and technology organisations (RTOs), in order to bring back Europe at the leading edge in the design and manufacturing of micro- and nano-electronics.[107] The so-called "10/100/20" strategy which was launched intended to (i) make available €10 billion in public/private research funding; (ii) facilitate industry investment of €100 billion; and (iii) double the value of EU micro-chip production (i.e. from 10% to 20%) by 2020 and, in the process, create 250,000 new direct jobs in Europe.

In order to execute that strategy, public and private resources had to be effectively combined and the idea of a large JTI assembling the whole electronics value chain was conceived. The ECSEL (Electronic Components and Systems for European Leadership) Joint Undertaking was set up as a PPP between the EU, participating states and 3 private-member industry associations: AENEAS, ARTEMIS-IA and EPoSS.[x] The AENEAS association also manages PENTA (Pan European partnership in micro and Nano-Technologies and Applications), a cluster launched in 2015 as part of the intergovernmental network EUREKA.[y] The purpose of PENTA is – similar to that of AENEAS – to catalyse research, development and innovation in areas of micro- and nanoelectronics enabled systems and applications but in the case of PENTA, there is more focus on shared high national and industrial interest. PENTA also puts special emphasis on the inclusion of SMEs in the research projects it will generate. AENEAS is active in building project consortia and offers its members the coordination of access to the best suited support programme and funding instrument (either through ECSEL JU or PENTA).

The ambitious goals of ECSEL are in tune with the needs of industry and the long-term vision of Europe and the participating regions and countries. It develops essential capabilities (from advanced semiconductor processes to smart integrated systems), which in turn will enable key applications and 'lighthouse' initiatives addressing societal challenges (in transportation; connectivity and digital networks; energy efficiency; health and the aging society; safety and security; and smart manufacturing).The most recent AENEAS Strategic Agenda is a cornerstone document,[z] describing the ambitions in co-operative R&D&I activities, and

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[x] The 3 constituting industry/RTO/university associations are: (1) AENEAS = Association for European NanoElectronics ActivitieS (a network of nearly 200 R&D&I actors working along the electronic components and systems value chain); (2) ARTEMIS-IA = Advanced Research & Technology for Embedded Intelligent Systems – Industry Association (with 170+ members and associates); (3) EPoSS = European Technology Platform on Smart Systems Integration (40+ members).

[y] PENTA is managed by the association AENEAS, driven by industry and works with national public authorities across Europe. Submitted project outlines are evaluated by a PENTA technical experts group, the AENEAS management committee and the participating PENTA public authorities based on jointly established selection criteria.

[z] The AENEAS strategic agenda is a pan-European guideline for implementing public-private R&D&I partnerships and gives direction to the EUREKA cluster PENTA, the ECSEL JU, the H2020 program – in particular LEIT – as well as to national and regional instruments. Conversely, access to such cooperative programmes is key to the success of realising the ambition of the strategic agenda.

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providing essential roadmaps towards resolving societal challenges and strengthening the competitiveness of Europe along the electronics value chain.[108]

The AENEAS Strategic Agenda explicitly mentions “the human factor”, realising that society is becoming dependent on services from ubiquitous electronics devices and systems, e.g. through automated driving, smart cities and e-health. However, it is noted that public policy and decision-making often still dwells in the realm of the Second Industrial Revolution, where there was time to study issues and develop responses in a linear fashion. The Agenda, therefore, notes that innovations in the field of micro- and nanoelectronics-enabled components and systems need “to be accompanied by deep studies in socio-economic sciences and humanities”. This is a laudable call from the R&I community in ICT for collaboration between public and private actors, SSH scientists and civil society organisations in order to accomplish responsible research & innovation.

7. SMEs and RRI

So far, this paper has dealt with RRI in relation to the ICT and nanoelectronics eco-system as a whole, without referring to the size or annual turnover of the industrial actors involved, the reason being that most observations made are thought to be generic. At this point, however, I would like to devote some specific considerations to SMEs,[aa] as they are the focus group of the COMPASS project.

SMEs are the backbone of the European economy. They are primarily responsible for economic growth and prosperity. There are approximately 23 million SMEs in the EU, representing 99% of all enterprises and providing about 90 million jobs (i.e. two out of every three private sector jobs) and contributing 57% of the total added value created by businesses in the EU.[109]

Their flexibility in a changing business environment makes SMEs crucial for Europe’s success in the global economy. As innovation is a key component of economic growth, the EC’s framework programme devotes special attention to the capacity for innovation of SMEs and special support lines are made available. EASME (Executive Agency for Small and Medium-sized Enterprises) manages a.o. the H2020 “SME Instrument” with a budget (2014-2020) of € 3.1 billion; and COSME (the EU programme for the Competitiveness of SMEs) with a budget of € 800 million. The “I4MS” initiative (ICT Innovation for Manufacturing SMEs) with a budget of € 110 million in H2020 is intended to enable and foster the collaboration of manufacturing SMEs along their value chains with the help of digital innovation hubs.

As mentioned above, in the conviction of the need to innovate responsibly, the EC has devoted ample attention and financial resources to deploying the RRI concept; see e.g. the report “Options for strengthening responsible research & innovation”.[110] Given the extent to which SMEs contribute to the economy, it is reasonable to expect that the engagement of SMEs in

[aa] According to the EC definition, SMEs are economically independent companies with less than 250 employees and less than €50 million annual turnover (or €43 million annual balance sheet). Nine out of ten SMEs are actually micro-enterprises with less than 10 employees.

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responsible innovation (RI)[bb] receives special attention and is stimulated. But the 78-page document refers only succinctly to SMEs: apart from the support instruments (CIP;[cc] COSME), SBIR[dd] is the only tool mentioned in terms of instruments dedicated to promoting RRI projects in SMEs.

There are various favourable factors concerning the engagement of SMEs with RI. Compared to large firms, their entrepreneurial attitude allows for more willingness to take risk, they are less hierarchical and more flexible to respond to changing market conditions, they can interact more directly with their customers and value chain partners, and they can more easily transition to new technology landscapes using new business models and monitor the direct impact of their innovation and the knock-on effect on other sectors (such as e.g. the use of rare materials).[111]

On the other hand, there are also various factors hampering the engagement of SMEs with RI. They often have restricted access to existing financial or fiscal incentives, due e.g. to insufficient knowledge or expertise concerning the application procedures, which are known to be tedious and time-consuming. Also, the inclusion of stakeholder interactions with the aim of understanding societal acceptability of an innovation results in additional costs and delays in technology development and, perhaps more importantly, competitive advantage is based on advanced knowledge, which is at risk if knowledge is shared widely.[112] As a result, SMEs often consider the return of putting effort into RI too small or even negative: they typically perceive RI as a cost and not as an investment.

The latter is important as some researchers have found that corporate social and environmental orientation has a positive impact on the growth performance of university spin-offs[113] and on their financial performance.[114] However, in view of the opportunities and challenges faced by SMEs and of the potential positive impact related to engaging in RI, it is remarkable that very few studies have been published on the extent to which SMEs engage in RI.

7.1. Motivators for RI engagement

Public funding (both from national/regional and from EC programmes) is increasingly linked to policy objectives that include economic but also environmental and societal objectives. Hence RRI is seen as a comprehensive approach to link R&I to a range of policy objectives. While private companies cannot easily be coerced into serving such policy objectives when using *privately* funded R&I initiatives, public institutions have various means of stimulating them to also promote public goods (such as e.g. soft laws, incentives, tax benefits).

[bb] The term 'Responsible Innovation' (RI) is used here in connection with SMEs, as they often engage to a larger extent in innovation than in research; the difference between 'RRI' and 'RI', however, is a matter of nuance rather than of content.

[cc] The Competitiveness and Innovation Framework Programme (CIP) (2007-2013, with a budget of over € 1 billion) was designed to provide SMEs with better access to finance, as well as support for innovation and regional business support. In 2013 it was replaced by COSME.

[dd] The Small Business Innovation Research (or SBIR) programme is a US government programme, intended to help small businesses conduct R&D. The new SME instrument (in H2020) is inspired by the US SBIR model.

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In the UK corporate responsibility (CR) is relatively well institutionalised which leads for example to conspicuous CR reporting, to partnerships between companies and NGOs and growing attention to CR issues from the press and from civil society organisations (CSOs).[115] But this mainly applies to large firms, whereas SMEs often are not able to allocate the necessary resources to CR issues and, moreover, often think they run limited reputational risk when not (or insufficiently) complying with public obligations.

Scholten et al. have provided insights that can help policymakers to develop instruments in order to achieve higher levels of RI in SMEs and research institutes.[116] Authorities in various countries have indeed taken initiatives to implement RRI. As an example, I want to mention the agreement signed in 2015 by the Italian Association for Industrial Research (AIRI) and the National Research Council to develop policy recommendations for the advancement of RRI, with the scope of bringing together the experiences from various stakeholders (authorities, research organisations and industry) and promote a common view on RRI.[117]

The "Japan Summit" during the recent CeBIT show[ee] featured the vision for a super-smart society which is at the core of Japan's 5th Science and Technology Basic Plan (2016-2020).[118] It is remarkable that the Japanese plan aims at realising "Society 5.0", a comprehensive vision which involves also addressing societal challenges – unlike similar European plans which focus mainly on industry competitiveness (e.g. "Industry 4.0" in Germany).

A study of technology-based academic spin-offs has developed a model to capture the RI practices of the spin-offs and investigated how these practices affect the capacity of the firms to recognise external knowledge, absorb it and apply it in the innovation process.[119] The study finds that the firms' potential absorptive capacity is increased by both stakeholder engagement and social responsiveness. Such academic spin-offs are representative for the group of SMEs which I focus on in this section, as they are small-sized, innovation-driven and based on an emerging technology. Several studies have elaborated on the absorptive capacity in SMEs; one of these studies with South-Korean semiconductor SMEs[120] finds that an increased absorptive capacity leads to better performance in terms of new product development. A recently published study with Spanish SMEs provides an empirical demonstration of a positive link between social responsibility (SR) management and championing behaviour and stakeholders' satisfaction leading to improved competitive success.[121]

Investors increasingly want to know about companies' performance related to environmental, social and governance issues. They understand that creating shareholder (or stakeholder) value is not the same as maximizing short-term profits.[122] That requires managers to think about the long-term horizon, about management credibility and about communicating how they will create value in a way that investors – and increasingly also consumers - care about.

Among SMEs the practice of sustainability reporting is not yet widespread. The Global Reporting Initiative (GRI) and the International Organisation of Employers (IOE) have released

[ee] CeBIT is a German acronym for "Centrum für Büroautomation, Informationstechnologie und Telekommunikation". It is a large and internationally represented computer trade fair held annually in Hannover.

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a joint publication to inspire SMEs to take action and report on their main sustainability[ff] impacts.[123] It is argued that reporting according to the GRI Sustainability Reporting Standards will help SMEs understand and communicate their impact on critical global issues, improve risk management and foster responsible business practices.

7.2. Pathways to RI operationalisation

Pavie et al. have introduced a process for achieving RI based on an extension of the model suggested by Nidumolu et al. for achieving sustainability.[124] The reader is referred to ref. 111 for a detailed discussion of that process.

While implementing such a process is in principle possible regardless of the size of the firm, it is suspected that large firms will be able to do so much more easily than SMEs. Using a sample of 3,626 Italian firms, Russo and Tencati have found that micro-enterprises and SMEs use *informal* SR strategies to describe their activities of managing relations with and the claims of their stakeholders – while formal SR strategies characterise large firms.[125]

Global industry leaders are increasingly integrating sustainability into their core activities, not only from a sense of "moral correctness" but often because they realise that societal challenges are offering business opportunities. The new source of competitive advantage requires a disciplined approach to integrating shareholder and stakeholder value. In his book "Sustainable Value", Laszlo has discussed the new competitive environment and proposed a toolkit for business managers who want to take advantage of it.[126] In their landmark paper, Porter and Kramer elaborate on the concept[gg] of "creating shared value" (CSV),[127] which involves policies and operating practices that enhance the competitiveness of a company while at the same time moving forward the economic and social conditions of the communities around the company. The authors explain that the shared value approach can involve (i) reconceived products and markets; (ii) redefined productivity in the value chain; and (iii) supportive industry clusters at the company's location. While the CSV principle is similar to the "Sustainable Value" introduced by Laszlo, SMEs will probably find the CSV approach for strategy development more accessible.

Flipse and Puylaert have proposed an approach for innovators to identify important societal values and organise the involvement of external stakeholders in their innovation process to come to a co-creation process for the design requirements.[128] In a first step, the value profiles of the group of involved actors are developed; in a second step, a participatory workshop is organised in which the actors discuss these values and transform them into norms and design requirements. The implementation of the 'workshop' as proposed requires the interaction between various actors in a structured way.

[ff] The GRI-IOE publication refers to 'sustainability' in the frame of the UN's Sustainable Development Goals (SDGs) providing a vision of a sustainable future which overlaps to a large extent with the vision expressed by the EC's set of Societal Challenges.

[gg] The authors first introduced the business concept of 'creating shared value' in a 2006 HBR publication entitled "Strategy and Society: The Link Between Competitive Advantage and Corporate Social Responsibility".

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At this point, one should consider the “Living Lab” format to structure the stakeholder interactions: typically, it provides an open innovation system and a central infrastructure, around which the exchanges among the various actors (utilisers; enablers; providers; end-users; researchers) result in the unlocking of knowledge at various levels and in the co-creation of value.[129,130,131] The innovation approach involving multi-stakeholder interaction and collaboration in a Living Lab makes it particularly suited for RI. ‘Enablers’, for example, are often public sector actors - providing financial resources or policy support - having as primary objective the generation of social and/or economic value.

Niitamo et al. describe how a small energy-IT system provider applied the Living Lab approach to co-create an energy-efficiency management system.[132] The perceived benefits and managerial challenges of using the Living Lab approach from a small-firm perspective are described and it is demonstrated that the methodology worked well in the examined energy-efficiency case.

The Living Lab approach has become a key asset of European research and innovation, coordinated by the European Network of Living Labs (ENoLL).[hh] The latter is the international non-profit association of benchmarked Living Labs founded in 2006, with imec holding the ENoLL secretariat in Brussels.

8. A few concluding reflections

The ongoing process of aligning research and innovation to the values, needs and expectations of society – as requested by RRI – demands the intertwining of science, technology, innovation and society. While society’s Grand Challenges are ambitious and noble, they are not mission-oriented but open-ended and, therefore, not unambiguous which means that the corresponding policies have to cope with contestation, non-linearity and bifurcations during development. This calls for transformative system-wide changes allowing for “concerted action” among the involved actors.[133] Kuhlmann and Rip see an *additional* Grand Challenge in the modification of our R&I systems, so that Grand Challenges can be productively addressed. In this context, van Oudheusden asks the resounding question: “*Where are the politics in responsible innovation* (RI)?”[134] He concludes that “*Because RI proponents act to change the world, so to speak, they engage in politics in a broad sense. Yet, politics, as well as power, are not sufficiently theorised or acknowledged within the RI framework.*”

Even when the overarching priority areas of society’s challenges (see section 3.2) are dismantled into more amenable goals, solutions seem to remain beyond reach as the interests of companies and society-at-large are often perceived as being opposed – or the available ‘tools’ all but inadequate. This is where the principle of shared-value creation can bring relief, as it cuts across the traditional divide between the responsibilities of businesses and those of government or civil society. Societal problems often arise from (and persist because of) a complex combination of actions and omissions by various players in an ecosystem and

[hh] http://www.openlivinglabs.eu

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therefore can be solved only by the coordinated effort of the same players (businesses, government agencies, research actors, CSOs and citizens). Bringing stakeholders together in a collective-impact initiative is likely to lead to a common understanding of the issue at hand which is the first step towards solving it. The five essential elements of a collective-impact initiative (see section 3.4.4) are simple to describe, but challenging to implement. A new kind of “system leadership” will be called for (i) to change the system and make progress towards shared value; and (ii) to make stakeholders understand how the ‘health’ of the whole system benefits each individual party.

It is clear that the multi-faceted digital transformation that we are experiencing – and that has been a major topic of discussion in this paper – has a “horizontalising” effect on society: the networked relationships cause disruption and diffusion of power. At the same time, they allow connecting all stakeholders (citizens, CSOs, companies, authorities). Therefore, they create possibilities for active exchanges and a networked intelligence for outcome-setting and process control in our endeavour of meeting the societal challenges.

As a final thought, I want to emphasise the intimate relationship between society’s Grand Challenges and education. The Grand Challenges are an important catalytic force in education – also at pre-college level. Cohn has looked at engineering career trends worldwide and examined the large disconnect between the messages school-age students are (not) hearing about engineering and what they value in life.[135] He proposes some new ways of talking – and even thinking – about engineering that can bridge this message gap. He suggested to use the worldwide consensus on the problems e.g. around climate change, energy, and the environment as a rallying set of "grand challenges" that can help motivate a whole new generation of engineers. Conversely, science and engineering have been instrumental throughout history in advancing mankind’s conditions and bringing major innovations in food production, shelter, energy supply, transportation, communication, health and security – and I am confident that they will continue to do so. Thus we must be aware of our pressing need for talent familiar with (natural and social) science and technology and capable of formulating answers to our daunting Grand Challenges. The concerns that have generated the call for RRI are the result of our enhanced awareness of the tremendous power of modern science and technology: with great power comes great responsibility. Rather than looking for the silver bullet that overnight will make science and innovation ‘responsible’, we must patiently but confidently foster that mindset in the next generation.

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