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IS THIS THE DAWN OF A HYBRID AGE?

THE CONVERGENCE OF TECHNOLOGY AND BIOLOGY

Study (abridged version)

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Summary of key findings

Objective of the study

Human brains with WiFi interfaces and living robots with feelings? An extraordinary future lies ahead. The aim of this study is to shed light on what the future might look like. It comprises an investigation into the **current technological and social developments** that could lead to a **blurring of the boundaries between biology and technology** in the future. Specific **scenarios** are used to put these possibilities into context – in which areas of our lives could technology be used in the future? How will this impact our daily lives?

The convergence of biology and technology, i.e. the shifting of the boundaries between the two fields, is not a new phenomenon, but a new dimension of this trend has begun to emerge recently.

There is an increasing convergence of biological and technological – especially digital – systems. This is taking place with a new level of intensity and a quality that increasingly tends towards the reciprocal merging of these systems, thus resulting in the creation of hybrid biodigital entities.

The impetus to break down the boundaries between biology and technology comes from both sides. Progress in these sectors increasingly has a reciprocally stimulating effect.

Technologisation of biology (especially in humans): living organisms are optimised by using technology to intervene in how they function.

Biologisation of technology: digital technologies are optimised by integrating them with living organisms or processes that reproduce the characteristics of living organisms.

Current research findings show that there is still a long way to go before we see a major breakthrough in biodigital innovations or "hybrid beings". Nevertheless, the momentum within this research field is increasing rapidly.

Perceptions about the potential of merging biology and technology change dynamically as what is possible also changes.

Public discourse concerning the convergence of biology and technology is constantly changing. What is perceived as convergence changes as technology develops, becomes more widespread and accepted. Much of what used to be considered a convergence of two fields has become part of everyday life. In general, a shift in human capabilities is more quickly and strongly perceived by the public as a convergence of fields than a shift in technological boundaries is. Technologies that enhance performance or enable new capabilities are also perceived as representing a greater shift of the boundaries between technology and biology than technologies that restore damaged capabilities.

Convergence does not happen in a vacuum. It is influenced by technological developments and social trends that will shape the future.

Applied biodigital technologies such as smart contact lenses, neuroprostheses, exoskeletons, brain interfaces, intelligent medicines or artificial organs connect the human body with the digital world (technologisation of biology). At the same time, technology is becoming increasingly lifelike with human-like robots, hybrid nanorobots and data processing technologies (e.g. bio-computers) or biologic technology used as a means of production (e.g. cell factories). These advances meet the changing needs and attitudes of society. The speed at which these fields are converging is fundamentally

increasing, motivated by ageing, health trends, changing values and the accelerated spread of technology.

The practical application of biodigital technologies could provide society with great potential for change in the future, especially in the environmental and health sectors. However, development prospects are associated with long development periods and many challenges.

Journals and patent publications show that research activities have increased considerably in recent years. With regard to the technologisation of humans, research is primarily focused on smart medicines, exoskeletons and brain interfaces. In terms of expanding technological boundaries, R&D activities are directed at humanoid and soft robotics and biosensors. Research is mainly conducted into these technologies for medical and military purposes. In future, challenges will also arise from the energy and environmental sectors, although the medical sector will continue to be a top priority.

There are a number of challenges involved in launching biodigital innovations to market, including long development times (use after 2030), scalability, the balance between potential benefit and damage (dual-use technologies) and demonstrating added value when compared with conventional technologies. Issues such as data protection, cyber security and the controllability of technologies are crucial for social acceptance and expansion; they have the potential to slow down or even stop the momentum that drives the rate of convergence.

The consequences of blurring the boundaries between biology and technology are reflected in six future scenarios. These depict a broad spectrum of possible convergence dynamics.

- **Scenario 1: The European Route**
  Strict technology standards apply in the Germany of the 2030s. High-risk technologies, particularly those from non-European countries, are not permitted. Many technologies bear the label "Made in Europe". Their potential to bring together technology and biology is low to moderate.
- **Scenario 2: Competition Mode**
  Technology is developing in a very dynamic way in Germany in the 2030s and there is great potential to shift technological boundaries. Merging biology and technology is legitimate as long as there is real social or economic added value and the risks remain predictable.
- **Scenario 3: Return of the Blocs**
  In the extremely difficult geopolitical environment of the 2030s, the primary purpose of convergent technologies is clearly defined: security, external profiling and guaranteeing national supplies. Technological breakthroughs mainly occur in the military sector.
- **Scenario 4: Multi-speed Society**
  The spread of convergent technologies in the 2030s is a reflection of societal polarisation. The knowledge elite use them progressively at work and in their free time, whereas those parts of society with insufficient purchasing power and a lack of market access due to poorly developed infrastructures do not.
- **Scenario 5: Bonus System**
  In 2030, convergent technologies are mainly used in Germany for recording data and behaviour for a points system. Throughout the day, in all situations, they are used to control, monitor and suggest optimisations. The use of specific convergent technologies, such as ones to reduce an individual's environmental footprint, is also positively rewarded by the points system.
- **Scenario 6: Ecological Regionalization**
  In Germany in the 2030s, many convergent technologies originate from regional open-source communities. The central field of application for these technologies is environmental protection. They also play an important role in creating new opportunities for personal fulfilment and societal participation.

In all scenarios key components of convergence between biology and technology can be identified.

- Advanced forms of digital androids, smart wearables and comfortable exoskeletons are used in all of the scenarios. Digital androids and smart wearables are already widespread today. Exoskeletons, on the other hand, are only used occasionally in niche areas.
- Biohybrid living materials and biosensors will likewise play a significant role in the future. They are used in five of the six scenarios. They will be particularly important in tackling critical challenges in the environmental and energy sectors, e.g. for increasing the energy efficiency of processes or for reducing harmful emissions.
- In addition to the environment and the energy sector, health and work are the most important fields of application for converging technologies in all of the scenarios. These technologies deliver considerable benefits within these sectors in terms of control, comfort and relieving physical and mental strains.
- The more closely a piece of technology is integrated with other fields, the greater the challenges associated with its use. How this is dealt with and whether a technology is permitted or socially accepted varies from scenario to scenario. This is heavily influenced by the economic situation and the political environment within the respective scenario. It is highly likely that the boundaries between technology and biology will merge in the environmental and health sectors, but development prospects are associated with longer development times and challenges.

Note on the full version of this study

This is an abridged version of the study. The full version with detailed descriptions of the results and methodology used is available for download from vorausschau.de (German version only).

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TRANSFORMATION IN PROGRESS: BIODIGITAL INNOVATIONS

It is part of human nature to search for explanations and solutions to societal challenges. So too is the pursuit of performance optimisation.[1] Motivated by these goals, existing technology and (human) capabilities are continuously being improved and expanded. The phenomenon of merging biological and technological systems, i.e. shifting the boundaries between the two fields, has always been central to these efforts. Recently, a new dimension has emerged in this trend – increasing convergence between biological and technological – especially digital – systems. These are being combined with a new level of intensity and a quality that increasingly tends towards reciprocal fusion and the creation of hybrid biodigital entities.[2]

Various methods are being applied in many sectors to merge biological and technological or digital elements. Both sides are working to shift boundaries and the advances that are being made are characterised by their increasingly reciprocal nature:

- **Technologisation of biology (especially in humans):** living organisms are optimised by using technology to intervene in how they function (e.g. implants, exoskeletons and wearables). What is new here is the intervention in increasingly sensitive areas such as the brain and the view that humans, as living beings, function according to predictable rules and mechanisms that can be replicated through technology.[3]
- **Biologisation of technology:** digital technologies can be optimised by integrating living organisms or processes that reproduce the characteristics of living organisms (e.g. self-organisation, self-healing, reproduction and cognition). This trend focuses on the approximation of technology with a living model in terms of shape, appearance, behaviour or capabilities, hence the term "living" technology is sometimes used.[4]

Current research efforts show that there is still a long way to go before we see a major breakthrough in biodigital innovations or "hybrid beings". At present, there are a number of major hurdles to over-

1 Cf. Fellmann, M. & Krause, T. (2015) and Woopen, C. et al. (2020).
2 A key characteristic of the convergence of technology and biology is the dynamic nature of its development. This is reflected in public discourse in particular: what is perceived as convergence continuously changes in line with current technological developments and how widespread and accepted they are.
3 Cf. van Est, R. et al. (2011), 13.
4 Cf. van Est, R. et al. (2011) and Bedau, M. A. et al. (2009).

come, such as ensuring compatibility between living organisms and machines. Nevertheless, momentum within this research sector is increasing rapidly. This is partly fuelled by transformative scientific and technological advancements (technology push, see Chapter 2.1), but also driven by various social trends (demand pull, see Chapter 2.2).

Convergence and future potential for change

The reciprocal merging of technology and biology promises to push forward wide-reaching expansions in human and technological capabilities. The fusion of biology and technology could combine the advantages of both worlds. Biological organisms and functions could become controllable and programmable to an unprecedented degree and "rigid" technologies could develop characteristics of independent life. Biodigital innovations affect numerous key areas of life and could transform our understanding of humans, society and the way we will live in a new "hybrid age".[5]

Transformative potential applications could emerge, e.g. by networking digital technology and the human body (see Chapter 2.1 for descriptions of specific technologies). Brain interfaces to directly integrate thoughts into the flow of digital information, novel wearables to monitor biodata and supportive robotic suits could optimise and enhance human performance in unprecedented ways. Convergence could also have a disruptive potential in the medical field with smart medicines, microrobots, neuroprostheses and artificial organs. In the health sector, there is an emerging possibility of individualised and customised medicine with reduced costs and greater efficiency.

In contrast, the combination of biological structures with technological tools could open up new pathways for using technology in nature and the environment. Biosensors, microrobots and hybrid solar cells could make a lasting contribution to nutrition, climate protection and biodiversity in the future. The biological transformation of industry, e.g. using cells or semi-living materials as production resources, could also make manufacturing processes more sustainable. While we may begin interacting with humanoid robots and human simulation software in our daily lives, we may also see boundaries shifting in fields such as data processing using biological computers and DNA data storage. The reciprocal merging of technology and biology could fundamentally and permanently change not only the relationship between humans and technology, but also that between humans and nature. Some visions even go so far as to postulate a "posthumanistic age". The human being, or specifically the brain, would then become entirely one with superintelligent machines, thereby redefining human nature.[6]

The explosive power of the increasing convergence of biology and technology is thus also reflected in far-reaching ethical and regulatory challenges. For example, questions would have to be considered such as "to what extent could individual groups be excluded or social divisions be promoted by biodigital innovations?" or "what new diseases could emerge?". It therefore seems essential to facilitate scientific and social debate on this topic at an early stage of the process.

Note on the full version of this study

A detailed description of the convergence of technology and biology can be found in Chapter 2 of the full version of this study (available for download from vorausschau.de; German version only).

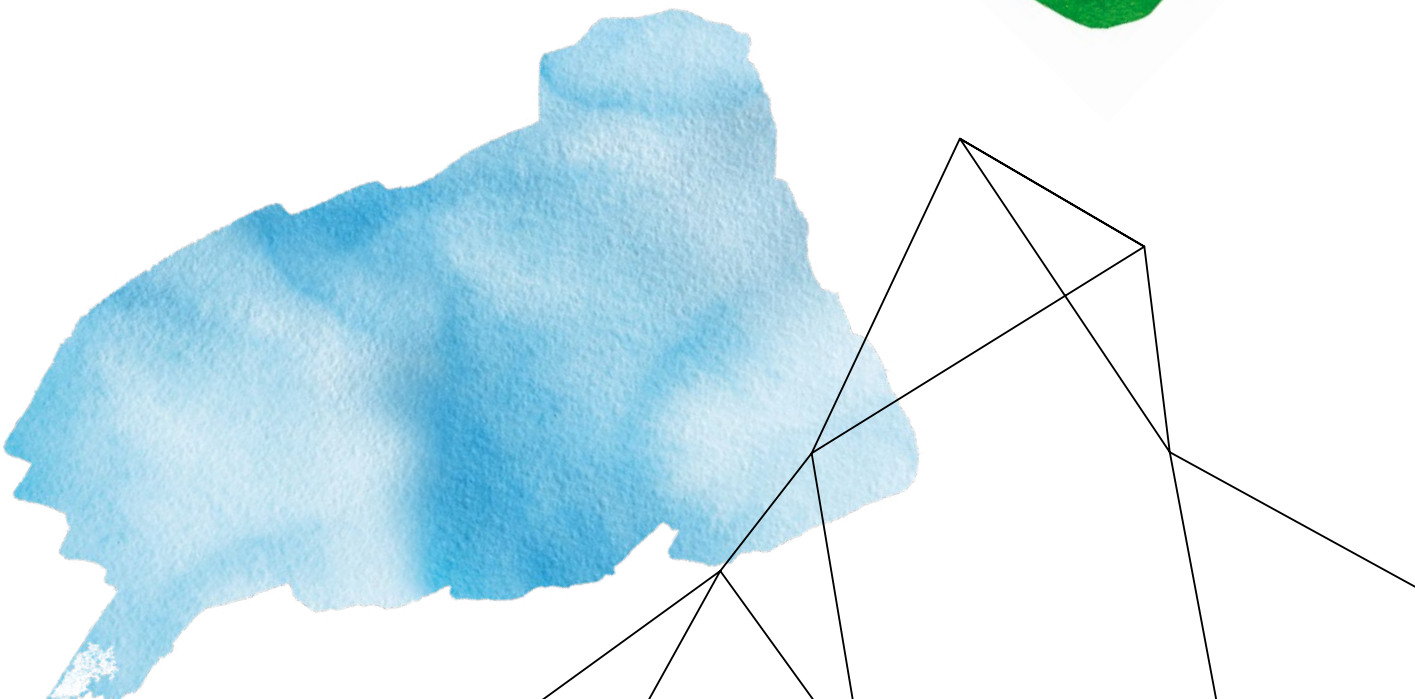
5 Cf. Chui, M., Evers, M. & Zheng, A. (2020).

6 Cf. Dermühl, K. (2015), 51 and Kehl, C. & Coenen, C. (2016), 143.

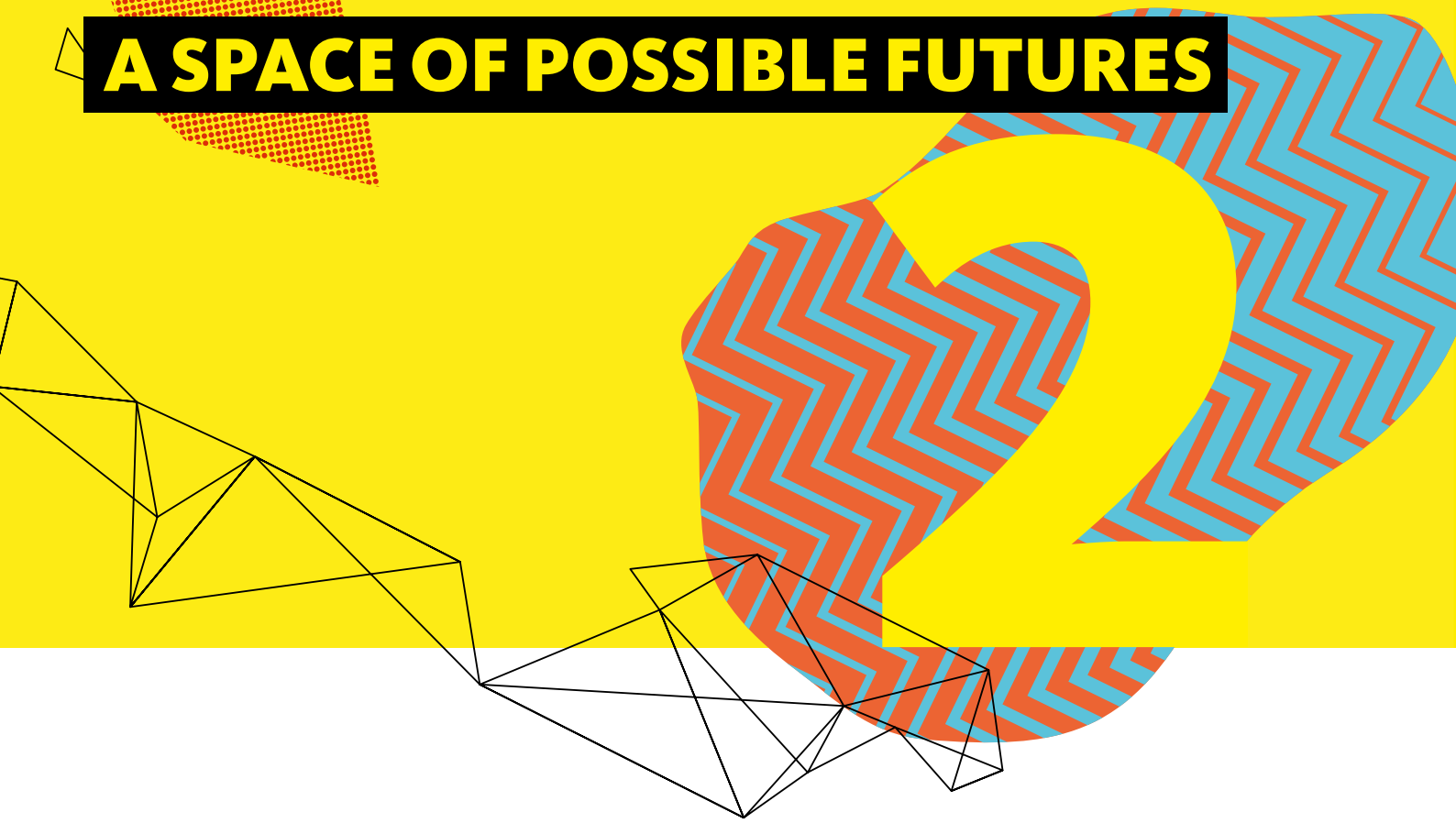
Objective of the study

Summary of aims

- Presentation of relevant trends and drivers through the identification of applications for biodigital technologies (technology push) and social developments (demand pull)
- Description of the current state of research and of promising future application prospects for biodigital technologies
- Description of different futures (scenarios): contextualisation of development opportunities of relevant technologies and social trends



2 A SPACE OF POSSIBLE FUTURES



What forms of convergence are conceivable in Germany in the 2030s? What forms of technology might be used for this? Which social developments might promote the acceptance of these technologies and which practical applications and areas of life would be significantly affected? This chapter seeks to answer these and other questions. Future scenarios are used to outline six different visions of the convergence of biology and technology in Germany in the 2030s. These scenarios were developed (see Chapter 2.3) based on three key pillars:

- technologies that could be decisive in the development of biodigital innovations in the future and have high convergence potential
- social developments that could promote the acceptance of convergent technologies
- the framework provided by one of the six scenarios from the study "The future of values held by people in our country" (global scenarios) [7]

The synthesis of the global scenarios, applied biodigital technologies and social developments allows for the creation of complex interdependencies, thus resulting in six future scenarios. These scenarios set out the potential development and impact of convergent technologies in the 2030s.

7 Prognos AG; Z_punkt GmbH The Foresight Company (2020).

2.1 Technology push: technologies shaping possible futures

The fusion of technology and biology is facilitated at least in part by the increasing interdisciplinary synthesis of the following four key areas: nanotechnology, biotechnology, information and communication technology (ICT) and cognitive science, also referred to as "NBIC convergence". This is considered to be a crucial foundation for novel and promising (biodigital) innovations in the "new technology wave".[8] Increasingly, the synergetic interplay between certain disciplines is fuelling opportunities to develop other fields in a reciprocal manner. Advances in information technology allow biologists to cost-effectively record, process and analyse large amounts of data. In turn, advances in life sciences make it possible to apply technological concepts to living beings, such as the individually tailored programming and synthesisation of living organisms.[9] In this context, the progressive convergence of biology and technology can build on growing computing capacity, new developments in big data and cloud computing and the continuous miniaturisation of end devices and individual electronic components. Advances in AI methods that optimise the necessary data processing in a large number of cases, are also particularly relevant for future convergence dynamics.[10]

The interplay between these disciplines increasingly gives rise to innovation processes that combine approaches from both biology and technology to create fundamental future technologies. In order to depict the possible scope of a future society, core technologies for the convergence of biological and technological systems were identified (see Tables 1 & 2). These were systematised within the framework of the two converging dimensions and summarised in main categories.

From smart medicines to brain interfaces: new technologies connect the human body with the digital world

Using technology to connect the human body with technological artefacts satisfies medical interests and also focuses on replicating (damaged) biological functions. Huge progress has already been made in the development of smart medicine, neuroprostheses and other artificial replacement body parts. In the future, smart medicines could enable efficient and individual treatments for patients where active substances are only released in response to external digital signals or created specifically at the damaged site.[11] Micro- and nanobots are being developed for similar purposes: precisely designed molecular robots that monitor bodily functions and can act as multi-purpose agents, e.g. to transport active substances.[12] Connecting the body's own nerve pathways with prostheses could create assistive devices with a "lifelike feeling". From robotic hands to retinal implants with an extended functional spectrum, human sensory organs could even be enhanced to superhuman dimensions.[13] In the future, synthetic organs and artificial blood could be used to alleviate the chronic shortage of donor organs.[14] The targeted cultivation of cells to create artificial organs competes with methods for 3D printing of biological tissue.

In addition to this, research efforts are aimed at increasing and surpassing existing human capabilities. Technological access to the human nervous system is key to this endeavour. Brain-machine interfaces are at the heart of a development that seeks to forge a link between human brain activity and digital computing power.[15] In the future, complex machines (connected to the body) such as

8 Nordmann, A. (2004) and cf. Roco, M. C. & Bainbridge, W.S. (2002).
9 Nowogrodzki, A. (2018).
10 Webb, S. (2018).
11 Results of interviews with experts and Deutsche Apothekerzeitung (2017). See also developments by the US start-up Proteus in cooperation with Novartis.
12 See Gutierrez, B., Bermúdez, C. V. & Ureña, Y. R. C. (2017). See also developments by companies such as Bionaut Labs.
13 Cf. Normann, R. A. (2007).
14 Cf. Wenzel, S. & Schwarz, T. (2020).
15 Kehl, C. (2016), 11. See also the efforts of companies such as Neuralink or Kernel.

Table 1: Core Innovations for the technologisation of human beings

Fields of innovation	Relevant technologies
Smart wearables	› Smart glasses and smart contact lenses › RFID chips and digital tattoos
Exoskeletons & neuroprostheses	› Exoskeletons (with brain interfaces) › Motor and sensory prostheses
Neuro-electrical interfaces	› Non-invasive, unidirectional conductive or stimulating procedures (electroencephalography, transcranial magnetic and direct current stimulation, deep brain stimulation, electroceuticals) › Invasive bidirectional methods (brain-to-machine, brain-to-brain & brain-to-cloud interfaces) › Whole brain emulation / mind uploading
(Liquid) organs based on synthetic biology	› Artificial blood and organs
Smart medical technologies	› Smart medicines, nano- and microbots

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drones or exoskeletons could be controlled by "mind power".[16] However, given sufficient scientific progress, it might also be possible to create a connection between human consciousness and the internet using brain-to-cloud interfaces or mind uploading. It is currently uncertain whether users will initially only accept procedures that are conductive and non-invasive (e.g. EEG) or if they will also accept procedures that are stimulating, invasive and bidirectional. Less sensitive forms of digitally enhancing human capabilities are also being explored. Wearables such as smart glasses or smart contact lenses could be used to reversibly connect the digital flow of information with the human body.[17] Miniaturised circuits, such as digital tattoos on the skin or RFID chips embedded under the skin, could be used to integrate the body into a comprehensive digital ecosystem in the Internet of Things and living beings.[18] Exoskeletons in particular could help to increase abilities from a mechanical point of view. These wearable devices could assist physical activity in situations ranging from the workplace to the military.[19] Overall, a differentiated image emerges of the potential for convergence, in which invasive and irreversible technologies would have a strong impact on people's understanding of values.

From robots to biocomputers: biosystems serve as a model and optimisation method for technology

The boundary-shifting technologies used in the biologisation of technology present very different approaches and are sub-divided into three quite independent fields: robotics, biocomputing and biology-based production methods. Robots are becoming noticeably more human. They are learning to walk on two and four legs (walking robot)[20] or have developed "soft grip" and formability (soft robotics). Increasing efforts are being made to make them usable in human environments (humanoid robotics)[21] or to make them as unmistakably similar to humans as possible (androids)[22].

16 Cf. Collinger, J. L. et al. (2013). See also Facebook Reality Labs projects.
17 See experimental developments by Samsung, Google and Sony or medically focussed developments from Mojo Vision.
18 Cf. Chadwick, L. (2020). See products from the Swedish start-up Biohax in cooperation with NXP Semiconductors.
19 Results of the Delphi survey. See also the HAL exoskeleton robot from Cyberdyne.
20 See products from Boston Dynamics.
21 See Boston Dynamics' "Atlas" walking robot or Agility Robotics' "Digit".
22 See products from the Hanson Robotics company.

Table 2: Core Innovations used in the biologisation of technology

Innovation fields	Relevant technologies
Humanoid and animal-like robots	› Walking robots and soft robots › Humanoid robots, digital androids and androids
Micro- and nanobots made from living material	› Biohybrids and biological robots › Synthetic cells
Data processing technology	› Biological (DNA & RNA) computers, hybrid processors, DNA data storage › Biosensors › Organs-on-a-chip
Biology-based production methods	› Biomanufacturing and biohybrid materials › Semi-artificial photosynthesis

Source: © own illustration by Prognos AG and Z_punkt 2021.

Equipped with AI software, they could soon be able to understand our emotions and enhance our everyday lives by performing tasks such as providing shopping advice or working in the service industry.[23] The most likely form this technology will take is as human simulation software without a robot body (digital androids) to accompany our virtual lives.[24] But robots that increasingly use biological structures are also being developed at the micro and nano levels. As micro-agents, they can carry out tasks in the body or in nature for which technical instruments were previously too large and destructive. From sustainably cleaning up pollution to cleaning arteries, biohybrid and biological robots or even synthetic cells can act as autonomous agents serving the human interest.

Biocomputing attempts to take advantage of biological structures for use in data processing. The material in our genes, DNA, can be used as a medium for storing digital data. This offers an enormous advantage over current magnetic tape storage thanks to space-saving, cost-effective, long-term storage options. DNA data storage could facilitate a huge increase in data processing through an extensive Internet of Things.[25] Biological structures such as DNA and mRNA could also be used as computers. These "biological computers" could provide an alternative technology to quantum computing due to their high degree of parallelism and energy efficiency. Biosystems are currently already used as standard in data processing as biosensors. Biosensors use biological structures to measure information such as environmental pollution, food toxins or blood sugar. Future developments and special design could make biosensors environmentally friendly and enable them to be used autonomously in the human body or in nature.[26]

There is also growing interest in the field of biodigital connections in industry. At the forefront of biomanufacturing is the concept of the biological cell as a new production system. Specially designed cells create the required products or processes as part of their metabolism (e.g. chemicals, fuels or active ingredients[27]). The changeover to bio-based (renewable) means of production and materials could make an important contribution to sustainability while still promoting concurrent growth in the bioeconomy.[28] The materials themselves will come to life as biohybrid resources. Biological cells and inanimate material are fused together to combine the advantages of both substances.[29] This process can for example be used to create self-healing basic

23 See Sonnenberg, V. (2016).
24 See Samsung's NEON project.
25 Cf. Lee, S. Y. (2019). Microsoft, in particular, actively promotes this topic.
26 Cf. Ibrahim, A. U. et al. (2020). See Dynamic Biosensors GmbH, a company funded by the BMBF as part of its "BIO Go" programme.
27 Cf. Wu, Y. et al. (2019). See BASF, Bayer or AGC Biologics.
28 See BMBF (2020).
29 See INM - Leibniz Institute for New Materials (2020).

substances that build themselves according to an internal blueprint.

In the context of biologisation, the main area in which there is potential for convergence is in autonomous technologies and technologies that are barely distinguishable from biological systems.

Note on the full version of this study

A detailed description of areas in which biodigital technologies can be applied can be found in Chapter 4 of the full version of this study (available for download from vorausschau.de; German version only).

2.2 Demand pull: social developments shaping possible futures

The development of future technologies and their areas of application are not independent of social processes and the continuing development of needs. Innovation processes are not only influenced by the technology push, but also by the demand pull. Changes in demand behaviour mean that social and societal trends enter into a complex reciprocal relationship with technological development. In addition to major overarching dynamics such as demographic change, social trends that focus specifically on health and body awareness are also significant for the convergence of biology and technology. Emerging changes in societal values and greater technological penetration into everyday life will also have a decisive effect on future acceptance and the direction in which converging technologies develop (see Table 3).

Ageing, assessing health, changing values and the spread of technology increase the demand for and acceptance of biodigital technologies

Demographic change will see a reduction in the number of younger people combined with a simultaneous increase in the number of older people. This development will increase the demand for technologies that enable participation and a healthy life even in old age. Particularly in the medical sector, we can expect to see an impact on the demand for and acceptance of technologies such as smart medicines, neuroprostheses or artificial replacement body parts.

Certain specific health trends, such as e-health and the quantified self movement, health enhancement and the growing acceptance of body design are directly related to biodigital innovations. The e-health and quantified self movements seek to maximise the benefits of digitalisation by pursuing digital penetration in the health sector and the complete measurement of health data. The increased measurability of health data also facilitates the trend towards health maximisation, e.g. through incentives ("nudging") when setting health insurance rates and bonuses for healthy lifestyles. These developments coincide with an increasing social acceptance and greater value placed on body modifications. The prevalence of plastic surgery, tattoos, piercings or bodybuilding could also lay the foundation for the acceptance of even more extensive "body design" through technological enhancements. Although a niche phenomenon, do-it-yourself (DIY) biology, i.e. biological, chemical or technical interventions in organisms with the aim of changing and improving the body, in the form of human enhancements could merge the boundaries between biology and technology. DIY biology allows skilled amateurs to optimise their bodies.[30] The willingness to carry out more extreme interventions for the purpose of preventive health care and self-optimisation is likely

30 Zoidl, F. (2019).

Table 3: Overview of social trends

Trend areas	Specific social trend
Overall social development	› Demographic change
Health and body trends	› E-health and quantified self movement › Increasing social acceptance of "body design" › From health maintenance to enhancement
Change in values	› Growing awareness of sustainability issues › Increasing individualisation › Loss of importance of religion › Professionalisation of leisure activities
Pervasive use of digital technologies in all areas of everyday life	› Smart living and virtual assistants › Human-machine collaboration in the workplace › Spread of robotics in education and care › Spread of mixed realities

Source: © own illustration by Prognos AG and Z_punkt 2021.

to increase in the future. The biodigital movement could also accelerate the technological adoption of data-producing innovations in wearables such as smart devices, RFID chips, digital tattoos and biosensors.[31] In the more extreme convergence scenarios, it is conceivable that there will be widespread use of micro- and nanobots for measuring individual biological processes inside the body or for enhancing sensory abilities with neuroprostheses.

Changes can also be seen in the alignment of societal values; this could support greater acceptance of innovations that are characterised by the convergence of biology and technology. Web 2.0, with its potential to turn the individual into a mass medium, reinforces already existing individualisation tendencies. A "society of singularities" is in the making, where increased comparability online means that uniqueness is rewarded and people with original interests and curated biographies are in demand.[32] Biodigital technologies could therefore be used in the future to make people and things "special" through the incorporation of technology. Biohybrid materials could be used to personalise living environments, synthetic cells and smart medicines could release body-specific active agents in precise locations or brain-machine interfaces and artificial organs could promote the uniqueness of mind and body. Increasing individualisation will coincide with the diminishing importance of religion and ecclesiastical authorities.[33] The loss of trust in religious institutions could also lead to dwindling support for religiously motivated moral taboos. This lack of resistance means fewer obstacles on the path to convergence. Awareness of environmental issues is growing within German society as the consequences of climate change become more and more tangible.[34] This realignment of values could have conflicting effects on the adoption of biodigital innovations in technology. Many biodigital technologies such as biomanufacturing or the use of biohybrid materials promise sustainable and environmentally-friendly production methods.[35] The use of micro and nano agents also offers an opportunity to solve global environmental problems such as microplastics in the ocean. However, biological technologies pose unprecedented risks to existing ecosystems due to their high levels of autonomy and self-replication. Existing concerns about gene-modified biosystems could continue to grow. Therefore, a population that advocates the "natural state" could delay the

31 Ingenieur.de (2019).
32 Reckwitz, A. (2017).
33 Federal Agency for Civic Education (2020).
34 Federal Environment Agency (2020).
35 Cumbers, J. (2020).

use of products created from the convergence of technology and biology.

In the wake of digitalisation, new technologies are rapidly spreading into all areas of everyday life. Not only are collaborative robots becoming increasingly important in the workplace, but there is also significant potential for robotic assistance in care work and education. Smart living systems, i.e. the intelligent networking of smart devices, are becoming more widespread and, for an increasingly large section of the population, it has become completely normal for them to converse with their phones in their native language using smart assistants (e.g. Apple's Siri). The triumph of digitalisation increasingly merges the physical and virtual worlds, so that augmented and virtual reality are leaving their niche via holograms and 3D glasses and attracting an ever larger audience. This contact with new and digital technologies could shift the standard of normality in human-technology interactions and lead to a growing desire for proximity in the digital world. In principle, this societal trend could affect all applied biodigital technologies, but it is digitalisation-relevant interfaces such as brain-machine interfaces and robotics that stand to benefit most from a shift in what is considered normal. At the same time, if innovations are too close to human biology, this could reduce social acceptance, as the constant controllability of biosystems at the same level as technical systems is not to be expected initially.

Note on the full version of this study

A detailed description of relevant social trends can be found in Chapter 3.2 of the full version of the study (available for download from vorausschau.de; German version only).

2.3 Convergence in the 2030s: possible scenarios

The six value scenarios from the "The future of values held by people in our country" study serve as the basis for the scenarios used here. They describe six possible visions of the future of German society in 2030. The different framework conditions within the scenarios act as key drivers and influencing variables governing how the fields of biology and technology might converge in Germany in the 2030s. They form the global guiding framework for the scenarios. The scenarios address the following questions with a view to the 2030s:

- How will we see the convergence of biology and technology evolving within our everyday lives and in the workplace?
- What role will convergence play in science and research?
- What will political frameworks and regulations look like with regard to convergence?
- How will we see the convergence of biology and technology evolving within our everyday lives and in the workplace?

Figure 1 provides an overview of which technologies are used in which of the scenarios.

rapidly spreading into all areas of everyday life. Not only are collaborative robots becoming increasingly important in the workplace, but there is also significant potential for robotic assistance in care work and education. Smart living systems, i.e. the intelligent networking of smart devices, are becoming more widespread and, for an increasingly large section of the population, it has become completely normal for them to converse with their phones in their native language using smart assistants (e.g. Apple's Siri). The triumph of digitalisation increasingly merges the physical and virtual worlds, so that augmented and virtual reality are leaving their niche via holograms and 3D glasses and attracting an ever larger audience. This contact with new and digital technologies could shift the standard of normality in human-technology interactions and lead to a growing desire for proximity in the digital world.

In principle, this societal trend could affect all applied bio-digital technologies, but it is digitalisation-relevant interfaces such as brain-machine interfaces and robotics that stand to benefit most from a shift in what is considered normal. At the same time, if innovations are too close to human biology, this could reduce social acceptance, as the constant controllability of biosystems at the same level as technical systems is not to be expected initially.

Note on the full version of this study

A detailed description of relevant social trends can be found in Chapter 3.2 of the full version of the study (available for download from vorausschau.de; German version only).

2.3 Convergence in the 2030s: possible scenarios

The six value scenarios from the "The future of values held by people in our country" study serve as the basis for the scenarios used here. They describe six possible visions of the future of German society in 2030. The different framework conditions within the scenarios act as key drivers and influencing variables governing how the fields of biology and technology might converge in Germany in the 2030s. They form the global guiding framework for the scenarios. The scenarios address the following questions with a view to the 2030s:

- What role will convergence play in science and research?
- What will political frameworks and regulations look like with regard to convergence?
- How will we see the convergence of biology and technology evolving within our everyday lives and in the workplace?

Figure 1 provides an overview of which technologies are used in which of the scenarios.

- How will we see the convergence of biology and technology evolving within our everyday lives and in the workplace?

Fig. 1: Matrix of biodigital technologies and their occurrence in the future scenarios

	scenario					
	1 The European Route	2 Competition Mode	3 Return of the Blocs	4 Multi-speed Society	5 Bonus System	6 Ecological Regionalisation
Exoskeletons	■	■	■	■	■	■
Smart glasses and smart contact lenses	■	■	■	■	■	■
Sensory neuroprostheses					■	
Artificial blood	■	■		■	■	
Smart drugs				■	■	
Non-invasive brain interfaces	■					
Invasive brain interfaces			■	■		
Mind uploading				■		
Brain-brain interfaces						
Artificial organs		■	■	■		
Nano-/microbots		■		■	■	
Transcranial magnetic stimulation		■				
Biohybrid robots	■		■	■		■
Synthetic cells	■	■	■			■
Biosensors	■	■	■		■	■
Biohybrid living materials	■	■	■	■		■
Bioproduction and biomanufacturing	■	■	■			■
Hybrid processors	■					■
DNA-based data storage			■		■	
Humanoids and soft robots	■	■	■			■
Digital androids	■	■	■	■	■	■
Androids with all-round functionality		■		■		

Source: © own illustration by Prognos AG and Z_punkt 2021. Blue colouring indicates occurrence of a certain technology in a specific scenario.

Note on the full version of this study

A detailed description of the scenarios can be found in Chapter 3.3 of the full version of this study (available for download from vorausschau.de; German version only).

2.3.1 Scenario 1: The European Route

Scenario outline

You can't talk about Germany in the 2030s without talking about Europe. The EU and its member states pursue a confident and independent industrial policy in the face of fierce global competition.

Mechanisation of biological systems

Potential for convergence

Applications for biodigital technology

- not invasive brain-interfaces
- Smart glasses & smart contact lenses
- Artificial blood
- Exoskeletons

Biologisation of technical systems

Potential for convergence

Applications for biodigital technology

- Digital androids
- Humanoid robots
- Biosensors
- Bioproduction
- Biohybrid materials
- Synthetic cells
- Biohybrid robots
- Hybrid processors

Key points of the scenario

- People in Germany have a **positive attitude** towards technology and the merging of biology and technology.
- Europe upholds **high technology standards**. Risk profiles determine the use of technologies, which is why people trust **technologies that are "Made in Europe"**.
- Compared with other countries, convergence is relatively **moderate**: permanent transparency and control over technologies are important approval criteria.
- **Enhancement and relief** facilitated by shifting technological boundaries is in great demand, i.e. the expansion or enhancement of "natural" human potential capabilities.
- Environmental protection is a **controversially discussed field of application** for convergent technologies, especially with regard to the use of technologies that increasingly integrate biological properties. Their future controllability is more difficult to gauge than that of the digital world.

Example applications for the convergence of biology and technology

Work

- Smart wearables as "digital companions" with context-relevant information
- Digital androids as virtual assistance systems
- Biohybrid materials used to improve occupational safety and health
- Exoskeletons provide physical relief

Research & development

- Bio-robots, organs-on-a-chip and synthetic cells as alternatives to animal testing
- Artificial simulation of complex natural systems for risk assessments
- Biohybrid processors for European ecosystem computers

Health & care

- Exoskeletons in physiotherapy treatments
- Artificial blood supplements blood transfusion shortages
- Humanoid robots as support for carers responsible for the elderly

Environment & energy

- Digital assistants for energy consulting
- Biosensors for detecting emissions
- Biomimetic energy storage
- Biohybrid materials that absorb CO_2, biomanufacturing (e.g. for green hydrogen)

2.3.2 Scenario 2: Competition Mode

Scenario outline

Germany is experiencing a phase of new economic liberalisation in the 2030s. The guiding principles of fair competition and personal initiative lead to new economic momentum.

Key points of the scenario

- Do it yourself: **ingenuity and initiative** open up entirely new dimensions of technological progress.
- The fusion of biology and technology is legitimate as long as there is a real **social or economic benefit**.
- In order to overcome the challenges of everyday life, people enthusiastically accept everything that promises **relief**.
- The labour market is very skills-focused and geared to short-term activities. It increasingly requires the temporary **optimisation of specific skills**.
- The use of convergent technologies creates **new pressure situations**. The risks of the extreme use of "biotechnical substances in a professional context" provoke criticism.

Mechanisation of biological systems

Potential for convergence

Applications for biodigital technology

Artificial organs	Nanobots
Artificial blood	Exoskeletons
Transcranial magnetic stimulation	Smart glasses & smart contact lenses

Biologisation of technical systems

Potential for convergence

Applications for biodigital technology

Digital androids	Humanoid robots
Biosensors	Bioproduction
Biohybrid materials	Synthetic cells
Android with all-round functionality	

Example applications for the convergence of biology and technology

Free time

- Digital androids for organising private and family lives
- All-round androids as household "butlers"
- Extreme climbing and survival activities with exoskeletons
- Soft robots for coping with stress and high pressure situations in everyday life

Communications

- Initial experiments with 3D-printed suits made of synthetic cells for haptic feedback from digital androids
- Communications between digital androids owned by citizens and organisations is standard

Work

- Magnetic stimulation for optimising cognitive performance and promoting creativity
- Artificial blood and nanobots for improving concentration and performance

Construction

- Simulation of urban planning projects using self-learning, biohybrid computer simulations
- Biohybrid materials: self-repairing, energy generation, CO_2 absorption using smart building materials

2.3.3 Scenario 3: Return of the Blocs

Scenario outline

Isolation instead of export nation: in the 2030s, Germany is characterised by social challenges and a difficult geopolitical environment.

Mechanisation of biological systems

Potential for convergence

Applications for biodigital technology

- Invasive brain interfaces
- Smart glasses & smart contact lenses
- Artificial organs
- Exoskeletons

Biologisation of technical systems

Potential for convergence

Applications for biodigital technology

- Digital androids
- Humanoid robots
- Biosensors
- Bioproduction
- Biohybrid materials
- Synthetic cells
- Biohybrid robots
- DNA-based data storage

Key points of the scenario

- **Shifting boundaries to strengthen borders**: converging technologies primarily serve national security, external profiling and the safety of national supplies.
- **Virtual bodyguards**: digital androids identify attacks spread by foreign AI. The state uses them to ensure everyone adheres to strict online security requirements.
- Hack-proof **biological data storage** is experiencing a boom: in addition to the classic microchips, biological compounds such as nucleic acid (DNA) are used as portable storage devices or tokens for unlocking digitally secured access.
- Technological breakthroughs in 2030 arise mainly as a result of **military investments** in preparation for a feared "cybergeddon".
- Researchers are focused on developing new **biohybrid materials** to reduce the dependence on risky supply sources.

Example applications for the convergence of biology and technology

Family & friends

- Perception of personal use as a loss of control
- Convergence perceived as the lifestyle of the elite: digital androids for communications or concealment, biosensor implants for monitoring of vital data

Health

- Establishment of exoskeletons for health prevention in old age
- Soft robots with empathetic ability to treat loneliness
- Use of smart glasses for diagnostics in the medical sector

Military

- Tests with artificial organs and synthetic cells for healing or optimizing the performance of (digital) soldiers

Work

- Brain-computer interfaces for creating 3D models through pure imagination and transferring skills and abilities
- Biohybrid robotics in production

2.3.4 Scenario 4: Multi-speed Society

Scenario outline

Unintended boomerang effects: in the 2030s, Germany's attractiveness as a business location has declined as a result of low reform activity, whereas social polarisation has increased.

Key points of the scenario

- **Social polarisation** in Germany in the 2030s is also reflected in the use and spread of convergent technologies, which is progressive in cities but low in rural areas.
- In many companies, convergent technologies have become an indispensable **part of corporate culture**. Without them, entire value creation processes would collapse.
- **Robots shape work routines**. It is almost impossible to distinguish between human workers and robots any more. Robot clones act like their human counterparts.
- Increasing **time and performance pressures** force people to use even more technology to meet growing demands. Mental stress is growing.
- In the interests of the economy, there is an **absence of strict technology regulations** so as not to discourage progressive companies and not to endanger Germany's strength as a centre of industry.

Mechanisation of biological systems

Potential for convergence

Applications for biodigital technology

Invasive brain interfaces	Smart glasses & smart contact lenses
Mind uploading	Exoskeletons
Nanobots	Smart drugs
Artificial organs	Artificial blood

Biologisation of technical systems

Potential for convergence

Applications for biodigital technology

Digital androids	Biohybrid robots
Biohybrid materials	Android with all-round functionality

Example applications for the convergence of biology and technology

Security

- Biohybrid security robots as technical guards
- Biohybrid materials as intelligent alarm systems

Work

- Education and training conducted by uploading data using brain-computer interfaces
- All-purpose androids used as humanoid employees
- Digital androids used as negotiating partners

Environment

- Intelligent medications or artificial blood therapies for optimising the body's thermal regulation to protect against extreme heat
- Biohybrid exo-suits with active climate regulation
- Climate-adaptive building shells with biohybrid materials

Everyday life & leisure

- Digital androids used for virtual game worlds
- Digital androids used as "best friends" and for universal support in all life situations (embedded in smart contact lenses or invasive brain interfaces)

2.3.5 Scenario 5: Bonus System

Scenario outline

Germany in the 2030s is defined by a points system used as a central political instrument of control. Despite its voluntary nature and democratic rules, there is great social pressure to participate, e.g. through constant competition on social networks.

Mechanisation of biological systems

Potential for convergence

Applications for biodigital technology

- Sensory neuroprostheses
- Smart glasses & smart contact lenses
- Nanobots
- Exoskeletons
- Smart drugs
- Artificial blood

Biologisation of technical systems

Potential for convergence

Applications for biodigital technology

- Digital androids
- DNA-based data storage
- Biosensors

Key points of the scenario

- In the bonus system, convergent technologies are used as enabling elements for **recording behaviour and data**. The use of technology in everyday life is taken for granted.
- The vast majority of people can hardly imagine a life without digital assistance systems, personalised avatars or digital androids. They regularly provide **suggestions for optimisation.**
- The idea of selective optimisation has prevailed in the healthcare system; there has been a complete paradigm shift **from a healthcare system focused on treatment to one focused on prevention**.
- In the context of **environmental and climate protection** in particular, points are awarded to promote the use of technologies that document one's own environmental behaviour.
- Policy makers draw or define **ethical boundaries** around technologies which do not jeopardise the aim of building a sustainable, healthy and competitive society.

Example applications for the convergence of biology and technology

Leisure & consumerism

- Autonomous purchasing decisions and planning of leisure time carried out by digital androids
- Smart wearables (contact lenses or smart glasses) record purchasing and leisure behaviour

Environment & energy

- Biosensors for extensive recording of emissions and material flows
- Smart wearables used to document consumption and disposal behaviour

Health & nutrition

- Use of exoskeletons for physically strenuous activities
- Smart wearables and nanobots used to document health data
- Digital androids give decision-making support

2.3.6 Scenario 6: Ecological Regionalization

Scenario outline

In the 2030s, the market economy in Germany is guided by social and ecological issues. New key indicators include sustainability, quality of life and "time wealth". Almost all of society is guided by these principles.

Key points of the scenario

- People have a positive view of the progressive merging of boundaries through technologisation and biologisation if it enables a **more sustainable lifestyle**.
- People thus **openly embrace every technological opportunity** to reduce their ecological footprint and improve their quality of life at the same time.
- **Convergent technologies are often tailored to suit local circumstances**. The development of many solutions, e.g. digital androids and corresponding apps, is crowd-based in local communities.
- Many of the technologies that are now established can be traced back to citizens' **willingness to experiment** and their creative input.
- Convergent technologies not only make a positive contribution to **protecting the environment,** but they also provide new opportunities for **personal fulfilment and social participation**.

Mechanisation of biological systems

Potential for convergence

Applications for biodigital technology

- Exoskeletons
- Smart glasses & smart contact lenses

Biologisation of technical systems

Potential for convergence

Applications for biodigital technology

- Digital androids
- Humanoid robots
- Biosensors
- Bioproduction
- Biohybrid materials
- Synthetic cells
- Biohybrid robots
- Hybrid processors

Example applications for the convergence of biology and technology

Industrial processes

- Biosensors for monitoring the release of pollutants into the environment - also in agriculture
- Small biorobots for pollution control in wastewater treatment and recycling infrastructure

Mobility

- Exoskeletons as a new form of micromobility (via rental systems)
- Substitution of real mobility with converging technologies: virtual meetings with soft, clothing-style exoskeletons and a forced feedback function

Living & household

- Digital androids used for sustainable energy and heat management
- Biohybrid materioals help with energy management
- Humanoid robots assist with everyday activities and the care of family members

Research & development

- Intensive research into biohybrid materials
- Widespread use of DNA storage devices and biological computers
- Experimenting with new methods of biomanufacturing, such as artificial meat

3

LATEST RESEARCH AND DEVELOPMENT PROSPECTS

The applied technologies identified as relevant to the convergence of biology and technology generate lively interest in research and patenting that grows year on year. Both the technologisation of humans and the biologisation of technology are developing in a very dynamic way. When measured in terms of the volume of research publications, the technologisation of humans has become more dynamic in the last decade and has the potential to clearly overtake the biologisation of technology. In contrast, more patents have been registered related to the biologisation of technology. This could indicate that there are very specific and narrowly defined usage scenarios in the biological technology sector. On the other hand, the larger number of scientific publications on the technologisation of humans could indicate that scientists are investigating a broader range of potential applications and that there is a fundamental interest in the possibilities offered by the technologisation of humans. There are indications of a future interaction and synergy of both converging dimensions, e.g. in the dual potential uses of micro- and nanobots with living or inanimate materials in the body and in nature. In this context, progress in shifting boundaries on one side can also be used to shift boundaries from the other side as well. It is conceivable that biohybrid materials and biomanufacturing methods might be used, both in product manufacturing and in the body, e.g. to make artificial organs.

How technology is making its way into the body: a rapid rise in research into smart medicines and a huge number of patents for exoskeletons and brain interfaces

In the Delphi survey, many experts predict that innovations for the technologisation of people in particular will launch to market before 2030 (for 9 of the 12 technologies surveyed). Only bidirectional invasive brain interfaces, brain-to-brain interfaces and mind uploading are considered to be future technologies with significantly longer development times. Whereas the technologies that are closer to a market launch are said to have a medium to high potential for convergence, the convergence potential of technologies that are further away from market launch is even higher. There has also been a huge increase in publication activity on topics related to

the technologisation of humans since 2017. This trend is primarily driven by a rapid increase in publications in the smart medicines sector, with a sudden rise of 180 percent to almost 6,900 publications. Patent applications for smart medicines have also surged since 2017, but there are still fewer patents registered annually overall compared with exoskeletons and brain interfaces despite the fact that research publications focus less on these technologies. Health-related applications for technology such as neuroprostheses, artificial blood, artificial organs and micro- or nanobots are the focus of smaller research communities that have grown somewhat moderately in recent years. Public discourse, interviews with experts and the Delphi survey all consider the technologisation of people to be more relevant in terms of its potential for convergence. In this context, a shift in human capabilities is perceived more quickly and more strongly as a form of convergence than, conversely, a shift in technological boundaries. This is particularly true for performance-enhancing technologies, but less so for restorative technologies.

Technology comes to life: biosensors dominate research and patents, but humanoid robotics is also a key area for R&D

The majority of experts currently consider technologies for the biologisation of technology to be further away from a market launch, although there are some exceptions. It seems that biosensors, biohybrid materials, biomanufacturing and humanoid robots will all be in commercial use before 2030. Publications on the biologisation of technology have also seen less dynamic development, but have remained at a high level for a long time with moderate growth. In contrast, there is a stronger trend for patent development than the patent figures for the technologisation of humans. Here, as with the scientific publications, developments are dominated by the topic of biosensors, which accounts for the largest share of both publications and patents. In addition to this, a number of patents have also been registered in the fields of humanoid and soft robotics, as well as synthetic cells. This partly overlaps with the significant growth in the research fields of humanoid and soft robotics and biomanufacturing. However, even the smallest topics such as DNA data storage have become established as research fields with great growth, which is not yet reflected in increased patent activities.

Germany can play a leading role in Europe; in an international comparison, the USA and China currently occupy pole position

International comparison reveals strong scientific research competition between the USA and China, which come first and second in the publication rankings for all applied biodigital technologies. China, in particular, has seen a dramatic increase in its publishing activity. Overall, Germany covers a very broad range of research activities and can usually be found in third to fifth place. However, in recent years, Germany has not been able to keep pace with the dynamic developments in other countries such as China and South Korea. The USA and South Korea are also leaders in patent applications and account for a high proportion of total patents. Chinese activities are also particularly frequent among the notifying parties. Germany plays a leading role in Europe, in third place among the notifying countries and with a higher volume of patents registered than France, Great Britain or Switzerland.

Note on the full version of this study

A detailed description of the current research landscape and the development prospects for applied biodigital technologies including background sources can be found in Chapters 3.1 and 4.4 of the full version of the study report (available for download from vorausschau.de; German version only).

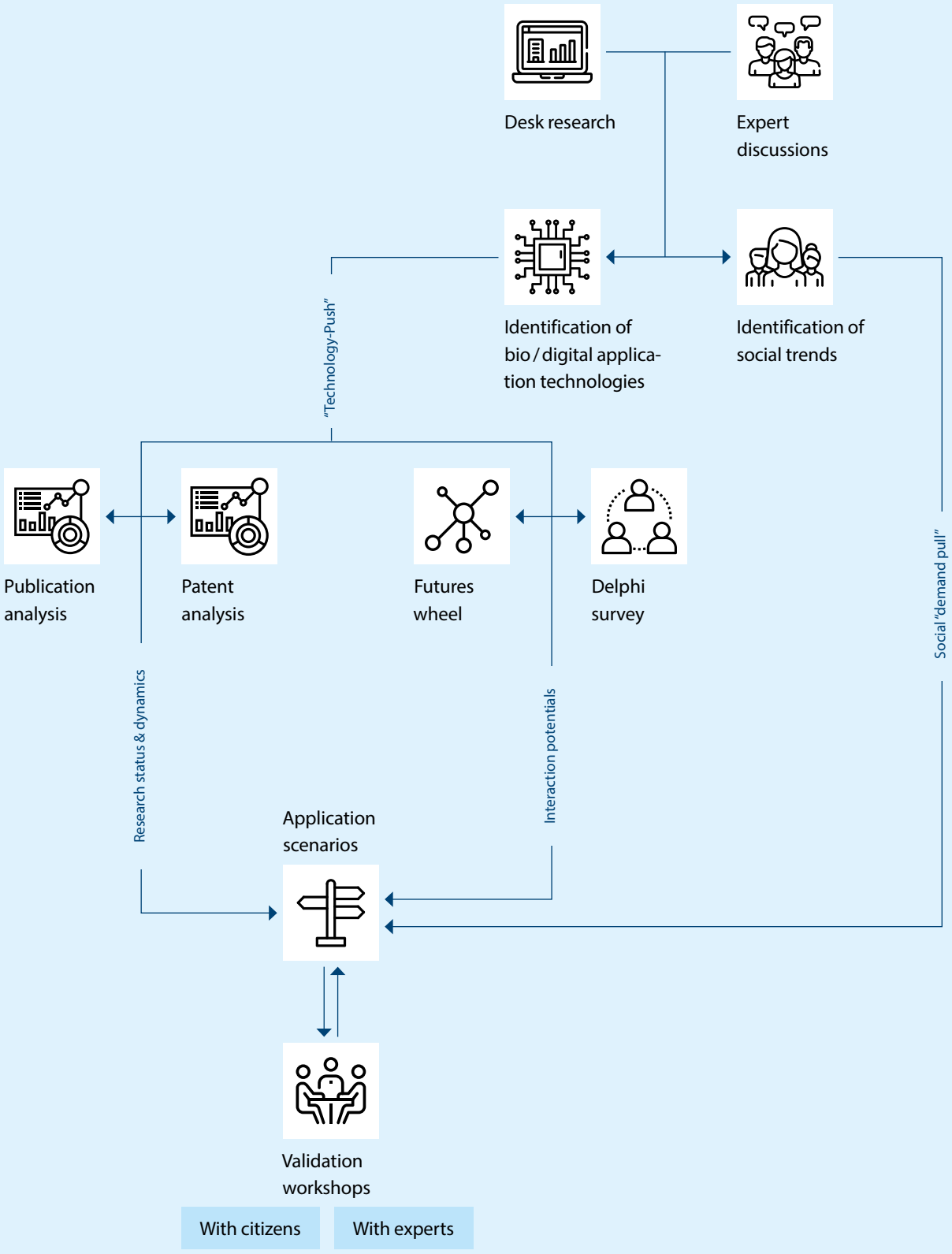
4 METHODOLOGY

The study is based on a comprehensive repertoire of methods, consisting on the one hand of standard scientific methods, such as literature, patent or publication analysis and expert interviews. In addition to this, established foresight and participation methods are also used, such as a Delphi survey, a futures wheel workshop, the development of possible scenarios, as well as a scenario validation workshop with experts and a citizens' workshop to discuss potential forms of future convergence. Explorative, forward-looking and dialogue-oriented foresight methods thus rely on a solid empirical basis that portrays research dynamics and depicts development prospects at the same time.

Note on the full version of this study

A detailed description of the methodology can be found in Chapter 5 of the full version of this study (available for download from vorausschau.de; German version only).

Fig. 2: Overview of applied methods



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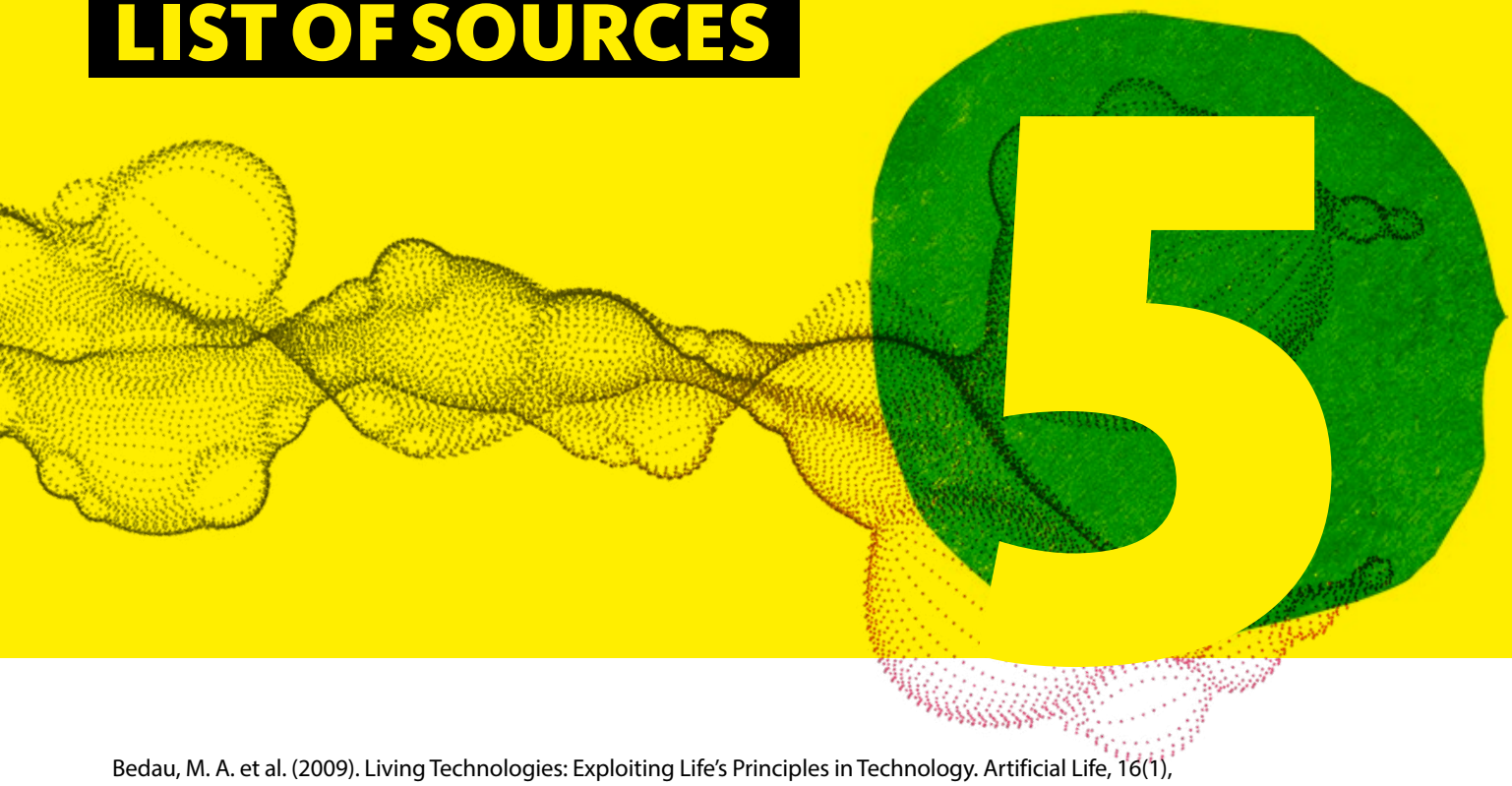
5
LIST OF SOURCES



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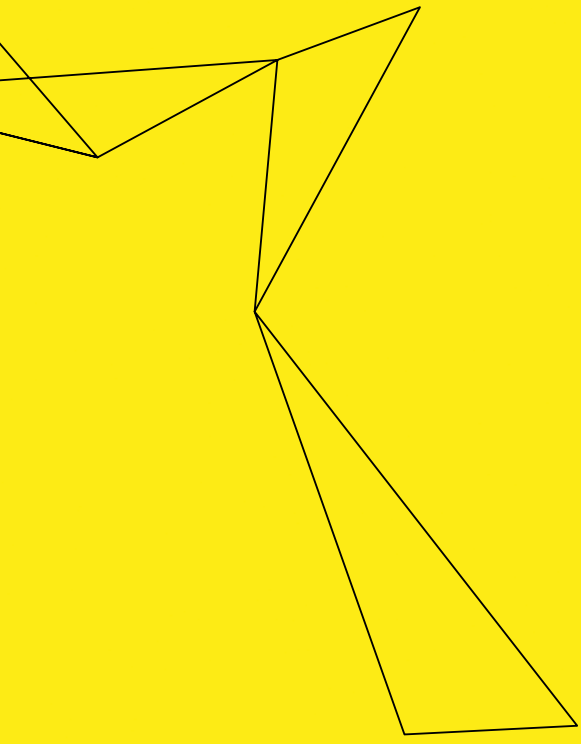

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