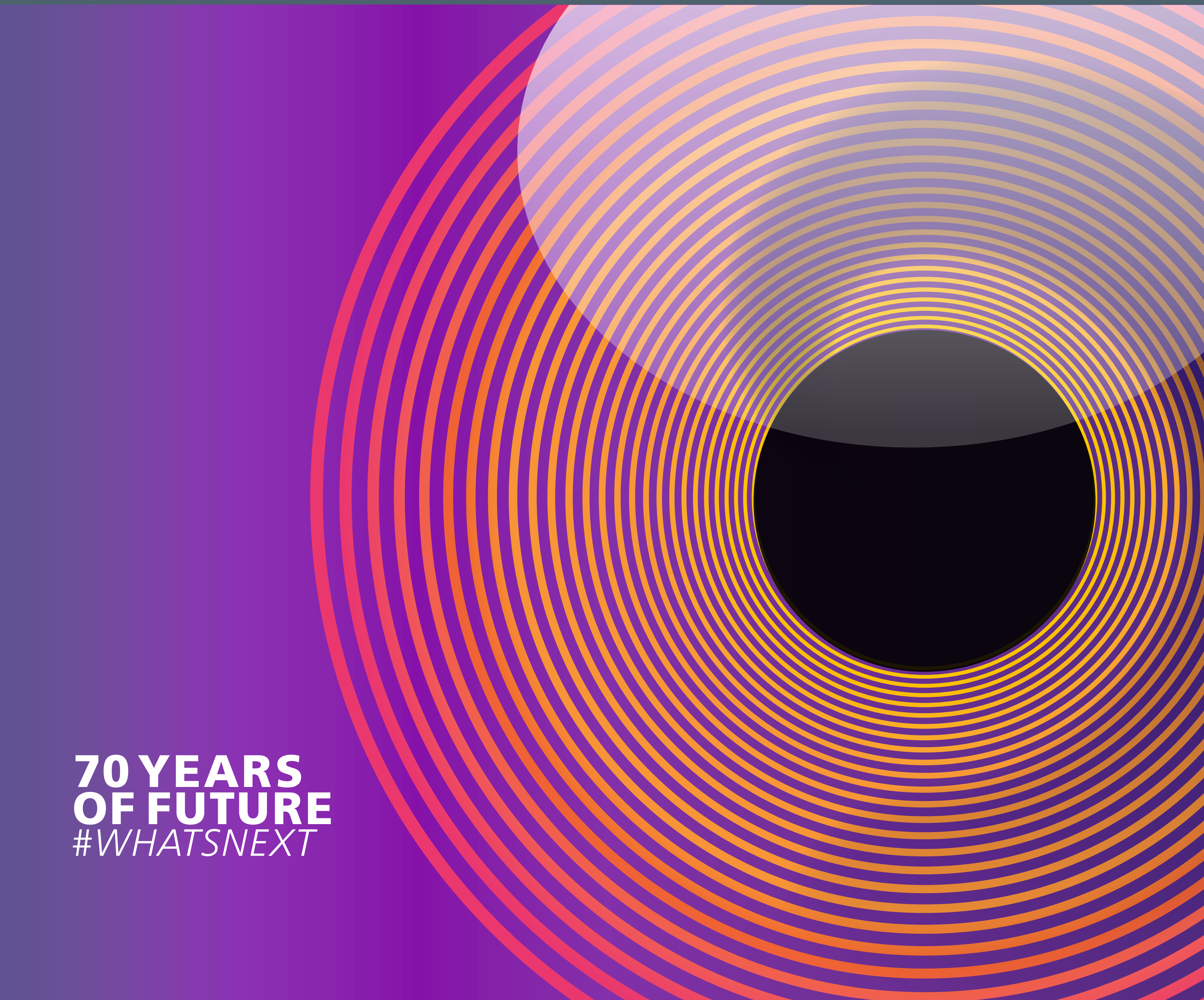
Fraunhofer

FUTURE TOPICS WITH RELEVANCE TO APPLICATION-ORIENTED RESEARCH

FORESIGHT FRAUNHOFER



The Fraunhofer-Gesellschaft is the leading organization for applied research in Europe. Its research activities are conducted by 72 institutes and research units at locations throughout Germany. The Fraunhofer-Gesellschaft employs a staff of more than 26,600, who work with an annual research budget totaling 2.6 billion euros. Of this sum, 2.2 billion euros are generated through contract research. Around 70 percent of the Fraunhofer-Gesellschaft's contract research revenue are derived from contracts with industry and from publicly financed research projects. International collaborations with excellent research partners and innovative companies around the world ensure direct access to regions of the greatest importance to present and future scientific progress and economic development.

CONTENT

FOREWORD

For many years, the Swedish scientist Hans Rosling dealt intensively with facts aimed at opening people's eyes on the basis of statistical data. In his award-winning book, "Factfulness", which was published posthumously last year, he convincingly demonstrates that people perceive the world to be far more dangerous, violent and negative than it actually is. Rosling's intention was to convey a realistic view of the world, one which is based on facts and describes the positive progress which is actually being made in combating diseases, in improved access to drinking water or in reducing child mortality, for instance. Mapping out human progress on the basis of facts instead of feelings and prejudices offers reassurance and opens our eyes to what is important.

To mark the 70th anniversary of the Fraunhofer-Gesellschaft, we will focus on the interaction between technology and society throughout recent decades. Ground-breaking progress which facilitates or improves everyday (working) life through technical support and which contributes in part to a significantly higher life expectancy and better quality of life has been made in all areas of work and life – in communication, production, health or mobility. In our opinion, looking ahead to the future is therefore not a cause for pessimism but instead offers an opportunity to concentrate with a certain degree of confidence on primary challenges such as climate change, health, and food security or the scarcity of resources and to further improve economic and societal conditions.

For example, what form will the energy supply of the future take? The future path has not yet been mapped out in detail. Fraunhofer is conducting research in various directions with openness to technology as a fundamental factor in order to remain a strong partner to industry in the future. The importance of the early strategic positioning of our preliminary research in emerging trends is clearly revealed in the broad competency portfolio of energy research: at Fraunhofer, energy and storage technologies, materials research, electricity networks, electromobility, and information and communication technologies are closely intermeshed with economic systems analysis and innovation research so that we are able to understand energy industry trends in system contexts and translate them into specific road maps or scenarios. Ultimately, a certain path independence, decades of being in the lead, and constant efforts to be the scientific world leader result in the fact that we are able to shape the transformation of the energy system with superiority – and are not driven by it.

We shape the future! 70 years on, this Fraunhofer-Gesellschaft motto is truer than ever before. In order to take a look into the future, we have conducted an internal project for the anniversary

year that draws on the foresight competencies of our Fraunhofer futurologists as well as on the broad-based technical expertise of our institutes. Futurology is occasionally a topic of controversial discussion; selection and interpretation services are required, particularly when assessing trends in a complex, dynamic system. The role of science is ambivalent: it is the source of crucial stimuli; in turn, it is involved with its expertise to provide assessments; at the same time, science can also contribute to undesirable developments through misinterpretations.

The results of the Fraunhofer foresight process are therefore initially valid raw results and show an astonishing range of future topics. As in the case of diamonds, a certain amount of polishing is still required to shape these trends, which are focused very extensively on technological development, to form future visions that provide answers to urgent questions, offer solution approaches to major challenges, and reflect our value orientation. They also show us that Fraunhofer is positioned well in structural and thematic terms.

The foreseeable merging of topic contents recognized in the foresight process necessitates an increasingly interdisciplinary approach and synergistic interaction in the organization as well as in the research and innovation landscape. The Fraunhofer agenda 2022 is aimed at elevating cooperation and collaborative work within and outside of the organization to a new level of quality and agility. Key technologies with enormous relevance for all economic sectors, such as micro and nanoelectronics or artificial intelligence (AI), must be extensively driven forwards with precisely the same degree of competence as we should now already be picking up on new research fields from quantum technology, although market demand for them is still low. Information and communication technology (ICT) and life science technologies necessitate comprehensive support from state, societal, and economic actors as part of systematic governance processes in order to prevent legal or ethical issues from becoming obstacles to innovation. The Fraunhofer-Gesellschaft is not only scientifically active in all of these fields, but is also acting to structure them – as an initiator or driver and a reliable cooperation partner.

The Fraunhofer foresight process identifies future topics from research and technology that could have decidedly positive impacts on economic and societal developments. In dialogue with politicians, commerce, and society, we would like to use these to develop visions for a good and worthwhile future in those areas that can be influenced by Fraunhofer and – entirely in keeping with Fraunhofer's 70-year-old diction – to contribute to the realization of these visions through excellent, result-driven research and development.

Reimund Neugebauer
Fraunhofer-Gesellschaft President

1 EXECUTIVE SUMMARY

The requirements on the strategic management of organizations have risen sharply due to societal and macroeconomic development dynamics. Foresighted actions to set the right course at the given time are based on well-founded visions of the future and are one of the greatest challenges that organizations must face.

In the context of a foresight process, the Fraunhofer-Gesellschaft has taken a systematic look into the future in order to derive strategic orientation knowledge from potential technologies and societal challenges and to foster the further development of the foresight methods at the same time. In addition to the systematic, very broad scanning of future topics, one special feature of this project is the comprehensive use of Fraunhofer expertise across all 72 research institutes. This means that it is significantly more extensive than in the case of previous foresight processes.

51 topics of high relevance to applied research in 2030 were identified.

- We initially selected and analyzed these 51 topics through extensive research of international foresight studies.
- Some 400 Fraunhofer experts then evaluated them in terms of their relevance to the future of research, the economy, and society.
- The results were confirmed by 20 national and international experts from the fields of science and industry through interviews in a review process.

The survey results were used as the basis for identifying topics which will bring about **fundamental changes** and therefore require special attention. These topics include **deep learning – AI, re-economy** and the use and maintenance of **biodiversity**. We additionally identified topics that are particularly **dynamic in terms of innovation**. Some of these topics, such as **biohybrid, water harvesting membranes,** and **pHealth**, are already highly relevant to applied research today, while others are thus far niche topics that are developing dynamically and could therefore soon encounter broader interest. Many topics from this group are related to microelectronics, such as **neuromorphic chips** or **quantum communication**. The study also identified a further topic group with particular **societal relevance**. These topics, some of which are highly controversial, include **geoengineering**, **civic technologies,** and **reprogramming of human cells**, for instance.

Further findings concerning the perspective development of the selected 51 topics can be derived as follows on the basis of the survey results:

- Numerous topics with a very broad impact on entirely different research and economic sectors could develop into key technologies.
- Topics with converging technologies could dissolve the boundaries between areas of research and thus radically change the still predominantly disciplinary character of the sciences.
- Topics with far-reaching, sometimes controversially discussed effects on society and the environment could significantly increase the need for governance processes and societal involvement in the development and introduction of advanced technologies.

We have designed the foresight process as a broad look into the future which particularly analyzes emerging technologies but also shows societal developments and the connections between the technical topics (technology, economy, and society). The results form a sound knowledge base and numerous starting points for further projects with specific questions with cooperation partners from commerce, politics, and the public sector.

2 OVERVIEW OF THE RESULTS

The objective of the "Fraunhofer foresight" project was to identify future topics with relevance to application-oriented research on the basis of a broad-based search radar and a potential analysis. Future topics that could have a crucial influence on research activities, economic development, society, and the environment over the next 10 to 15 years are of interest.

The foresight process was based on around 300 predominantly technological topics that have been identified as future topics by international foresight projects. In a multistage, systematic process based on publication, patent, and social media analyses, we have selected 51 so-called spotlights from these topics which could be in the "spotlight" of applied research in the future. The 51 spotlights cover very different areas; they encompass both specific technological topics as well as societal changes. They have been assigned to the clusters of **data, materials, society, algorithm & hybrid architecture, human,** and **planet**.

In an online survey, some 400 selected Fraunhofer-Gesellschaft experts evaluated the 51 spotlights in terms of their future relevance to applied research. The participants came from all Fraunhofer-Gesellschaft institutes so that the entire spectrum of Fraunhofer expertise was used. We asked managers, future decision-makers, and outstanding young scientists which spotlights will influence the strategic orientation of the institutes in the next 10 to 15 years. The survey was conducted in English, as a review by international experts was important to us.

The analysis of the results not only gave consideration to the expected relevance in 2030 but also to current importance and the possible impacts on research areas and economic sectors. The topics were also analyzed in terms of their possible impact on society and the environment.

We have typologized the spotlights on the basis of their temporal positioning and their future effects. Figure 1 shows an overview of the four groups with the assigned spotlights.

"Long-runners" with very extensive importance

Seven spotlights were grouped together as what are called **long-runners**. They are already of great relevance today and could become even more important in the future. **Deep learning – AI** was rated highest. Long-runner topics such as **re-economy: reduce, reuse, recycle** and **exploitation of biodiversity** will have a very fundamental, extensive influence on economic development but also on the environment. This group also includes somewhat more specific topics such as ***optoelectronics*** or **liquid biopsy**.

Optoelectronics: *Photonic-based chips, which are currently used mostly in high-end military equipment, might be extensively employed in data centers within a few years.*

"Hot-shots" with dynamic development potential

Particularly dynamic development and also a very high relevance are anticipated in 2030 for a second group of the spotlights, **called hot-shots**. These include topics such as **pHealth, global protein supply,** and ***biohybrid***. Already known as niche topics in certain cases, they could become significantly more relevant for applied research in the future.

Biohybrid *technologies could replicate tissues or organs that could help us to better understand human physiology or to design new drugs or drug delivery methods.*

"Future options" with high potential for change

The third group of topics, which currently play a much smaller role in application-driven research and whose relevance for the year 2030 is estimated to be slightly lower than that of the **long-runners** and **hot-shots**, promises similarly high innovation dynamics. However, these topics would be suitable for shaping research and innovation in the longer term. They have been allocated to the future options group. The **future options** group is dominated by developments in connection with microelectronics; it includes the spotlights of **neuromorphic chip, *artificial brain,*** and **quantum communication**, for instance.

*The learning flexibility and low-power trait of **artificial brain** could make it suitable for any kind of AI devices.*

It is expected that these three groups will have a major impact on economic development; a potential for major societal change is also anticipated. The spotlights reveal a very high correlation between the potential for springboard innovations and their relevance to economic development in Germany as well as their expected pace of innovation. The assessment of the change or disruption potential of technological and societal developments is tied closely to the assessment of future relevance for Germany as an economic location: whether a topic will be of great importance to applied research in the future depends particularly on its assumed potential to create a new, dynamic market in a short space of time or to achieve significant market shares in existing markets.

Reprogramming of Human Cells: *Researchers might create human induced pluripotent stem cells (iPSC) from a patient´s blood or skin cells and use these patient-specific cells to study.*

Smart contracts *can be used in almost all areas of B2B markets. The elimination of an intermediate entity between the contracting parties greatly increases the efficiency of cooperation.*

"Social shapers" with impacts on society and the environment

Nine further spotlights whose relevance to research and industry is still uncertain or more indirect were also identified in addition to the 21 spotlights from the three groups described above. It is nevertheless assumed that they could have a major impact on societal developments and environmental aspects. Spotlights from this group have been grouped together under the term **"social shapers"**. Some of the topics in this group are particularly controversial, such as **geoengineering** and ***reprogramming of human cells***. The impacts on societal development reveal a link to several digitalization topics such as ***smart contracts*** and **civic technology**.

Topics whose future relevance to applied research is regarded as less direct than that of the long-runners, hot-shots and future options could initially generate less attention. Due to their greater impact on society, and the environment and the controversial discussions that are parly foreseeable as a result, these topics could necessitate value orientation in the future. If clear and ethically justifiable positioning can be achieved, these topics could develop dynamically and also play a strategically relevant role.

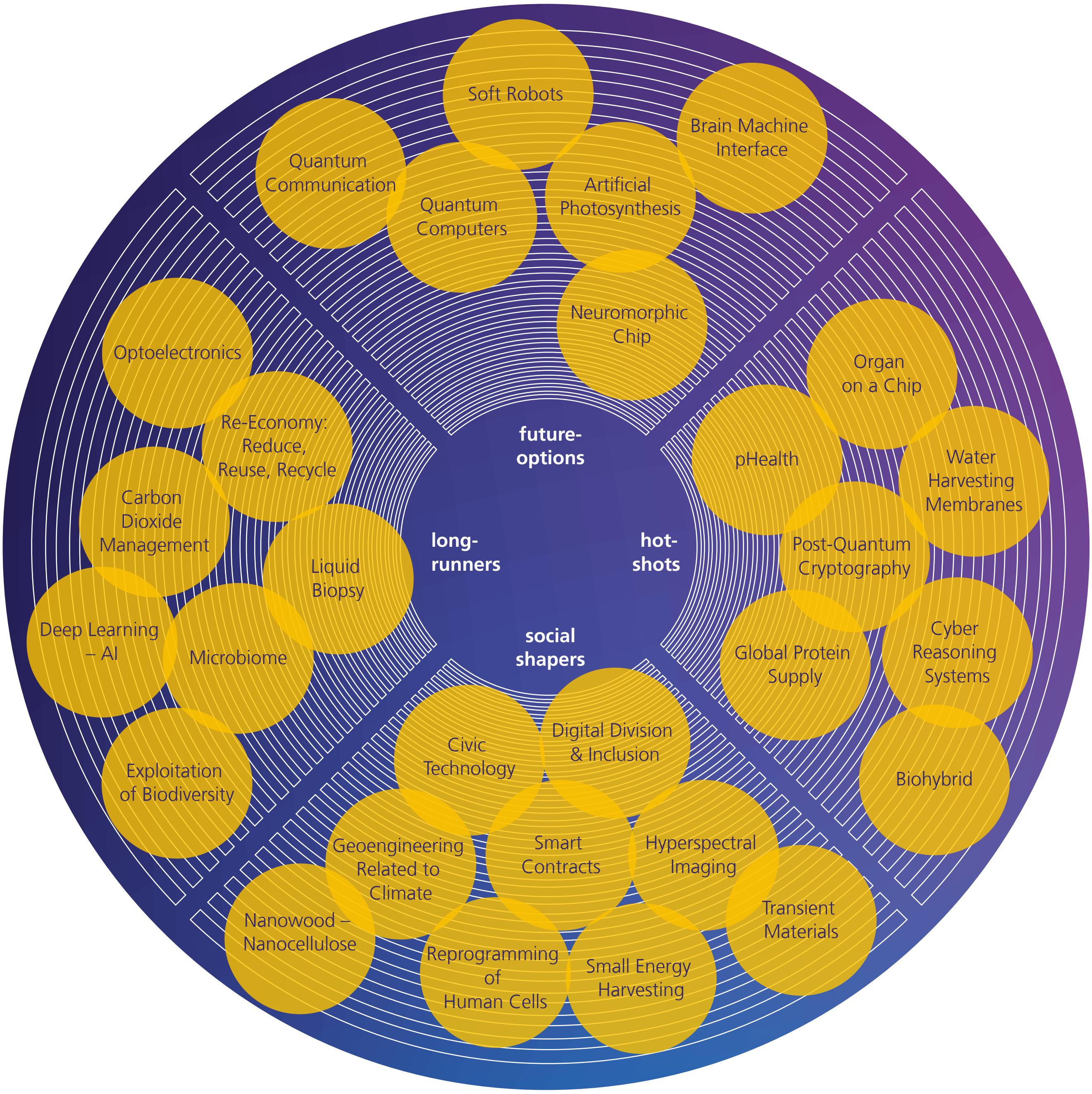


Figure 1: Overview of the 30 spotlights with particular relevance to the future.

Influence of the spotlights on the development of fields of research
In order to classify the relevance of the spotlights for current scientific disciplines, we have defined ten fields of research based on the German Research Foundation's subject systematics. The survey results show that the spotlights could have a particularly strong influence on the **medical, information, and materials sciences** and will not only affect individual areas of research. The spotlights are not a representative indicator of the innovation dynamics of the research fields and economic sectors but nevertheless provide clear indications of very high innovation dynamics in information technology, information science, and medical and material sciences in the next 10 to 15 years.

Conversely, a sharp increase in the interdisciplinary nature of many research fields can be seen for the next 10 to 15 years. Innovation dynamics in the research fields of medical, materials, and information science but also in **mechanical engineering, process engineering and, electrical engineering** will not be inspired and fostered by a single technology but through a wide variety of diverse technological developments. This could promote the increasing softening of the established boundaries between areas of research and foster spill-over effects.

In the future, **agricultural and food sciences** could also be digitalization to different degrees by spotlights from all six clusters such as **swarm robot intelligence**, ***microbiomes,*** and ***water harvesting membranes***.

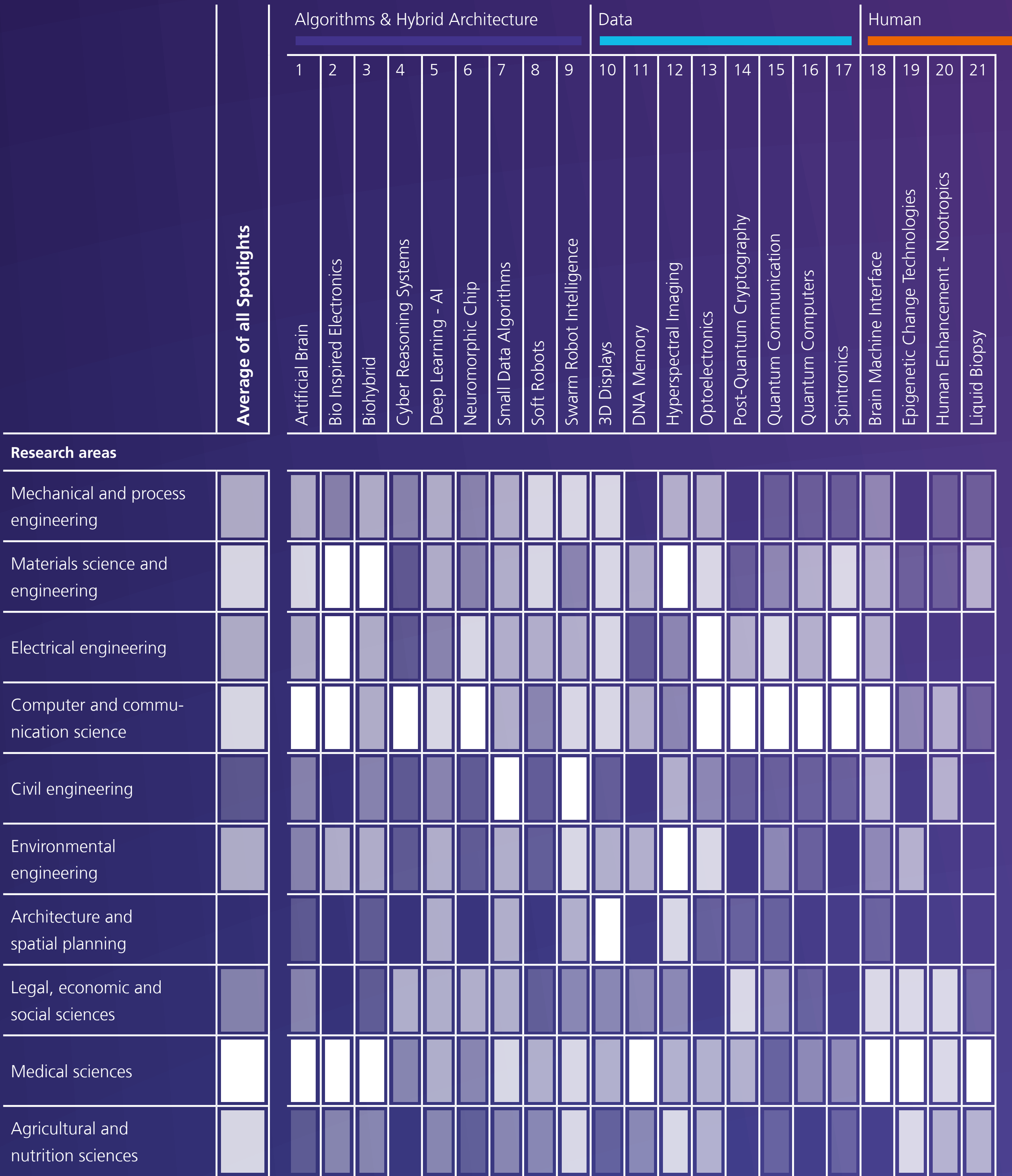
A direct influence not only on **medical and information science** but also on **civil engineering and environmental technology** is foreseen for the spotlights from the **society** cluster. Not only an interdisciplinary, but also a transdisciplinary, mode of research involving non-scientific actors from society and politics could increase in relevance in these areas.

*Metagenomics analysis of the **microbiome** will open the door to intestinal bacteria being able to directly alter the activity of our genes. This will lead to future therapeutics for mental and physical conditions such as depression or diabetes.*

Water Harvesting Membranes: *The combination of functionalized bio-inspired surfaces with condensation seems to be a promising approach for the extraction of water from the air. New precision filtration technologies could have a massive impact on the global economy by reducing costs of water filtration.*

OVERVIEW OF THE RESULTS

RESEARCH AREAS INFLUENCED BY THE TOPICS UNTIL 2030



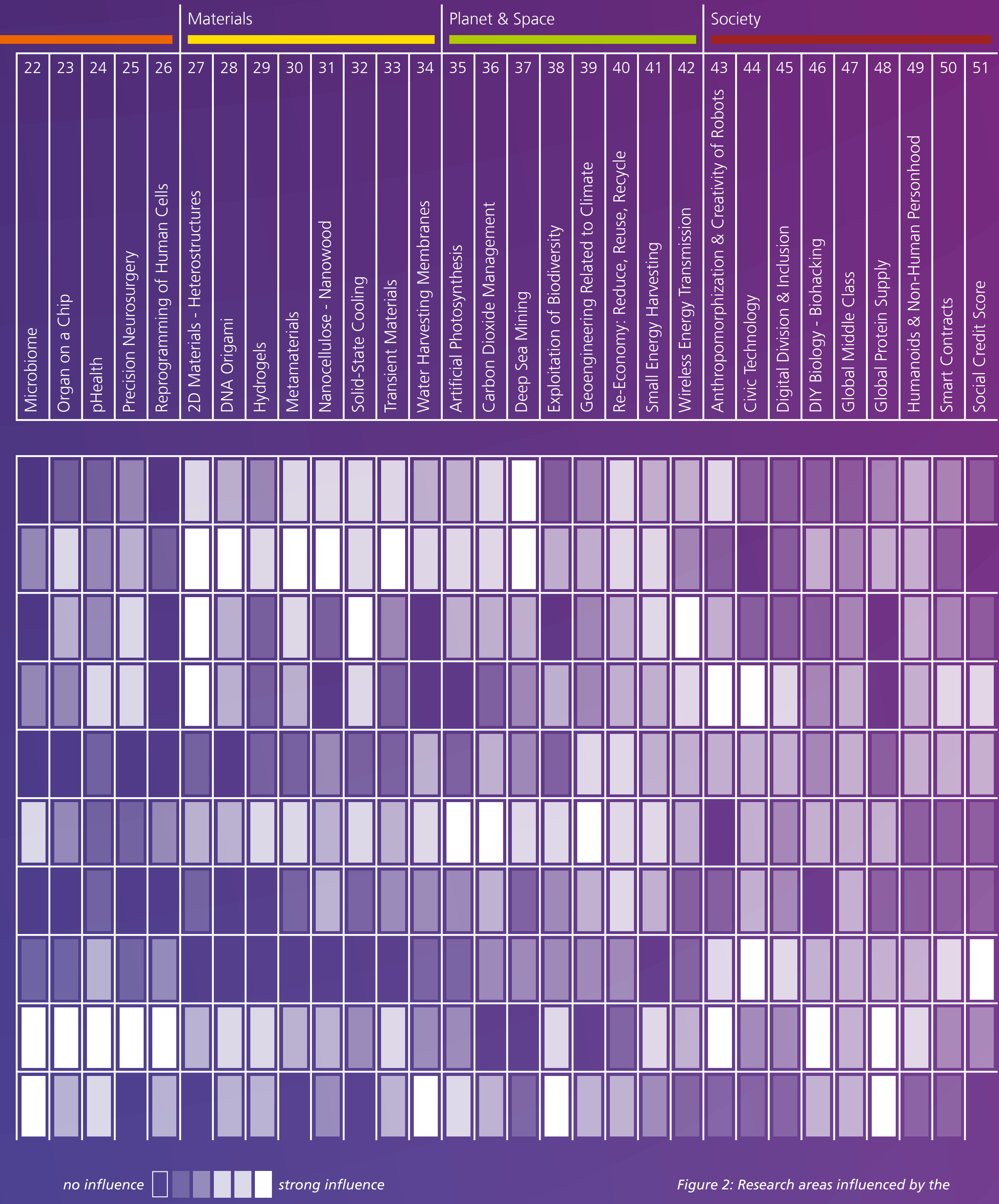


Figure 2: Research areas influenced by the spotlights.

Influence of the spotlights on the development of economic sectors
We have assessed the relevance of the spotlights to the economy based on the current economic sectors; this reveals parallels with the analyses for the areas of research. A particularly close link to the **health sector** can be seen for the spotlights. **The chemicals and pharmaceutical industries** as well as **mechanical engineering, information technology Membranes** and the **food industry** are sectors which will also be influenced by the majority of the 51 spotlights.

The analyses provide indications of the direction which research could take in the next 15 years and which individual topics deserve particular attention. The broad spectrum of the spotlights and their consistently high relevance show that innovations are not only to be expected in a few selected research disciplines or areas over the next 10 to 15 years but that a wide diversity of innovations can be anticipated. At the same time, however, this diversity goes hand-in-hand with the increasing convergence and interdisciplinary nature of research areas.

3 HOLISTIC ASSESSMENT OF THE SPOTLIGHTS' RELEVANCE

In the Fraunhofer foresight process, we have identified 51 future topics after systematically scanning around 300 predominantly technological future trends (see also chapter 7 and Fig. 3). Criteria for the selection of the future topics included dynamic development over the next few years, relevance to applied research, and the potential to become a "rising star" for Fraunhofer research. For selection purposes, we conducted patent researches and performed supplementary bibliometric analyses (Web of Science, LexisNexis, Watson Social Media Analysis), which we used together with the above criteria for the final selection of topics. As the result of this, we summarized each of 51 topics – so-called spotlights – on a "one-pager". These "one-pagers" contain a short description, explanations on recent developments, the long-term perspective of the topic as well as the results of the patent research and the publication analysis. We made these "one-pagers" available during the subsequent online survey of the Fraunhofer experts. We were then able to identify 30 spotlights that were assigned special future relevance on the same basis.

HOLISTIC ASSESSMENT OF THE SPOTLIGHTS' RELEVANCE

Data
- 3D Displays
- DNA Memory
- Hyperspectral Imaging
- Post-Quantum Cryptography
- Quantum Communication
- Quantum Computers
- Spintronics

Algorithms & Hybrid Architecture
- Artificial Brain
- Bio Inspired Electronics
- Biohybrid
- Cyber Reasoning Systems
- Deep Learning – AI
- Neuromorphic Chip
- Small Data Algorithms
- Soft Robots
- Swarm Robot Intelligence

Society
- Anthropomorphization & Creativity of Robots
- Civic Technology
- DIY Biology – Biohacking
- Digital Division & Inclusion
- Global Middle Class
- Global Protein Supply
- Humanoids & Non-Human Personhood
- Smart Contracts
- Social Credit Score

Human
- Brain Machine Interface
- Epigenetic Change Technologies
- Human Enhancement – Nootropics
- Liquid Biopsy
- Microbiome
- Organ on a Chip
- pHealth
- Precision Neurosurgery
- Reprogramming Human Cells

Planet & Space
- Artificial Photosynthesis
- Carbon Dioxide Management
- Deep Sea Mining
- Exploitation of Biodiversity
- Geoengineering Related to Climate
- Re-Economy: Reduce, Reuse, Recycle
- Small Energy Harvesting
- Wireless Energy Transmission

Materials
- 2D Materials – Heterostructures
- DNA Origami
- Hydrogels
- Metamaterials
- Nanocellulose – Nanowood
- Solid-State Cooling
- Transient Materials
- Water Harvesting Membranes

Figure 3: The spotlights of particular relevance to the future come from all clusters.

Identifying the key future topics for applied research was made possible thanks to the willingness of the Fraunhofer experts to take part in the survey:

- **Consistently high interest in all spotlights:** All spotlights were processed (evaluation by an average of 50 persons per spotlight, whereby the choice of which and how many spotlights were evaluated was left to the discretion of the respondents).
- **Broad participation in the online survey:** All 72 Fraunhofer institutes took part in the survey.
- **Outstanding participation:** Around 400 persons (primarily managers) completed the survey.

Participants included current and future Fraunhofer-Gesellschaft decision-makers across all institutes and networks. Persons from different hierarchical levels were invited to participate, from group management to institute management, supplemented by selected groups in order to give consideration to age and gender diversity. Many of the participants requested additional information and revealed an interest in the results of the survey.

3.1 Relevance to applied research today and in 2030

In assessing the future relevance of a topic, we gave consideration not only to the absolute relevance evaluation but also to the change compared with the current relevance evaluation and thus the anticipated innovation dynamics. The absolute relevance evaluation (Fig. 4) enables the identification of a number of topics that are already considered to be "quite relevant" on average today and whose relevance is likely to be very high in 2030. These topics, whose importance is anticipated to continue developing over many years, were termed **long-runners** (Fig. 4):

- Re-Economy: Reduce, Reuse, Recycle
- ***Deep Learning – AI***
- Optoelectronics
- Liquid Biopsy
- ***Exploitation of Biodiversity***
- Microbiome
- ***Carbon Dioxide Management***

Deep Learning – AI: *In the future neural net architectures will be handling more abstract and integrated knowledge beyond the processing of video, audio, and text data.*

*The potential of **biodiversity** is seen as the most important resource for drug development. About 60 % of today's cancer drugs contain substances from nature.*

Carbon Dioxice Management: *Combining direct air capture with carbon storage can fulfill a dual function: as a carbon dioxide removal technology and as a form of climate engineering.*

HOLISTIC ASSESSMENT OF THE SPOTLIGHTS' RELEVANCE

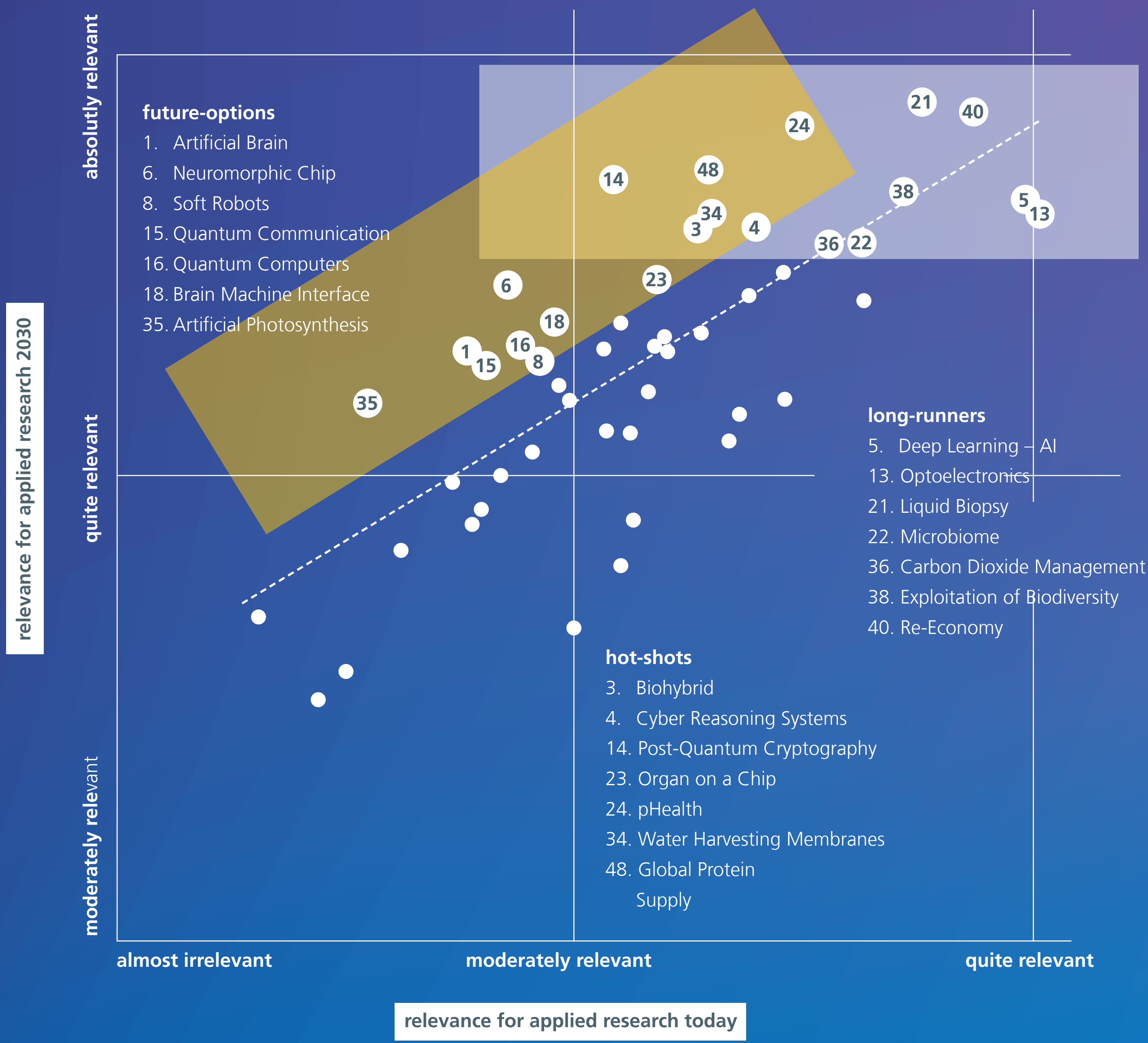


Figure 4: Correlation between current and future relevance of the spotlights.

Figure 4 also shows the characteristic correlation between current and future relevance (dashed trend line) as found in numerous foresight studies. In futurology, this correlation is explained using the cognitive mechanism of the "end of history illusion". This mechanism leads to cognitive distortions (biases), with the result that the importance and stability of the current state are overestimated compared to the dynamics of change in the past and future. In the light of this, future relevance must be assessed depending on the current relevance in each case.

This means that topics above the trend line will have an above-average relative relevance in 2030 if their relevance today is used as the basis (spotlights highlighted in yellow in Fig. 4). A distinction is made between two sectors within the area marked in yellow: located further to the left are topics that are still of rather low relevance today (below "moderately relevant today" on average) but which are likely to develop very dynamically and are therefore above "quite relevant" on average in terms of future relevance.

As yet, these topics are generating little attention in applied research today. They could increase in importance very quickly and are therefore grouped under the term **future options**:

- ***Neuromorphic Chip***
- Brain Machine Interface
- Quantum Computing
- Artificial Brain
- ***Quantum Communication***
- Artificial Photosynthesis
- Soft Robots

Neuromorphic chips *could be used wherever real-world data needs to be processed in real-time environments, e.g. to create smart-city infrastructures designed for autonomous vehicles.*

Quantum Communication: *The transmission of information encrypted into the quantum could solve the global challenge presented by the exponential growth of recorded information.*

The overlapping area of the yellow and blue sectors contains topics which currently lie in the middle range of relevance (to the right of "moderately relevant" on average) and for which dynamic development can be foreseen. These topics are on the threshold of broad relevance for applied research and are bundled under the term **hot-shots**:

- Global Protein Supply
- pHealth
- Water Harvesting Membranes
- Biohybrid
- Post-Quantum Cryptography
- Cyber Reasoning Systems
- Organ on a Chip

Organ on a Chip: *These models could inform a predictive response to drugs or other chemical compounds and replace most animal tests.*

Topics that are related to **microelectronics** but are still in an early development phase are found particularly in the **future options**, but also amongst the **hot-shots**. The hot-shots are distributed across all clusters. Topics from the **human cluster** such as **pHealth** or ***organ on a chip***, but also from the **material cluster** such as **water harvesting membranes**, are found here.

The following three groups of topics were accordingly identified, each of which will play a different role in the development of applied research and necessitate specific funding instruments:

Long-runners: Spotlights that are already very relevant today and whose enormous importance will continue until 2030. The current research activities are of considerable importance, as a fundamental change and a very broad impact are anticipated. Many topics are related directly to environmental aspects or the health sector.

Hot-shots: Spotlights that are of medium relevance today and will increase significantly in importance by 2030. These topics may require preliminary research or start-up funding. They are on the cusp of broader relevance and are distributed across all clusters (human, materials, etc.).

Future options: Spotlights whose relevance is still low or medium today but for which particularly dynamic development is to be anticipated. These topics are likely to undergo very fast further development, which is why early positioning may be important. These are technological topics that are primarily related to microelectronics but are still in the early stages of development.

Its relevance in 2030 must be taken into consideration to assess whether a topic has the potential to be a springboard innovation or a disruptive development: with one exception, all of the topics with particular springboard innovation potential are considered to be hot-shots or long-runners. The highest potential for disruption is foreseen for ***post-quantum cryptography*** and **pHealth**; disruptive developments are also anticipated for the topic of **reprogramming of human cells.**

*The experimental work performed in **post-quantum cryptography** could lay the groundwork for a future quantum Internet where all transactions are safeguarded.*

3.2 Relevance to society and the environment

It was very important to us to evaluate the impact of the spotlights on society and the environment in order to identify additional topics which may have been disregarded in a purely economic relevance assessment.

There is no correlation between the dimensions of environment and society (Fig. 5). There are nevertheless six topics which will have a major impact on both dimensions:

- Water Harvesting Membranes (hot-shots)
- Global Protein Supply (hot-shots)
- Carbon Dioxid Management (long-runners)
- Exploitation of Biodiversity (long-runners)
- Artificial Photosynthesis (future options)
- Geoengineering related to Climate Change

Geoengineering related to climate change is estimated to be less relevant to current and future applied research in comparison with the other topics. However, its future significance could arise due to impacts on the environment and society. Other topics of future societal relevance, which could become highly important for applied research rather indirectly, are spotlights related to digitalization such as ***digital division & inclusion***, **civic technology** or **smart contracts**. The results of the foresight process indicate that the societal dimension of digitalization processes, in particular, could play a major role in the next 10 to 15 years (Fig. 5).

__Geoengineering__ might become economically feasible to combate effects of climate change and require systemic research to assess the impact on complex ecosystems and biodiversity.

__Digital Division & Inclusion:__ The digitalization of everyday life offers great opportunities to create equal conditions for all. It could trigger a displacement of global centers of power.

Focus on spotlights from the **materials cluster**, such as **transient materials** or **nanocellulose**, is also lost if only economic relevance is taken into consideration. However, the above-mentioned topics are of particular importance to environmental aspects and were therefore combined with other spotlights to form the group of social shapers (area highlighted in gray in Fig. 5):

Small Energy Harvesting *promises no maintenance and unlimited performance for wireless sensor networks, battery-free medical implants, install-and-forget house automation, and many others.*

- Geoengineering related to Climate Change
- Digital Division & Inclusion
- Civic Technology
- Smart Contracts
- Transient Materials
- Nanocellulose – Nanowood
- ***Small Energy Harvesting***
- Hyperspectral Imaging
- Reprogramming of Human Cells

"Social shapers": Spotlights that could become particularly relevant due to their contribution to the future development of society and the environment. These topics are only of indirect relevance to applied research. The involvement of new actors from society and politics in research activities could become increasingly important.

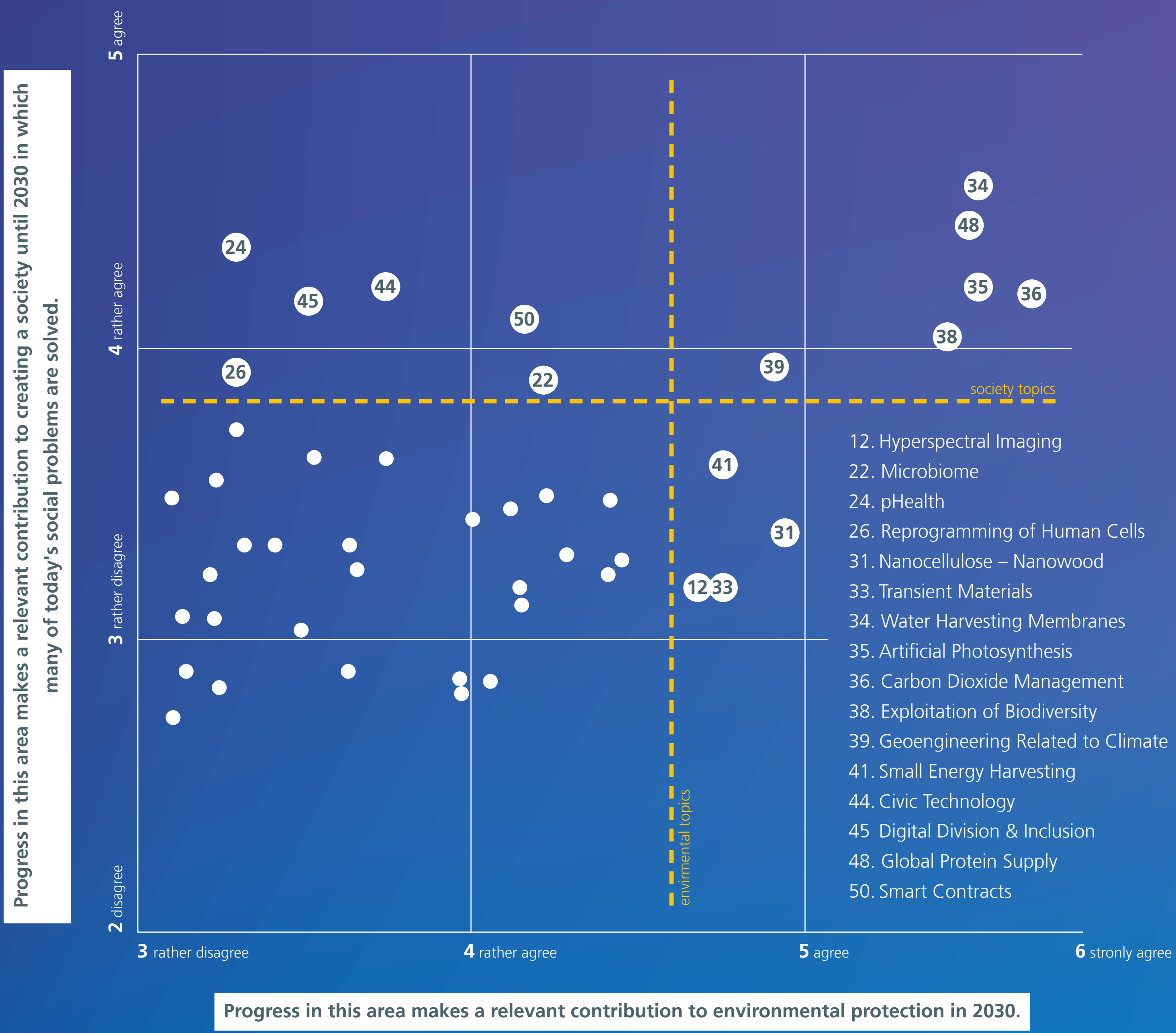


Figure 5: Relationship between contribution to environment and society.

4 INFLUENCE ON AREAS OF RESEARCH AND ECONOMIC SECTORS

The influence of the spotlights on research in 2030 will extend far beyond the research area assigned to it today, as clearly indicated by the impact evaluation (Fig. 2). This therefore confirms the broad research relevance of the 51 spotlights in their entirety. Which spotlights will have a particularly broad impact, both on research and on the economy? Called cross-section spotlights, these include:

- Deep Learning - AI
- Small Data Algorithms
- Smart Contracts
- Digital Division & Inclusion
- Global Middle Class
- Re-Economy: Reduce, Reuse, Recycle

The cross-section spotlights all reveal a close relation to global changes and shifts in data flows, material flows, and market power.

Cyber Reasoning Systems: *Automated cyber defense systems could support human IT security experts but may also pose a threat if used aggressively by criminals.*

Quantum Computers *can solve new classes of problems (e. g. chemistry and supply chain types) that are not able to be solved by today's supercomputers.*

Cyber reasoning systems, quantum computers, and **post-quantum cryptography** also have a noticeably broad relevance to numerous economic sectors. The crucial factor for the broad economic relevance of these spotlights is their relation to data security, which will play an enormous role across all economic sectors in the coming years.

Medicine and health

Spotlights from the **human** cluster are particularly relevant to the medical and health sector and research activities in this area. Spotlights from the **data** and **society** clusters will also have an impact on this sector. The reason for this is that hybrid data structures and social change will also play a crucial role in future innovations in both medical research and the health sector in addition to information and communication technologies. The most relevant spotlights for medicine and health are (see Fig. 2 and Fig. 6):

- Epigenetic Change Technologies
- Liquid Biopsy
- Microbiome
- Organ on a Chip
- Reprogramming of Human Cells
- Brain Machine Interface
- pHealth
- Precision Neurosurgery
- Exploitation of Biodiversity
- Hydrogels
- DNA Origami
- Soft Robots
- Anthropormophization & Creativity of Robots
- DIY Biology – Biohacking
- Global Protein Supply
- Social Credit Score

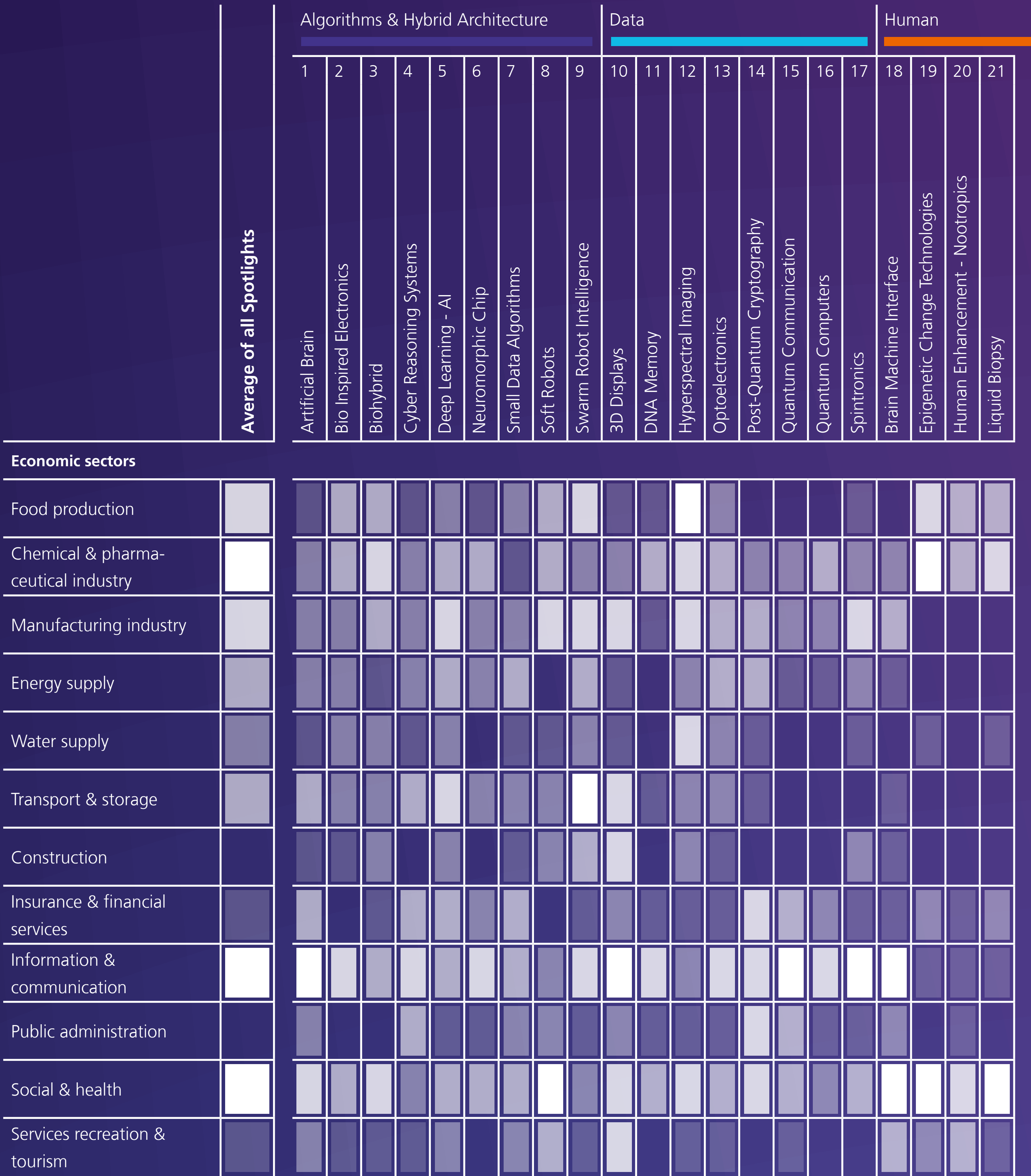
Information and communication

All spotlights of relevance in the area of information and communication are expected to provide stimuli for both research and the economy. The spotlights of importance here are distributed across the clusters of **algorithms & hybrid architectures, data, materials, and society**. The correlation between digitalization and social development which was identified for the "social shapers" is shown here in the opposite direction. For instance, information sciences, computer science, and communication sciences are also characterized by certain social developments. The following spotlights have the greatest influence on the information sciences in this case:

- Quantum Computing
- Quantum Communication
- Post-Quantum Cryptography
- Spintronics
- Brain Machine Interface
- Optoelectronics
- 3D Displays
- Anthropormophization & Creativity of Robots
- Neuromorphic Chip
- Cyber Reasoning Systems
- Artificial Brain
- 2D Materials – Heterostructures
- Solid-State Cooling
- Small Energy Harvesting
- Wireless Energy Transmission
- Social Credit Score
- Civic Tech

INFLUENCE ON AREAS OF RESEARCH AN ECONOMIC SECTORS

ECONOMIC SECTORS AFFECTED BY THE TOPICS UNTIL 2030



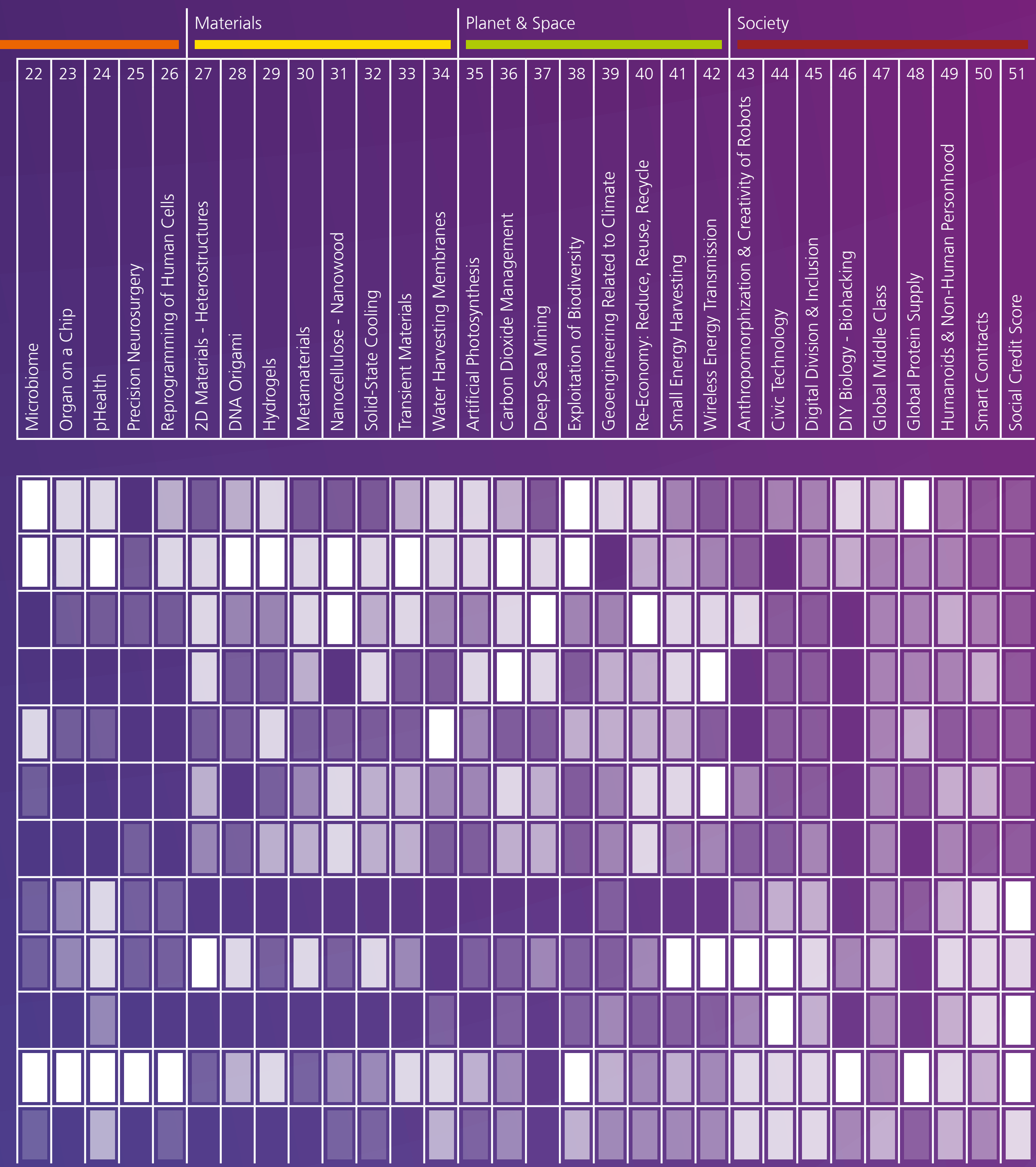


Figure 6: Economic sectors affected by the topics until 2030.

Materials, mechanical engineering, and production

The research areas of materials sciences, mechanical engineering, and process engineering, which are closely related to the manufacturing industry, reveal a clear match in terms of their spotlights with the greatest influence; the spectrum of these spotlights is very broadly scattered here. Only the spotlights from the **human** and **society** clusters have a minor impact on the research areas mentioned above. Spotlights with particular relevance for materials sciences, mechanical engineering, and process engineering include:

***Coupling Hyperspectral Imaging** engines with machine learning algorithms promises to enable the interpretation of spacial and spectral information.*

***Nanocellulose:** Genetically modified wood and other plant strains might be used for the industrial production of new sustainable bio-nanomaterials to replace a range of polymers.*

- Soft Robots
- Swarm Robot Intelligence
- 3D Displays
- ***Hyperspectral Imaging***
- 2D Materials – Heterostructures
- Transient Materials
- Metamaterials
- ***Nanocellulose – Nanowood***
- Carbon Dioxid Management
- Deep Sea Mining
- Re-Economy: Reduce, Reuse, Recycle
- Biohybrid
- Small Energy Harvesting

Chemicals and pharmaceuticals

The extremely broad influence of all spotlights on the chemicals and pharmaceutical industries is noticeable (Fig. 6). Not only the spotlights from the **materials** and **human** clusters have an impact, but also the spotlights from the **hybrid architectures** cluster. In 2030, the chemicals and pharmaceutical industries could make a major contribution to amalgamating the research results of very different scientific disciplines.

5 REVIEW BY INTERNATIONAL EXPERTS

We compared the results of the Fraunhofer relevance evaluations with the assessments by international experts in more in-depth interviews. In this process, the external participants not only completed the online questionnaire but also discussed how differences between the spotlights are to be evaluated in interviews with the project team. Only minor deviations from the Fraunhofer average arose on the whole; clear differences were focussed on a very few spotlights.

The external experts confirmed the general future relevance of the spotlights. However, deviating assessments relating to the dynamics of development and the link to society and the environment occurred for some of the topics. In terms of the possible applications and effects in the next 10 to 15 years, the future expectations of the Fraunhofer participants were considerably more optimistic than those of the external participants in some cases.

The external expert opinions underscore the current relevance and again highlight the great future potential of the **"long-runners"**, i.e. spotlights such as **deep learning – AI**, ***liquid biopsy***, **microbiomes,** and **carbon dioxide management**. In the field of deep learning, for example, the future will yield methodological standards that necessitate adequate context integration, explainability and solution transparency (particularly in the case of neuronal networks). Liquid biopsy is also deemed to have great potential for the future in terms of sample collection and processing, technology development, therapy planning and therapy monitoring. Future research needs in the field of microbiomes are seen in the acquisition of microorganisms, the evaluation of data with AI technologies, and the individual use of this data for patients.

Liquid biopsy *may become the main method of diagnosing cancer. It can also be beneficial to other diagnostic fields such as dentistry, pharmacotherapy or infectiology.*

The **"hot-shots"** are consistently regarded as very relevant for the year 2030, although they are only of medium relevance in the current research arena. According to experts, too little has happened in terms of the **global protein supply** despite its future importance for alternative global food security; impacts on the environment but also on the German economy (e. g. changes in value chains in the meat and food industry) are anticipated. The experts also put forth similar arguments concerning the spotlight of **water harvesting membranes**, where they see great potential for the future. Conversely, progress can already be seen in personalized medicine **(pHealth)** today; this will become even more important in the future and indicates a growing market for the German economy (also taking into account the use of AI). Particular action areas are seen in the affordability of personalised medicine, in the legal field (e.g. ethical questions, exchange of patient data), in information and communication as well as in patient-centred therapy planning. The experts underscore the very high future relevance of **cyber reasoning systems** in the context of cyber security and the resilience of critical infrastructures and of **organ on a chip** for conducting toxicological studies.

__Soft-matter machines and robots__ will allow for safe and biomechanically compatible interactions with humans. Miniature soft robots promise to help in drug delivery and surgery.

__Brain Machine interfaces__ aim at creating a man-machine symbiosis for compley tasks and at interpersonal wiring for sharing of emotions, moods and states of mind.

__Artificial photosynthesis__ could stop global warming by significantly reducing the carbon footprint of human-kind, even more efficiently than natural leaves could on their own.

The **"future options"** include spotlights whose current relevance is still low or medium but which are expected to develop particularly dynamically in the future. From an external expert perspective, this particularly applies to ***soft robots***, as they are seen as a key technology of the future. The experts view other future options somewhat more sceptically. For instance, they regard the topic of the ***brain machine interface*** far more critically due to the complexity of brain functions. Their arguments concerning the topic of ***artificial photosynthesis*** are similarly critical. The experts thus confirm the argument that the future options are technological topics that are still in a very early phase of development and are characterized by major uncertainties.

The **"social shapers"** include future trends that will make an important contribution to the future development of society and the environment. The expert discussions confirm that it is increasingly necessary to involve new actors from society and politics in research activities on these topics. For instance, the experts name incentive systems for promoting real laboratories and citizen science. In the future field of ***civic technology***, technological developments will not only have a major impact in the public sector but also in the financial sector, for example. The spotlights of s**mart contracts, reprogramming of human cells**, ***transient materials,*** and **nanocellulose – nanowood** are viewed slightly more sceptically by external experts than by the Fraunhofer experts. They do not completely share their optimistic assessment of the solution to numerous technological challenges.

The interviews with external experts underscore the need to focus even more extensively on sustainable development goals in foresight activities and to strengthen their link with technological developments.

Civic Technology *increases the confidence and legitimacy of political citizen participation. Application areas are e. g. publicly accissible development plans or open data maps on air quality and noise levels.*

Transient Materials: *Transient electronics could make a significant contribution to sustainability and the controlled self-destruction could prevent the misuse of identitiy documents.*

6 PROJECT BACKGROUND AND CONCEPTUAL APPROACH

The Fraunhofer project essentially has two objectives: firstly, we identified topics with the potential to have special relevance for applied research in 10 or more years' time. Secondly, we tested methods that could become part of a future, systematic Fraunhofer-Gesellschaft foresight process. In the first project phase (2018), we identified and evaluated possible future topics. In the second project phase (2019), we further developed the foresight methodology.

The starting point of the project was the analysis of recently completed international foresight processes such as the European Union-funded RIBRI (Radical Innovation Breakthrough Inquirer) project, which identified 100 opportunities for radical innovations over the next 5 to 20 years. From the results of these projects and an additional screening, we compiled a selection of approximately 300 topics. During a systematic selection and evaluation process, the interdisciplinary cross-institute project team condensed these topics into an initial 150, then 100 and finally 51 topics (Fig. 7).

For over 15 years, the Fraunhofer-Gesellschaft has been using foresight processes to identify future topics for the strategic further development of its research portfolio. Different approaches were used in each case in this process. All processes were designed to make foresight from Fraunhofer for Fraunhofer without disregarding the external perspective. In 2004, 50 technologies were identified for the first time on the basis of foresight studies and then evaluated in an expert workshop. 10 years ago, a major survey within Fraunhofer was used to identify future topics. A few years later, the "grand societal challenges" were the starting point for a further Fraunhofer foresight process.

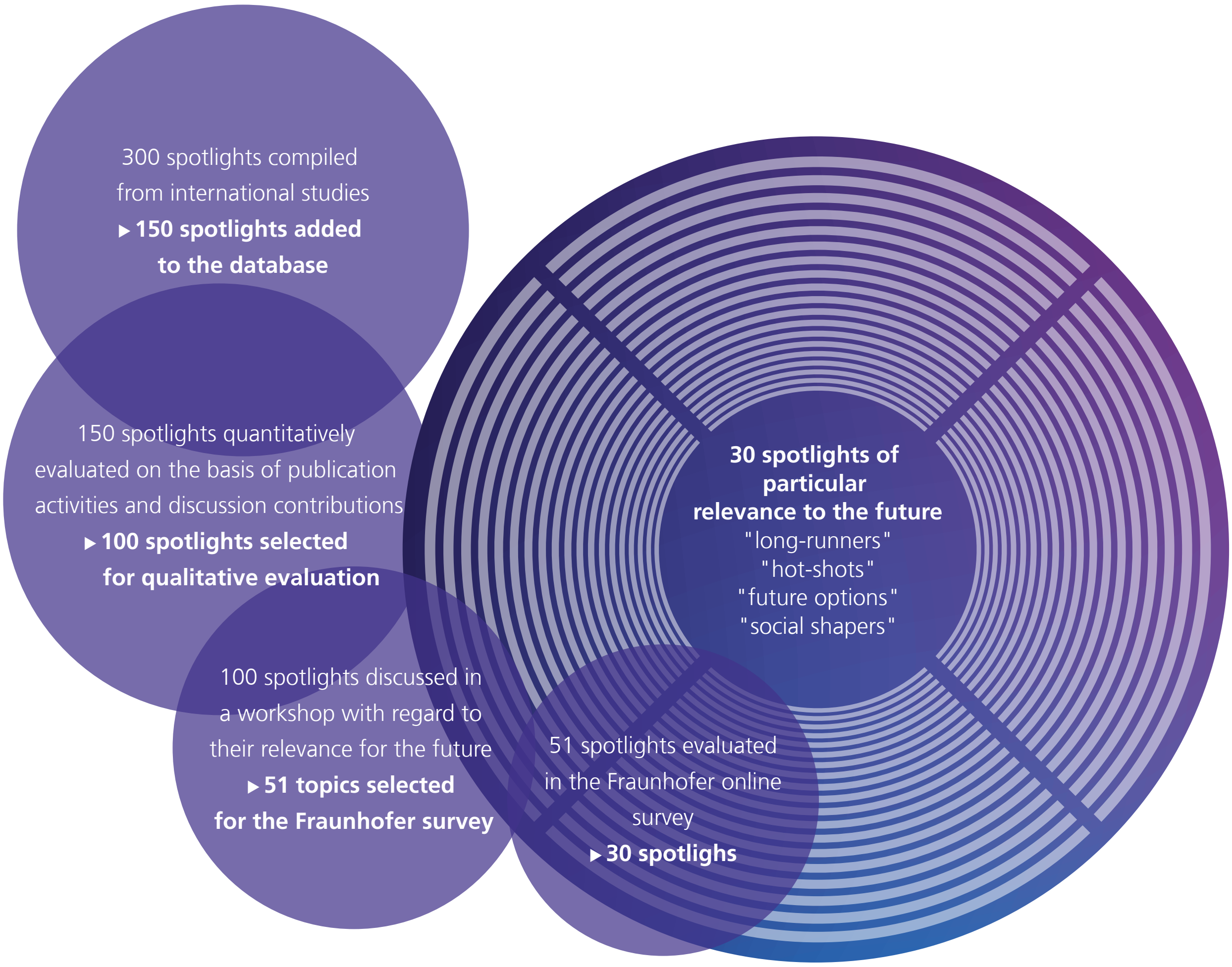


Figure 7: Systematic selection and evaluation process.

The current Fraunhofer foresight cycle takes a systematic look at technological and societal developments in the outside world and makes particularly extensive use of quantitative approaches to identify and evaluate the "spotlights". The assessment of future relevance is based on the breadth and diversity of Fraunhofer's expertise (validated through interviews with externals) so that a neutral view of the outside world and the specific perspective of applied research are combined. Giving consideration to scientific findings in terms of cognitive biases in future expectations, the holistic, multi-criteria evaluation of the spotlights enables suitable typologization of the 30 identified spotlights with specific future relevance.

APPENDIX

Topics	Short Description
Artificial Brain	Artificial brain is a brain-like computer system build with physical components that processes and stores information like a human brain. This technology may be used to design computers that function like biological neural networks. As supercomputers reach a huge number of connections, that would allow a level of computing previously unattained and could revolutionize our lives, perhaps even more than the digital revolution.
Artificial Photosynthesis	Artificial photosynthesis is a chemical process that mimics the natural process of photosynthesis by converting sunlight, water, and carbon dioxide into carbohydrates (glucose) and oxygen. In the context of ever increasing fuel consumption and levels of CO_2, this field of research focuses on a "win-win" solution inspired by nature: artificial photosynthesis that both reduces CO_2 level in atmosphere and generates power.
Biohybrid	Biohybrid is the field of science research technologies that combines biological with artificial systems. Biohybrid systems integrate living, biological parts into artificial machines. Biohybrid technologies can be applied in medicine, nanotechnology, brain machine interface, robotics.
Brain Machine Interface	A brain machine interface (BMI), also known in some incarnations as a mind-machine interface (MMI), direct neural interface (DNI), or brain computer interface (BCI), is a direct communication pathway between the brain and an external device. A BMI can both collect information from and feed it into the brain, for example by restoring a lost sense and enabling the brain to interact with the environment.
Carbon Dioxide Management	Carbon dioxide emissions are considered to drive climate change. To avoid the loss of carbon to the atmosphere, it is captured for storage or further processing at the source of a high carbon dioxide output such as smoke stacks in various industries and carbon-based power plants. Combining direct air capture with carbon storage can fulfill a dual function: as a carbon dioxide removal technology and as a form of climate engineering if deployed at large scale.
Civic Technology	Civic Tech (not to be mixed up with civil tech) refers to applied information technologies that enable government, business, science, associations, and individual citizens to participate in an inclusive discourse. These include platforms, portals, apps, and other software enabling eDemocracy and Open Government in the future.

Topics	Short Description
Cyber Reasoning Systems	Cyber Reasoning Systems (CRS) are automated cyber defense systems. Without human support, they find security holes in software and then eliminate them. Accordingly, CRS can be considered as a form of automated cyber defense. Because of the potentially high speed of such automated processes, CRS could generally significantly improve the security of IT systems in the future.
Deep Learning - AI	Deep learning is one of the key technologies in the AI domain. It is one of the machine learning algorithms which is composed of a multi-layer (deep) neural network. Each layer of this network corresponds to different levels of abstraction. Deep neural networks have had amazing successes lately in processing multiple sources of data, including images, video, audio, and to a lesser extent, text.
Digital Division & Inclusion	The progressive digitalization of everyday life offers great opportunities to create equal conditions for all, one should bear in mind that there could be a division. The digital access simultaneously leads to a changed group access like inclusion and division. At the same time, it could trigger a displacement of global centers of power.
Exploitation of Biodiversity	Biodiversity refers to the total richness of biological variations, including the genetic variations within populations and species, the numbers of species, and the patterns and dynamics of these over large areas. Biodiversity is a relevant source for innovations especially in pharmaceutical research. Furthermore, biodiversity continues to decline on a global scale and has proven much more fragile than initially understood.
Geoengineering Related to Climate	Climate change induced geoengineering comprises the attempts to engineer the climate itself (e. g., greenhouse gas removal and solar radiation management) and the attempts to counteract the effects of climate change by geological engineering of landscapes (e. g., geoengineering of glaciers).
Global Protein Supply	The exploration of alternative protein sources promises potential to meet the growing global demand for food and feed. The current production and the consumption of meat is associated with significant environmental, human health and ethical challenges. Nascent technologies like cellular ag-riculture can provide sustainable solutions to meet these challenges.
Hyperspectral Imaging	Hyperspectral Imaging (HSI) is one of the powerful analytical imaging tools based on the detection of both spatial and spectral information within a single data set referred to as a HSI cube. Hyperspectral imaging creates images across hundreds of wavelengths and can be used to determine materials at a distance. Hyperspectral imaging holds promise for the use in fields ranging from security and defense to environmental monitoring and agriculture.

Topics	Short Description
Liquid Biopsy	Liquid biopsy is a quick test for DNA mutation analysis of potential disease markers present in non-solid biological tissue (typically blood, but also urine, saliva, cerebrospinal fluid or other body fluids), either in the form of cell-free DNA (cfDNA) or miRNA fragments, circulating tumor or immune cells, or extra-cellular vesicles. Liquid biopsy may become the main method of diagnosing cancer as well as provide a fast and easy screening test for detecting diseases and determining their type plus setting a treatment course.
Microbiome	Microbes that are found on our skin and inside the human body form microbiomes that can have both beneficial and harmful effects on human health. The composition of the microbiome can be very different from one person to the next. Microbiomes play a crucial role in human health. Intestinal bacteria are being able to directly alter the activity of our genes. Future therapeutics will provide options for mental and physical conditions such as depression, pre-diabetes, and type II diabetes.
Nanocellulose - Nanowood	Materials obtained from nanocellulose fibers might replace an entire range of polymers in different industries. These materials can be applied in nanocomposites, films and foams, surface modifications, and medical devices. One especially interesting material is nanowood that is stronger than titanium alloys and at the same time lighter. It can be used for cars, airplanes, or buildings.
Neuromorphic Chip	The best AI algorithms already use brain-like programs called simulated neural networks, which rely on parallel processing to recognize patterns in data, including objects in images and words in speech. Neuromorphic chips take this idea further by etching the workings of neural networks into silicon. Neuromorphic chips could be used wherever real-world data needs to be processed in real-time environments such as smarter security cameras, real-time communication with autonomous vehicles, or glasses for the blind that use visual and auditory sensors to recognize objects and provide audio cues.
Optoelectronics	Optoelectronics is a subfield of photonics which is focused on combining electronics and light to transmit data. Further research in optoelectronics will open the way to the commercialization of 5D data storage. With a new type of transistors based on excitons, it would be possible to integrate optical transmission and electronic data-processing systems into the same device.
Organ on a Chip	An organ on a chip is a multi-channel 3D microfluidic cell culture that simulates the activities, mechanics, physiological response of entire organs and organ systems. An organ-on-a-chip is a type of an artificial organ. One day, they will perhaps abolish the need for animals in drug development and toxin testing.

Topics	Short Description
pHealth	The basis of the pHealth model is the evaluation of extensive data sets ranging from everyday behavior patterns to molecular person profiles. Personalized health is not only aimed at pharmaceutical products, it covers health from research to patient care. Some approaches to pHealth are already being applied in practice, e. g., in the fields of predictive genetic diagnostics, pharmacogenetics, or oncology.
Post-Quantum Cryptography	The global encryption standards would fail in minutes after the appearance of quantum computers because all the information, encrypted using prime factorization problem, could be then cracked easily. Post-quantum cryptography assumes that the attacker has a quantum computer and strives to remain secure against post-quantum hacking. New global encryption standards are being discussed for the quantum communication Internet of the future.
Quantum Communication	Quantum communication is the transmission of the information encrypted into the quantum states of particles from one place to another. It is a field of applied quantum physics, which relies on the principle of quantum mechanics, entanglement, and superposition. The information transmitted through quantum communications is impossible to intercept or crack. Quantum communication opens a new page in the development of future global communication networks and it is a big boost to the space industry.
Quantum Computers	Quantum computers are based on the quantum mechanics principles and work instead with quantum-bits or qubits. IBM, Google, and Intel are making progress on quantum hardware. Quantum computers will be able to solve new classes of problems that are not able to be solved by today's supercomputers. The changes this will bring will be far-reaching, revolutionally, and hard to predict.
Re-Economy: Reduce, Reuse, Recycle	The aim of recycling management is to reduce the raw material consumption by using less resources for products and services and by preserving the value of products and components at the end of their useful life as optimal as possible through "Reduce, Reuse, Recycle". Proponents of the circular economy envisage a world where production and consumption systems are waste free. Concepts like "cradle2cradle" expect that artefacts would be either endlessly reused or decomposed organically.
Reprogramming of Human Cells	Over a decade ago, scientists learned how to reprogram human adult cells into cells that behave like embryonic stem cells. These cells are called induced pluripotent stem cells (iPSCs). Researchers now create iPSCs from a patient‹s blood or skin cells and use these patient-specific cells to study diseases or even create new tissues that could be transplanted back into the patient as a therapy.

Topics	Short Description
Small Energy Harvesting	Energy harvesting is the capture and conversion of small amounts of readily available energy in the environment into a usable electrical energy. Energy harvesting systems could prolong the life of self-powered medical implants or battery-free wearables. They could be used in smart clothes, install-and-forget home automations, IoT devices, and many other applications requiring only small amounts of energy with zero maintenance.
Smart Contracts	A smart contract is a digital version or an algorithmic protocol of a treaty between two parties. The relatively young method is based on the blockchain concept. The codes operate depending on relevant parameters, following a set of fixed rules, and is therefore able to enforce agreed rights or sanctions automatically. Smart contracts offer great potential in particular for cooperation in B2B markets.
Soft Robots	Soft Robots are robots built from highly compliant materials, similar to those found in living organisms. In the application domains such as medical and personal co-robotics, soft robots will allow for safe and biomechanically compatible interactions with humans. Miniature soft robots promise to help in medical applications such as drug delivery and surgery.
Transient Materials	Transient materials are full-featured materials and components that terminate clean of residuals under specific conditions and in a controlled way. They differ from conventionally degrading materials primarily by their precisely determined process of self-dissolution that is controlled by a trigger. Normally, their compounds dissolve relatively easy under physical, chemical, or biological conditions and decay to physiologically and ecologically harmless breakdown products. A wide variety of implementations could be in electronics, medicine, and security technology.
Water Harvesting MembranesS	Water filtration on a nanoscale for desalination, direct solar desalination and atmospheric water generation (AWG) are examples for technologies making use of new materials to contribute to the supply of fresh water in regions where it is a scarce resource. Passive systems and self-cleaning membranes will be a precondition for large-scale use.

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