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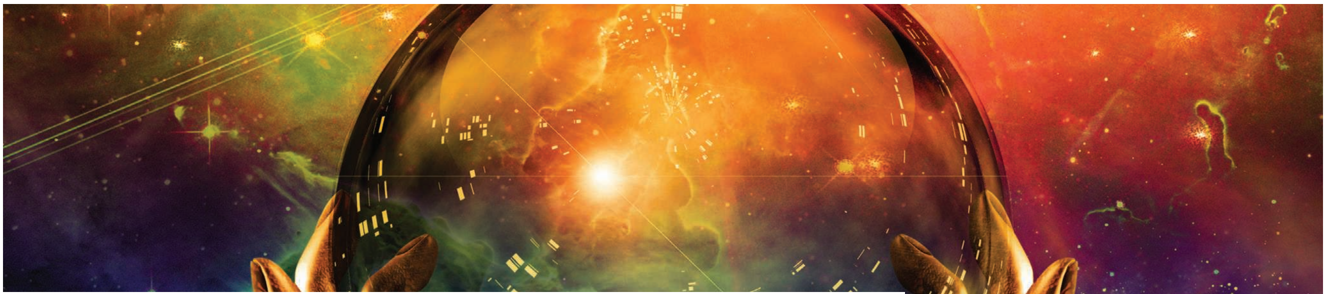

Megatrends

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Understanding megatrends allows individuals and organizations to align with and benefit from the richness of trending technologies.

Megatrends are major movements at a global scale likely to have a significant impact on the global economy, society, and ecology. Megatrends are composed of many correlated, mutually dependent trends. A megatrend is both the sum of trends and a guiding force since it influences its component trends. A megatrend impacts the evolution of these multiple trends, hence the importance of understanding megatrends. Trends are hard to predict, and megatrends are hard to recognize. Evolution is easier to observe at the trend level because it is more dynamic with more immediate results. However, the impact of megatrends is broader and larger.

INTRODUCTION

We have been working on predicting technology trends for over 15 years.[1,2,3,4,5] During the last few years, we decided to also explore megatrends. Predictions are difficult to make due to the uncertainty and the complex interplay of a multitude of factors. Megatrends both impact and depend on four factors that are the source of this continuous interplay: economic, sociopolitical, ecological, and technological factors. Each factor is associated with several megatrends and many trends.

Technology factors may be the simplest, but technology also depends on other factors, especially business, which is driven by the economy. Sociopolitical factors can disrupt other factors as they inherently depend on human and humankind behavior. The ecological factor presents its own complexities. Consequently, understanding megatrends is nontrivial. Figure 1 presents these relationships from the perspective of technology (center). Factors are represented by associated megatrends, all of which influence each other. Relationships, dependencies, and correlations between these factors can be quite complex.

If we focus on technology megatrends only (see Figure 2), three distinct megatrends are digital transformation,[6]

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sustainability,[7] and artificial general intelligence (AGI).[8] The three megatrends dovetail, from mature (e.g., digital transformation) to emerging (e.g., AGI).

issue identification,[9] ranking, voting, discussion, reranking, and agreement (which is described in subsequent section). The selection of the three megatrends was the outcome. It was not trivial to make the final selections. To better understand the selection, we created a diagram, listing all the grand challenges that humanity is facing, applications of technology, emerging technologies, and finally megatrends in the center (see Figure 3).

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IDENTIFYING MEGATRENDS

How did we choose these three megatrends, and why not others? We established a process within the IEEE Future Directions Committee that resembles our annual predictions process. This process involved Delphi-like rounds of

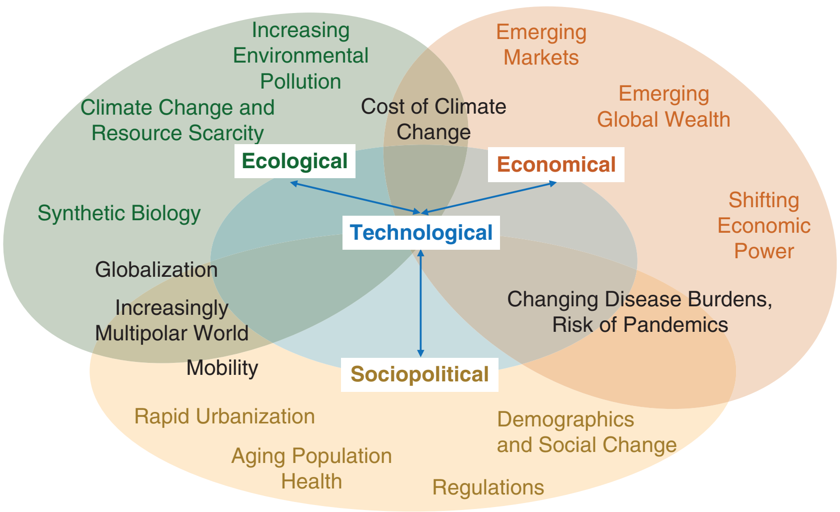

FIGURE 1. Technology versus other megatrends.

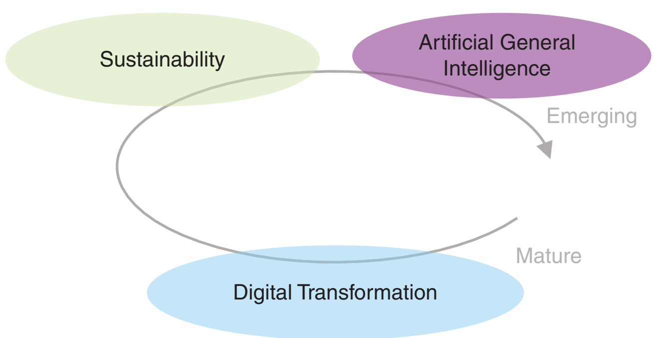

FIGURE 2. The technology megatrends.

People who work with modern technology are usually enamored with it and believe that it is a megatrend. Examples we faced were quantum computing, digital health, and climate change. While all three are extremely important, they are not megatrends—quantum computing is a technology, digital health is the application of technology, and climate change is a grand challenge.

For this reason, we established the following criteria to identify megatrends:

- global, worldwide importance with geopolitical implications
- critical enough to require regulation
- encompasses multiple technologies and technology trends
- evolves over years if not decades.

We also identified a loose definition of what megatrends are not:

- a temporary popular or fashionable technology
- coming from a single contributing community or a society
- of interest to a limited region or a group.

All three megatrends we listed meet the above criteria. They are all of global, worldwide importance with numerous geopolitical implications. For example, sustainability is important for many areas of the world, be it rainforests, ice melting, or flooding around the world caused by climate change. AGI has caused concerns and excitement equally in many countries. Even though staged in their maturity, all three megatrends have been around for many decades and are likely to continue for more. They each encompass numerous technologies and their trends.

Some participants in the process believed that ethics and diversity, equity, and inclusion (DEI) are megatrends. We felt that, while critically important, they are not megatrends. Human rights apply to everyone (rather than society as a whole) and are listed in the Universal Declaration of Human

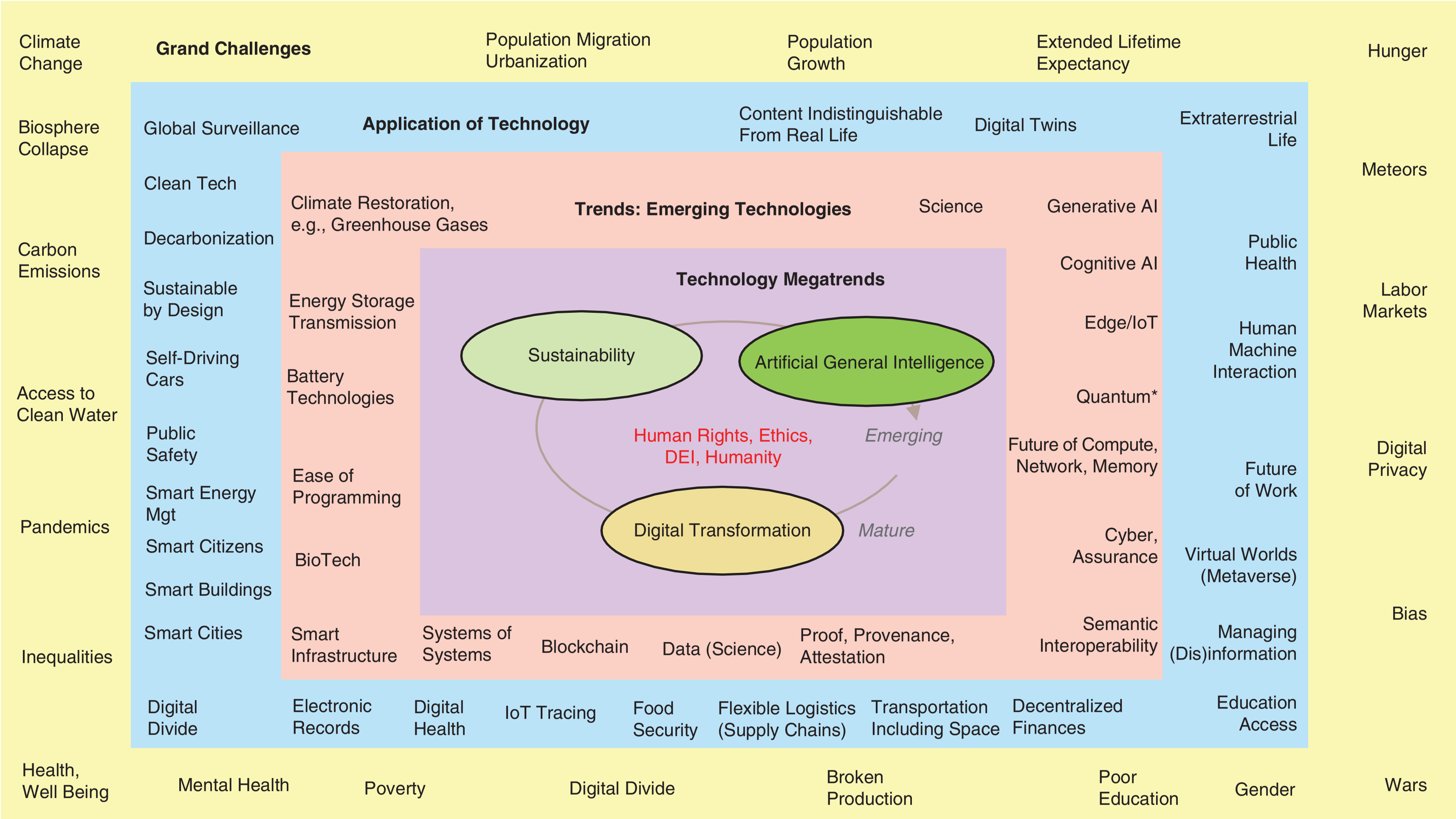

FIGURE 3. The landscape of megatrends, emerging technology trends, applications of technology, and grand challenges. AI: artificial intelligence; IoT: Internet of Things.

Rights. Since these principles should guide all decisions and activities we pursue related to any of the factors or megatrends, we placed human rights, ethics, DEI, and humanity as a whole in the center of Figure 3.

TRACKING AND QUANTIFYING MEGATRENDS

Most technologies tend to follow the so-called Gartner hype curve.[10] Megatrends, however, follow an S curve (see Figure 4), which follows given that they typically involve multiple technologies that aggregate into this one curve.

Over the years, we have developed a process for grading annual technology predictions along four dimensions: the likelihood of success during the next year, the impact on humanity they will have once eventually developed, maturity, and relative market adoption. For megatrends, we added a fifth dimension: which megatrend these technologies belong to. Because we are still selecting and grading megatrends and technologies, we used the 2023 technology predictions process and marked them with megatrends as an outer ring (see Figure 5).

Instead, we track the evolution of technologies that compose them and then draw conclusions about the evolution of megatrends.

In addition, megatrends dovetail and overlap. They do not stop but continue to evolve over the years. Even if their momentum slows, they never stop.

Consequently, it is hard to track megatrend evolution. Instead, we track the evolution of technologies that compose them and then draw conclusions about the evolution of megatrends.

The annual technology prediction team is a coherent team conducting all activities online in multiple wideband Delphi-like phases of selection, grading, and qualifying. Two teams conduct the megatrends process. In-person meetings occurred during the IEEE Board series (three times a year, lasting two hours). The outcomes are provided to the online team, and both teams proceed with similar phases.

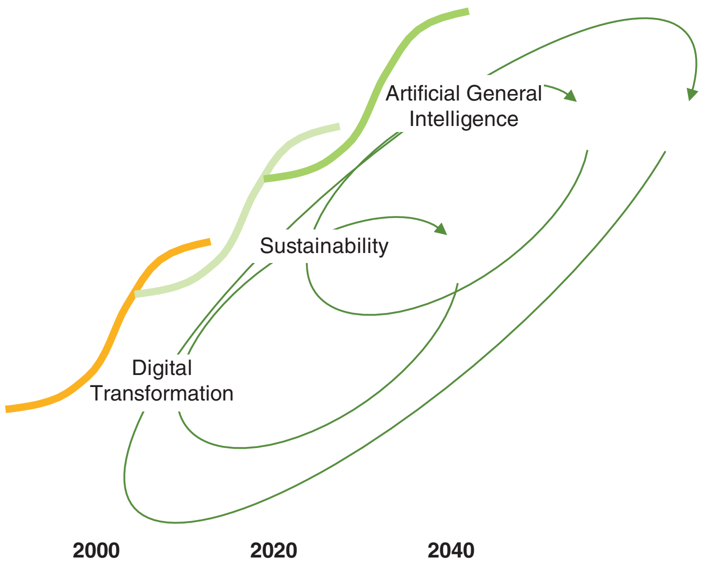

FIGURE 4. The megatrend evolution.

The modified technology prediction process as applied to megatrends consists of the following phases and steps:

- The selection phase is as follows:
  - The Future Directions Committee (FDC) Industry Advisory Board (IAB) internal team develops a list of key technologies (per megatrend) that will advance over the next year. This multistage effort starts with an initial list that is voted upon, and some technologies may be merged, changed in scope, or evolved throughout the process.
  - The FDC IAB external team reviews and extends the list.
- In the grading phase, each of the technologies is graded (A+ to F−) for
  - predicted technology success in the coming year (2024 in this case)
  - (potential for) impact on humanity during its lifetime
  - predicted maturity in the coming year (2024 in this case)
  - predicted relative market adoption in 2024
  - (one year, three years, five years, 10 years, and 15 years) for horizon to commercial adoption.
- In the qualifying phase, for each selected technology, we prepare a slide: problems/demand, opportunities, impact, and sustainable solution/business opportunity.
- In the self-evaluation phase, a year later, the team conducts a scorecard (self-evaluation) of how the predictions succeeded.

We will evaluate whether we can merge the processes for future annual technology predictions and megatrends into a single coherent one. Over the years, we have improved the roster of the teams by expanding participation across geographies (e.g., adding members from Latin America, Africa, and Asia), improving gender representation, and broadening the scope of expertise of the teams. This has resulted in much more inclusive outcomes and stronger predictions.

A frequent question posed to us is, how accurate are your predictions? While megatrend predictions are still in the early stages, and we do not have sufficient evidence to reflect on our effectiveness, we have years of experience in predicting individual technologies. Approximately one year after the original predictions, we conduct a self-evaluation. We are quite rigorous in self-evaluation, and average grades range from B/C (2022) to A– (2017). We were rather successful in some predictions and very unsuccessful in others. It is interesting that in some cases, for similar or even the same technologies, we were successful one year only to fail in the other. See Figure 6 for the scorecard history from 2016 to 2022.

It is important to point out that in a few cases, prospective technologies failed because they were not successfully developed. In almost all cases, it was the timing and interplay of economic forces that influenced market adoption. The typical examples include artificial intelligence, which had its successes in the 1980s, only to vanish and then have a rebirth with the introduction of modern computational accelerators. Another example is digital currencies, which have had their ups and downs.

> The annual technology prediction team is a coherent team conducting all activities online in multiple wideband Delphi-like phases of selection, grading, and qualifying.

In the context of professional organizations, such as IEEE, megatrends inform about opportunities for roadmaps and eventually standards (see Figure 7). Technology trends influence megatrends, which drive technology initiatives. In some cases, initiatives cause the creation of roadmaps. From roadmaps, standards may evolve.

Each megatrend includes the evolution of its technologies in some sequence of stages. We presented an example of the evolution of digital twins as applied to digital transformation in our previous paper.[6] Figure 8 represents the evolution of sustainability megatrend technologies.

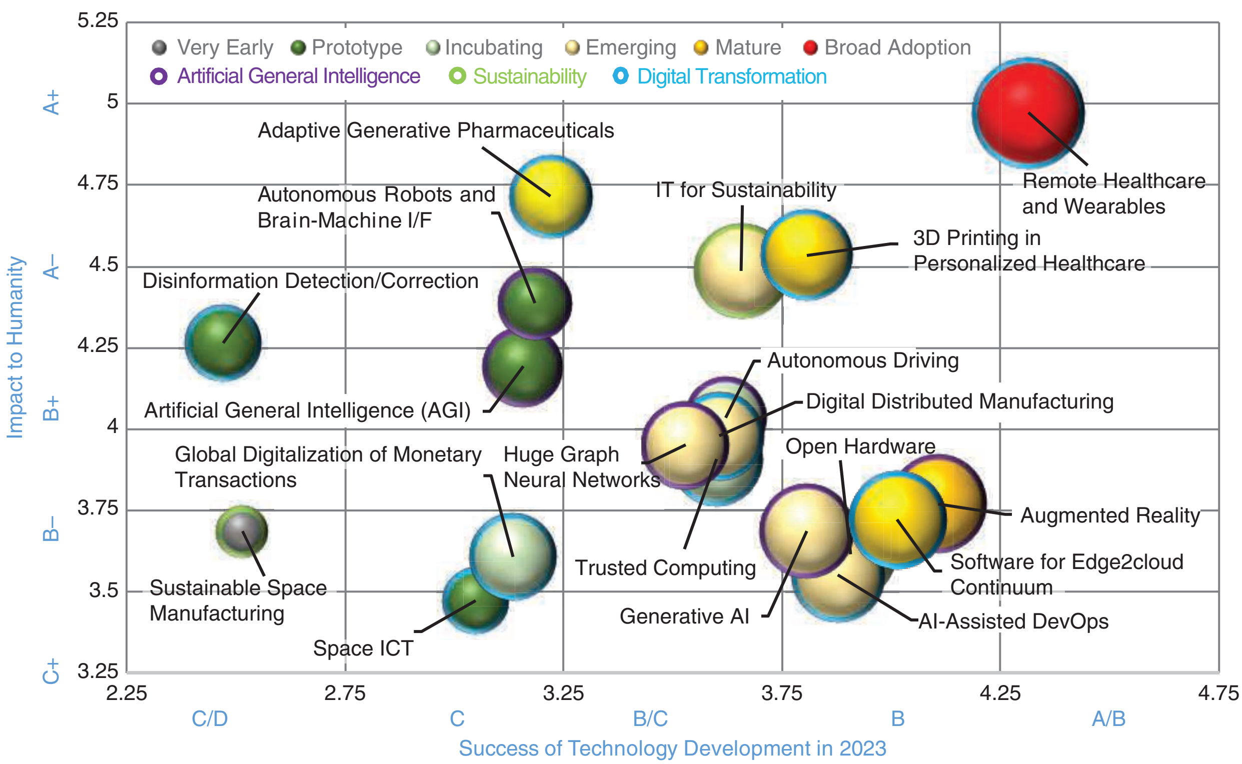

FIGURE 5. Five dimensions of technology and megatrends predictions. ICT: information and communication technologies; I/F: interface.

2022: B/C	2021: B–	2020: B–	2019: B	2018: B	2017: A–	2016: B+
Convergence of HPC, AI, HPDA: **B+**	Remote Workforce Technologies: **A**	AI at Edge: **A–**	Deep Learning Accelerators: **A**	Industrial IoT: **A+**	AI, ML, Cognitive Computing: **A+**	Advanced ML: **A**
Datacentric AI: **B+**	HPC as a Service: **B+**	Additive Manufacturing: **A/B**	Assisted Transportation: **A/B**	Accelerators and 3D: **A**	Accelerators: **A**	Data Science: **A**
Remote Medicine: **B+**	In-Memory Computing: **B+**	Adversarial ML: **B+**	Virtual (VR) and Augmented Reality (AR): **B+**	Blockchain: **A**	Blockchain (Beyond Bitcoin): **A**	Containers: **A**
Digital Twins in Manufacturing: **B**	ML for additive and Subtractive Manufacturing: **B**	AI and Critical Systems: **B+**	Active Security Protection: **B**	Deep Learning: **A–**	Sensors Everywhere and Edge computing: **A–**	Cyber Physical Systems: **B+**
Health, Safety, Wearable Biomed Tech: **B**	Advanced Cyberweapons: **B**	Non-Volatile Memory Products, 1/F, Applications: **B**	Chatbots: **B**	Assisted Transportation: **A–**	Industrial IoT: **B+**	Virtual and Augmented Reality: **B+**
Safety for Autonomous Systems: **B–**	Social Distancing Technologies: **B**	Legal Related Implications to Reflect Security and Privacy: **B**	Social Credit Algorithms: **B–**	Robotics: **B+**	5G: **B**	5G: **B**
3D Print in Healthcare: **B–**	Reliability/safety for intelligent Autonomous Systems: **B–**	Digital Twins, including Cognitive Twins: **B–**	The Internet of Bodies (IoB): **B/C**	Assisted Reality and Virtual Reality (ARNR): **B–**	Hyper-Converged Systems: **B**	Network Function Virtualiz. (NFV): **B**
AI@Edge, Federated Learning: **B–**	Synthetic Data for Training ML Systems Free of Bias: **B/C**	Reliability and Safety for Intelligent Systems: **B/C**	Advanced (smart) Materials and Devices: **B/C**	Ethics, Laws, Policies for Privacy, Security, Liability: **C+**	Self-driving cars: **B–**	Nonvolatile Memory: **B–**
Trustworthy AI: **B–**	Low Latency Virtual Musical Rehearsal and Performance: **B/C**	Practical Delivery Drones: **B/C**	Technology for Humanity (Specifically ML): **B/C**	Cybersecurity and AI: **C**	Disaggr ./Fabric-Attached Nonvolatile Memory: **C+**	Capability-Based Security: **C**
Metaverse: **B/C**	Disinformation Detection: **B/C**	Applying AI to Cybersecurity: **B/C**	Automated Voice Spam (Robocall) Prevention: **C**	Digital Currencies: **C–**		
Confidential Computing: **B/C**	Trustworthy and Explainable AI/ML: **C+**					
Cybersecurity of Critical Infrastructure: **C+**	Election Security / Social Media Controls: **C**					
Commoditization of Space Tech: **C+**						
Low-Code/No-Code: **C+**						
Disinformation Detection/Correction: **C**						
Non-Fungible Tokens (NFTs): **D+**						

FIGURE 6. Technology predictions scorecard (2016–2022). HPC: high-performance computing; HPDA: high-performance data analytics; ML: machine learning.

IMPACT

Engineers like to measure things to show impact. Often, impact is estimated by the number of references to published work. With the Technology Predictions, we targeted nontraditional publications, expressed in terms of press releases and social media, rather than traditional publications. Therefore, impact is better measured by the number of readers (as measured by downloads). For example, the total potential target audience for the 2023 Technology Predictions press release was close to 230 million. The report was also picked up by over 300 media outlets that further distributed it. This audience is four orders of magnitude higher than the 46,000 members of the IEEE computer community to which the report was also distributed. The report was downloaded 3,700+ times. On social media, a campaign conducted by the IEEE Computer Society achieved 25,000+ impressions and over 650 engagements.

As a result of the audience's interest in predictions, in 2019, we started special issues of *IEEE Computer* dedicated to predictions and have been organizing them ever since.[1,2,3,4] In the first special issue, we discussed our approach to predictions, which is a subset of this paper.[5]

Finally, our predictions resulted in significant interest from various communities, and we organized numerous related panels (e.g., the 2022 IEEE Global Communications Conference; the IEEE 41st International Conference on Consumer Electronics, 2023; the 2023 IEEE Consumer Communications & Networking Conference; and the IEEE IndustryHUB Silicon Valley office launch), keynotes Eta Kappa Nu 2023, and the 2022 IEEE World Congress on Services (SERVICES 2022)], and presentations (IEEE SERVICES 2023, Solid State Lighting Annex, IEEE Region 2 meeting).

RELATED WORK

Many organizations issue predictions, such as market analysts, for example, Forrester,[11] Gartner,[12] and IDC[13]; consulting agencies, such as Deloitte[14]; magazines, such as *MIT Review*[15]; and the World Economic Forum (WEF).[16]

Our predictions are tied to the mission and purpose of IEEE, best expressed by its tagline, "Advancing technology for the benefit of humanity."

These predictions reflect the purpose of the issuing entity; for example, market analysts predict industry megatrends, consulting companies cater to their customers, magazines cater to their readership, and WEF addresses a global audience. Our predictions are tied to the mission and purpose of IEEE, best expressed by its tagline, "Advancing technology for the benefit of humanity."

SUMMARY AND FUTURE WORK

In this paper, we have presented our work on megatrends, which

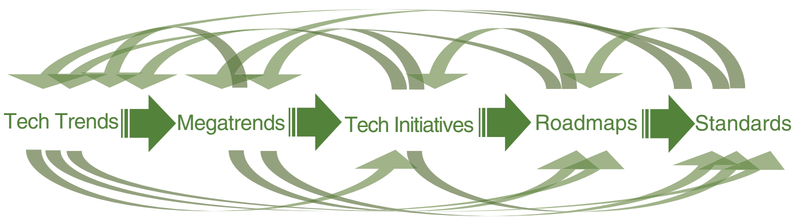

FIGURE 7. A workflow of megatrends and other activities.

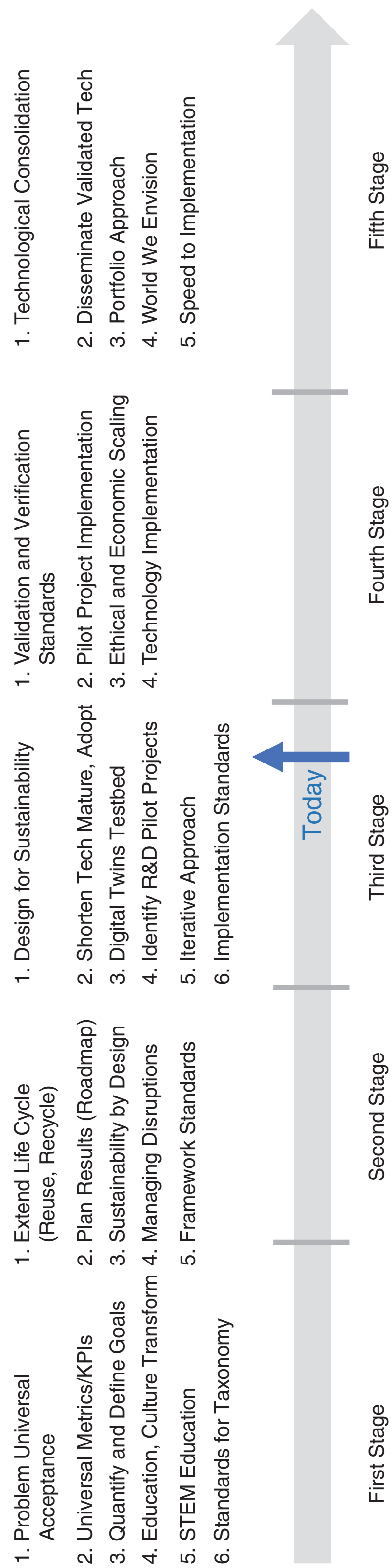

FIGURE 8. The evolution of sustainability technologies. KPI: key performance indicator; STEM: science, technology, engineering, and mathematics.

evolved from almost fifteen years of working on technology predictions. Every year, we improved our approach, processes, and deliverables. We became more diverse and inclusive, and we served a broader audience.

In the immediate future, we will be talking to market analysts to explore cooperation and mutual benefit. Next, we will talk to venture capitalists to include their distinct angle on megatrends. We plan to release an annual megatrend report midyear and annual technology predictions at the end of the years to come.

We welcome your opinion and solicit your help to review our predictions and make them more useful to the world. C

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REFERENCES

1. D. Milojicic, "Technology predictions," *Computer*, vol. 52, no. 12, pp. 31–33, Dec. 2019, doi: 10.1109/MC.2019.2944708.
2. P. Laplante and D. Milojicic, "Technology predictions," *Computer*, vol. 54, no. 7, pp. 14–16, Jul. 2021, doi: 10.1109/MC.2021.3074265.
3. P. Laplante and D. Milojicic, "Predicting technologies that advance humanity," *Computer*, vol. 55, no. 7, pp. 15–17, Jul. 2022, doi: 10.1109/MC.2022.3170600.
4. P. Laplante and D. Milojicic, "Predicting technology and its impact on humanity," *Computer*, vol. 56, no. 7, pp. 17–20, Jul. 2023, doi: 10.1109/MC.2023.3271429.
5. P. Faraboschi et al., "Technology predictions: Art, science, and fashion," *Computer*, vol. 52, no. 12, pp. 34–38, Dec. 2019, doi: 10.1109/MC.2019.2942286.
6. P. Faraboschi, E. Frachtenberg, P. Laplante, D. Milojicic, and R. Saracco, "Digital transformation: Lights and shadows," *Computer*, vol. 56, no. 4, pp. 123–130, Apr. 2023, doi: 10.1109/MC.2023.3241726.
7. C. Bash, N. Hogade, D. Milojicic, G. Rattihalli, and C. Patel, "Sustainability: Fundamentals-based approach to paying it forward," *Computer*, vol. 56, no. 1, pp. 125–132, Jan. 2023, doi: 10.1109/MC.2022.3219173.
8. P. Faraboschi, E. Frachtenberg, P. Laplante, D. Milojicic, and R. Saracco, "Virtual worlds (Metaverse): From skepticism, to fear, to immersive opportunities," *Computer*, vol. 55, no. 10, pp. 100–106, Oct. 2022, doi: 10.1109/MC.2022.3192702.
9. G. Rowe and G. Wright, "Expert opinions in forecasting: The role of the Delphi technique," in *Principles of Forecasting: A Handbook for Researchers and Practitioners*. Boston, MA, USA: Springer, 2001, pp. 125–144.
10. A. Linden and J. Fenn, "Understanding Gartner's hype cycles," in *Strategic Analysis Report N° R-20-1971*, vol. 88. Stamford, CT, USA: Gartner, 2003, p. 1423.
11. "Predictions." Forrester. Accessed: May 4, 2023. [Online]. Available: https://www.forrester.com/predictions
12. D. Groombridge, "Gartner's top technology trends for 2023," Gartner, Inc., Stamford, CT, USA, 2023. Accessed: May 4, 2023. [Online]. Available: https://www.gartner.com/en/information-technology/trends/top-tech-trends-gb-pd
13. R. Villars et al., "IDC FutureScape: Worldwide IT industry 2023 predictions," IDC, Needham, MA, USA, IDC FutureScape Rep., Oct. 2022. Accessed: May 4, 2023. [Online]. Available: https://www.idc.com/getdoc.jsp?containerId=US49563122
14. "Deloitte TMT 2023 predictions," *Deloitte*, Nov. 2022. Accessed: May 4, 2023. [Online]. Available: https://www.deloitte.com/global/en/about/press-room/deloitte-tmt-2023-predictions.html
15. "10 breakthrough technologies," *MIT Rev.*, Jan. 2023. Accessed: May 4, 2023. [Online]. Available: https://www.technologyreview.com/2023/01/09/1066394/10-breakthrough-technologies-2023/
16. "Transformation map," World Economic Forum, Cologny, Switzerland, Nov. 2017. Accessed: May 4, 2023. [Online]. Available: https://www.weforum.org/agenda/2017/11/what-is-a-transformation-map/
17. D. Milojicic, "The art of prediction," in *Proc. IEEE Service Congr., Carl K. Chang Symp.*, to be published.

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