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Anticipatory alignment work: The politics of anticipation in an emerging innovation ecosystem of neuromorphic computing

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ABSTRACT

The alignment of science, technology, and innovation with societal values and concerns is a key objective of governance approaches that include technology assessment, responsible (research and) innovation, and anticipatory governance. Such alignment is supposed to take place, inter alia, in anticipatory practices involving technoscientific experts, stakeholders, and publics, whose views are then integrated into research and development. However, we lack knowledge on how alignment is accomplished in practice, and the conditions under which it perpetuates or challenges the anticipation of technocratic and market-oriented futures, especially in commercially competitive environments. This article aims to fill this gap by introducing the concept of *anticipatory alignment work*. Through a case study on an innovation ecosystem emerging around neuromorphic computing technology, the article demonstrates the analytical potential of the concept. In analyzing different modes of anticipatory alignment work, the study reveals how politics shapes alignment and keeps anticipation locked in dominant constructions of the past and present. The article casts doubt on the optimism typically implicit in science, technology, and innovation governance approaches that promise the advancement of societal alignment, while also discussing opportunities for these approaches to foster novel forms of anticipation.

1. Societal alignment in science, technology, and innovation governance

A number of governance approaches that include technology assessment, responsible (research and) innovation, and anticipatory governance, seek to advance "societal alignment" (Böschen, Grunwald, Krings, & Rösch, 2021; Guston, 2014, 2018; Owen, Macnaghten, & Stilgoe, 2012; von Schomberg, 2013). Societal alignment is broadly defined as "democratising science, technology and innovation, addressing divergent stakeholder perspectives, and ensuring a closer correspondence between their benefits and the needs of diverse publics" (Ribeiro et al., 2018, p. 318). It is pursued, inter alia, in and through "anticipatory practices" (Anderson, 2010;

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Alvial-Palavicino, 2015; Alvial-Palavicino & Konrad, 2019) that seek to foresee and evaluate alternative futures in participatory processes. These processes, involving technoscientific experts, stakeholders, and publics, aim at integrating their needs, values, and concerns into research and development processes.

Studies have shown that anticipatory practices are shaped by politics (Beck & Mahony, 2018; Hajer & Oomen, 2025; Oomen, 2023). The "politics of anticipation" (Granjou, Walker, & Salazar, 2017) refers to the practices through which constructions of the future preordain what future appears as self-evident, if not inevitable, and what is left unimaginable. Research indicates that the politics of anticipation constrains practices of societal alignment especially in commercially competitive environments (Alday et al., 2025), such as industry (Martinuzzi, Blok, Brem, Stahl, & Schönherr, 2018), business contexts (Lubberink, Blok, van Ophem, & Omta, 2017), and profit-oriented innovation ecosystems (Dreyer, von Heimburg, & Schofield, 2020; Visscher, Hahn, & Konrad, 2021), where economic interests tend to prevail over public interests. Stilgoe, Owen, and Macnaghten (2013) argue that "the project of responsible governance requires understanding this 'alignment work'" (p. 1573). However, we have a limited understanding of how the politics of anticipation emerges and shapes this alignment work (cf. Hajer & Pelzer, 2018; Oomen, Hoffman, & Hajer, 2021).

In this article, we pose two research questions, one: *How does the politics of anticipation shape alignment work in competitive environments?* And, two: *What constraints and opportunities for the governance of science, technology, and innovation does the analysis reveal?* In answering these questions, we shed light on how and why governance approaches have struggled to advance societal alignment in practice, and how opportunities for promoting societal alignment could be secured. This research is crucial to understand the conditions under which the politics of anticipation risks reinforcing the hegemonic imaginaries of technocracy and market imperatives that governance approaches set out to critique and challenge (Smolka, Doezema, & von Schomberg, 2024). Such in-depth understanding can inform the development of practices and strategies for avoiding the undermining of societal alignment.

This article is structured as follows. We review literature on the politics of anticipation to highlight a gap in research (2) before introducing the novel concept of *anticipatory alignment work* (3), which is central to analyzing our empirical case study. The case study (4) focuses on an innovation ecosystem emerging around a German high-tech innovation cluster, which develops brain-inspired computer hardware and software – also known as neuromorphic computing technology – for artificial intelligence (AI). Three of the authors adopted the role of embedded social scientists in the cluster (MS, PN, SB) working with the methodology of transformative vision assessment (5) to contribute to the responsible governance of research and development (Smolka & Böschen, 2023). In analyzing the data generated through transformative vision assessment, we unpack three modes of anticipatory alignment work: *narrative alignment*, *multi-level alignment*, and *postponed alignment* (6). In the discussion, we elaborate on how the politics of anticipation underpinning these modes largely curtails transformative vision assessment, while also highlighting opportunities for anticipating plural, alternative futures (7). The final section presents the academic contributions and governance implications of this article (8).

2. Politics of anticipation

Literature on the politics of technoscientific projects, policy arenas, and deliberative processes have suggested that governance approaches tend to be curtailed by pressures towards closure around research and innovation pathways favored by incumbent actors (Penttilä, 2024; Stirling, 2024). Politics can be defined as the processes through which actors make their claims authoritative in situations and contexts that matter for decision-making (Hajer, 2009). Hajer & Oomen (2025) distinguish between two types of practices through which politics operates: first, there are examples of traditional practices of persuasion such as lobbying and the intentional fabrication and deployment of uncertainty; second, there are more subtle practices (intentional or otherwise) that work to make some futures seem self-evident and inevitable while others become sidelined as implausible or even unthinkable. This latter type finds its expression in implicit biases in societal discourse and decision-making (cf. van Oudheusden, 2014) as well as in narrow issue framings that bypass participation (Ludwig, Blok, Garnier, Macnaghten, & Pols, 2022), or that "close down" (Stirling, 2008, p. 264) anticipation around a limited set of envisioned futures (Urueña, Rodríguez, & Ibarra, 2021). As Hajer & Oomen (2025) show in their seminal book *Captured Futures*, anticipation becomes "captured" (p. 2) around constructions of futures that are akin to those of the past and present.

The majority of social science research, in particular in Science & Technology Studies (STS), have investigated what such imagined futures do in the present. They have used the notion of politics in relation to dynamics of expectations (Borup, Brown, Konrad, & van Lente, 2006; van Lente & Rip, 1998), visions (Hausstein & Lösch, 2020), myths (Mosco, 2004), and imaginaries (Jasanoff & Kim, 2015) to analyze their performative effects: how such images of the future structure decision-making and social organization in the present. For example, Beckert's (2016) monograph on the "politics of expectations" (p. 11) uncovers how expectations of the future drive capitalist dynamics. However, "*how* and *why* images of the future become influential, credible, and desirable" remains underexplained (Hajer & Oomen, 2025, p. 86). Oomen, Hoffman, and Hajer (2021) observe that social science researchers often approach images of the future as *explanans* (an explanation), but rarely as *explanandum* (that what requires explanation). If researchers explain how futures gain traction, they tend to focus on power structures and the role of existing imaginaries, while neglecting the specific *practices* through which some futures become collectively shared while others become marginalized (for exceptions, see Hajer & Versteeg, 2019; Hilgartner, 2015; Jasanoff, 2015; Neudert, Smolka, & Böschen, 2024a). A notable exception is Granjou, Walker, and Salazar's (2017) editorial of a special issue in *Futures* on "the politics of anticipation", which examines how anticipatory formats, methods, and practices shape the selective construction of the future of biodiversity, ecosystems, and the biosphere.[1]

[1] In line with this special issue, studies have highlighted how the "politics of anticipation" operates in and through the Intergovernmental Panel on Climate Change, narrowing down mitigation pathways around visions based on speculative negative emissions technologies (Beck & Mahony, 2018; Beck & Oomen, 2021).

Building on this research, we shed light on the politics of anticipation by focusing on a particular set of practices which we call 'anticipatory alignment work.' As we explain in the section below, the concept refers to specific anticipatory practices, which actors perform to overcome perceived socio-technical problems in working towards desirable futures. The concept highlights the *how* (anticipatory practices) and the *why* (socio-technical problems) of the politics of anticipation. An empirical analysis guided by this concept can help reveal the roots of governance setbacks. Governance approaches, such as technology assessment, responsible (research and) innovation, and anticipatory governance aim at "opening up" (Stirling, 2008) alternative futures that align science, technology, and innovation with public interests. However, this aim has repeatedly not been (fully) realized (e.g., Felt, Öchsner, Rae, & Osipova, 2023; Lee, Gans, Grohman, & Brown, 2019; Viseu, 2015). In studying the "social origin" (Oomen, Hoffman, & Hajer, 2021, p. 253) of the politics of anticipation, we learn *how* and *why* governance approaches struggle with advancing societal alignment.

3. Anticipatory alignment work

The concept of alignment has been widely used in STS research where it is often traced back to Fujimura's (1987) study on constructing "do-able" research problems. In her study on cancer research, she points out that scientists only spend their time and other resources on problems which have the potential of becoming do-able. For example, they must cohere with the quality standards (e.g., originality) of academic journals (cf. Sorgner, 2022). Hence, Fujimura defines the do-ability of research problems not only in terms of their technical feasibility, but also in terms of alignment – and the practical work of aligning – across levels of organization: the laboratory, institute, and wider social worlds. In her study, such work involved "creating strategies which allowed the scientists to juggle and balance multiple simultaneous demands at multiple levels" (p. 275) – for example the availability of skills and lab equipment, the interests of colleagues and scientific communities, and the goals of research sponsors. Informed by Fujimura, the concept of alignment work has been used to study how multi-disciplinary projects (Penders, Horstman, & Vos, 2009), scientific collaborations (Jackson, Ribes, Buyuktur, & Bowker, 2011), big science (Habets, Zwart, & Smolka, 2025), and doctoral dissertations (Sorgner, 2022) are made do-able through the practical labor of negotiating, coordinating, and holding together disparate temporalities, organizations, infrastructures, elements, and actors. STS researchers have also shown that such practical labor is necessary to move knowledge and technologies from one site or epistemic community to another. For instance, the contributions to Kruse & Silvast's (2023) special issue on alignment work analyze how actors in several settings (e.g., health services and childhood education) managed to coordinate between different epistemic communities despite the tensions and incommensurability that their differences produce.[2] In a similar vein, Engel (2020) examines how technology developers and implementers adapted diagnostic technologies to different contexts of use through ongoing alignment work.

STS studies on alignment work reveal the activities through which researchers and developers handle practical challenges, epistemic tensions, and competing demands *in the present* to complete technoscientific projects. We expand on this literature by conceptualizing alignment work as an "anticipatory practice" (Anderson, 2010; Alvial-Palavicino, 2015; Alvial-Palavicino & Konrad, 2019), meaning an activity in which explicit or implicit assumptions about the future are defined. Examples of anticipatory practices are the articulation, negotiation, and enactment of expectations (Borup, Brown, Konrad, & van Lente, 2006), promises (Parandian, Rip, & te Kulve, 2012), and visions (Schneider & Lösch, 2019). Drawing on Alvial-Palavicino and Konard (2019), we distinguish between *de facto* and *curated* practices of anticipatory alignment work. The former are implicit and already embedded in technoscientific and professional work, such as grant proposal writing, prototyping, standardization, roadmapping, and future-oriented shoptalk. The latter are performed in explicit and structured formats, for instance in backcasting exercises and scenario workshops, which promise to enhance participants' anticipatory capacities, helping them to imagine plural futures in greater nuance, detail, and richness (Fischer & Mehnert, 2021; Lehoux, Miller, & Williams-Jones, 2020; Macnaghten, 2017, 2020a; Mulgan, 2022).

Combining the concept of alignment work with the anticipatory practice lens, we coin the concept of *anticipatory alignment work*: social, material, embodied, and discursive practices of anticipating selective futures through which actors with divergent expertise, values, and interests plan, coordinate, evaluate, adjust, integrate, and otherwise organize their actions for making research and development do-able. Through anticipatory alignment work, actors articulate and handle socio-technical problems seen as relevant to be resolved for what they anticipate to be desirable futures for a technoscientific project. In contrast to STS studies which primarily focus on how alignment work 'gets the job done,' the anticipatory practice lens enables us to inquire how and for whom 'getting the job done' promotes desirable futures. This is important because anticipatory alignment work is never innocent (Moberg, 2023): it is shaped by existing power asymmetries and may thus perpetuate the privileging of certain interests and dominant practices of knowledge production and technology development. This political dimension of alignment work has so far received little attention in STS. An exception is Penders et al. (2009) study on a large-scale, multi-sited nutrigenomics project. The study indicates that the construction of do-able research problems at specific sites led to the successful completion of a scientific project, but came at the expense of pursuing the project's overarching societal goal of health promotion.

In this article, we shed light on the political nature of anticipatory alignment work. We analyze how actors pertaining to an innovation ecosystem performed anticipatory alignment work in workshops, which we curated by following the methodology of transformative vision assessment. We also analyze anticipatory alignment work in de facto practices to trace whether and how transformative vision assessment modulated actors' imaginations of the future, internal and external communication, as well as

[2] In inter- and transdisciplinary contexts, alignment work is mainly a matter of coordinating between "epistemic cultures" (Knorr Cetina, 1999). However, the concept of alignment work is broader than coordination work for it also encompasses "planning, organizing, monitoring, evaluating, adjusting or integrating activities" (Engel, 2020, p. 53).

research and innovation activities. Although we observed a range of social, material, embodied, and discursive practices of anticipatory alignment work, our analysis primarily focuses on discourse. This focus is inspired by analyses of the rhetoric of anticipation (e.g., Blue, Davidson, & Myles, 2022; Hanson, 2010; Joly, 2010; van Lente & Rip, 1998). Joly (2010) identifies a range of rhetorical devices, tools, and resources which stabilize particular technoscientific futures and economic interests. Similarly, we analyze how the politics of anticipation operates through rhetorical patterns, assumptions about innovation, and boundary drawings, which underpin and organize the discursive practices of anticipatory alignment work.

4. Case study on a high-tech innovation ecosystem

The analysis draws on empirical data gathered in an innovation ecosystem emerging around the high-tech innovation cluster NeuroSys, funded within the Clusters4Future scheme by the German Federal Ministry of Research, Technology and Space. Within this scheme, NeuroSys can apply three times for a three-year funding phase. The cluster secured funding for the first phase (2022–2024) and the second phase (2025–2027), but the analysis presented here focuses on the first phase. The cluster aims to develop neuromorphic computing hardware and corresponding software for AI applications. Neuromorphic computing takes inspiration from the human brain for the design of hardware and software.[3] Neuromorphic chips are expected to be of higher performance and energy-efficiency than hardware that is currently used for running AI models (Prytkova & Vannuccini, 2022). Due to the presumed energy-efficiency, they are particularly useful for AI on mobile edge-computing devices, such as sensors and smart watches, that process data locally. NeuroSys aims to develop such applications for personalized healthcare, autonomous driving, smart cities, and the Internet of Things.

For this purpose, the cluster pools experts from “science” (researchers from multiple disciplines employed at a university or research center), “business” (regional and transregional businesses and industry partners) and “society” (regional stakeholders representing economic and societal interests). These categories are used in project presentations by the cluster coordination (Fig. 1). The category “society” includes some stakeholders representing economic interests (e.g., the chamber of commerce and industry and a university technology transfer unit) and others who also represent the interests of citizens living in the Rhenish area, where the nucleus of the innovation ecosystem is located (e.g., a future agency coordinating the structural change process of the area and an initiative within the municipality of Aachen organizing public engagement). We refer to this conglomerate of actors as ‘regional stakeholders’ – instead of using the actors’ category “society” – to emphasize the combination of economic and public interests within this group.

Around the NeuroSys cluster, an innovation ecosystem of neuromorphic computing is supposed to emerge through the attraction and involvement of an increasing number of partners, branching out from the Rhenish area to partners across Europe. The innovation ecosystem is conceived of as a network of heterogenous actors, distributed across multiple levels of organization, including not only “science”, “business”, and “society”, but also the German policy arena of district, state, and federal governments. It relates to broader policy programs aiming to transform the Rhenish lignite mining area into an “Innovation Valley” (Zukunftsagentur Rheinisches Revier, 2021, p. 3). The emergence of a competitive innovation ecosystem is viewed as a necessary condition for fulfilling the cluster objective of timely technology transfer and regional transformation. This ecosystem is a case of a competitive environment, in which our involvement as social scientists is seen as relevant to foster its responsible governance (Neudert, Smolka, & Böschen, 2024b; Smolka & Böschen, 2023).

5. Methodology of transformative vision assessment

Our research was guided by the methodology of transformative vision assessment, combining analytical-observational and engaged-interventionist methods to use insights from the monitoring of existing visions of the future to inform the curation of interactive multi-stakeholder workshops (Lösch, Roßmann, & Schneider, 2021). In these workshops, existing visions of the future, which often tend to be vague and technology-focused, are transformed into more socially robust, detailed, and complex scenarios (Schneider, Roßmann, Lösch, & Grunwald, 2021). Transformation has two meanings: one refers to “transformative acts of modulating visions towards the sociotechnical scenarios” (Dobroć & Lösch, 2023, p. 4), the other meaning the act of “breaking with existing patterns of interpretation” (Dobroć & Lösch, 2023, p. 3). The modulation of visions is usually seen as a pre-condition for the act of breaking with existing patterns of interpretation.

We pursued a three-step transformative vision assessment process. First, we studied visions circulating among members of the NeuroSys cluster by conducting semi-structured interviews (N = 29), participant observation, and document analysis. The aim of the interviews was to study existing visions about the future of NeuroSys among researchers from different disciplines, business representatives, and regional stakeholders involved in the cluster. In hour-long interviews, we inquired into interviewees’ understandings of innovation and neuromorphic computing, the goals they would like the cluster to achieve, and the perceived obstacles and adopted strategies to overcome these obstacles. Details about this multi-method approach and the results of the empirical analysis, including synthesized accounts of visions about the future of NeuroSys, are documented in Neudert et al. (2024a).

In a second step, we presented the identified visions in a scenario workshop with interview participants (N = 18). Drawing on Fischer & Mehnert’s (2021) framework for speculative worldbuilding through storytelling, we facilitated a co-creative process in which visions were transformed into scenario narratives about desirable futures. The process comprised: (1) a mapping exercise in

[3] While the meaning of neuromorphic computing is multiple and contested within and between academic communities (Mehonic & Kenyon, 2022; Schuman et al., 2022), this generic definition captures how the notion is deployed within the NeuroSys cluster.

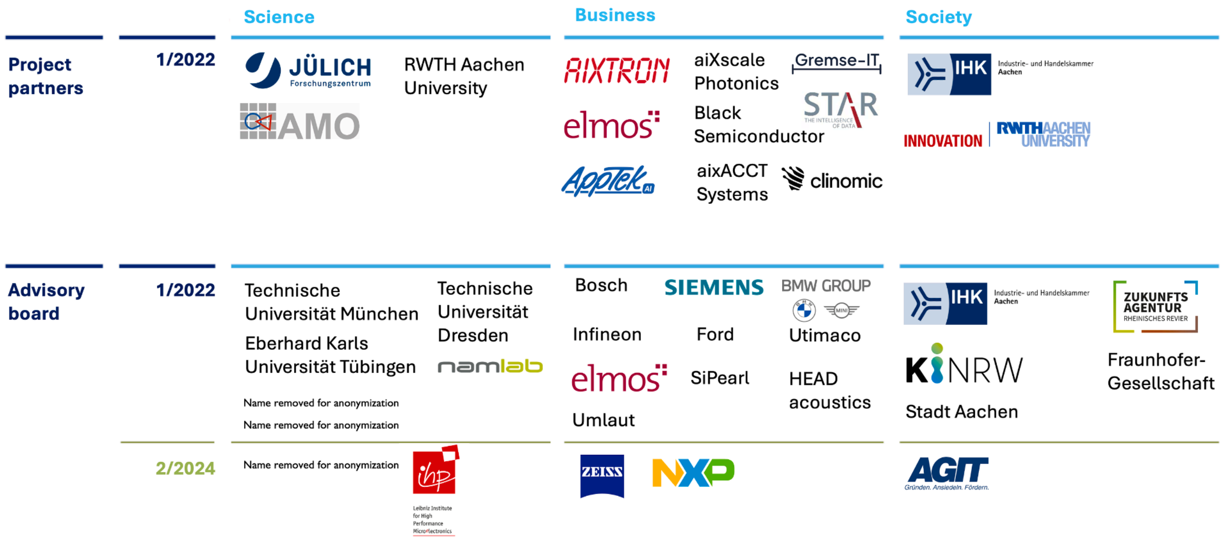

Fig. 1. NeuroSys cluster members and advisory board.[41] Internal project presentation on May 17, 2024. The original figure was reconstructed to replace logos with names if permission for the use of copyrighted material could not be obtained.

which participants identified and described actors relevant to establishing an innovation ecosystem of neuromorphic computing; (2) a timeline exercise to anticipate future events impacting the emergence of the innovation ecosystem; (3) a writing exercise for creating short narratives about desirable futures of NeuroSys from the perspective of a self-chosen actor. Based on the material generated during the workshop, we composed four scenario narratives, each depicting a desirable future and a pathway to reach it. We enriched and revised the scenario narratives with information gathered in feedback dialogues with selected experts both from within and beyond the NeuroSys cluster (N = 13) who could provide insights into specific aspects of the narratives. The resulting scenario narratives are included in the Appendix of this article.

For the third step, we invited all cluster members to join a strategy mapping workshop (N = 40), where we presented the scenario narratives. Inspired by the causal analysis method (van Mierlo et al., 2010), we guided interactive group processes in which participants reflected on potential obstacles to the realization of the futures portrayed in the scenario narratives and possible actions as well as strategies to overcome them. To trace and evaluate the effects of transformative vision assessment on NeuroSys, participants completed feedback forms after the workshops and we have engaged in cluster-related participant observation and document analysis since August 2022.

Throughout the transformative vision assessment process, we made efforts to recruit a balanced sample of natural scientists and engineers, social scientists and humanities scholars, business representatives from regional and transregional companies, and regional stakeholders. We managed to recruit a fairly balanced sample in the scenario workshop and feedback dialogues, but there was a predominance of scientists and engineers among participants in the strategy mapping workshop. We did not broaden participation in the scenario workshop and strategy mapping workshop beyond the NeuroSys cluster.[5] This admittedly limits scenario and strategy development to the futures imagined by those who are positively inclined towards and have a stake in the general conception of the cluster as well as its initially defined vision. Nevertheless, we made this methodological decision to build trust and establish a solid foundation for collaboration in the already heterogeneous cluster.

The data generated through transformative vision assessment comprise: audio-recordings, transcripts, and feedback forms of workshops; fieldnotes from participant observation and feedback dialogues; NeuroSys-related documents (funding applications, progress reports, reports by the external advisory board).[6] For the analysis, the first author engaged in two rounds of qualitative coding of the entire data set, which were cross-checked by the second author. In the first round of inductive coding, we noticed that discussions at workshops and other NeuroSys activities (e.g., status seminars, symposia, outreach events, meetings with the public research sponsor) were recurringly revolving around a set of problems, which we clustered under the following codes: *diverging visions of the future*, *chicken-and-egg problem*, *diffusion of responsibility*. We then looked for ways in which actors were responding to these problems, which we later coded as different modes of anticipatory alignment work by moving back and forth between the data and academic literature. In the second round of deductive coding, we applied the identified codes to the empirical material. We further refined the different modes of anticipatory alignment work – *narrative alignment, multi-level alignment, postponed alignment* – by coding

[5] We made exceptions for two regional stakeholders who showed high interest in participating in NeuroSys; one of them became a member of the advisory board at the end of the first funding phase.

[6] We do not share the data due to its sensitivity. Whenever we provide a direct quote, we mention in which context the statement was made and, if relevant to the analysis, which type of actor expressed it. The language of the data is both English and German and all translation of quotes from German to English are our own.

their diverse situated performances. Considering that actors develop and transform opinions and imaginations in curated formats (Macnaghten, 2020a; Wynne, Waterton, & Grove-White, 1993/2007), we examined how these situated performances changed over time. The analysis and a draft of this article were discussed with selected members of the NeuroSys cluster.

6. Analysis of modes of anticipatory alignment work

We now present the results of the empirical analysis in three sections (Table 1). In each section, we first present empirical material which illustrates a problem whose resolution actors perceived as necessary for making research, development, and transfer of neuromorphic computing technology do-able. We then analyze how actors responded to this problem through different situated performances of a specific mode of anticipatory alignment work and the politics underpinning these discursive practices.

6.1. Narrative alignment

In anticipating desirable futures of NeuroSys, cluster members performed narrative alignment to hold together diverging visions. To reconstruct the emergence of diverging visions, we examined how the cluster came into being. Prior to its official launch in early 2022, one of the main activities was to work on NeuroSys' vision statement. The aim of the statement was to line up a range of actors behind a common goal and present a promising innovation plan in line with the Clusters4Future funding scheme. The initial vision statement was crafted by a small group of science coordinators and principal investigators of cluster projects. Our analysis of the statement reveals that it frames research, development, and manufacturing of neuromorphic computing technology in the Rhenish area as a "solution" to three "societal challenges": (1) sustainability of AI, (2) European technological sovereignty, and (3) structural change.[7] Drawing on the initial NeuroSys vision statement, we summarize and paraphrase the challenge-solution framing as follows:

> First, increasing use and data-intensity of ever-larger AI models, often relying on fossil fuel-generated energy, exacerbates climate change-inducing greenhouse gas emissions. Energy-efficient neuromorphic hardware for AI applications promises to reduce energy consumption and related environmental impacts. Second, AI is assumed to become increasingly important for economic growth and for organizing private and professional activities in a range of societal spheres. However, international markets are dominated by American and Chinese AI products, and Europe's access to computer hardware could be affected by geopolitical tensions between the PRC and Taiwan, where the world's most advanced microelectronics producer TSMC is located. By bringing the production of both AI hardware and software to Europe, NeuroSys could advance technological sovereignty. European technological sovereignty implies securing economic competitiveness, enhancing value chain resilience, and developing AI informed by European values. Third, the Rhenish area is currently undergoing a structural change, a reorganization of the region's economy, due to the phasing out of lignite mining. Bringing the semiconductor industry to the area promises new employment opportunities and enhanced economic welfare. Taken together, NeuroSys aims to address these challenges through research and development of neuromorphic computing technology culminating in a semiconductor fabrication plant – also referred to as "chip fab" – built in the Rhenish area.

This vision statement was shared at the kick-off meeting of the cluster and at several other NeuroSys events. However, doubts surfaced in informal conversations and at the scenario workshop. Researchers questioned whether energy-efficient hardware alone would improve the sustainability of AI in light of rebound effects (see 6.3) and the environmental impacts of chip manufacturing stemming from its energy intensity, the use of hazardous chemicals, and freshwater consumption. Some considered European technological sovereignty as unattainable. The vision that Europe would be able to catch up with the PRC and USA in AI hardware and software development was viewed as implausible, partly because of a history of underfunding of the European semiconductor industry. Since future and intense American and Chinese innovation in these technologies was viewed as a given, whereby both countries would strive to maintain their forerunner position and market share across much of the globe, the vision of a growing European industry and the protection of European values would depend largely on European regulation, rather than on technological innovation alone. Finally, cluster members questioned whether building a chip fab in the Rhenish area would indeed be desirable. Some appeared less concerned where the fab would be located because their research or company did not rely on the regional supply of neuromorphic chips. Besides, the promise of providing employment opportunities to former lignite miners was considered as implausible considering the highly skilled personnel required for semiconductor manufacturing.

Since cluster members expressed some criticism of NeuroSys' overarching vision, they dedicated time and other resources to pursuing diverging visions that were locally important to their research groups or companies – for instance, generating novel insights in basic material research whose relevance to neuromorphic computing was at best indirect; optimizing an instrument for measuring electrical currents on a chip; creating an algorithm for an artificial pancreas that would run on conventional AI hardware – while, at the same time, making efforts to align these visions with NeuroSys' initial vision statement. They engaged in narrative alignment by

[7] The challenge-solution framing which presents technology development as a response to so-called "societal challenges" is common in technoscientific projects. Social scientists have analyzed the politics implicit in this framing (Ludwig et al., 2022). In a similar vein, our analysis does not endorse this framing, but sheds light on its critiques.

Table 1
Structure of the empirical analysis.

Section	6.1.	6.2.	6.3.
Problem	Diverging visions	Chicken-and-egg problem	Diffusion of responsibility
Response	Narrative alignment	Multi-level alignment	Postponed alignment
Anticipatory alignment work	a) Switching between narratives b) Transformation of narratives c) Opening up & closing down narratives	a) Assumption of a linear process of innovation b) Assumption of oligopolistic governance of innovation c) Assumption of a dialogic emergence of innovation	a) Imagined actors b) Ambiguous goals c) Silence
Politics of anticipation	Rhetorical patterns	Assumptions of innovation	Boundary drawings

performing "strategic switching" (Brown & Michael, 2001, p. 19; Gilbert & Mulkay, 1984) between 'frontstage' and 'backstage' narratives depending on the audience (Goffman, 1959).[8] The narrative of how neuromorphic computing could respond to societal challenges was told frontstage in presentations to the research sponsor, at conferences, and in public communication (e.g., Forschungszentrum Jülich, 2022; Waser, 2024). The alternative narrative of NeuroSys creating a platform and providing resources for multiple diverging visions to flourish was unfolding backstage at internal cluster meetings. Through strategic switching, both frontstage and backstage narratives could be maintained in parallel.

Another situated performance of narrative alignment occurred through the transformation of existing visions into scenario narratives about the innovation ecosystem of NeuroSys. After diverging visions had been made explicit at the scenario workshop, a lead engineer concluded in the final plenary discussion:

> The chip fab here would be a very desirable side effect of what we're doing because it would bring jobs to the region. I always say that if Intel had come here, the structural change would have been complete, but no politician understood that.[9] A chip fab would be a visible outcome of our activities. If, on the other hand, aixACCT [provider of systems for material characterization and testing] has twice as many employees in ten years and Black Semiconductor [photonics start-up] has put something here, then we will also have reached our goals, just not as visibly. I don't want to say that the chip fab is unimportant, but I don't think that it is the only goal.

Acknowledging that NeuroSys was about more than just a chip fab, the cluster coordination team welcomed our initiative to write four scenario narratives which are included in the Appendix and summarized in Table 2. These scenario narratives describe alternative desirable futures of the nascent innovation ecosystem: first, a chip fab built on the ground of a former open-pit mine in the Rhenish area; second, a center for interdisciplinary basic research at the intersection of physics, material science, neuroscience, computer science, philosophy, and other adjacent disciplines; third, an innovation platform that unites companies, research institutes, and universities for prototype development, technology transfer, and a "holistic" education program; and fourth, a transfer agency organizing participatory formats, artistic performances, and cultural events for deliberation on potential societal impacts of novel computing technologies. These narratives became starting points for strategy development and project planning during the strategy mapping workshop. We were subsequently asked to help revise NeuroSys' vision statement in the application for the second funding phase and include summaries of the narratives. The depictions of NeuroSys' innovation ecosystem in the applications for the first and second funding phase (Figs. 2, 3) indicate that the cluster moved from one dominant vision to multiple, co-created narratives of desirable futures (cf. Dobroć, Krings, Schneider, & Wulf, 2018).[10] In this way, alignment was created between the dominant official vision and diverging non-official visions because the cluster pursued multiple envisioned futures simultaneously, considering all of them as both pathways to and target images of the successful completion of NeuroSys.

The creation of scenario narratives can be considered as a process of "opening up" (Stirling, 2008) options, goals, and solution spaces around a narrow set of closely-related alternative futures (Stirling, 2024). However, in line with van Mierlo, Beers, and Hoes (2020), we found that opening up was immediately followed by closing down. In the application process for the second funding phase, cluster members and the public research sponsor participated in a meeting where the new vision statement of NeuroSys was presented. The presentation of the vision statement emphasized: "we stick to the idea to build a chip fab in the Rhenish area." Upon probing questions by the sponsor regarding the relevance of alternative scenarios, members responded that these scenarios could be pursued in parallel and sequentially lead up to the building of a chip fab in the region. The opening up of alternatives futures was closed down by foregrounding the regional chip fab against the background of other conducive albeit less relevant scenarios. This situated performance of narrative alignment held together multiple scenarios by presenting them as an unfolding sequence that culminated in a dominant construction of the future.

[8] Goffman (1959) introduced a "dramaturgical approach" (p. 240) to the study of impression management in social interaction. 'Frontstage' performances refer to an actor's fulfillment of specific social roles and audience expectations. The actor's behavior can deviate from these roles and expectations in the absence of the audience 'backstage.'

[9] In spring 2022, it was officially announced that Intel would build a chip manufacturing facility in Magdeburg, Germany, with the support of considerable federal subsidies (Intel, 2022). These plans were canceled in 2025 (DIE ZEIT, 2025).

[10] Fig. 3 was removed from the final version of the application for the second funding phase, but summaries of the scenario narratives remained included.

Table 2
Summaries of the scenario narratives about the future of NeuroSys.

Scenario	Memristor Fab Aachen	Center for the Future of Computing (CFC)	Platform for Holistic Computer Engineering	*Transfer*mation Agency Aachen
Fictional character	Cornelia, scientist and chair of the Holistic Computer Engineering Board	Ada de Santis, computer scientist and scientific director of the CFC	Claudiu Dimoiu, entrepreneur and alumnus of the *School of Holistic Computer Engineering*	Thomas, former NeuroSys co-coordinator
Time	2050	2040	2047	2034
Center	Manufacturing plant where neuromorphic chips with electrical components (memristors[k]) are produced	Research center for interdisciplinary basic research with satellite offices at European universities	Innovation platform that unites companies, research institutes, and universities through a polycentric organization	Pop-up-network with institutional affiliation and office at RWTH Aachen University
Place	Abandoned open-pit mine in the Rhenish area	Triangle of Germany, Belgium, and the Netherlands	Triangle of Germany, Belgium, and the Netherlands	Aachen and transregional events
Funding	€10 billion, consortium of companies led by TSMC	National funding from Germany, Belgium, and the Netherlands, and commercial research contracts	The platform is a non-profit company that receives starter grants from the German Federal Ministry of Education and Research and is also financed through cooperations between companies, industrial contract research, and public-private projects	Public funding, foundation grants, and commercial contracts
Narrative	Cornelia gives a speech at the ground-breaking ceremony of the memristor fab. In her speech, Cornelia attributes the success of the fab project to four building blocks: 1. research, 2. technology transfer, 3. innovation ecosystem, 4. coordination work.	Ada de Santis gives a newspaper interview about her Leibniz Prize. She received the prize for her contribution to Alzheimer's research, which stems from her interdisciplinary collaboration at the CFC.	Claudiu completed his PhD in NeuroSys. 15 years later, he runs a company that solves optimization problems for public transport. At the 20th anniversary of the Platform for Holistic Computer Engineering, he talks to his former PhD supervisor and an employee from the German Federal Ministry of Education and Research about the relevance of trust for the development of the platform.	Thomas writes a letter to his colleague Sergio in which he reports on his experiences with the *Transfer*mation Agency. The agency offers various event formats (theater, exhibitions, workshops, etc.) to identify technology needs and discuss societal impacts.

[k] Memristors are material components which change their resistance depending on the applied voltage or current. They are suitable for representing the weights between neurons in an artificial neural network (Zidan, Strachan, & Lu, 2018). As NeuroSys seeks to develop memristor-based neuromorphic hardware, the aspired chip manufacturing plant is also referred to as the “memristor fab.”

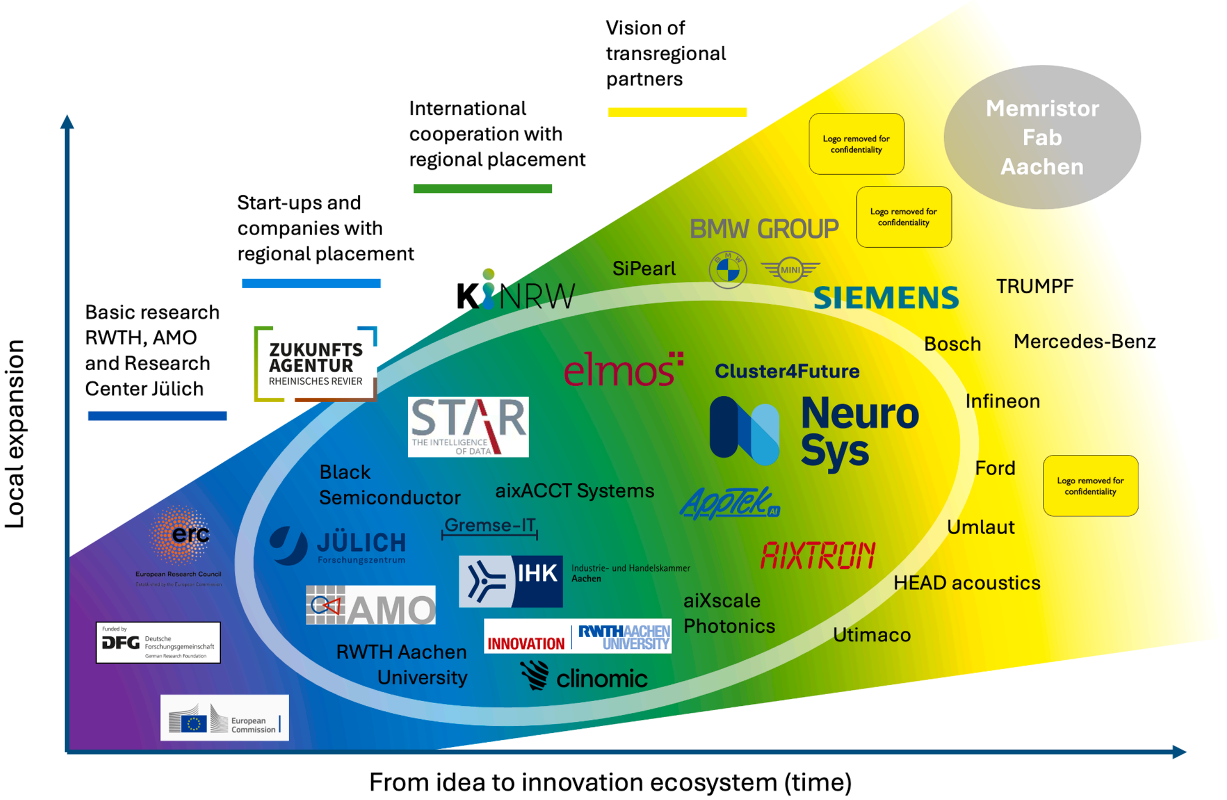

Fig. 2. Innovation ecosystem of NeuroSys. Vision statement in the application for the first funding phase. The original figure was translated to English and logos were replaced with names if permission for the use of copyrighted material could not be obtained. © NeuroSys.

Narrative alignment was thus accomplished through three performances of anticipatory alignment work: switching between frontstage and backstage narratives; transforming visions into scenario narratives; opening up and closing down narratives. The practical labor of narrative alignment was enacted through rhetorical patterns which researchers and innovators commonly deploy to secure funding and facilitate public communication (Connor, 2009; Philipps & Weißenborn, 2019). These patterns are rhetorical because they are supposed to have persuasive effects on different audiences, here the sponsor and wider publics. Narrative alignment also enabled the cluster to negotiate diverging visions of desirable futures and engage in collective planning and strategy development.

6.2. Multi-level alignment

Discussions on strategy development revolved repeatedly around what some NeuroSys members called the "chicken-and-egg problem." Solving this problem was seen as a necessary pre-condition for building a chip fab and for accomplishing transfer of neuromorphic computing technology from research to markets. According to a scientific coordinator, building a chip fab depended on the investment of an established fab owner (e.g., Intel, Global Foundries, TSMC). He explained:

> They [the fab owner] not only need the technological impulse, which we [NeuroSys] deliver, but they also need 100 % (fully) dedicated customers who will buy the produced wafers in large amounts.[11] If we do not deliver the customers, they do not even bother to start. And this is a real chicken-and-egg problem.

He further pointed out that fab owners would only invest if local conditions were conducive – for instance, in the form of subsidies by the federal government and societal acceptance of a regional chip fab. Yet, without a potential customer base to motivate investment by a fab owner, government subsidies alone could not bring the industry to the region. At the scenario workshop and strategy mapping workshop, participants debated whether NeuroSys should prioritize enhancing technological readiness, attracting a financial investor, building a customer base, gaining political support, or fostering societal acceptance. They asked how alignment could be created between these interdependent levels of organization in the innovation ecosystem (see 4), whose communicative exchanges were rather limited. In response to this problem, NeuroSys members engaged in multi-level alignment: they made suggestions for how

[11] In the chip fabrication process, integrated circuits are built up in successive layers on a round slice of purified silicon, i.e. a wafer (Brown & Linden, 2011, p. 11).

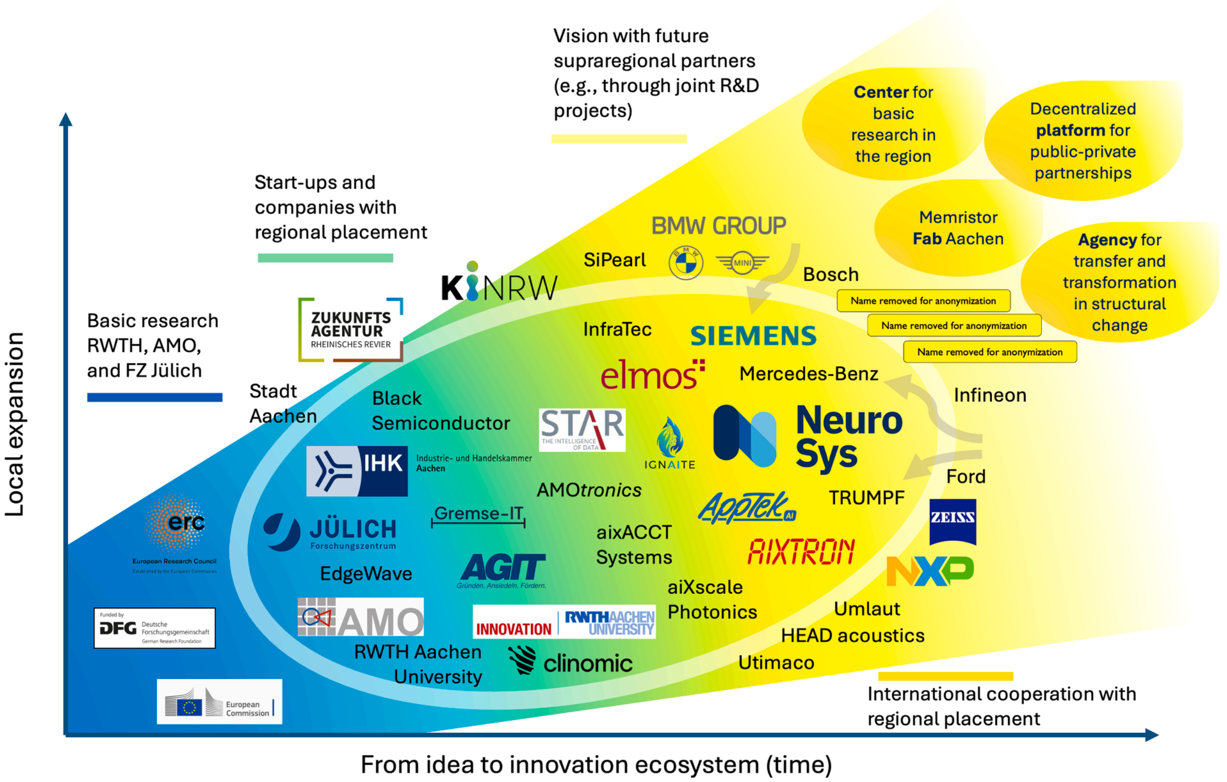

Fig. 3. Innovation ecosystem of NeuroSys. Vision statement in the application for the second funding phase. The original figure was translated to English and logos were replaced with names if permission for the use of copyrighted material could not be obtained. © NeuroSys.

coordination between different levels of organization could be achieved and thereby mobilized different assumptions about innovation.

Some NeuroSys members suggested that the cluster should prioritize developing a proof of concept for neuromorphic hardware because technology was assumed to “push” political and economic developments. For example, an economist projected:

> One thing is quite clear: if, let’s say, we have the hardware, then it will go into the software and the application relatively quickly. We’re now talking about €8 million, and then we’ll be talking about at least €8 billion. After that, we’ll have a factor of at least 1000. Then you have all the big companies, Siemens will also be queuing up here when that happens. A lot will happen. It’s a technological breakthrough worldwide. So, we’re not talking about something small here.

In a similar vein, a member of NeuroSys’ advisory board claimed:

> If you have a good [scientific] concept, then politicians will go along with it. Then there will be money. And then someone will come from the corporate sector and we won’t have to pretend that we have to be Silicon Valley first. In principle, this is also possible in Germany and especially in NRW [North Rhine-Westphalia].

These responses to the chicken-and-egg problem invoke a linear assumption about the relation between science, technology, economy, and policy which is widely shared among industry actors, consultants, and economists (Godin, 2006). They assume that technological innovations arise from basic research, which is followed by applied research and development, independently of social, political, or economic forces. Afterwards, technology results in innovative products and services, which diffuse and, ultimately, impact civil society. Civil society appeared implicitly as a passive receiver who would not play any significant role other than adapting to the “technological breakthrough” mentioned by the economist.

Other cluster members assumed that established fab owners would direct technological innovation and commercial production in the semiconductor industry. They thought that these companies planned more than ten years ahead where the next fabs would be built. On the feedback form about the scenario workshop, a participant noted down:

> The process changes and technological innovations in a fab to produce neuromorphic computing hardware are a high risk [for the fab-owner]. This must be offset by a great opportunity (sustainable technology leadership and market sales figures, growth). This is not solved by a NeuroSys team visiting the office of the chancellor. The decisions are made in the strategy departments of the foundries or IDMs,[12] which think 10 + years ahead. The ball is not yet in the politicians' court and not in their court alone.

The decisions made by established fab owners were assumed to drive the alignment between the different levels of NeuroSys' innovation ecosystem. This assumption reveals that the semiconductor industry is imagined as an oligopoly (cf. Miller, 2022; Suarez-Villa, 2023) where only a handful of companies produce irreplaceable machinery (e.g., ASML) and have the capacities to design and produce the most advanced computer chips (e.g., Samsung and TSMC). Accordingly, the power to control innovation in the semiconductor industry ultimately rests among these companies. The assumption of oligopolistic governance of innovation leaves small room for the maneuvering of cluster members. Their potential efforts to lobby for political support were viewed as having at best a minor impact on the decision-making of fab owners. If a fab owner decided to invest in the area, civil society actors, in particular local residents, were expected to go along with it.

A few NeuroSys members viewed it as their responsibility to engage in dialogue not only with established fab owners, but also with other companies, politicians, and civil society. At the strategy mapping workshop, participants brainstormed what they should do and to whom they should talk to influence politicians. The attraction of business partners and industry connections was perceived as a central task for the technoscientific projects within NeuroSys to facilitate technology transfer. Echoing the views of several cluster members, a lead engineer stated that "stakeholder management" was a shared responsibility of the cluster: "to become aware of connecting communication channels between different levels [of the ecosystem] and to make use of these channels again and again." Some perceived societal engagement as part of stakeholder management. Civil society was framed in two ways: on the one hand, it was reduced to potential users with whom one should engage to develop user-centered and value-sensitive AI applications (see scenario of the *Transfer*mation Agency Aachen); on the other hand, dialogue with civil society actors was understood as crucial for the societal acceptance of innovation. In this understanding, as articulated by a scientific coordinator at the scenario workshop, diverse publics and civil society organizations "should be taken along" – through communication and participation – to ensure societal acceptance, for "otherwise activists may protest [against the chip fab], and people may be unwilling to pay tax money for NeuroSys."

This framing emphasizes that innovation is assumed to emerge in dialogue between actors from multiple levels of an innovation ecosystem, rather than being pushed by technology or directed by fab owners. Hence, alignment is thought to arise from dialogic engagement across these levels and corresponding actor groups (te Kulve & Rip, 2011). Although the assumption of a dialogic emergence of innovation does not frame civil society as a passive receiver, but as an active group with the ability to spark a backlash, their role in innovation is assumed to be rather limited.

All in all, NeuroSys members seemed to agree that multi-level alignment was the solution to the chicken-and-egg problem, but they had different views on how to create such alignment. Their performances of anticipatory aligned work were discursive expressions of linear, oligopolistic, and dialogic assumptions of innovation. In and through these performances, they imagined different ways in which multi-level alignment would unfold, who/what would steer it, and what this implied for members of NeuroSys. The assumption of a linear innovation process absolved cluster members from any responsibility since technological development was assumed to drive multi-level alignment between different levels of organization. The assumption of oligopolistic governance of innovation portrayed established fab owners as those who determined what happened at and between other levels of organization, which reduced the responsibility of NeuroSys to accommodate to the decisions of powerful actors. Moreover, linear and oligopolistic assumptions left barely any room for politicians and civil society actors to intervene or shape the technology trajectory (cf. Wyatt, 2008). The assumption of dialogic emergence of innovation, by contrast, ascribed responsibility for fostering multi-level alignment to cluster members and framed civil society as a relevant, but less prominent party than political and economic actors.

6.3. Postponed alignment

As the preceding analytical section reveals, NeuroSys members made promises to assume responsibility for engaging in dialogue with actors across the innovation ecosystem. At the strategy mapping workshop, we probed these promises, inquiring into the capacity of cluster members to take responsibility for incorporating collectively defined goals into their local work practices. For this purpose, we asked participants to state which activity they would be willing and able to pursue to work towards the realization of a future described in a particular scenario narrative. In response to this question, we observed what a participant called the "diffusion of responsibility": the decreased sense of responsibility someone feels when they are part of a group. Another participant described this observation as follows:

> What I found really exciting was the last task with the blue post-its: What is your own contribution to this? Somehow, all the participants were quite modest, despite the very lively discussion. No one said: 'It's me, I'll do it!' And then everyone said: 'I'm just a small cog, and I'll see what I can contribute. I have a satellite position.' But there was no debate about who was going to do it.

This observation echoes the findings of Neudert et al. (2024a) analysis of interviews with NeuroSys members, which uncovered that

[12] Integrated Device Manufacturers (IDMs) design and manufacture integrated circuits, i.e. computer chips. Foundries only manufacture devices for other companies, without designing them (Brown & Linden, 2011). Both IDMs and foundries fall under the umbrella term 'chip fab.'

they engaged in "responsibility boundary-work." The concept refers to the strategic conferral and deferral of responsibilities in anticipatory practices – the articulation of visions – to delineate the limits of their responsibilization. We expand on this concept here by suggesting that a specific form of responsibility boundary-work is postponed alignment. NeuroSys members drew discursive boundaries between local actions and broader goals. They found it difficult to align their day-to-day work routines with the "societal challenges" motivating the cluster: sustainability of AI, European technological sovereignty, and structural change (see 6.1). Therefore, they postponed alignment into the (indeterminate) future. Postponed alignment resulted from responsibilizing an imagined actor, formulating ambiguous goals, and silencing sustainability concerns.

An imagined actor filled a responsibility gap created by the absence of a "focal actor" (Adner, 2017, p. 41) in the nascent innovation ecosystem of NeuroSys. In the innovation ecosystem literature, a focal actor or firm is often assumed to orchestrate co-evolutionary dynamics in the pursuit of materializing a specific value proposition, that is the promised benefit(s) of a service, product, infrastructure, etc. (Adner, 2017; Clarysse, Wright, Bruneel, & Mahajan, 2014; Shen, Shi, Parida, & Jovanovic, 2024). NeuroSys, by contrast, is structured in a decentralized manner: an executive board including a coordination team, project leaders, and three company representatives organize and coordinate cluster-wide activities and work on the cluster strategy. Against this backdrop, cluster members suggested that a "key player" was required to build a chip manufacturing facility. They imagined different types of actor roles: a "visionary" who circulated expectations and built agendas, a "political banner-bearer" who would lobby for NeuroSys in policy arenas, and a "big investor" who was perceived as providing a solution to the chicken-and-egg problem analyzed in 6.2. However, NeuroSys members did not specify who could fulfill these roles. Instead, they postponed the arrival of an imagined actor into the future and assumed that this actor would shoulder responsibility for pursuing the collective goal of bringing the production of neuromorphic hardware to Europe.

Collective goals often remained ambiguous. Both the scenario workshop and the strategy mapping workshop aimed to render scenario narratives of desirable futures more concrete. Yet, the more concrete the narratives became – defining time horizons, actor groups, and technology trajectories – the more cluster members emphasized that they should not lose sight of the big picture in quarrels over insignificant details. For example, we had defined time horizons in the scenario narratives based on the material generated at the scenario workshop and feedback dialogues with selected experts. After we had presented the narratives at the strategy mapping workshop, a few participants criticized them for having too wide time horizons, especially considering entrepreneurs' immediate interests in generating sales, profits, and employment opportunities. In response to such critiques, a member of the cluster coordination team said reassuringly: "I think it's more about the visions, and whether it [a scenario narrative] says the year A or B doesn't matter at all. It's about the big picture. I think that's how we should interpret it." This remark kept participants engaged and facilitated the workshop process. It also left the scenario narratives ambiguous enough for participants from different professions and disciplines to find them agreeable. In a similar manner, scientists left material decisions open by postponing them into the future. They asserted that it was too early to decide whether NeuroSys should concentrate on building neuromorphic computing hardware on the basis of oxidic or 2D materials. By pursuing both technology trajectories in parallel, they enhanced the chances of developing functional, competitive hardware, and ensured that different research groups – those studying oxidic materials and those focusing on 2D materials – could continue working in the cluster. As long as objectives remained inconclusive, their alignment with corresponding actions – often those that required uncomfortable or disagreeable decision-making – could be delayed.

NeuroSys members also postponed alignment between local actions and sustainability goals. NeuroSys' promise of sustainable AI was often framed as a matter of energy-efficiency, for instance in the initial vision statement and project presentations. At several internal status seminars and a workshop about technology transfer, cluster members warned against equating sustainability with energy-efficiency. They pointed out that increased energy-efficiency could stimulate energy demand, which is why efficiency improvements could fail to translate into absolute reductions of energy consumption – a phenomenon also known as the "rebound effect" (Santarius, 2015; Santarius, Walnum, & Aall, 2016). However, whenever such considerations were mentioned at cluster events, silence followed. Cluster members nodded, acknowledging the importance of recognizing the complexity of defining and achieving sustainable AI, but then plenary discussions swiftly moved on to other topics. A company representative described this behavior as follows: "Sustainability is like sports: something you know you should do and that it is good for you, but then you end up putting it off." Cluster members shelved the practical labor of aligning cluster activities with deeper explorations of sustainability: developing sustainability design criteria for semiconductor chips, participating in standardization efforts, and investigating circular economy approaches to neuromorphic computing devices. For instance, research on circular economy approaches was postponed to the second implementation phase of NeuroSys, in which it would become the theme of a work package.

Such situated performances of anticipatory alignment work were enacted through discursive boundary drawings between local actions and broader goals. These performances postponed alignment into the future to generate specific effects in the present. The responsibilization of an imagined actor kept the project going despite responsibility gaps. The formulation of ambiguous goals smoothened workflows by delaying contestable decisions and by mobilizing support for NeuroSys as diverse actors could attach their own ideas and aspirations to the cluster.[13] The silencing and delimiting of sustainability concerns obscured the complexity of the proposed problem (unsustainable AI) and the short-sightedness of the solution (energy-efficient hardware). At the same time, it gave leeway to NeuroSys members to develop the expertise required for more robust conceptualizations of and approaches to sustainability (e.g., circular economy) before incorporating them in cluster projects (cf. Neudert et al., 2024b).

[13] Breuer & Müller (2024) observe similar functions of ambiguity in public policy documents, which they subsume under the concept "governance through vagueness" (p. 8).

7. Constraints and opportunities in science, technology, and innovation governance

The empirical analysis has responded to the first research question: *How does the politics of anticipation shape alignment work in competitive environments?* We have introduced the concept of anticipatory alignment work to analyze how actors in the innovation ecosystem emerging around NeuroSys addressed problems whose resolution they considered relevant for making research and innovation do-able and for working towards selective desirable futures. This novel concept has enabled us to uncover how the accomplishment of do-ability was shaped by the politics of anticipation: narrative alignment was structured by rhetorical patterns, multi-level alignment was based on different assumptions of innovation, and postponed alignment resulted from discursive boundary drawings. Similar discursive practices have been identified in STS research on the rhetorical strategies mobilized in technoscientific projects to acquire funding, maintain authority, and protect integrity (e.g., Burri, 2008; Greiffenhagen & Sharrock, 2011; Hilgartner, 2002; Macnaghten, 2020b). By analyzing them through the lens of anticipatory alignment work, we learn not only *how,* but also *why* they emerge in science, technology, and innovation governance.

In this way, we understand the roots of subtle dynamics which limit the realization of governance approaches, and can thus answer our second research question: *What constraints and opportunities for the governance of science, technology, and innovation does the analysis reveal?* To answer this question, it is important to reiterate that the central goal of such governance approaches is to challenge the dominance of technocracy and market imperatives through societal alignment. Societal alignment is assumed to be best fostered through the *foresight* of plural futures in *engagement* between technoscientific experts, stakeholders, and civil society actors, in which values, needs, and concerns emerge whose *integration* in research and development practices reshapes science, technology, and innovation trajectories.[14] In what follows, we scrutinize how the different modes of anticipatory alignment work constrained and facilitated foresight, engagement, and integration, and propose opportunities for enhancing societal alignment. We develop these propositions as constructive responses to the *how* (modes of anticipatory alignment work) and the *why* (socio-technical problems) of the politics of anticipation.

Narrative alignment: We interpret the rhetorical pattern of switching between frontstage and backstage narratives as constraining foresight because it made diverging visions disappear in external communication to conference audiences, research sponsors, and publics. Foresight and engagement were facilitated in scenario and strategy mapping workshops, where visions were transformed into scenario narratives in a participatory process with diverse stakeholders. This process of opening up futures, however, was directly followed by them being closed down when NeuroSys members prioritized a technology-driven scenario narrative over scientifically, socially, and regionally oriented alternatives. We therefore propose that iterative scenario development, in which the balance between opening up and closing down is continuously re-evaluated (cf. van Mierlo et al., 2020), could help promote societal alignment. Such an iterative process should explore divergences between scenarios. As participants in narrative alignment, embedded social scientists should make efforts to stimulate narrations of plural futures underpinned by different sets of values, interests, and concerns, rather than orienting story-telling towards specific normative goals. They should not seek to reach a particular kind of closure because "forms of power – and their associated kinds of closure – may confidently be expected to take care of themselves" (Stirling, 2014, p. 90). Instead, social scientists should support ongoing "agonistic deliberation" (Macnaghten, 2020b, p. 54, drawing on Mouffe, 2005), contrasting hegemonic constructions of the future with diverse alternatives. In this way, even when decisions are made and some futures are shut out, there is awareness that "it could be otherwise" (Nowotny & Schot, 2018), which keeps anticipation open to other possibilities for political action.

Multi-level alignment: Linear and oligopolistic assumptions about innovation constrained foresight, engagement, and integration by implying that these activities would not be relevant for creating alignment between different levels of organization in an innovation ecosystem. Instead, alignment was presumed to follow automatically from market-ready technology or the decisions of powerful actors. The assumption of dialogic emergence of innovation, by contrast, facilitated engagement because it responsibilized NeuroSys members for making efforts to engage with diverse stakeholders, including civil society, to address the chicken-and-egg problem of alignment. To prevent that dialogue becomes unidirectional (from technoscientific experts to civil society actors), we suggest that "bridging events" (Rip & te Kulve, 2008, p. 6) could be curated to enable bi-directional exchange. These events should be complemented with guided practices for revealing assumptions that inform judgements about how to address chicken-and-egg problems. An example of such practices is defamiliarization (Hajer & Oomen, 2025). Defamiliarization renders the taken-for-granted absurd and brings into view elements, which are usually left out. Techniques of irony, provocation, and other dramaturgical or artistic techniques (cf. Orchard & O'Gorman, 2024) could highlight the problematic implications of linear, oligopolistic, and dialogic assumptions of innovation. For example, in framing environmental and social impacts of scaling up neuromorphic computing as internal properties of the technology, it becomes evident that these impacts originate in choices about technological design; they stop appearing as unavoidable externalities of innovation.

Postponed alignment: Boundary drawings between local actions and broader goals constrained the integration of values, needs, and concerns into research and development. More specifically, integration was constrained by imagining an elusive actor for filling responsibility gaps, by formulating ambiguous goals, and by silencing sustainability considerations. These situated performances of anticipatory alignment work postponed activities in response to the challenges motivating the cluster (see 6.1.) into the future, leaving them unaddressed in the present. However, they could also be interpreted as facilitating integration, because they created time for

[14] Anticipatory governance assumes that societal alignment can be fostered by cultivating capacities of foresight, engagement, and integration (Barben, Fisher, Selin, & Guston, 2008; Guston, 2018). They are also embedded in responsible innovation (Stilgoe et al., 2013) and technology assessment (Grunwald, 2019).

NeuroSys members to carefully deliberate on which actors to enroll, which objectives to pursue, and which sustainability strategies to develop. Methods that translate scenario narratives into concrete actions (e.g., the dynamic learning agenda by van Mierlo et al., 2010) could help ensure that alignment is, if at all, postponed for an 'appropriate' amount of time (cf. Woodhouse, 2016). Such methods may motivate actors to make uncomfortable decisions, including those related to sustainability. These decisions involve tradeoffs between costs and benefits that emerge at different points in time (Becker, Walker, & McCord, 2017); they can be advantageous in the short term (e.g., gain in economic profit) but incur negative long-term effects (e.g., environmental pollution and destruction). To avoid short-termism and motivate actors to incur costs of making a change now for the sake of future sustainability, governance approaches could cultivate reflexive engagement with intertemporal decision-making in technology development, for instance by means of serious games (e.g., Becker, Tsang, Booth, Zhang, & Fagerholm, 2020). By gaining a deeper understanding of the intertemporal nature of everyday decisions, actors in competitive environments may refrain from unintentionally "discounting the future" (Doganova, 2024) and rethink whether to postpone the alignment between their current actions and future (environmental) impacts.

In addition to these propositions, we suggest that engaged social scientists should be reflexively critical of their own methodological choices, considering which futures these choices may have organized out of discourse and action (cf. Stirling, 2014). The alternative scenario narratives which we helped develop with the methodology of transformative vision assessment focused on a narrow subset of closely related innovation pathways. These pathways were agreeable to members of the NeuroSys cluster and in line with incumbent interests in scientific progress, economic profitability, and competitiveness (cf. Stirling, 2024). Radically different visions and scenarios – such as a future of sufficiency rather than a future oriented towards growth (Becker, 2023), resistance to rather than endorsement of AI (McQuillan, 2022), or community-driven rather than innovation-oriented structural change (Förster, Paegert, Böschen, & Letmathe, 2024) – are largely absent from our empirical data. These accounts of alternative futures were mentioned at rare occasions in informal conversations, but they were neither elaborated on in workshops nor interviews; they seemed to be out of scope of what was imaginable in NeuroSys.

The politics of anticipation was partly rooted in our research methodology. Transformative vision assessment engages with and seeks to transform conceptions of the future articulated by researchers, developers, and innovators "to question the existing order and support change" (Dobroć & Lösch, 2023, p. 3). The methodology thus presupposes that change from within the existing order and dominant anticipatory practices is possible. Following this methodology, we involved actors who were already more or less lined up behind the promises of NeuroSys and kept discussions centered on the futures that were relevant to them. In this way, we could demonstrate our "usefulness" (Bruun Jensen, 2007) to the steering of its emerging innovation ecosystem, which also animated cluster members to participate in activities aiming to cultivate foresight, engagement, and integration. Moreover, we were able to shift imagination of the future from a single dominant vision towards more openly chosen ends. Although NeuroSys cluster members operate in a competitive environment characterized by fast-paced innovation and commercial interests, they started to picture futures with citizen participation in innovation, critical engagement with technology through arts and culture, life cycle approaches to semiconductor chip development, and "holistic" education formats for computer engineers (see Appendix). Nevertheless, societal alignment was limited because the anticipatory formats were biased towards the inclusion of actors supportive of NeuroSys. In these formats, the politics of anticipation kept the dominance of technocratic and market-oriented decision-making intact.

8. From captured futures towards non-hegemonic alternatives?

We conclude by highlighting how the concept of anticipatory alignment work and the empirical analysis address two research gaps: one on the politics of anticipation, and the other on alignment work. In reviewing literature on the politics of anticipation (2), we have emphasized that STS research and related fields have generated a good understanding of how images of the future influence the present. However, they have thus far neglected to explain how specific futures become central to societal discourse and action whereas others move to the periphery. In studying different modes of anticipatory alignment work, we shed light on the social origins of dominant futures: rhetorical patterns that are supposed to appeal to specific audiences, persistent assumptions about the emergence, process, and governance of innovation, and the discursive boundary drawings between local activities and wider (societal) goals. While our study concentrates on the discursive practices through which dominant futures come into being and persist, future research could examine the role of visuals, symbols, material objects, embodiment, and other social practices.

In preparing theoretical ground for introducing the concept of anticipatory alignment work (3), we have highlighted that STS research has paid little attention to the political dimension of alignment. Most research focuses on how alignment work makes research problems do-able, but does not consider who benefits from this and who is put at a disadvantage. Our research reveals that alignment work in practices of anticipating futures often operates in the interest of incumbent actors by stabilizing the status quo. For example, in postponing alignment between their work practices and profound engagement with sustainability, NeuroSys cluster members could carry out business as usual and save resources in the short term. In the long term, however, the environmental footprint of computing is likely to incur large costs and mainly affect the young and unborn who cannot yet speak for themselves. In reconceptualizing alignment work as an anticipatory practice, we unpack the future implications of completing a job in the present. In this way, we scrutinize the political dimension of alignment work, revealing whose and what kinds of futures the completion of a job promotes or sidelines.

In this vein, our analysis of anticipatory alignment work illuminates the politics limiting societal alignment in and through science, technology, and innovation governance. We find that societal alignment can be curtailed by discursive practices which actors mobilize to make research and innovation do-able. These practices keep actors' anticipation locked in dominant constructions of the present and the past, and foreclose radically different alternatives. Therefore, transformative vision assessment in NeuroSys enabled participants to imagine a limited set of "captured futures" (Hajer & Oomen, 2025). Recognizing the practices that capture anticipation is an important condition for developing governance approaches which can meaningfully engage with alternatives. To this end, we have made multiple propositions, which we intend to put into practice in NeuroSys: agonistic deliberation in iterative scenario-development, guided defamiliarization complementing bridging events, and reflexive intertemporal decision-making. Furthermore, future research in NeuroSys will show whether anticipatory focus groups with diverse publics (Macnaghten, 2020a) can unearth non-hegemonic futures, and whether feeding those alternatives into the cluster will unsettle the forces seeking to justify and advance dominant directions of innovation in competitive environments.

CRediT authorship contribution statement

Mareike Smolka: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Philipp Neudert:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Frieder Bögner:** Writing – review & editing, Methodology, Investigation. **Wenzel Mehnert:** Writing – review & editing, Methodology, Investigation. **Phil Macnaghten:** Writing – review & editing, Conceptualization. **Stefan Böschen:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Author contributions

Mareike Smolka designed, guided, and participated in the data collection process. She drafted and revised the scenario narratives. She also conducted the data analysis, wrote the first draft of the article, and revised subsequent versions. Philipp Neudert co-designed and participated in the data collection process. He drafted and revised the scenario narratives. He also cross-checked the data analysis and commented on several versions of the article. Frieder Bögner participated in facilitating the scenario and strategy mapping workshops. He commented on the scenario narratives, data analysis, and several versions of the article. Wenzel Mehnert co-designed and facilitated the scenario workshop. He wrote initial short drafts of the scenario narratives. He commented on initial versions of the article. Phil Macnaghten contributed to developing the problem definition of the article and commented on several versions. Stefan Böschen contributed to the problem definition. He co-designed and participated in the data collection process. He also commented on the scenario narratives and several versions of the article.

Ethics approval

This study was approved by the Ethics Commission of the Medical Faculty of RWTH Aachen University on July 6, 2022 (EK 236/22). Informed consent was obtained from research participants.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Appendix: Scenario narratives

Memristor Fab Aachen

Breaking ground in the Rhenish area on May 5, 2050

Everyone is there, really everyone. The Chancellor. The Prime Minister. The Federal Minister of Economics. The CEO of TSMC. The Commissioner for Economic Affairs. They sit side by side in the front row, legs crossed, conversations animated, on a lawn with chairs next to the 400-hectare site on the edge of the former open-pit coal mine. Where large bucket-wheel excavators once dug lignite out of the torn-up earth, a consortium of companies led by TSMC is now building a new 10 billion memristor fab based on the ESMC model. The fab is supposed to go into operation by 2055 at the latest. Many high-ranking guests have shown up to celebrate the ground-breaking ceremony and the joint success. State secretaries, high-ranking consultants, and financial experts sit next to industry executives, prominent researchers, and leading members of parliament.

The sheer number of high-ranking guests makes Cornelia feel queasy. Never in the past three decades of her scientific career has she spoken to such an audience. But now she cannot cop out. Her speech is on the program and the moderator is already inviting her to come on stage.

Her speech takes the audience back to the humble beginnings of semiconductor technology in the Rhenish area. She traces how visionary ideas from university chairs grew over the years into research projects and research clusters, such as NEUROTEC and NeuroSys in the 2020s. She describes the first spin-offs and courageous companies that formed a regional network over the years.

She recalls the shock caused by the chip crisis during the Covid-19 pandemic. The technological dependence on foreign countries, the shortage of skilled workers, and the troubled industry caused many to doubt what role Europe could still play on the world stage. The Chancellor nods again and again. Still a young member of parliament at the time, looking for opportunities to raise her profile, she strongly advocated a new direction for Germany's industrial policy. By the mid-2020s, Cornelia continues, the wind had fortunately changed. Instead of sinking into lethargy, Europe did everything it could to work its way back to the top.

But easy? The path was never easy. In fact, the task initially seemed like squaring the proverbial circle. How to mobilize billions in investment for a factory whose revolutionary products were not yet in demand? How to attract a major partner like TSCM, even though such companies could count on generous subsidies in many countries? How to convince politicians to support the Rhenish area in particular when there were already so many attractive hotspots for semiconductor production in Germany and Europe? How to persuade companies to come to a European country which was already considered to be over-regulated? Should political support be sought first in order to attract industrial partners, or vice versa? And more specifically: what areas were available for building a factory; where should the infrastructure and green energy come from?

According to Cornelia, the success of semiconductor technology in the Rhenish area rests on four important building blocks. The first is cutting-edge research. *"Based on our experience, we believe that cutting-edge research is not everything, but without cutting-edge research, everything is nothing. The successful spin-offs and intrapreneurship in industry, the numerous patents and licenses, the computer chips that will soon be produced here in the Rhenish area – none of this would have been possible without excellent research."*

Cornelia is building momentum: *"But the best ideas and research results cannot have any impact," she continues, "if they do not find fertile ground. In order to lay this ground, the second building block was and is needed: effective technology transfer. For many years, this has been more of an afterthought than a practice at German universities. With the Platform for Holistic Computer Engineering, a public-private partnership with strong industries on board, we created the basis for translating the latest findings into new technologies and for integrating these technologies quickly into existing business models. The platform's doctoral school not only trained the next generation of scientists, but also visionary innovators for industrial companies. These scientists and innovators were able to put their theoretical knowledge directly to test in practice through industry collaborations. At the same time, they were establishing valuable business contacts. Many spin-offs, which were incubated with the support of constantly expanding RWTH infrastructures, took advantage of the spatial and personnel-wise proximity to research and were able to either scale up or be vertically integrated by industry partners after a few years. Finally, the supra-regional Transfermation Agency allowed us to establish channels of communication between research and the public. The agency specifically addressed various social groups, especially those of us who are less tech-savvy. The result was a lively dialogue that stimulated co-creative innovation with positive impacts on society as a whole, going far beyond the success of individual commercial enterprises. Through this process, the social legitimacy of a memristor fab in the Rhenish area emerged of its own accord."*

Simultaneously, changes took place at the European level. The European Chips Education Act, which addressed the shortage of skilled workeds in the long term, and a large-scale de-bureaucratization program significantly improved the conditions for building a memristor fab in the Rhenish area.

"The preliminary decision in favor of a fab," Cornelia emphasizes, *"gave the project a big boost. But the difficulties did not stop there. Finding a site for this factory with a transportation infrastructure, energy and water supply suitable for production and logistics proved to be a difficult challenge to solve. However, in collaboration with the Aachen Society for Innovation and Technology Transfer, we were able to find a site close to a former open-pit coal mine that could be sealed for the construction of the factory. I remember exactly how I stood here a few years ago with a hundred citizens on the site, who were initially not very enthusiastic about the prospect of a new factory in their vicinity. Many complaints were voiced: about the ecological footprint of semiconductor chip production, about the use of German taxpayer money for a foreign company, and about the environmental costs of sealing the land. Yet, with the Transfermation Agency, we organized numerous events to weigh up critiques against potentials in discussions with citizens and interest groups, and were ultimately able to work out a stable and workable compromise together in a long process."*

Cornelia adds: *"The third element – and in my view the heart of our work – was creating a strong, strategically positioned ecosystem. For the spin-offs, we initially focused on risk-averse fabless design companies that created customized chips for industrial customers in various sectors and produced them in partnership with renowned factories. Some of these companies also settled in the Rhenish area. They benefited from the proximity to basic research at the Center for the Future of Computing and the application-oriented research at the Platform for Holistic Computer Engineering. On the one hand, they were able to gain technological advantages over their competitors because they were always at the bleeding edge of scientific and technological progress, especially in the use of memristive elements in computer hardware. On the other hand, contacts to established industrial companies, which were mediated via the Platform for Holistic Computer Engineering, helped them to adapt their offerings to their customers' expectations. It is not least thanks to these partnerships, which have grown organically over many years, that TSMC decided to invest in the Rhenish area."* Without the ecosystem, however, the chicken-and-egg problem of supply and demand would have been difficult to resolve. Nor would it have been possible to address the fundamental question of whether political support had to be gained first in order to attract an industrial partner, or vice versa. Moreover, it would have hardly been possible to successfully scale up processes that worked in the laboratory to an industrial level and thus bring the innovation through the dreaded "Valley of Death" of process development.

"The fourth building block was the coordination achieved by the Holistic Computer Engineering Board, which I had the privilege of chairing over the last years. In this steering group with high-ranking representatives from industry and politics, we were able to set the course for building a memristor fab in the Rhenish area. I am delighted that all these efforts were ultimately successful and I am thrilled to celebrate together with you today."

At the end, Cornelia thanks her scientific colleagues and political supporters, as well as regional politicians and international industry. The applause does not stop. Cornelia feels how the weight of the past decades, the endless negotiations and the nights of committee work suddenly fall off her shoulders. They have reached their goal. *She* has reached her goal. Cornelia's gaze rests on the applauding audience as she notices that she is beaming like a child on Christmas day. She does not even consider her reaction to be inappropriate, not on this day. Everyone is there, really everyone.

Center for the Future of Computing

Scientist from the Rhenish area receives the Leibniz Prize for her contributions to research on Alzheimer's disease

Frankfurter Allgemeine Zeitung (FAZ) from May 18, 204*0*

FAZ Interview with Ada De Santis, Scientific Director of the Center for the Future of Computing (CFC) and designated Leibniz Prize winner, on the special features of her scientific career.

FAZ: Prof. De Santis, last week the German Research Foundation announced that your research on Alzheimer's disease would be honored with the prestigious Leibniz Prize. Congratulations! How were you able to achieve the decisive breakthroughs where so many researchers before you had failed?

De Santis: To answer this question, we have to go way back to the beginning of my work at the Center for the Future of Computing, in short CFC, which has been my institutional home for the last ten years. I am a neuroinformatics researcher by training, not a medical doctor. When I started my career, I did not imagine that, one day, my research would make contributions to medicine. But first things first. How were we able to develop these novel findings? It was only possible because we at the CFC adopted a genuinely interdisciplinary perspective right from the start. Initially, this implied tackling major challenges because different disciplines speak different technical languages, approach problems differently and often prioritize other questions and challenges. They differ in their knowledge interests and claims. However, an interdisciplinary perspective enabled us to illuminate blind spots within disciplines and jointly formulate new, groundbreaking questions. In this respect, the Leibniz Prize honors the CFC as an idea and a community. Neuroscience and neuropsychology, computer science and mathematics, theoretical philosophy and data science – they have all existed side by side on an equal footing from the very beginning. The big question on everyone's mind in the mid-2020s was: How can we think about the future of computing – beyond the then dominant von Neumann architecture of computer chips? Brain-inspired computing, analogue computing, quantum computing, advanced packaging – these were all big things back then; they were *the future.* **At that time, it was also becoming increasingly impossible to ignore the disastrous ecological and energy footprint of computing. There were calculations indicating that within two decades, the earth's entire energy supply would have to be used just for computing if computing demands continued to grow as expected! Moreover, it had also become clear during the COVID-19 pandemic that Germany and Europe were completely dependent on foreign countries for computer technology. This moment of shock, together with the expected ecological catastrophe, paved the way for important public investments in research. Luckily, politicians were far-sighted enough to invest in research for the coming decades. But it was a big effort to convince them (*laughs*). I would therefore like to take this opportunity to thank the European taxpayers: without all of you, our scientific achievements would never have been possible!**

FAZ: You suggest that it was not easy to convince politicians that a large research center was needed. How was this possible, and why was the center built in the Rhenish area, which was practically unknown in terms of computer technology at the time?

De Santis: You are absolutely right, politics, business, and the public did not perceive Aachen or the Rhenish area as a hotspot for computing at the time. We had some outstanding visionaries here at the Research Center Jülich and at RWTH Aachen University whose work was widely cited. We were already well known in the scientific community back then. We were also able to carry out some outstanding projects, such as the NEUROTEC structural change project or the NeuroSys cluster, both of which performed groundbreaking work in the 2020s. But at some point, we were faced with the question of how to continue. How to pool expertise, combine scattered results, and think ahead together? One source of inspiration was CERN, the universally acclaimed large-scale research facility, which was so popular because Europe put its full weight behind this facility. This is what we also wanted to achieve for computing. Technology sovereignty was at the top of the political agenda at the time. It was therefore clear that the center had to have a European character. However, it was difficult to mobilize EU funding for such a center. In the end, the geographical location within the triangle of Germany, Belgium, and the Netherlands was decisive. We decided to turn the CFC into a tri-national project. This made strategic sense: all countries already had good research, but it was spread across different institutions. It lacked the lighthouse character needed to be recognized outside Europe. Specifically, we were and are located in the triangle of TU Eindhoven – KU Leuven – RWTH Aachen University, with Maastricht University within the triangle and the Research Center Jülich in the immediate vicinity. It was important to us not to create competition between established centers and universities, but rather to offer them something they were all looking for: an institutional home for the big questions of tomorrow and the day after tomorrow. Asking and answering such questions is often not possible at established institutions, which too often get bogged down in small-scale day-to-day business and excessive bureaucracy. We said to ourselves: "for these really big questions, there has to be a place where you are not held back by these everyday problems." The three governments sponsored us from 2030 onwards, and we expanded the budget with commercial research contracts, following the example of CERN. Fundamental research can have a very concrete, positive impact on society in the long term. That is why I received the Leibniz Prize. We have experienced something similar with lasers in telecommunication and machine learning.

FAZ: It sounds difficult to be accountable to three governments at once. How were you able to reconcile the interests of so many different funding bodies?

De Santis: First of all, we were able to offer everyone something that they did not have yet and that they would not be able to achieve on their own. And there was a general shared interest in building European expertise and fundamentally rethinking computing. For setting long-term strategic goals, we set up an advisory body, the Research Excellence Board, in which national governments and the participating institutions – from Jülich, Aachen, Eindhoven and Leuven – as well as high-ranking partner institutions, such as ETH in Zurich, were represented and could introduce strategic impulses and contribute assessments. However, we did not interfere with the day-to-day activities of the CFC. That would have run counter to the objectives of a center for basic research.

FAZ: How were you able to attract excellent researchers to the Rhenish area?

De Santis: First, we were in contact with researchers from all over the world from the very beginning, especially within Europe. We maintained satellite offices at the most important European universities, such as the ETH in Zurich. This increased our visibility – in addition to influential publications and conference contributions. We envisioned the CFC as a place where new scientific perspectives could be formed, where personalities could grow within and beyond disciplinary boundaries. Over time, we were able to establish ourselves as a European cadre for science, which in turn attracted the best young researchers. Second, we offered talented researchers a long-term perspective. In this way, we minimized brain drain and were able to set ourselves apart from other institutions, which at the time often still relied on the hire-and-fire principle, that is hire-and-don't-renew-the-fixed-contract of researchers below full professorship level. Nevertheless, we were never able to keep everyone. Stanford and MIT made good offers from time to time (*laughs*). **Another factor was the region itself, which was in the process of phasing out lignite mining and invested heavily in improving the quality of life for local residents. Living close to nature with urban gardening, self-driving buses, and lots of cycle paths became standard in the area. This reflected a commitment to achieving something positive for society and the planet. This motivated me personally to return to the Rhenish area after living for many years abroad. The lesson for politicians should be to place greater trust in researchers. If we had sticked to the usual roadmap-driven logic, we would never have achieved such a high quality of results in such a short time – and society could not benefit in the same way now.**

FAZ: Energy-efficient architectures, circularity-by-design, state-of-the-art encryption technology, so-called post-quantum cryptography – your track record at the CFC is really impressive. We would like to talk more about the research achievements for which you were recently honored: How did you deepen our understanding of Alzheimer's disease, and what does this mean for future therapies?

De Santis: As I said, it was not our main interest or even goal from the outset to generate knowledge about this disease, much less develop therapies. Rather, our motivation was to understand how the human brain works and to use this knowledge to improve chip architectures. To achieve this in-depth understanding, we used our interdisciplinary approach on the one hand and the enormous additional computing power from the quantum and supercomputing sector on the other, for example for simulations of learning processes that would have been impossible with previous technology. In turn, we were able to use the performance gains from these findings for better research – a wonderful, self-reinforcing mechanism. In recent years, we have realized that a deeper understanding of the brain's learning and memory capacity holds great potential for constructing more efficient architectures in the sense of in-memory computing. Gaining a better understanding of the brain can be both an end in itself and an input for computer science, and as a neuroinformatics researcher, I am positioned right at the interface. We were not necessarily looking for knowledge on Alzheimer's disease directly. However, when we recognized that our findings would be relevant to this area of research, we set up a working group, which went pretty smoothly due to the flexible structure of the CFC. That's how we started collaborating with our colleagues from medicine …

Platform for Holistic Computer Engineering

"The Platform for Holistic Computer Engineering is celebrating its twentieth anniversary and would like to extend a warm invitation to you, Dr. Dimoiu." (Invitation from November 5, 2047)

For Claudiu, the invitation comes as a pleasant surprise. Twenty years ago, he came to Germany from the Romanian city of Timisoara, where he was a top student at his university. He took part in the Doctoral School of Holistic Computer Engineering, which was funded by Mercedes and BMW. The Doctoral School brought together Europe's brightest minds. The interdisciplinary educational program prepared doctoral students for the next stage of AI development: algorithm hardware co-design inspired by the structure and functions of the brain. So-called neuromorphic technologies – from microprocessors to AI applications – attracted international attention due to their high performance and energy efficiency. The Platform for Holistic Computer Engineering was therefore supported by the German Federal Ministry of Education and Research (BMBF) as part of the funding initiative "Polycentric platforms of public-private partnerships for technological innovation."

In the 2010s, the BMBF began to promote the establishment of research factories in order to support long-term collaborations between science and industry. However, experience in the research factories has shown that technology transfer requires more than bringing researchers and companies together "under one roof." It rather depends on a shared platform. A platform provides an environment that supports the creation, development, and implementation of innovative ideas within a network of diverse actors. This is why the BMBF has been funding innovation platforms since 2025, including the Platform for Holistic Computer Engineering. Today, this platform brings together companies, research institutes, and universities in the Germany-Netherlands-Belgium border triangle. Members of the platform work in the research and production infrastructures of Imec, ASML, RWTH Aachen University, and many other organizations. They regularly exchange information digitally and in face-to-face meetings every six months. Thanks to a polycentric organization, existing infrastructures can be used and expanded. Hence, additional space is not required, which is hardly available in this border triangle anyway.

The Platform for Holistic Computer Engineering has established itself as a non-profit organization that opens up cooperation opportunities for actors from various disciplines and domains in the value chain of neuromorphic technologies. The unique combination of competencies makes it possible to continuously identify and set up new subject areas that strengthen both scientific excellence and the training of young scientists. The collaboration between various actors is structured in three branches: (1) co-operations between large corporations, SMEs and start-ups, (2) industrial contract research, (3) public-private research and development projects.

The second and third branches provided the funding basis for the Doctoral School of Holistic Engineering. Claudiu recalls that funding for the Doctoral School did not always flow easily. Nevertheless, the school did succeed in introducing small cohorts of doctoral students to the field of neuromorphic technology development in an interdisciplinary way. Doctoral students were supervised by researchers from technical and scientific disciplines as well as by humanities scholars and social scientists. This arrangement taught them to understand new computer technologies as socio-technical systems that should not only be technically effective, but also economically sustainable and socially desirable. Doctoral students were able to specialize in qualification profiles, such as "Sustainable Computer Engineering" and "Industrial Engineering for DeepTech," and gain a direct insight into the dynamics of companies through company internships. Claudiu remembers that doctoral students were affiliated to different universities in the border triangle, but many of them worked at RWTH Aachen University and Research Center Jülich. For Claudiu, the events at the Collective Incubator in Aachen were filled with inspiring moments. The place was and is the organizational hub of the Doctoral School, the vibrant meeting place where he exchanged ideas about research and development projects with doctoral students, lecturers, and supervisors from companies.

Claudiu had come to Jülich as part of the School of Holistic Computer Engineering to work in NeuroSys. The cluster was one of the first members of the innovation platform and had set up the Doctoral School. Claudiu became a research associate at the Peter Grünberg Institute. He investigated whether and how neuromorphic hardware could contribute to solving optimization problems. After German Railways became a project partner of NeuroSys, Claudiu had the opportunity to work on optimization problems in the public transport system. He developed a computer program implemented on neuromorphic hardware that could take into account tens of thousands of trains and buses in order to achieve an optimal result for the design of timetables. After completing his doctorate, he returned to Timisoara, where he founded the start-up *OptiTren.* Exciting times. During his interdisciplinary training at the Doctoral School, he was mentored by economist Maria Lindgren, who prepared him well for the corporate world. Claudiu now runs a company with more than 200 employees. His company not only works with Romania's national railroad company, but also contributes to smooth public transportation in other European countries.

When Claudiu enters the festively decorated event hall in the Collective Incubator, he immediately recognizes Maria Lindgren and vivid memories of his time as a doctoral student emerge. Claudiu had witnessed the development of the innovation platform and remembers that Maria did not always have an easy time. As the founder of the Doctoral School, she did not only have to solve the legal difficulties of public-private partnerships in Europe, but also coordinate scientists and entrepreneurs with different interests and perspectives. One of the first hurdles was to define key performance indicators that would be used to monitor the development of the platform in order to identify opportunities for improvement at an early stage. At the time, Maria had spoken to Claudiu about her doubts as to whether ethically robust and socially desirable research and development could be captured by quantitative measures.

Despite the first sip of wine, Claudiu becomes slightly nervous and wonders whether Maria still remembers him. But then she turns her gaze and beckons to him. Claudiu approaches her bar table and she greets him happily: "Claudiu… Dimoiu, if I'm not mistaken?" He nods and smiles. "How nice to see you here again! How are you?" she asks curiously. "I'm glad you remember me. I'm still working on solving optimization problems in the railway system. I would like to thank you for your trust in my work. Your support has opened many doors for me." Maria smiles and points to the third person at the bar table: "Trust, yes. We were just talking about that too. Let me introduce Benedikt Huber to you. He works at the BMBF. Without his trust in our project, the Platform for Holistic Computer Engineering would not have come into being." Benedikt shakes Claudiu's hand. "Nice to meet you!" he says and continues, turning to Maria: "Neuromorphic computing came at the right time. It was what we needed in Germany to make us more technologically independent. What am I saying – not just in Germany, but in Europe. The transnational focus of your platform went hand in hand with the increasingly European orientation of the BMBF funding lines." Maria nods: "Yes, back then only a few people could have imagined that neuromorphic chips would be everywhere these days." Benedikt holds up his cell phone: "Made in Europe." Maria clears her throat: "And soon also made in the Rhenish area." The three of them laugh and Maria raises her glass: "Let's drink a toast to trust."

Transfermation Agency Aachen

Letter from a former NeuroSys co-coordinator dated September 7, 2034

Dear Sergio,

I hope this letter finds you well! How long has it been since we last met? Was it in 2028 at the International Sustainability Transitions Conference in Amsterdam? I am therefore all the more pleased that you have contacted me with your request.

I am excited about your project "La Transformación Digital y Sostenible" which you are setting up in Madrid. I'm keeping my fingers crossed that the project application goes through! I am happy to share some of my own experiences with technology transfer issues in the hope that they can inform the development of your project.

I joined the coordination team of NeuroSys ten years ago. As co-coordinator of the cluster, I worked closely with social scientists and humanities scholars from RWTH Aachen University, the Aachen Chamber of Industry and Commerce and RWTH Innovation on the topic of technology transfer. Our vision was to redefine technology transfer as something truly transformative. Therefore, our transfer concept revolved around a supra-regional transfer agency that combined the market transfer of state-of-the-art computer technologies with social transformation processes, for example in the context of digitalization, sustainability transitions, and structural change. This is why we chose the rather unusual name "*Transfer*mation Agency".

In the NeuroSys cluster, the agency initiated activities such as “transfer dialogues.” These dialogues were meetings of stakeholders from science, industry, politics, and society who engaged in serious discussions on how brain-inspired neuromorphic computer technology could shape society. The end result? A strategic plan with 21 key points, with topics such as “AI development for climate change adaptation,” “independence from Big Tech,” and “international social justice” at the top of the list.

Originally, we wanted to call the strategic plan the “NeuroSys Manifesto,” as it set out our principles for value-sensitive technology development. However, I have to admit that a “manifesto” might not have made as much sense to the German Federal Ministry of Education and Research as the “strategic plan” that was then developed and motivated the Ministry to subsidize the *Transfer*mation Agency in 2027.

Funding was and remains a challenge. The agency has kept its head above water with a mixture of public funding, foundation grants, and corporate contracts, but the constant search for funding sometimes feels like a second full-time job. I’m sure you can relate to that, too …

In the meantime, the *Transfer*mation Agency, which has established itself institutionally at RWTH Aachen University, has grown into a lively pop-up network. Although we have a permanent office, it is more of a dynamic association of researchers, students, and people from business, politics, art, and culture. We have held events in numerous different places, for example at the Heinz Nixdorf MuseumsForum in Paderborn, the QuellPunkt in Aachen, the Academy for Theater and Digitalization in Dortmund, the MakerSpace in Garching, and at DemoLabs on Aachen’s market square.

At these events, needs for new technologies are identified and their social impacts discussed. The events are intended to provide impetus for established companies and start-ups that are keen to tap into the broad application potential of computing. The events are also intended to contribute to the development of a basic understanding of computing technologies in civil society.

But that is easier said than done. It’s a big challenge to counter growing participation fatigue and to develop inclusive formats that various social groups recognize as a productive forum for themselves. I would be very interested to find out how you do this with your projects in Spain. I was impressed by your last publication in *Technological Forecasting and Social Change.* How did you manage to attract more than 80 participants for stakeholder workshops?

Fortunately, working with companies is a little easier for us. We are part of this great network called Platform for Holistic Computer Engineering, which helps us establish contacts with various start-ups, SMEs, and large corporations. Thanks to these contacts, we can advertise our services widely. Our focus is on user-centered innovation. We give design thinking workshops and advise companies on ethical, legal, and social aspects of technology development. Through this contract work, the agency secures part of its funding and supports companies in the responsible development and marketing of new computing technologies.

Not every venture is a success. The co-creative processes that the *Transfer*mation Agency initiated in NeuroSys revealed that promising AI applications based on neuromorphic hardware would not be the best solution for all societal challenges. In the second funding phase, NeuroSys wanted to work with a traffic planning office to use AI to optimize the traffic flow in Aachen’s city center. However, during a scenario workshop at the OecherLab, it turned out that the use of AI, despite neuromorphic hardware, would be energy-intensive and costly. Workshop participants realized that established planning methods and experiments with traffic-calmed streets would be more economically and ecologically sustainable. The cooperation with the traffic planning office did not come into being.

Despite a number of stalled projects, the *Transfer*mation Agency has made contributions to the emergence of a colorful landscape of start-ups and companies working with neuromorphic technology. Intelligent energy systems, Agriculture 4.0, and AI-supported medical technology are already benefiting from energy-efficient neuromorphic hardware and are being used across Germany.

My personal favorite is ChipCycle. The company was founded by scientific employees in the NeuroSys cluster. ChipCycle’s mission is to improve the sustainability of neuromorphic computer chips through AI-supported material and process development. I still remember the bright economist who argued at a status seminar: “If we want to rethink semiconductor development, then we have to take a different route than the Americans. We have to think about life cycle issues from the outset and develop recycling concepts for neuromorphic chips in the spirit of a circular economy. AI-supported material and process development can help here.” Together with NeuroSys colleagues from technical disciplines, he founded the AI company ChipCycle, which is now headquartered in Aachen and offers its services to chip design companies and chip manufacturers in Europe.

“Taking a different route” also means taking questions of social justice seriously. As part of a research project at the Human Technology Center at RWTH Aachen University, the theater project “Glocal Semiconductor Development” was initiated. This project mapped social injustices in semiconductor production and used this map as the basis for theater productions. The *Transfer*mation Agency established a connection to the Academy for Theater and Digitalization in Dortmund where the theater performances took place. I found the first performance remarkable. It presented the negative effects of European semiconductor production in the Global South in such a tangible way that I had to chew on it for a long time.

There is so much more to tell, Sergio. If you would like to expand on any of the points mentioned above, please write to me and we can have a call in the next few days! In any case, I wish you the very best for your project proposal. You can do it!

Warm wishes,

Thomas

Data availability

Due to the sensitive nature of the questions asked in this study as well as confidentiality agreements within the NeuroSys cluster, the data underpinning this manuscript (transcripts, feedback forms, fieldnotes, cluster-internal documents) cannot be shared.

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