Prospective technology assessment in the Anthropocene: A transition toward a culture of sustainability

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Abstract
In the Anthropocene, humankind has become a quasi-geological force. Both the rapid development as well as the depth of intervention of new technologies result in far-reaching and irreversible anthropogenic changes in the Earth’s natural system. However, early and development-accompanying evaluation of technologies are not yet common sense. Against this background, this review article aims to compile the current state of knowledge with regard to the early sustainability assessment of technologies and to classify this status quo with respect to the key challenges of the Anthropocene. To that end, the paper initially outlines major existing definitions and framings of the term of sustainability. Key milestones, concepts and instruments with regard to the development of sustainability assessment and technology assessment (TA) methodologies are also presented. Based on this overview, the energy sector is used as an example to discuss how mirroring ongoing transformation processes can contribute to the further development of the TA framework in order to ensure an agile, goal-oriented, and future-proof assessment system.

Keywords
2030 Agenda, Anthropocene, life cycle thinking, sustainability, sustainable development goals (SDG), technology assessment, tiered approach, transformation

Introduction
For the first time in history, human development is characterized by a coupling of technological, social and geological processes. In this new geological epoch of the Anthropocene (Crutzen and
humankind has become a quasi-geological force that profoundly and irreversibly alters the functioning of the Earth’s natural system (Potsdam Memorandum, 2007).

The main reasons for this extraordinarily high range of human activity are the exponential increase in the world’s population, production and consumption, as well as an increasing acceleration of industrial processes. New technologies are being developed that enable a particular high sectoral depth of intervention as well as a fast marketing of products and applications. As a result, they impose significant pressure on a wide range of sectors to change and adapt to the speed of innovation. Ultimately, society as a whole is urged to react to the impacts generated by the new technologies. A prominent example of a technology with such a high level of intervention is additive manufacturing. Also known as 3D printing, additive manufacturing is seen as a key technology for digitalization due to their production flexibility, the possibilities for function integration and product individualization. Beyond acceleration of innovation times, however, their use also allows for a reduction in component weight and thus a reduction in operating costs, which can promote resource-efficient manufacturing (Bierdel et al., 2019). However, additive manufacturing can create new consumption incentives due to faster product cycles and poses risks to new producers by shifting work and related hazardous substance risks to residential environments (Umweltbundesamt, 2018).

Both the rapid development as well as the depth of intervention of new technologies and materials result in anthropogenic changes in Earth system processes that can otherwise only be caused by meteorite impacts, continental drift and cyclical fluctuations in the Sun-Earth constellation. For example, the effects on the Earth’s nitrogen cycle are particularly serious. Through the ability to synthesize artificial nitrogen compounds by means of the Haber Bosch process, humans have managed to feed 48% of the global population. With increases in fertilizer usage, however, the nitrogen cycle has been pushed far beyond sustainability and nitrate pollution being responsible for increasing dead zones in coastal areas. Furthermore, due to the use of fossil fuels and intensive agriculture, CO₂ concentrations in the atmosphere have reached a level last approached about 3 to 5 million years ago, a period when global average surface temperature is estimated to have been about 2°C–3.5°C higher than in the pre-industrial period (NAS and Royal Society, 2020).

The harmful effects of the technologies on the biosphere are fueled by the fact that technological developments are usually faster than political and technical countermeasures. Moreover, in many cases, technical countermeasures still focus on efficiency improvement strategies, less hazardous substitutions of substances as well as end-of-pipe cleaning technologies. While this approach has yielded some success in the past, it also entails the risk of rebound effects.

Against this background, there is an increasing need for comprehensive approaches to analysis and solutions. Hence, the following key questions arise how to deal with the challenges regarding the prospective assessment of technologies in the era of the Anthropocene:

- Firstly, which applications of technologies are beneficial with respect to a sustainable development, and which ones we should rather abandon?
- Secondly, which methodological approach can be used to assess and influence the development of new technologies right from the beginning and with sufficient certainty of direction?
- Thirdly, who is responsible and competent to perform the evaluation on the sustainability performance of technologies and to make corresponding decisions concerning their future roadmap?
- Ultimately, how can we transform technosphere and society to a culture of sustainability, in other words: “Can humanity adapt to itself?” (Toussaint et al., 2012)
In order to elaborate viable answers to these fundamental questions, this paper aims to review existing definitions of sustainability as well as approaches of sustainability assessment of technologies and associated tools within the era of the Anthropocene. Hence, it first addresses the issue of framing the term of sustainability in the era of the Anthropocene (section 2). Based on a brief overview in section 3 how sustainability assessment methodologies evolved in the past, major milestones and concepts with regard to the technology assessment (TA) framework are described in section 4, with particular focus on the concept of prospective TA. In section 5, we use the energy sector as an example to discuss how mirroring ongoing transformation processes in major areas of need can contribute to the further development of the TA framework. Finally, section 6 is dedicated to conclusions and outlook.

**Sustainability in the Anthropocene**

Sustainability is a delicate term. Its inflationary use in politics, science and society has rendered it increasingly arbitrary and often blurs the view of its core meaning. Sustainability as a concept was introduced more than 300 years ago by chief miner Hans-Carl von Carlowitz on the occasion of a serious raw material crisis: Wood, at that time the most important raw material for ore mining, had become noticeably scarce and without appropriate countermeasures, the operation of smelting furnaces and consequently silver production would not have been further possible within a foreseeable future. Driven by these economic requirements, von Carlowitz proposed a new principle of forest management, which envisaged taking only as much wood from the forests in a given period of time as could grow back again in the same period (Töpfer, 2013; von Carlowitz, 1713).

In the discussions about the scarcity of natural resources in the 1970s (cf. Meadows et al., 1972), the concept of sustainability was taken up again and experienced a renaissance through its further development in terms of content. Environmental and social aspects of sustainability have been placed more and more in the foreground. Hence, sustainability has increasingly been understood as a major global transformation process (Grießhammer and Brohmann, 2015; see also section 5), which is reflected in particular in the term of a “sustainable development.” Another milestone in the framing of sustainability as a concept with normative relevance has been achieved in the World Commission on Environment and Development. In its report, the so-called “Brundtland Report,” the commission defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987: without page). With this definition, the aspects of *intra-* and *inter*-generational equity were introduced and particularly emphasized in the sustainability debate. Furthermore, the “Brundtland Report” frames sustainable development as a necessary transformation process of economy and society as it points out that:

> “Sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs” (World Commission on Environment and Development, 1987: without page).

Since the 1990s, the debate on how intergenerational justice is to be achieved has been dominated by two diverging perceptions of the concept of sustainability, referred to as “strong sustainability” and “weak sustainability”:

- Strong sustainability postulates to preserve the entire natural capital of the Earth. Human capital and natural capital are perceived to be complementary, but not interchangeable. This
means that humans, as users of nature, may live only from the “interest” of the natural capital. Any consumption of non-renewable resources would therefore be ruled out, and renewable resources could only be used within their regeneration rate (Som et al., 2009).

- Weak sustainability calls only for preserving of the Earth’s total anthropogenic and natural capital. Accordingly, humanity could reduce natural capital to any degree if it was substituted in return by anthropogenic capital with the same economic value (Solow, 1986).

At the UN Conference on Environment and Development at Rio de Janeiro in 1992, the concept of sustainable development was recognized as an internationally guiding principle. The underlying idea was that economic efficiency, social justice and the safeguarding of the natural basis of life are interests that are equally important for survival and complement each other. Although 27 fundamental principles for sustainable development are enshrined in the Rio Declaration on Environment and Development (United Nations, 1992), for more than 10 years no concrete sustainability goals and indicators existed that would have been suitable in particular for the sustainability assessment of products and technologies.

With the adoption of the 2030 Agenda and its Sustainable Development Goals (SDGs) in 2015, the member states of the United Nations for the first time agreed upon a universal catalog of fixed time-specific targets. These 17 SDGs (see Figure 1) and the corresponding 169 targets can be considered as the interdisciplinary normative basis of sustainability research, covering all three dimensions of sustainable development, that is, environmental, economic, and social aspects (United Nations, 2015).

The 2030 Agenda is universal in scope, which means that it commits all countries to contribute toward a comprehensive effort for global sustainability in all its dimensions while ensuring equity,
peace and security. Furthermore, with its central, transformative promise “leave no one behind,” it is based on the principle to take on board even the weakest and most vulnerable. Hence, it seeks to eradicate poverty in all its forms as well as to combat discrimination and rising inequalities within and amongst countries (BMUV, 2022; SDGF, 2016; United Nations, 2021).

As a major specification of the 2030 Agenda, the concept of Planetary Boundaries focusses on the environmental dimension of sustainability. This approach put forward by Rockström et al. (2009) echoes the concept of “strong sustainability” (see above) and has been updated and extended by Steffen et al. (2015). At its core, it identifies nine global biophysical processes, whose significant changes can lead to conditions on Earth that are no longer considered a “safe operating space for humanity.” According to Steffen et al. (2015), several of the global biophysical processes are already beyond an uncertainty range with a high risk of dangerous changes on the planetary scale. These include the integrity of the biosphere (expressed as genetic diversity) and biogeochemical material flows, especially nitrogen and phosphorus. Others (e.g. climate change and land use change) are considered to be in an area of high uncertainty with an increasing risk of dangerous changes.

In 2016, Rockström and Sukhdev presented a new way of framing the SDGs of the 2030 Agenda. According to the concept of “strong sustainability” they argued that economies and societies should be perceived as embedded parts of the biosphere (Stockholm Resilience Center, 2016). This perspective is illustrated by the so-called “Wedding Cake” model (see Figure 2) and
challenges the predominant understanding expressed by the “Three Pillars” model of sustainability (cf. Barbier, 1987) that environmental, economic and social development can be regarded as separate parts. Hence, the “Wedding Cake” model of sustainability can be understood as a combination of the 2030 Agenda and the concept of Planetary Boundaries since it calls for a transition toward a world logic where the economy serves society so that both economy and society can evolve within the “safe operating space” of the planet.

The link between SDGs and Planetary Boundaries is of paramount importance in the age of the Anthropocene. Even though the SDGs have been lauded for amplifying the global development agenda by including environmental, social and economic concerns, the 2030 Agenda remains committed to a growth-oriented development that potentially conflicts with keeping human development within the Planetary Boundaries as defined by Rockström et al. (2009). A striking example of the growth-oriented concept can be found in SDG target 8.1, which requires to “sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7% gross domestic product growth per annum in the least developed countries” (United Nations, 2015).

Against this background, substantial changes toward more sufficient consumption patterns that help to remain within the Earth’s environmental carrying capacity need to be established and promoted by setting corresponding political framework conditions (Fischer and Grießhammer, 2013).

**Evolution of sustainability assessment methodologies**

The scientific methodology for assessing the sustainability of technologies, material or products is far less developed than the debate on sustainable development and sustainable consumption would suggest. However, initial approaches in this respect were developed by the Öko-Institut as early as 1987 (Öko-Institut, 1987). The concept of the *Produktlinienanalyse* (English “product line analysis”), representing a pioneering step in the development of methods for life cycle-based analyses, made it possible to record the environmental, economic, and social impacts of products along the whole product line.

Nevertheless, at the end of the 1990ies, the product-related Life Cycle Analysis (LCA) became established and standardized on the international level, representing a methodology which assesses only the environmental impacts of a product over its entire life-cycle. The decisive standards of LCA are ISO 14040 (2006) and ISO 14044 (2006), which have become widely applied. These international standards essentially describe the process of conducting LCAs, examining the impact of a product from “cradle to grave.” Particular attention is paid in ISO 14040 and ISO 14044 to the scoping of a LCA study, with concrete requirements on the choice of the system boundaries, the functional unit (i.e. the quantified performance of the investigated product system for use as a reference unit) and the data quality requirements. In addition, the performance of a critical review by an independent third party is envisaged as a quality assurance step.

Sustainability assessments, however, did not advance until the 2000s, with the detailed method descriptions PROSA (Product Sustainability Assessment) by the Öko-Institut (Grießhammer et al., 2007) and SEE-Balance (Socio-Eco-Efficiency Analysis) by the chemical company BASF (Kicherer, 2005; Saling, 2016). Even for the sub-methods of Life Cycle Costing (Swarr et al., 2011) and Social Life Cycle Assessment (Grießhammer et al., 2006; UNEP-SETAC Life Cycle Initiative, 2009), method descriptions were presented comparatively late. There are also proposals to combine the three sub-methods of Life Cycle Assessment, Life Cycle Costing and Social Life Cycle Assessment to form the Life Cycle Sustainability Assessment (LCSA) (Feifel et al., 2010; Finkbeiner, 2011). However, in contrast to PROSA, the aim is not to analyze and evaluate needs and the realized product benefits, even though meeting basic needs through products is one of the central demands of Agenda 21. Whereas initially the sustainability of only relatively simple products such as food, textiles, or detergents had been assessed, in recent years the sustainability
performance of complex products such as notebooks (Manhart and Grießhammer, 2006) and telecommunications services (Prakash et al., 2016) as well as emerging technologies and materials (Möller et al., 2012) has also been analyzed.

For many years, the comparatively open or specific selection of indicators for conducting sustainability assessment case studies was justified by the lack of a relevant normative framework as well as a generally accepted set of indicators. With the adoption of the United Nations’ 2030 Agenda in 2015, this has fundamentally changed (cf. section 2). In addition to its 17 SDGs and 169 targets, the 2030 Agenda provides a globally accepted system of indicators for measuring the SDGs. However, only a few dozen of the 169 targets explicitly refer to products and companies. In a recently completed research project (Eberle et al., 2021) funded by the German Federal Ministry on Education and Research a method was developed which provided for a reasoned restriction to those indicators to the achievement of which products, services and companies can actually contribute. By means of the method, it is possible for the first time to measure the contribution to the achievement of the SDGs at the level of products and services and thus to establish a link between LCA and SLCA results and the 2030 Agenda (Eberle and Wenzig, 2020). To complete the assessment, an in-depth analysis of societal benefits according to Möller et al. (2021a) can be supplemented, which is also based on the 2030 Agenda. In this way, additional benefit aspects of the products and services considered beyond their core benefits can be identified with a view to the SDGs.

As our experience from practice has shown, for the sustainability assessment of any object of investigation, the respective functionality is of utmost importance and must therefore be considered and defined in detail. In this context, a careful definition of the functional unit as defined in ISO 14040 and ISO 14044 is considered to be essential. In addition, a detailed analysis of the various benefit aspects of the studied object is recommended. Against this background, there is no technology, material or product that is sustainable per se. Only the way a technology, material or product is handled and used over its whole life-cycle may be more or less sustainable. Therefore, their sustainability performance always has to be analyzed and evaluated in the context of the intended application and with regard to a possible contribution to a sustainable development. Absolute statements such as “sustainable plastics,” often combined with the addition “due to recyclability,” must therefore be rated very critically. Recyclability, which is often regarded as synonymous with sustainability in the marketing of materials, depends on available recycling infrastructure, which typically only exists in the materials sector where it is economically viable.

Another important lesson learned from several decades of sustainability assessment is that assessment systems have changed and evolved significantly in the past. As sustainability assessment has been driven by emerging environmental risks, further developments in the normative framework and societal developments, the assessment methodology had to evolve as well. Notable examples of additions to the assessment methodology with respect to the environmental dimension of sustainability are the issues of greenhouse effect and ozone depletion in the 1980s and the microplastic problem in the recent past. It can be assumed that the aforementioned drivers will continue to influence sustainability assessment in the future. For a future-proof sustainability assessment methodology, it is therefore essential that newly emerging risks can be identified at an early stage. This calls for a flexible and adaptive assessment framework as well as an interdisciplinary exchange, especially between natural and social sciences (Möller et al., 2021b).

Evolvement of technology assessment

Roughly in the second half of the 20th century, undesirable side effects of progress in science and technology increasingly manifested themselves in the form of risks and concrete damaging events and thus found their way into the collective consciousness of society. The almost ubiquitous
The emergence of persistent pollutants like the pesticide DDT (Dichlorodiphenyltrichloroethane) in the environment and the risks of nuclear power can be regarded as particularly controversial examples in this respect (Carson, 1962; Grunwald, 2019). Accordingly, the appearance of these phenomena is considered to mark the beginning of the Anthropocene era. As a result, a consensus previously largely in place, which equated scientific and technological progress with social progress, was increasingly questioned. Against this background, researchers were more and more confronted with the challenge of reflecting not only on the possible consequences of science-based technologies, but also on the epistemological foundations of their own actions (Kollek and Döring, 2012).

Consequently, the concept of TA became established in the 1960s, particularly in the United States, with early studies focusing on the issue of environmental pollution, but also issues like the supersonic transport, and ethics of genetic screening (Banta, 2009). One of the basic motivations of TA is to deal with possible short- and long-term consequences of scientific and technological progress (e.g. societal, economic, ethical, and legal impacts) as early and comprehensively as possible, in order to enable formative interventions (Grunwald, 2010, 2019). The ultimate goal of early TA studies was to provide policy makers as primary target group with information on policy alternatives (Banta, 2009).

One of the key challenges for TA relates to the question of how to respond to emerging technologies, that is novel technologies that are still at an early stage of their development. Especially in the case of basic research-oriented R&D work, the new developments are characterized by low technology readiness levels (cf. Mankins, 1995), that is the R&D results are still relatively far away from entering the market in the form of tangible products. The relatively low maturity of the technologies results in a very limited availability of quantitative data on subsequent product specifications and potential environmental impacts. On the other hand, addressing sustainability aspects at such an early stage in the innovation process basically offers an excellent window of opportunity.

**Figure 3.** Dependencies between the maturity of a technology, the knowledge about environmental, health safety and social (EHS/S) impacts as well as the ability to prevent corresponding risks. Source: Köhler and Som (2014).
to avoid possible weaknesses with regard to sustainable development and to identify existing strengths. This situation is often referred as the Collingridge Dilemma (Collingridge, 1980): In the infancy of an emerging technology, the potential to influence its properties is particularly high, but the knowledge about its sustainability impacts is comparatively low. Later on, the understanding on the consequences of an emerging technology is expected to increase, yet the possibilities for shaping its design may already be significantly reduced by already existing path dependencies (see Figure 3).

Against this background, an ideal period for the assessment and eco-design of emerging technologies would be during the innovation stages of “applied technology development” or “product design.” In these stages, the ability to prevent sustainability risks is still relatively high (cf. curve with solid line in Figure 3) and, at the same time, the quantity and quality of data required for a sustainability assessment are increasing significantly. However, a sustainability assessment in the stage of “basic science and material research” is well before this ideal period.

Basically, the dilemma outlined by Collingridge presupposes a fundamental separation between cognition and action as well as between science and technology. With the emergence of the concept of “technosciences,” however, this hypothesis has been increasingly challenged since about the mid-1980s by postulating a constitutive relationship between science and technology (Haraway, 1997; Hottois, 1984; Latour, 1987). Hence, the characteristic feature of technosciences is a far-reaching convergence of science and technology on all levels of action and effect, of materiality and culture (Kastenhofer, 2010).

The concept of technosciences has been adopted by anthropologists, philosophers and sociologists in science and technology studies as well as in the field of philosophy of science (e.g. Hacking, 1983; Nordmann, 2006; Pickering, 1992). Other TA concepts attach less emphasis to the intertwining of science, technology and society, but rather aim to start TA as early as possible. These include the “constructive Technology Assessment” developed by Schot and Rip (1997), which does not focus primarily on the possible consequences of a technology but aims to assist in shaping its design, development and implementation process. In this context, it was also proposed that a “real-time assessment” should accompany technology development from the outset and integrate social science issues as well as policy and governance aspects at a very early stage (Guston and Sarewitz, 2002).

Nevertheless, the concept of technosciences generated important impulses to scrutinize and reconsider some of the central assumptions underlying many existing TA concepts. In this context, Liebert and Schmidt (2010) point out that the goals and purposes of innovation processes, which are often clearly articulated and recognizable in the context of technosciences, offer the possibility of unlocking knowledge about the respective technology development. Hence, they challenge the assumption of general knowledge deficits as stipulated by the Collingridge Dilemma. Furthermore, they argue that technosciences are usually developed and applied by many different actors. In this respect, the fiction of a control of technology (especially by political actors) as advocated in early TA concepts will increasingly shift to a paradigm of collaborative design.

Consequently, TA should be framed as a “Prospective Technology Assessment” (ProTA) and initiate phases of science- and technology-related reflection as early as possible:

“ProTA aims to shape technologies by shaping the goals, intentions and attitudes from the perspective of the anticipated consequences and realistic potentials” (Liebert and Schmidt, 2010: 114).

According to Liebert and Schmidt (2010), ProTA requires a normative framework that can be derived from the history of philosophical reflection. Concerning the underlying ethical criteria, two antagonistic principles are outlined: The “heuristics of fear” (Jonas, 1979) and the “principle of
hope” (Bloch, 1959), which in combination serve as a mindset for shaping emerging technologies as well as technoscience as a whole and that entails four different types of orientation: human, social, environmental as well as future orientation.

Furthermore, ProTA is also strongly perceived as a participatory approach. In contrast to an observation from an external perspective (as practiced in earlier TA concepts), ProTA should become part of a of self-reflection and self-criticism among scientists and engineers within the R&D stage itself that also includes the perspective of societal and political actors (Fisher et al., 2006; Liebert and Schmidt, 2010).

Discussion

As the evolutionary history of TA has shown, an early assessment of technologies and their impacts on environment and society is possible in principle. Despite of the epistemic limitations caused by the Collingridge Dilemma, the concept of ProTA provides a participatory and incremental self-reflection process that facilitates data acquisition even during the early stages of R&D and thus enables the shaping of technologies throughout the innovation process. One of the most important features of ProTA is a well-defined normative framework. Yet Liebert and Schmidt developed the associated criteria several years before the establishment of the 2030 Agenda. With its 17 SDGs and the 169 SDG targets, however, substantial opportunities have been created to concretize the normative framework of TA, especially with respect to a sustainable development. Hence, by referencing to the 2030 Agenda, a comprehensive sustainability assessment of technologies has become possible (Eberle et al., 2021; Möller et al., 2021a). Even more than that, with the 2030 Agenda representing a globally accepted framework that all United Nation member states have committed themselves, sustainability assessment of technologies has become an obligation.

In order to ensure goal-oriented and future-proof assessments, TA methodology needs to be able to recognize changes regarding its assessment criteria at an early stage, as already pointed out in section 3. For early detection, the investigation of existing and predicted transformation processes plays an important role in this context.

Transformations can lead to structural paradigmatic changes at all levels of society, for example in culture, value attitudes, technologies, production, consumption, infrastructures and politics. The corresponding processes take place co-evolutionarily, simultaneously or with a time lag in different areas or sectors, and can significantly influence, strengthen or weaken each other. The decisive factor for a transformation is that those processes become more and more condensed over time and, in the sense of a paradigm shift, lead to fundamental irreversible changes in the prevailing system. Transformations can be unplanned or intentional, they can take several decades and proceed at very different speeds (Grießhammer and Brohmann, 2015).

In contrast to the non-targeted transformations of the past (such as the first and second industrial revolution), it is now presumed that intentional transformations (e.g. the “Energiewende,” i.e. the transition of the energy system in Germany) can be significantly influenced and accelerated in a desired direction, but nevertheless not controlled in detail. This assumption is based on the recently available knowledge and experience of complex control, governance and strategy approaches (Grießhammer and Brohmann, 2015). The fundamental possibility of influencing or even controlling transitions is expressed by the term “transition management” (Kemp and Loorbach, 2006).

For understanding transition management, a multi-level perspective is fundamental. Accordingly, three different levels exist in each system under consideration, referred to as niches, regime, and landscape, with interactions between these levels (see Figure 4).

At the level of the prevailing regime, Grießhammer and Brohmann (2015) distinguish eight fields of action or sub-systems of society in which transformative innovations and initiatives can
influence each other or proceed in a co-evolutionary manner. These eight fields of action are defined as follows:

- **Values and models**: normative orientations such as values, socially or legally formulated goals, guiding principles or ideas for society as a whole or for individual areas of need (e.g. “Limits to Growth” according to Meadows et al., 1972);
- Behaviors and lifestyles: individual and society-wide shared (consumption) actions, everyday practices and habits, which can often deviate significantly from values and consciousness (e.g. dietary habits);
- **Social and temporal structures**: social and culturally determining structures (such as different gender roles or demographic shifts) as well as temporal factors (such as the duration of the transformation, windows of opportunities or diffusion processes of innovations);
- **Physical infrastructures**: permanent material structures that influence or even dominate the action spaces for groups of actors (e.g. road network);
• Markets and financial systems: market structures (e.g. degree of concentration, globalization) and market processes such as supply, demand and prices of goods and services;
• Technologies, products, and services: individual products and services as well as overarching technologies that can act as a key driver of transformations;
• Research, education, and knowledge: science, research and development in practice as well as their institutional constitution, appropriate educational measures at various levels as well as knowledge stocks required for transformations;
• Policies and institutions: control instruments such as commandments and prohibitions, financial incentives or informational instruments, as well as the associated institutional and organizational framework (e.g. state bodies, competencies, separation of powers, course of the democratic process and legal framework).

The analysis of the determining factors of a transformation process and their possible impact on the method of sustainability assessment of technologies shall be exemplified by the transformation in the energy sector representing an area of need where general principles for the sustainability assessment of technologies have already been formulated (cf. Grunwald and Rösch, 2011). The following table summarizes the findings from this exercise and provides an overview of the determining factors for the fields of action in the energy sector. In this respect, it has to be noted that the scope of the investigation refers to the specific situation in Germany.

Many of the identified determining factors for the fields of action are transformation processes themselves. Digitalization, for example, is coupling the energy transition with the ongoing industrial revolution in information and communication technologies. Furthermore, the transition of the energy sector influences the energy supply for the transport system as well as for the building stock, and vice versa. The parallel transformations can influence, support, or hinder each other. For example, electromobility generates a higher demand for renewable electricity; on the other hand, the batteries installed in cars provide a storage option for electricity. In this context, it is also important to consider the various and partly rivaling innovations emerging from niches (cf. Figure 4). These include e-cars, for example, but also fuel cell cars and e-bikes as a fundamental alternative. The same is applicable for phenomena at the level of the greater landscape: The efforts of an increasing number of companies to achieve climate neutrality play an eminently important role here, as the demand for renewably generated energy will continue to grow significantly. However, the current consequences and long-term effects of the Corona pandemic could lead to significant energy savings through a reduction in air travel, at least in the short to medium term.

The concept of ProTA is currently implemented in the Cluster of Excellence “Living, Adaptive and Energy-autonomous Materials Systems” (livMatS) funded by the German Research Foundation. The vision of this cluster is to develop novel, bioinspired materials systems, which adapt autonomously to their environment and harvest clean energy from it. The research and development work in livMatS aims to provide innovative solutions for various applications, particularly in the field of energy technologies. Sustainability, psychological acceptance and ethical approval form essential claims of the work done in livMatS. Therefore, prospective reflection of the sustainability aspects as well as research into consumer acceptance and social relevance of the developed material systems form an integral part of livMatS work right from the very beginning (livMatS, 2022).

The prospective TA of the technologies and materials to be developed in the livMatS cluster is designed as a tiered approach called TAPAS (Tiered Approach for Prospective Assessment of Benefits and Challenges). The ultimate goal is the design of a new development-integrated sustainability assessment framework that starts with interactive early tools on a qualitative basis (e.g. questionnaires and prospective chemicals assessment) and also covers quantitative case studies. Development-integrated assessment entails that the methodology both encourages and enables the
innovators themselves to carry out assessments on sustainability, ethics and consumer issues as part of the innovation process (Möller et al., 2021c).

With regard to the livMatS materials, the ongoing transformation in the energy sector has considerable influence on the potential application fields: In their efforts to become climate-neutral, companies will make much greater efforts to harness previously unused (waste) energy. Energy harvesting in industrial processes as well as in the mobility sector and in buildings will consequently gain considerably in importance and may become common practice. For example, due to progress in digitalization, there will be more and more sensors at peripheral locations requiring power supply. Moreover, prosumers may also find it attractive in the future to feed harvested energy of their own solar systems into the grid, especially at times of high energy prices.

For the methodology of the prospective sustainability assessment, however, no fundamentally new issues can be identified on the basis of the available findings, which could not be captured by the existing toolbox. This can be justified with a closer look to the relevant technological approaches (digitalization, hydrogen technology, energy harvesting) presented in Table 1, as their respective designs do not reveal any radically new materials and process configurations. This assessment, however, needs to be subject to continuous review as the new material systems mature. Furthermore, it should be noted that for sustainability assessments in living labs and citizen science projects, instruments are required that provide meaningful and consistent results even when used by laypersons. In this context, a tiered approach as described in section 4 is also expected to be beneficial.

Conclusions and outlook

In light of the findings and the results of the previous sections, the four fundamental questions from the introduction will be revisited and answered as far as possible.

With regard to the first question, it could be demonstrated that universal and absolute statements on the sustainability of technologies are just as misleading as they are for materials or products. Possible contributions to a sustainable development can only be discovered in a case-by-case analysis of the entire product-line and in the context of the functionality and benefits of the object under investigation.

Secondly, an early and prospective assessment of sustainability of technologies requires a flexible and tiered approach. In this respect, we reference the TAPAS framework that aims to establish a new tiered development-integrated assessment methodology within the livMatS Cluster of Excellence. To enable assessments at an early stage and with sufficient certainty of direction, TAPAS starts with interactive early tools (e.g. questionnaires and prospective chemicals assessment) which are incrementally underpinned with quantitative case studies in an iterative process. In order to ensure an agile, goal-oriented and future-proof evaluation system, TAPAS also includes a careful reflection of ongoing transformation processes in application sectors (e.g. the energy sector) that are relevant to the technology. The prospective mirroring of the determinants of transformation processes of related areas of need as described in section 5 aims to provide a further feature for the continuous refinement of the TA framework, especially with regard to ProTA.

As of third, the assessment of the sustainability performance of technologies should include much greater involvement of those actors who are particularly good at overseeing and influencing the innovation process—the innovators themselves. To ensure sufficient feedback with society, science has to open up to the public and the participation of society in the sense of transdisciplinary research. In this respect, initial assessments of the technology developers need to be discussed in real laboratories, that is, open-innovation environments that focus on cooperation between science and the public in an experimental environment. Hence, suggestions from society should in return become part of the innovation process (Möller et al., 2021b).
Table 1. Determining factors for the fields of action in the energy sector.

| Fields of action               | Determining factors in the energy sector in Germany                                                                 |
|-------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Values and models             | “Energiewende” (English: “energy transition”) mission statement with a focus on renewable energies (Krause et al., 1980) |
|                               | **Rejection of nuclear energy** by a vast majority of the German population (Statista, 2021)                               |
|                               | **Fridays for Future** activities and demonstrations push debate about climate change and renewable energy back to the forefront of the political agenda (Marquardt, 2020) |
|                               | **Rejection of nuclear energy** by a vast majority of the German population (Statista, 2021)                               |
|                               | **Fridays for Future** activities and demonstrations push debate about climate change and renewable energy back to the forefront of the political agenda (Marquardt, 2020) |
| Behaviors and lifestyles      | **Prosumer movement** leads to a constantly increasing number of consumers who simultaneously consume electricity and supply it to the grid, for example via an own photovoltaic system (Agora Energiewende, 2017; BMWi, 2016) |
| Social and temporal structures| **Fukushima nuclear disaster** in 2011 as a major window of opportunity for the nuclear phase-out (Bernardi et al., 2018) |
| Physical infrastructures      | **Increase in the share of smaller households** with a specifically higher electricity demand (Umweltbundesamt, 2020)       |
|                               | **Flexible and time-dependent pricing structures** (e.g. variable electricity prices) and process conversions in industry and commerce (operating energy-intensive processes during the day instead of previously at night) foster load management (Agora Energiewende, 2017) |
| Markets and financial systems | Digitalization enables the networking of electricity generators and consumers, for example, through smart meter gateways, that is, intelligent metering systems consisting of a communication unit and a digital electricity meter (Agora Energiewende, 2017; BMWi, 2016, 2017) |
| Technologies, products and services | **Coupling of the electricity sector** with the building, mobility and various industrial sectors, turning (renewably generated) electricity into the most important energy source (Agora Energiewende, 2017; BMWi, 2017) |
| Markets and financial systems | Decentralization of power generation (formerly a few large fossil-based power plants to currently several million small and large renewable energy plants) creates new market players and enables new business models (Agora Energiewende, 2017) |
| Technologies, products and services | **Strong cost degression in electricity generation** from renewable sources (e.g. by 90% regarding photovoltaics) enables an energy system based on solar and wind power (Agora Energiewende, 2017) |
| Technologies, products and services | **New energy storage systems** (especially “green” hydrogen technology) for intermediate storage of electricity from renewable sources (Matthes et al., 2020) |
| Technologies, products and services | **Efficiency increase in the use of electricity** both at industrial plants and in household appliances (Agora Energiewende, 2017) |
| Technologies, products and services | **Energy harvesting technologies** enable the use of previously dissipated photonic energy, thermal energy or kinetic energy (Fraunhofer, 2018) |
| Research, education and knowledge | **Living labs and citizen science projects** explore sustainable energy technologies (e.g. hydrogen technology) under real conditions and on an industrial scale (BMWi, 2020) |
| Policies and institutions     | Liberalization of the electricity market since the 1990ies enables a flexible and efficient response to volatile power generation from renewable energy sources (DENA, 2021) |
| Policies and institutions     | **Substantial financial incentives** for renewable energy generation through the Renewable Energy Sources Act since 2000 (EEG, 2021) |
| Policies and institutions     | **Nuclear phase-out (by 2022) and coal phase-out (by 2038)**, that is political decision by the German federal government to stop operating nuclear power plants (Bundesregierung, 2011, 2021) |

Source: Own compilation.
Ultimately, in order to give humankind a chance to adapt to itself (Toussaint et al., 2012), technology and society need to co-evolve. Global agreements on normative goals such as the Sustainable Development Goals of the 2030 Agenda form a good starting point in this respect. For a culture of sustainability, however, policy should promote cooperation between actors for societally desirable transformation processes to a much greater extent. Equally important is a “greening” of ongoing transformations that are not induced by environmental policy (Grießhammer and Brohmann, 2015). The need to foster cooperation can be illustrated by the example of the energy transition: Driving forces for the “Energiewende” can already be found in all stakeholder groups, that is in civil society and governmental actors, but also in science and companies. Unfortunately, however, these players in many cases still act independently of each other. Instead, earlier and greater involvement of business and industry in ongoing transformation processes, support for new business models, and greater international cooperation would be needed.

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