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ASSESSMENT OF SOCIO-TECHNICAL CONFIGURATIONS

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ITA – INSTITUTE OF TECHNOLOGY ASSESSMENT

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TOWARDS A NEW FRAMEWORK FOR STUDYING SOCIETAL IMPLICATIONS OF ENERGY INNOVATIONS

MICHAEL ORNETZEDER[1], TITUS UDREA[1], STEFFEN BETTIN[1], TANJA SINOZIC-MARTINEZ[2]

[1] Institute of Technology Assessment (ITA), Austrian Academy of Sciences (ÖAW)
[2] Institute for Technology Assessment and Systems Analysis (ITAS), Karlsruhe Institute of Technology (KIT)

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Technology assessment (TA), TA infrastructures, energy transition, socio-technical innovations, configurational TA

ABSTRACT

Energy systems around the world are undergoing major changes. The transition towards renewable energies involves new technologies and infrastructures as well as changes in institutional arrangements and social practices. So far, however, transformations in the energy sector are driven by technological research and development activities proposing a wide range of competing and often inconsistent technical options and pathways. The emphasis on decarbonisation runs the risk of creating conditions for 'technocratic reductionism', in the form of technological quick-fixes and undesirable side effects. In order to avoid lock-ins and systemic inconsistencies, a broader and deeper understanding of innovations in the energy transition context is needed. In this paper, we propose a new framework to explore the socio-technical implications of energy innovations systematically. We aim to extend existing approaches to take account of the importance of societal implications and risk migration, thereby broadening and diversifying energy policy options. Analytically, our approach focuses on socio-technical configurations within the energy system instead of technologies or energy pathways. For illustration purposes, we draw on the empirical case of decentralised electricity generation and storage. Thus, we hope to allow for a better understanding of local, systemic, and wider societal effects of ongoing and future developments and enhance the societal value of energy innovation.

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INTRODUCTION

Due to the foundational nature of energy systems for our society's functioning, its decarbonisation will involve not only the replacement of physical infrastructure but also a substantial change in the associated social processes (Bettin 2020; D'Alessandro et al. 2020; Markard et al. 2020; Markard 2018; Thacker et al. 2019). Therefore, such a radical change requires system innovation. In other words, a transition from one status to another is characterised by substantially different qualities (Smith/Stirling 2010). Thus, ecological modernisation and a mere greening of industries and products will certainly not be enough to accomplish the required outcomes (WBGU 2011; D'Alessandro et al. 2020).

Dealing with innovation in the context of socio-technical transitions requires reflexive knowledge. Actually, there is a need to understand the impact of energy policy interventions better (Lutzenhiser 2014), and, more specifically, there is a need to systematically study the role of spill-overs and unintended consequences (Araújo 2014). In the context of transition processes, it has also been argued that research must consider not only the specific benefits and costs of particular policy options but also their wider systemic effects (Falkner 2014). Sovacool and Geels (2016) have suggested shifting the attention from analysing the temporal dynamics of transitions to assessing their wider impacts based on normative criteria. This seems all the more important as broad socio-technical variation very likely jeopardises the reliability of existing energy systems (Büscher/Sumpf 2015).

Insights about the implications and societal consequences of technology options and alternative development pathways represent a crucial element of energy policy decisions. Advocates of responsible research and innovation (RRI) emphasize that integrating societal values and anticipatory knowledge about possible societal consequences of new technologies is an essential precondition for actively taking care of the future (Owen et al. 2013; Stilgoe et al. 2020). Scientific ('knowledge for understanding') as well as policy-relevant knowledge ('knowledge for action') are both crucial in the context of the energy transition (Grunwald/Schippl 2013). Concerning responsible decision-making, scientific research must be able to actively contribute to 'opening up' the political discourse by showing and comparing alternative technological options and development pathways (Stirling 2014).

As might be expected, there are several approaches to define technologies as socio-technical configurations, but these attempts remain isolated and have not yet been systematically developed further for research on the consequences of new technologies (Miller et al. 2015; Walker/Cass 2007). Needless to say, we see incredible productivity in the field of energy technology development, which constantly leads to a multitude of new ideas, options and technical concepts. Thus, it is important to focus on what works in specific socio-technical contexts and not to reduce the analysis to technical feasibility (Ornetzeder et al. 2008; Carlsen et al. 2010). Of course, there are many approaches which deal with the effectiveness (and other properties, e.g., environmental performance) of new technical concepts (e.g., technical monitoring, life-cycle assessment) and with local effects and systemic consequences (e.g., for existing physical infrastructures). Moreover, there are approaches focussing on wider societal implications of technologies, risks, and ethical issues (e.g., Technology Assessment, ELSA, Risk and Safety Assessment). However, these approaches and research methods are hardly ever used consistently at the project level, allowing for an integrated comparison of alternative options for effectively shaping the transformation of the energy system. So far, this knowledge is only available in a rather fragmented way with very little meaningful interlinkage (Bardi 2013).

This article presents ideas for a new research framework to understand better the socio-technical consequences of the ongoing transition in the energy system. The main focus of this approach is to identify, describe and evaluate emerging socio-technical configurations in early phases of development to explore societal and ecological side-effects on this basis. Research guided by the framework may allow for a more robust understanding of direct (local and regional), systemic (e.g., energy system level) as well as wider societal effects (e.g., global implications) and risks of ongoing developments, and consequently enhance the societal value of innovation in the energy system. The framework integrates existing approaches such as technology assessment (TA), transition management (TM), life-cycle assessment (LCA), or energy system modelling to provide a comprehensive appreciation of alternative options.

In the following, we first briefly sketch the energy transition as the context for our framework (section 1). Although systemic perspectives are prevalent in the literature, the energy system will not transition on the whole but in smaller parts and at different paces. We then provide an account of existing approaches to energy transition, as well as argue for the need for a more integrative analytical framework (section 2). We then discuss the new framework (section 3), focusing on its unit of analysis and methodological issues. As a proof of concept, we include an empirical example showcasing a case study (section 4). In the last section (section 5), we summarize our findings, discuss the application of the proposed research framework and propose options for future research.

1 EMPIRICAL CONTEXT: THE ONGOING TRANSITION OF ENERGY SYSTEMS

Although today's global energy system is still heavily based on fossil fuels, the shift towards a post-fossil future is clearly under way (Burke/Stephens 2017; Burke/Stephens 2018). For several years now, global markets have undeniably moved towards clean energy. According to a recently published report, for the first time in 2021, "global electricity generation led to solar and wind power providing more than 10% of the world's electricity" (REN21 2022, p. 35). In 2021, despite the COVID-19 pandemic impacts, global new investments in renewables climbed to a new record 366B USD level (REN21 2022, p. 175). In addition, there are signs that growth in the global economy and energy-related emissions may be starting to decouple (IEA 2021). Today, it is assumed that within the next two years, renewable energy globally will become the main source of energy (IEA 2023). Comprehensive modelling studies show the feasibility of providing all energy for all purposes, everywhere in the world, from renewable sources at similar costs as today (Delucchi/Jacobson 2012). Building on such modelling, roadmaps for implementing energy systems based entirely on renewable sources were presented for 139 countries worldwide. These roadmaps are far more ambitious than the demands of the Paris Agreement but are still considered technically and economically feasible (Jacobson et al. 2017). All this is striking evidence that the energy system will fundamentally change in the upcoming decades. However, this transition's timing, pathways, and forms are largely open and unclear (Miller et al. 2013).

Transitions are conceptualised as radical changes from one socio-technical system to another. From this perspective, transitions involve co-evolutionary processes through the interplay between technology and society (Geels 2005). In transition processes, technology is shaped in social contexts and, in turn, contributes to shaping society (Carlsen et al. 2010). Based on this insight, we may assume that a decarbonised and renewable energy system will not only be based on new technologies and reconfigured infrastructures but also involve a more sustainable or otherwise different form of society. Alternatively, in more general terms, transitions will inevitably bring about a reorganisation of the material as well as social order.

Concerning the change of energy systems, Eikeland and Inderberg (2016) have rightly argued that energy transitions have to be conceptualised as situated processes, where different national or even regional settings, value systems, socio-technical regimes, and local contexts play an important role. Using an energy system modelling approach, Mathiesen et al. (2015) have shown that there is a need for cross-sectoral integration when we want to reach energy systems that almost completely rely on renewable sources. Consequently, a much broader understanding of what belongs to the energy system would be helpful. The mobility system, as one of the major energy users, would certainly be part of such an integrated view. Pegels and Lütkenhorst (2014) have pointed out that deep transformations of energy systems will certainly require energy diversification. Also, Sovacool and Geels (2016) have suggested that it might be useful to distinguish different 'parts' or 'layers' of energy systems when we investigate the temporal dynamics of transitions. Based on this, we should remember that, e.g., changes in national infrastructure systems will take longer than changes in power fuels or end-user equipment. Consequently, the energy system transition must be broken down into subsystems across at least four layers – extraction, conversion, delivery and use. In an earlier paper, Meadowcroft (2009) convincingly argued that the long-term transformation of energy systems would be a messy, conflictual, and highly disjointed process.

Moreover, addressing the effects of energy innovation under localized real-world conditions is crucial. Empirical research on the so-called energy performance gap, the rebound effect and energy efficiency measures, in general, has shown that introducing energy-efficient technologies does not automatically lead to substantial reductions in energy use or carbon emissions. In fact, the opposite often is the case (Backlund et al. 2012). From a transition point of view, this is a severe problem as most energy scenarios rely on tremendous reductions in total energy consumption (European Commission 2011). To overcome this dilemma, energy research has to shift from a product-consumption focus to a social practice or socio-material focus, which could help to get much closer to the intended energy performance targets in real conditions (Love/Cooper 2015; Ornetzeder et al. 2016). In order to deal with these challenges productively, a new approach must include the set-up of research projects in which all these aspects are addressed in an integrated way.

Markard (2018) argued for the electricity sector that the energy transition, at least in some countries, is already entering a new development phase. While the first phase was primarily about establishing renewables as technically and economically competitive alternatives, the second phase is characterised by increasing scope and speed of change, with far-reaching technical, social and institutional consequences and challenges. In this phase, issues such as the complex interplay of multiple technologies, the demise of established business models and technologies, intensified economic and political wrangling among key players such as utilities and industry associations, and challenges to the functioning and performance of the power sector as a whole (e.g., when integrating renewables) are becoming crucial (Büscher et al. 2020). For transition research, this means revising existing frameworks and applying new research strategies, methods, and data sources. Above all, comparative research designs (e.g., across countries and technologies) are considered essential for the future.

The transition of the energy system is well underway, while a new level of change is still ahead of us, which opens up various opportunities for innovation and variation. This new phase of change will be socio-technical and probably involve various implications that are not yet known today. A decarbonised and sustainable energy system of the future might involve an unprecedented integration of sectors, completely new technologies and business models, and solutions tailored to local and regional conditions. Consequently, we will have to widen our traditional understanding of energy systems. Different subsystems of the energy system will show distinct dynamics, including reproduction processes, transformation and transition (Geels/Schot 2007). A dedicated research framework has to take these diverse aspects into account.

2 EXISTING APPROACHES AND FRAMEWORKS

With a distinct focus on comparing emerging socio-technical configurations, the proposed research framework aims to contribute to a more integrative and reflective organization of energy transition governance. The framework builds on existing approaches relevant to socio-technical energy transitions, namely sustainability transition research, strategic niche management and experiments, transition management, energy systems modelling, risk and sustainability assessment, as well as technology assessment. It aims to integrate and thus transcend these individual approaches to account for societal implications and broaden energy policy options.

With the broad field of sustainability transition research, there is already well-established, significantly diverse literature exploring different ways to understand how transitions occur and what role individual radical innovations may play in this context (Smith/Stirling 2010). To date, however, the focus on transitions has precluded exploration of actual *technologies in use* (and *within* specific socio-technical configurations). While several approaches define technologies as socio-technical configurations, these attempts remain isolated and have not yet been systematically developed further for research on the *consequences of new technologies* (e.g., Walker/Cass 2007). More recent reviews of existing research topics in the field of socio-technical transitions (see Köhler et al. 2019) recognize the need for synthesis and reflection in terms of overcoming the fragmentation of research strands.

Current sustainability transitions research is largely rooted in socio-technical experimentation as the core element of the Strategic Niche Management (SNM) approach developed in the 1990s (Sengers et al. 2019, p. 3). Theoretically embedded within various fields such as Constructive Technology Assessment (CTA), Science and Technology Studies (STS) and evolutionary economics, SNM focuses on technological niches that facilitate innovations towards sustainability transitions (see Kemp et al. 1998; Geels/Schot 2007). In this sense, niches are defined as "protected spaces", loci where radical innovations develop, with fewer pressures and where radical learning processes take root at different levels (Smith/Raven 2012). Niche Experiments approaches (Sengers et al. 2019), therefore, further highlight several valuable concepts on the provision of innovation and stress the social dimension of technological development. Although configurational perspectives are central (through the use of the concept of socio-technical regimes), the focus remains on individual technologies offering radical innovation potential.

It is precisely such a broad, systemic, and policy-oriented view of technologies which is central to Transition management (TM) approaches. As both a governance approach and a policy-oriented framework, TM deals with ways of understanding and actively influencing long-term transitions in socio-technical systems. TM is also prescriptive in that it focuses on actors within policy decision-making and how these, in turn, shape policy options (Loorbach 2010). Relevant for our considerations is the broad, systemic-societal perspective of this approach. TM focuses on the complex adaptive systems nature of transitions (Köhler et al. 2019; Loorbach 2007; Loorbach 2010). Taking insights from complex systems theory and relating concepts (e.g., self-organization, attractors, feedback), TM can be used to analyse, shape, and structure governance processes and socio-technical regimes towards long-term sustainability goals (Foxon et al. 2009). Importantly, TM research offers a systemic, actor-led perspective to influence transition processes actively. However, the focus is on enabling and supporting transformation processes rather than critically reflecting potential drawbacks and risks of the chosen pathways. More systematic research into the side effects of various alternative options may complement TM research and practice, were policy makers and other social players have to make decisions (based on knowledge about e.g., possible risks or rebound effects) to bring about transformative change.

Turning to the field of energy transition research, we see incredible productivity, which constantly leads to many new ideas, options and technical concepts. Interactions between the components of technological and social systems and networks in the context of evolving governance structures (Bale et al. 2015) have introduced an increasing degree of complexity within the energy system (Geels et al. 2017; Camarinha-Matos 2016; Hansen et al. 2019). This complexity calls for approaches that include all relevant parts of the energy infrastructure in integrative energy systems modelling (e.g., Lund et al. 2017). One such research approach calling for a systemic perspective, which analytically includes interactions within the energy system as a whole, is Energy Systems Modelling. Modelling adds the focus on the roles of specific technologies within broad systems to our framework. While the literature on energy systems modelling has covered a wide range of technologies, "the network infrastructure is rarely considered" (Weinand et al. 2020). We, therefore, include the infrastructure perspective in our considerations as well as a strong focus on non-economic criteria, which usually is lacking within energy systems modelling. Indeed, while some of the studies focus on social and environmental aspects (e.g., Boon/Dieperink 2014; Kumar et al. 2019), overall energy systems modelling suffers from "a lack of attention paid to non-economic and non-technical criteria" (Weinand et al. 2020, p. 14). In this sense, our approach will add an important social level of potential implications, as we will discuss in Chapter 3 when detailing the multiple types of impacts included in the analysis.

As we will focus on the implications and consequences of socio-technical configurations, the concept of risk assessment and, more broadly, the field of risk analysis come to the fore. *Risk assessment* is understood as the "systematic process to comprehend the nature of risk, express and evaluate risk, with the available knowledge" (Aven et al. 2018, p. 8). A detailed definition is recently formulated, whereby risk assessment is conceptualized as the systematic process of identifying risks, uncertainties, and opportunities, based on reliable and relevant criteria (Aven 2020, p. 87). The available methods and tools for safety risk analysis of complex technical systems have developed in at least three distinct phases: early-, first-, and second-generation conceptual theories and tools (Mohaghegh et al. 2009). This development tracks the shift in understanding from more normative models to descriptive models (i.e., as "deviation from rational performance") and further to modelling "actual behaviour" (Rasmussen 1997; Mohaghegh et al. 2009). In the context of risk assessment, the perspective has become much more systemic and integrative in the last decades, where unknowns and uncertainty have also found their way in (Renn 2009). This contrasts conventional risk management, which is very technical in origin. While a configurational, systemic perspective is missing from risk analysis approaches, the assessment of socio-technical configurations takes the focus on "actual behaviour" further in a comparative research design (see Chapter 4).

Finally, some approaches focus on the wider societal implications of technologies, risks and ethical issues (e.g., comprehensive Technology Assessment, ELSA). Beyond more structured frameworks such as options assessments, so far, insights are only available in a rather fragmented way with little meaningful interlinkage regarding the manifold innovations in the energy field (Bardi 2013). An important research field and approach fundamental to understanding the implications and emerging effects of technologies is technology assessment (TA). TA has focused on publicly accessible knowledge on the unintended social, economic and environmental consequences of technological change (Grunwald 2018). Resisting straightforward categorizations, TA has been influenced by – and has influenced – "a wide variety of scientific disciplines, ranging from policy analysis, science and technology studies, ethics, philosophy, social and cultural studies to the communication sciences and political sciences" (Van Est/Brom 2012, p. 307). TA can, therefore, be considered both an area of research, as well as a collection of methodologies and practices, with a strong emphasis on advisory activities. TA offers a specific framework of relationships between practice and theory, realised in the technology assessment process (Grunwald 2018). This process is broadly understood as an "analytic activity, aimed at providing decision-makers with an objective analysis of effects of a technology" (Van Eijndhoven 1997, p. 269).

In all its types and frameworks, TA broadly focuses on questions relating to the (1) development of technologies, (2) the involved actors, (3) the potential social impacts (as side effects of particular technologies), (4) as well as potential policy options and recommendations to address these impacts. In this sense, two fundamental challenges exist for the various TA approaches already identified in the literature. These also serve as starting points for our proposed framework. The first relates to the technology focus of TA, or otherwhile the lack of a systemic, configurational perspective. When facing the prospect of monumental systemic change towards sustainable energy systems in the near future, the narrow concept of technology, namely a "physical (future) technology, which is normally used in TA studies, no longer suffices" (Van Est/ Brom 2012, p. 319). Such long-term systemic change involves technological but also social, political, and economic efforts, calling for a broadened research perspective where all these elements come together configurationally (Elder-Vass 2017; Walker/Cass 2007). The second challenge relates to how TA defines and understands social impacts as side effects of technologies (see Russell et al. 2010). Indeed, Maasen and Merz (2006) have already called for a TA practice that considers the social and cultural conditions of the emergence, acceptance, and use of particular technologies (see also Van Est/Brom 2012).

To conclude, this short review points to the need for a systematic framework for configurationally exploring technology-related implications. Current literature perspectives suffer from fragmentation in that numerous approaches and strands of literature exist studying specific aspects of the energy transition and its effects. Consequently, our main vision is to integrate these different approaches and, based on a concise framework, investigate the effects and consequences of emerging socio-technical configurations, and open up an anticipatory knowledge base allowing for a more reflexive governance of the energy transition.

3 TOWARDS A CONFIGURATIONAL TA OF ENERGY INNOVATIONS

The proposed research framework is defined as a systematic, transdisciplinary attempt to explore foreseeable consequences when introducing particular socio-technical configurations with respect to fundamental changes of the way energy is supplied, distributed and used in society.

The framework (1) focuses on the transition potential of emerging energy innovations; (2) identifies and describes emerging innovations as socio-technical configurations in real-world contexts on a semi-generic level; (3) supports the search for 'missing configurations' which will eventually broaden options for research and development as well as decision-making; (4) aims to produce knowledge about main properties, local and systemic effects as well as wider societal implications (including risks and ethical issues) of emerging energy innovations by form of comparison; and (5) provides knowledge to allow for a more systematic organisation of energy transition governance.

Research within the new framework should improve our understanding of side-effects and risks of already working or projected socio-technical configurations, identify interdependencies and synergies of new and existing configurations, and reveal promising but so far 'missing socio-technical practices'. To identify interdependencies and synergies of new and existing configurations is an important perspective as innovation in the energy system takes place in an already highly structured and well-established environment. From an energy transition point of view, it is, therefore, crucial to study both the potential for 'system improvement' as well as the potential for 'system innovation' (Meadowcroft 2009). Given the need to broaden policy options in the field of energy innovation, the new framework may also contribute to unveiling missing but fruitful socio-technical configurations (Jørgensen 2012). Dealing with heterogeneous elements that are required to have working configurations will very likely give us a toolkit for identifying new solutions.

Socio-technical thinking is an important foundation here. Of course, this kind of argument is not new. The term socio-technical system had first been introduced by industrial sociologists at the Tavistock Institute in London in the context of labour studies as early as the 1950s (Emery/Trist 1969). Using this approach, it was possible to show that the performance of a factory or a production unit is the result of the interplay of social (workers) and technical (machinery) subsystems. Later, Ropohl (1979) used this idea in a very similar way as a core concept for his general theory of technology. Ropohl was interested in defining empirical acting subjects and aimed to describe them as action systems that rely on human and technical function carriers. Technological artefacts, Ropohl (1979) has argued, only have the potential for action. Action, however, is necessarily performed by socio-technical systems.

A similar idea appears in actor-network theory (ANT). Here, human and non-human entities, which can act, are called actants. If we can deduce effects from causes, Latour has argued (1990), it is because a stabilised network is already in place. That is why the focus of actor-network theory is so much on the description of relations within these networks and their recurrent performance. Based on the same school of thought, Law (2003) has shown that all societal phenomena can be seen as the effect of heterogeneous networks. As a consequence, describing actor-networks may easily end up with endless network ramifications. A way to avoid such problems is to treat network patterns that are widely and regularly performed as packages – stable and closed elements called punctualisations in the context of the actor-network theory. This idea should be kept in mind when we describe working socio-technical configurations further below as it allows us to take certain elements as a given.

Winner (1980) has pointed out that the social consequences of renewable energy systems will certainly depend on specific configurations of technical infrastructure and social institutions. More recently, socio-technical thinking has been applied to better understand the consequences of renewable energy choices. Walker and Cass (2007) have argued that differentiated 'hardwares' (such as wind, solar power or biomass) and differentiated 'softwares' (ownership structures, modes of implementation, etc.) will lead to rather different outcomes, hence sociology of technology should address those configuring processes adequately. The paper by Miller et al. (2015) points in the same direction. Miller and colleagues have introduced the term socio-energy system to describe "sets of interlinked arrangements and assemblages of people and machines involved in the production, distribution, and consumption of energy, in their supply chains, and in the lifecycles of their technologies and organizations" (Miller et al. 2015, p. 31). Both papers place emphasis on the idea that we have to apply a socio-technical perspective to adequately understand intended functionalities as well as side effects and wider societal consequences of any energy innovation. Socio-technical configurations are structures with emergent properties, which means "properties or powers of a whole that are not possessed by its parts" (Elder-Vass 2010, p. 16). And only because configurations are composed in a specific way (parts and relations), they are able to produce intended effects and (often unintended) side effects and risks.

Putting socio-technical configurations at the centre of the analysis implies an ontological shift from generic technologies – as it is often the case in empirical technology assessment studies – to semi-generic socio-technical configurations; or, in other words, from 'technology in society' to 'technology in use'. The idea that the studied configurations have to be framed on a semi-generic level is crucial for our approach. Analytically the defined configurations (innovative ideas, concepts, etc.) have to represent real-world and context-sensitive solutions but without getting lost in too specific and hence too many variations. The aim is to come up with 'typical' but clearly differentiated configurations that work in practice and promise to contribute to larger transition goals. As a basic requirement, these descriptions will involve social (e.g., type of typical users, necessary skills, rules, contracts) as well as technical (e.g., end-user devices, interfaces, connections to existing infrastructure) elements and main relations that are required to accomplish the promised intentional functions (e.g., the efficient distribution of locally generated electricity).

Another purpose of this framework is to guide the empirical analysis of socio-technical configurations' various effects and implications using comparison. To assess the implications of emerging socio-technical configurations systematically and comparatively, we propose to consider three different types of effects: (1) direct local effects, (2) indirect systemic effects, and (3) wider societal effects. All three types of effects are relevant to allow implications of innovation in the context of the energy transition of larger socio-technical regimes to be thoroughly assessed. Another reason for distinguishing between these types is that different research strategies, methods and data sources must be used to explore them in more detail. We define these three different types of effects as follows.

Direct local effects are direct consequences of a socio-technical configuration being put in action (Adil/Ko 2016; Hodson/Marvin 2010; Bulkeley et al. 2010; Faller 2016). These can be intended and unintended side-effects or risks. Only those directly involved or in a definable geographical area are affected by this type of impact. Typical examples of local side effects are emissions (e.g., noise, exhaust gases), possible associated health problems (e.g., chronic diseases) or rebound effects (e.g., consumption increases through efficiency gains). Risks also initially arise in a local environment. A risk is a damage that does not occur permanently but with a certain probability (e.g., explosions, financial losses). Local effects can typically be studied in pilot projects or in early phases of market introduction.

An *indirect systemic effect* is the consequence of a local socio-technical activity that influences existing networks and infrastructures (Carroli 2018). These effects can also be intended or unintended. Usually, such effects arise as the sum of several individual activities with varying dynamics. As a rule, it is necessary to assume a range of scenarios to assess such effects. A well-known example is the consumption peaks in the electricity grid, which are caused by many simultaneous uses (Miller/Carriveau 2019; Kan et al. 2021). Risks also appear as systemic effects. One example would be blackouts, which may be caused by local phenomena that build up in the system. Effects that impact the security of supply in many cases are also systemic.

Wider societal effects are also associated with the activity of a particular configuration, but the impacts go far beyond the site of application and may be globally distributed (Metzner-Szigeth 2009; Buchmayr et al. 2021). These implications can be social, environmental or economic and can occur throughout the configuration's life cycle, particularly from their material elements. This puts the implications of raw material extraction, production processes and end-of-life disposal into the focus of the analysis. Examples include the environmental and social implications of manufacturing the products used in the configurations, but also the greenhouse gas emissions generated during operation. Economic distributive effects in society as a whole or legal or ethical implications also may fall into this category.

For a comprehensive assessment of the implications of emerging socio-technical configurations, we consider it necessary to investigate at least these three levels in an integrated and comparative manner. In the following, we will discuss the necessary methods and research strategies.

4 RESEARCH STRATEGIES AND METHODS

Technology Assessment is defined as both an area of research, as well as a collection of methodologies and practices with a strong focus on policy advice. Beyond consigning it to particular research fields, TA can be considered a specific framework of relationships between practice and theory, which expresses itself in the technology assessment process (Grunwald 2018). This process is broadly understood as an "analytic activity, aimed at providing decision-makers with an objective analysis of effects of a technology" (Van Eijndhoven 1997, p. 269).

Starting from methodological developments within the social sciences more broadly, several TA scholars have argued for a paradigm shift, away from focusing on interactions between single entities, towards emphasizing continuous, unfolding processes and relations (Ely et al. 2014; van Est et al. 2016; West et al. 2020; Grunwald 2020). This 'relational turn' in TA research poses a number of methodological challenges. A first challenge is to clearly distinguish between research strategies, methods of data collection, data analysis and interpretation. And the second challenge is to identify appropriate methods for each of the different research tasks needed (selecting and describing appropriate configurations, exploring local, systemic and wider societal effects).

In the following, we aim to contribute to the discussion about consistency in TA research. However, we do not go into detail on the various methods used in TA, as there certainly is sufficient literature on this subject (Haleem et al. 2019; Grunwald 2018; Grunwald 2009; Bütschi et al. 2004; Decker et al. 2004) and existing taxonomies have attempted to provide an appropriate overview (e.g., Tran/Daim 2008). Therefore, we focus primarily on the relationship between research strategies and methods.

The term research strategy refers to the "careful planning and implementation of the process of knowing." (Johnson 1998, p.97). It is the overall plan for conducting the research and will guide the researcher in planning, executing, and assessing the study (Johannesson/Perjons 2021, p. 41). Research methods, on the other hand, inform the subsequent data collection and data analysis (both different steps in the research process). Other social science literature defines the research strategy as "a coherent set of methods, techniques and procedures for generating and analysing the research material, as well as the way the researcher looks at reality and conceptually designs the research project" (Verschuren 2003, p.122). In other words, the research strategy is the methodological link between the researcher's ontological and epistemological basis and the choice of methods to collect and analyse data (Saunders et al. 2015). Research strategies, in this sense, locate the research "in specific empirical, material sites and in specific methodological practices (e.g., making a case an object of study)." (Denzin/Lincoln 2018, p. 555).

The key variable in choosing an appropriate research strategy is its intended purpose, i.e., how well it fits to explore the research questions. For example, a case study approach can be appropriate for studying specific instances of complex (social) relationships but perhaps less useful for measuring trends in broader populations. There are a number of research strategies most often identified within both social science and technical research (Denzin/Lincoln 2018; Johannesson/Perjons 2021; Saunders et al. 2015) relevant for TA, as detailed in Table 1.

Table 1: Overview of research strategies

STRATEGY	AIMS	KEY CONCEPTS	KEY ACTIVITIES	FORMS	CONCERNS
Experiment	• Investigate cause-and-effect relationships or correlations	• Hypothesis and verification • Dependent variable • Independent variable	• Control factors that may influence the dependent variable	• Laboratory experiments • Field experiments • Natural experiments	• Weak internal validity for laboratory experiments • Weak external validity for field experiments
Modelling/ Computer Simulations	• Imitation/ simulation of the behaviour of a real-world process or system over time	• Dynamic models with capacity to generate processes • Reproduces or predicts the behaviour of a system • Analysing and making predictions about complex systems	• Data specification, collection • Model build and specification (outsources, iterative, etc.) • Model calibration • Model documentation • Validation	• Conceptual • Physical • Computational (non/deter-ministic, static, dynamic, stochastic, agent-based, etc.)	• Difficulties in validating models • Difficulties in assessing the accuracy of models • Models can be very complex and difficult to explain • Models do not "provide proof"
Case study	• Investigate in depth a phenomenon with a well-defined boundary	• Case/instance • Natural setting • Holistic view	• Multi-source data collection • Triangulation	• Exploratory case study • Descriptive case study • Explanatory case study	• Weak generalizability
Survey	• Investigate some aspects of a phenomenon to get an overview	• Sample • Representative sample • Exploratory sample	• Sampling (random, purposive, and convenience)	• Interview survey • Observational survey • Document survey	• Weak external validity for field experiments • Lack of depth • Limitation to measurable aspects • Lack of theoretical grounding
Desk Research/ Secondary Research	• Overview, state-of-the-art of a research topic or area, especially in cases of inter-disciplinary research areas (disparate research) • Assess the col-lective evidence in a specific research area and synthesizing research findings either on a meta-level, or show gaps	• Integrating multiple findings and perspectives from various empirical research • Creating theoretical frameworks • Building conceptual models • Evaluate the state of knowledge	• Collecting, synthesizing, and comparing previous research • Either quantitative, qualitative, or mixed design analysis of existing research	• Systematic reviews • Semi-systematic reviews • Meta-analyses • Integrative reviews	• Clearly motivate the need for the review and connection to the research questions • Transparency and replicability: clarity regarding the standards and criteria for the literature selection

STRATEGY	AIMS	KEY CONCEPTS	KEY ACTIVITIES	FORMS	CONCERNS
Mapping	• Broadly structure a research area • Identifying research trends, gaps, and topic developments	• Inventory of papers on the topic area, mapped to a classification • Bibliometrics and state-of-knowledge maps	• Extracting, classifying and counting contributions according to systematic categories • Corpus building visualisation	• Iterative exploration • Manual search • Database search • Snowballing • Automated search	• Transparency of selection criteria and replicability • Quality of secondary research is often not assessed
Scanning	• Focus on early signs, and weak signals as indicators of potential change • Structured research of future risks and opportunities of technologies	• Horizon scanning • Futures-thinking, foresight frameworks • Observation, examination, monitoring and systematic description of various aspects	• Systematic examination of potential threats and opportunities, with emphasis on new technology and its effects • Defining scope of scan and identifying experts • Wide variety of methods	• Scanning techniques can be formalized, systematic and comprehensive	• Clarity regarding the selection and mix of methods and analysis tools • Reliance on experts • Transparency of selection criteria and replicability
Ethno-graphy	• Investigate cultural practices and social interaction	• Culture • Empathy • Researcher as active participant	• Field work • Capture social meanings	• Holistic study • Semiotic stud • Critical study	• Reflexivity • A-theoretical storytelling • Ethical dilemmas
Grounded theory	• Develop concepts and theories through analysing empirical data	• Categories and codes • Open-mindedness • Theory and concept generation • Theoretical saturation	• Theoretical sampling • Coding (open, axial, and selective)	• Positivist • Interpretivist • Constructivist	• Reflexivity • Lack of context
Action research	• Produce useful knowledge by addressing practical problems in real-world settings	• Active practitioner participation • Change in practice • Action and re-search outcomes	• Cyclical process • Diagnosis • Planning • Intervention • Evaluation • Reflection	• Technical action research • Practical action research • Emancipatory action research	• Weak generalizability • Lack of impartiality
Phenome-nology	• Describe and understand the lived experience of people	• Lived experience • Reflectivity	• Unstructured interviews • Participant observation • Focus meetings • Text analysis	• Lifeworld research • Post-intentional phenomenology • Interpretive phenomenologic al analysis (IPA)	• Lack of rigour

Source: adapted from Johannesson/Perjons (2021) with additional contributions from Petersen et al. (2015); Snyder (2019); Calder et al. (2018); Neubauer et al. (2019); Habegger (2009); Hines et al. (2019)

In empirical research, decisions have to be made on two different levels. Firstly, the research strategy is chosen, depending on the research questions and overall focus. Ethnographic or phenomenological approaches may be useful, for example, in identifying and describing relevant configurations. Modelling approaches, on the other hand, can be useful in analysing systematic dynamics and effects. Secondly, appropriate methods are selected. This second step involves the selection of methods for data collection and methods for data analysis. The former are further separated into qualitative and quantitative data analysis methods. Significantly, while traditionally some research strategies are associated with specific data collection methods, there is a wide range of possibility when it comes to how data is collected and analysed for each strategy. Case studies, for example, rely on a number of methods, like interviewing, observing, and document analysis (Denzin/Lincoln 2018, p. 555), while surveys can use questionnaires as well as other quantitative data collection tools (e.g., web scrapers).

Regarding the various methods used within the strategies mentioned above, it is important to differentiate between data collection and data analysis methods. In other words, data can be analysed using one of more methods: e.g., texts can be analysed using both qualitative and quantitative methods. As mentioned above, we do not aim to describe existing methods available in detail, as methods are available for TA developed in disciplines pertaining to the sciences and humanities. They are applied to TA problems to collect data, facilitate predictions, do quantitative risk assessment, identify economic consequences, investigate social values or acceptance problems, and do eco-balancing (Grunwald 2018). For example, various existing research methods have been used to operationalise TA activities in specific projects, with perhaps the most systematic available in the form of a "method toolbox" (see Decker et al. 2004).

However, the choice of data collection methods will produce different types of data that may require different handling – or otherwise data analysis methods. Among the most well-known ways to collect data are: questionnaires, interviews, focus groups, observation studies, and document studies (Johannesson/ Perjons 2021, p. 55). While some data collection methods are strongly connected with specific strategies (e.g., surveys and questionnaires), Johannesson and Perjons (2021) argue that "traditional associations should not restrain a researcher in choosing an appropriate data collection method." (Ibid.). The focus should always be placed on whether certain methods are suitable for answering the research questions.

Concerning the configurative TA suggested here, methodological considerations are not only relevant for exploring implications and risks, but they are also relevant for identifying and describing the semi-generic configurations that will be investigated. Empirical research, therefore, includes two main phases: (1) the identification, demarcation and description of relevant and typical configurations and (2) the comparative analysis of effects and risks on three different levels.

Each of the two main phases may include primary and secondary data collection and analysis methods, depending on the chosen strategy and the context or scope of the research. The mix of data collection and data analysis methods appropriate is different relative to the three types of effects identified: direct local, indirect systemic, and wider societal effects. Each type of effect entails specific contexts and requires specific research strategies and methods to provide meaningful results.

Describing configurations is about setting out functions and then asking which social and technical elements and relations are necessary to fulfil these functions. It is about describing technologies in typical contexts of use. The selected configurations should fulfil the same or at least a similar function to enable a meaningful comparison. In this context, Love and Cooper (2015) have pointed out that it is important to consider that empirical socio-technical research is more than just putting together data from different (technical and social) sources. In fact, new developments are needed in theorising, generating and interpreting research data that go beyond what we may call 'standard approaches' currently described in the literature.

Local effects are often associated with analysing the implementation of (local) pilot projects, or cases of early phases of market introduction, using a multiple-case study research strategy and design (Yin 2009). A basic example of such a design would be a comparison of different but reasonably comparable socio-technical configurations (e.g., two competing options to improve energy efficiency through sector coupling). Methods for researching local effects would include interviews, workshops, and other direct contact, participatory methods, along literature analysis.

Systemic effects relate to existing networks and infrastructures and often arise as the sum of several individual activities. As a rule, it is necessary to assume a range of scenarios to assess such effects. Methodologically, modelling and simulations is often used to assess various scenarios, indicators, and parameter interactions. Other scenario analysis methods and performance assessments can complement data on systemic effects.

The wider societal effects include results relating to social, environmental or economic impacts. They can occur throughout the life cycle of the configuration and, in particular, from their material elements (e.g., LCA). Examples include the environmental and social implications of manufacturing the products used in the configurations, but also the greenhouse gas emissions generated during operation. Economic distributive effects in society as a whole or legal or ethical implications also may fall into this category. Methods include frameworks designed for stakeholder inclusion, allowing for the expression of values as well as designing operational criteria to respect and include these values. Several methods, such as value sensitive design (VSD) and value case method (VCM), have been developed to "align economic and non-economic values of multi-actor and multi-value system" (Koirala et al. 2018, p. 581).

For the empirical showcase example in this paper, we base our cursory analysis on secondary data consisting of in-depth literature reviews and qualitative text analysis of selected publications for each of the three identified socio-technical configurations. However, future studies will very likely include both primary research and secondary analysis of existing sources.

The three cases presented below outline different ways of integrating a high density of PV systems into the local distribution grid. Firstly, by conducting an in-depth literature review including mapping of the relevant field, we demarcated and defined three typical configurations and gathered relevant academic publications. A structured and effective literature review, as a research method, "creates a firm foundation for advancing knowledge" (Webster/Watson 2002,p.xiii). It is specifically by integrating multiple findings and perspectives from various empirical research that the literature review may answer research questions beyond the power of a single study (Snyder 2019). Methodologically, systematic mapping and scanning approaches can provide an overview and structure of the research area or technology domain and allows the discovery of relevant configurations. Systematic mapping focuses on "the process of identifying, categorizing, analysing existing kinds of literature that are relevant to a certain research topic" (Petersen et al. 2008).

In a second phase, we conducted an in-depth qualitative text analysis of 42 selected articles, which enriched the analysis of the three types of effects for each socio-technical configuration. We coded 19 articles for the first configuration, with the second and third, 14 and 9 articles, respectively. Of course, some sections grouped for one configuration might also include results and mentions for other configurations (e.g., comparisons). Therefore, the corpus should be regarded as unitary[1]. Essentially, the qualitative text analysis involved a close reading of the selected articles to develop an understanding of the texts, focusing on the methods used and the results reported for each configuration.

We jointly developed a coding scheme, covering mainly the topics covered, the types of effects, and risks (important for marking sections either directly highlighted as risks or effects). Starting from the literature review, the codes for the topics included the following categories: Policy/Regulatory, Social (including Psychological), Inequality, Rebound Effects, Energy Use, Infrastructure, Environmental, and Economic. These codes served to capture the specific effects and facilitate the analysis in terms of relating each result reported in the articles to one of the three types of effects. We used MAXQDA 2022 (VERBI Software 2021) for the coding and analysis. In addition to coding, we wrote summaries for each text on key aspects such as topics covered and types of effects.

[1] For this reason, we also included a coding category "Configuration" to code sections from all corpus relevant to each of the three configurations.

As discussed above, this analysis is limited to secondary literature and serves only as a cursory example of the framework and not a complete methodological showcase. Ideally, various forms of data may be included in the analysis, and both research strategies and methodologies would vary across the three types of effects. However, notwithstanding this limitation, the literature analysed for our empirical showcase and the corpus of articles included a broad mix of research strategies and methodologies. Local effects were reported based on participant observations, interviews, and general descriptions of local pilot projects. Systemic effects in our corpus are most often based on (scenario) simulations and broad performance analyses. In contrast, the wider societal effects mostly include a mix of literature surveys, primary survey data, and modelling. To conclude, the results of our corpus analysis presented in the next section, in part, are based on secondary literature, which includes a wide range of methodologies specifically tailored for the effect type.

5 EMPIRICAL EXAMPLE TO DEMONSTRATE THE FRAMEWORK

In the following, we aim to demonstrate, using an illustrative example, how the configurational framework can be applied and what challenges are involved in describing and evaluating emerging socio-technical configurations. It is widely agreed that solar power will account for a large proportion of future electricity generation in Europe. In Austria, the current government aims to shift the electricity supply entirely to renewable sources by 2030. A large share of this is to be provided by decentralized solar photovoltaic (PV) systems (Mikovits et al. 2021). A "one million roofs" programme is being prepared for the increased dissemination of solar power generation (Bundeskanzleramt Österreich, 2020). However, such a substantial increase in rooftop solar PV requires appropriate measures for the grid integration of intermittent power generation (Bayer et al. 2018).

In particular, local low-voltage networks are ill-prepared to handle a high share of distributed generation (Walling et al. 2008). This part of the grid was originally designed to distribute centrally generated electricity to end consumers. To maximise electricity production from local renewable sources, measures must be taken to overcome capacity or voltage limitations. A variety of technical and organisational solutions have been proposed, and many of them have already been implemented, at least in the context of pilot projects. These solutions include active curtailment, reactive power provision of PV inverters, expansion and reinforcement of the grid infrastructure, use of voltage-regulated transformers, implementation of battery systems, and control of demand-side appliances (Bayer et al. 2018). Mateo et al. (2017) have argued that it might be helpful to consider the available measures from a stakeholder perspective. Consequently, the authors distinguish between Distribution System Operator (DSO) solutions, prosumer solutions and interactive solutions. To further explore the feasibility of the proposed framework, we may define three different but still comparable socio-technical configurations based on the available technical and social options described in the literature.

PROSUMER STORAGE

The first configuration is called prosumer storage or prosumage. This configuration results from a larger number of electricity consumers with PV-battery-systems connected to the same part of the distribution grid. So far, such configurations are mostly found in pilot projects. However, in countries with an already high share of PV, such as Germany, the popularity of stationary home batteries has increased significantly and strong growth rates are expected in this market segment in the coming years (Figgener et al. 2020). At the level of the individual consumer, the technical elements of this configuration include a small-scale PV system, a stationary battery, and various technical equipment to measure and control the power flows (Luthander et al. 2015). This constellation at the household level has recently also been referred to as prosumage because it combines the production, consumption and storage of energy (Schill et al. 2017). Prosumage allows for different modes of action: Electricity can be drawn from the grid, it can be self-generated and consumed immediately or at a later time, or it can be directedly fed into the grid. The main discursive rationale for prosumage is to increase self-consumption rates and allow for higher degrees of self-sufficiency (Kairies et al. 2019; Kalkbrenner 2019). The existing distribution network remains largely unchanged, and the individual prosumage entities, households or small businesses, are not required to have a functional or contractual relationship with each other. This configuration primarily comprises spatial clustering of many prosumage entities connected to the local grid.

COMMUNITY ELECTRICITY STORAGE (CES)

The second configuration allows for a shared usage of energy storage by multiple prosumers (consumers) using the public grid. It is hence called community electricity storage (CES). Although the regulatory requirements for this configuration must still be implemented in many countries, shared storage is considered a promising option. So far, community storage has also been realized mostly within pilot projects (Müller/Welpe 2018). The stationary battery is owned, operated, and maintained by a local energy cooperative and connected to the distribution grid. The individual prosumer households do not have any batteries. However, they are equipped with an energy management system (ESM) that communicates with the central ESM as part of the battery system (Terlouw et al. 2019). Energy sharing can be performed in two ways, directly or indirectly. Direct energy sharing means that prosumers share electricity with each other when their own demand is met and others require energy simultaneously. Indirect energy sharing is when the energy cooperative buys and stores energy in the battery system when the local demand is met and delivers it later when the energy is required (Rodrigues et al. 2020). For this configuration, we have also assumed that the grid fees and taxes for sharing energy in the local distribution grid are reduced. Thus, an economically viable situation is given (Müller/Welpe 2018). The existing distribution network remains largely unchanged. In parallel, however, a smart grid infrastructure is necessary to connect the prosumers with the central battery (Rodrigues et al. 2020). The discursive rationality of this configuration suggests that locally produced solar power should be distributed locally as cost-effectively as possible.

LOCAL DEMAND RESPONSE (LDR)

The third configuration is called local demand response (LDR). In this case, the aim is to avoid local distribution network overload by offering flexibility through demand response. LDR refers to shifts in end-user electricity consumption compared to normal consumption patterns in response to changes in the price of electricity over time or to incentive payments designed to reduce electricity consumption during periods of high market prices or when the system's reliability is threatened (Siano 2014). It can be used for congestion management and grid balancing (Stawska et al. 2021). In the present configuration, however, the focus is on congestion management in a local network (Fonteijn et al. 2019). An intermediary or aggregator is necessary to set up a local market for flexibility. The aggregator groups together and manages flexible loads of multiple grid users (Carreiro et al. 2017) and offers flexibility to both distribution system operators (DSOs) and balance responsible parties (BRPs). Consumers allow the aggregator to manage their flexibility in exchange for an offer of financial reward, making it the aggregator's goal to minimize the cost of electricity consumption (Stawska et al. 2021). This configuration includes a range of advanced smart grid technologies, control devices (e.g., heat pumps, e-vehicles, micro-CHPs), monitoring systems (e.g., smart metering, energy management systems) and communication systems (e.g., wired or wireless infrastructure) (Siano 2014). The relationship between the consumers and the aggregator is regulated by contract. The aggregator provides a signal, and the consumer adapts his or her consumption in response to the signal (He et al. 2013). The configuration is intended to provide reliable network operation and bring financial benefits for all parties involved. Table 2 gives an overview of the most important aspects of the three configurations.

Drawing on the description of the three typical configurations, we can now discuss possible side effects and risks. In this paper, this can only be done in a cursory manner and on the basis of the existing literature. The aim of this section is to show which effects are most likely to be associated with the three configurations. We are interested in testing how well the framework is already suited for analysing implications and risks, and want to find insights needed for the further development of the framework. The literature search showed that most of the available studies deal with our first configuration (Prosumage), which means that many of the findings and assumptions mentioned in the following refer to individual storage solutions. Based on this, however, substantiated arguments can be made as to which aspects and how the other two configurations (CES, LDR) differ from the first configuration.

Table 2: Three local distribution grid configurations in comparison

	PROSUMER STORAGE	COMMUNITY ELECTRICITY STORAGE	LOCAL DEMAND RESPONSE
Technical elements	• Large number of PV systems connected to the same power line • Existing distribution grid • Stationary individual battery systems • Inverters, charge regulators, MPPT trackers • Smart meters • Electricity consuming devices	• Large number of PV systems connected to the same power line • Stationary shared grid connected battery system • Energy management systems (central and at prosumer level) • ICT infrastructure • Smart meters	• Large number of PV systems connected to the same power line • Control devices (e.g., heat pumps, e-vehicles, micro-CHPs) • Monitoring systems (e.g., smart metering, energy management systems) • Communication systems (e.g., wired or wireless infrastructure)
Social elements	• Prosumers (private households and small businesses) in spatial proximity • PV systems, batteries and additional equipment privately owned and operated • Tariff scheme favour self-consumption • Prosumers strive for energy autonomy	• Private households and small businesses are prosumers • PV systems privately owned and operated • Battery system owned, operated and maintained by the energy cooperative • Regulation and tariff scheme enabling a business case for energy arbitrage (e.g., reduced grid fees and taxes)	• Private households and small businesses are prosumers • Demand response intermediary (aggregator) • Different consumer categories engaged through diversified contracts • Control devices are privately owned • Regulation and tariff scheme enabling a flexibility market
Main discursive rationale	• High levels of self-consumption and self-sufficiency	• Cost-effective and ecologically beneficial local energy sharing	• Grid-friendly and cost-effective distribution of electricity

DIRECT LOCAL EFFECTS

Local effects differ significantly among the three configurations. Existing research shows that both Prosumage and CES tend to increase self-consumption and self-sufficiency, which in turn has the effect of reducing (local) peak demand from the grid (see Roberts et al. 2019). While the LDR configuration also implies grid efficiency (and optimization) (JEM consortium. 2.0. 2018; Fonteijn et al. 2019; Carreiro et al. 2017), these effects tend to be stronger for both storage configurations. Related research shows how Prosumage reduce energy usage and lower overall network peak demand, replaced by storage consumption (Keirstead 2007; Strengers 2013; Say et al. 2020). Resulting from the inverse relationship between per-storage unit fixed cost, and the level of storage, local (grid) efficiency may increase even more for CES solutions.

In contrast to Prosumage, CES implies a different network architecture where grid peak-demand decreases community-wide, with overall lower emissions (Müller/Welpe 2018; Roberts et al. 2019). Research also shows how CES leads to lower material usage and presents a much lower fire hazard (relative to Prosumage and non-existent for LDR) (Van Der Stelt et al. 2018). However, relative to Prosumage, community solutions require more complex setup and cooperation frameworks with district network operators (Müller/Welpe 2018). While CES implementation is more sensitive to subsidies than individual solutions, the effect is that the operation of CES requires a higher reliance on and engagement with existing infrastructure and (energy) regulatory frameworks (Roberts et al. 2019). LDR solutions also impact energy governance in that these enable households to take part in energy system decision-making at the micro-level (Calver/Simcock 2021, p. 12).

Due to the higher initial costs of community storage (see Müller/Welpe 2018), implementation barriers are the highest for the CES configuration. Under specific conditions, however, CES solutions offer local cost efficiencies compared to individual storage. Existing findings indicate that “in terms of price per energy capacity, the technology that brings the most capacity to market is likely to become the most cost-competitive” (Schmidt et al. 2017, p. 5). In this sense, other studies have shown that compared to prosumage, CES can lead to lower operational costs per household served (Kalkbrenner 2019; Müller/Welpe 2018; Parra et al. 2015; Parra et al. 2017; Terlouw et al. 2019) and offer increased efficiency in exporting back to the grid (Barbour et al., 2018), and larger (local) cost savings with fewer ressources usage (Gupta et al. 2019; Schram et al. 2020; Van Der Stelt et al. 2018). In a UK study, Parra et al. (2016) found that a 100-household CES can reduce levelized costs by 56% by shifting demand or 37% by performing PV energy time-shift compared to Prosumage (see also Roberts et al. 2019). Of course, LDR, by providing grid flexibility, may, in turn, offer reduced local costs with no individual or community investments (storage implementation, operational, and maintenance costs) (Carreiro et al. 2017; Eissa 2011; Fonteijn et al. 2019; JEM consortium. 2.0. 2018; Roberts et al. 2019). The comparison of all three configurations further shows that the financial risks for the end user are highest with Prosumage (O’Shaughnessy et al. 2018; Quoilin et al. 2016; Parra et al. 2016).

Regarding local social effects, recent studies of CES configurations show increased community self-sufficiency from the grid (up to 60% in some studies) (see Barbour et al. 2018; Roberts et al. 2019; Syed et al. 2020) and the potential to strengthen the sense of community. Recent German pilot projects show how both Prosumage and CES solutions could further empower local households (see Koirala et al. 2018) as well as engage multiple local and regional actors, increasing (social) cohesion (Kalkbrenner 2019).

Finally, while Prosumage and CES nurture a vision of local independence and supply security (Balcombe et al. 2014; Kalkbrenner 2019; Merei et al. 2016; Oberst/Madlener 2014; Oberst et al. 2019), LDR is accompanied by uncertainties about the fair distribution of benefits and costs (Fonteijn et al. 2019). Furthermore, LDR is highly dependent on end-user engagement in that users need to modify their energy consumption patterns in order for it to work (Palensky/Dietrich 2011). Indeed, Palensky and Dietrich (2011, p. 381) have observed that DSM solutions are changing from being “utility-driven” to being more “customer-driven”. According to several authors, demand response also requires end-user learning, which needs to be delivered through marketing and training (Darby/McKenna 2012), and there is a risk that it will negatively impact consumer comfort (Carreiro et al. 2017; Siano 2014). Risks relating to (individual) privacy are also crucial for any individual or community storage solutions. As currently no framework or standards exist, some authors raised concerns about privacy and data protection issues arising from CES (e.g., Müller/Welpe 2018) and Prosumage solutions (e.g., Schill et al. 2017).

INDIRECT SYSTEMIC EFFECTS

Turning now to systemic and infrastructure effects, existing studies and pilot projects show significant diverging effects for the three configurations; some findings, however, are still disputed. For example, the effects of each of the three configurations on power consumption and, thus, indirectly on the power grid are still relatively unclear. Some authors indicate that Prosumage solutions might reduce energy usage (Dobbyn/Thomas 2005; Keirstead 2007; Say et al. 2020). Conversely, others suggest that inefficiently set up individual home storage systems that optimize financial rewards for end-consumers might even increase energy consumption (Fares/Webber 2017). A high concentration of Prosumage in the distribution grid indeed leads to a range of systemic consequences, most of which are yet to be sufficiently investigated (see O’Shaughnessy et al. 2018).

Still, several studies show that Prosumage leads to higher self-consumption (Figgener et al. 2020; Luthander et al. 2015), which could subsequently unfold systemic effects. The result is less electricity being drawn from the transmission grid, especially in summer. However, since this effect is absent in winter, Prosumage presumably will have no significant impact on investments (cost savings) in the higher-level grid (Figgener et al. 2020; Schill et al. 2017). Studies on the systematic effects of CES, in contrast, show that one larger battery may contribute to the stability and flexibility of the local grid, with a lower likelihood of short-duration consumption peaks (Barbour et al. 2018), through increased round-trip efficiency (Roberts et al. 2019).

Moving on to further potential effects on the energy infrastructure, grid friendliness is not a logical consequence of Prosumage (Haberschusz et al. 2017). On the contrary, self-consumption optimization may lead to technical problems (Moshövel et al. 2015). Furthermore, appropriate incentives, regulatory conditions, or centrally controlled battery charging can also determine such improvements (Schill et al. 2017). However, Terlouw et al. (2019) caution that such infrastructure effects, especially in CES, must be weighed against potential risks for the existing transformer infrastructure due to capacity changes. Similar effects have hardly been researched for LDR, but there is some evidence that demand response can reduce transmission and distribution losses (Carreiro et al. 2017).

Compared to LDR, both battery storage configurations potentially deliver energy back to the grid, and some studies show the value of this energy is priced higher relative to standard energy due to the importance of rapid response (e.g., Gupta et al. 2019). Such price differences can further affect energy pricing within networks. Other studies focused on economic effects indicate that an electricity system mainly based on Prosumage would eventually lead to high system costs (Say et al. 2020; Schill et al. 2017). With significantly higher costs than, for example, a system that relies primarily on LDR (Graulich et al. 2018). Another related effect is the financing of the electricity infrastructure by end consumers. Under current tariff systems, Prosumage leads to distributional effects that tend to be regressive. End consumers without their own electricity generation would pay disproportionately more for maintaining the infrastructure (Quoilin et al. 2016; Schill et al. 2017; Gomes et al. 2020). Such distributional effects would similarly apply to CES but likely not to LDR.

Recent research also discusses various societal effects, which arise from the widespread use of a specific configuration. For example, a high number of Prosumage households could lead to new path dependencies and lock-ins (Schill et al. 2017; Spindler et al. 2018). Medium- to long-term, Schram et al. (2020) show how communities could even be price setters in electricity spot markets, potentially empowering local communities vis-à-vis the energy markets. In this regard, CES systemic effects are connected more broadly to the transition to sustainable energy systems. In this sense, van der Schoor and Scholtens, in an earlier study (2015), find that community initiatives (and CES, more specifically) are “emergent organizations”, which provide engagement opportunities and a shared vision enabling the low-carbon transformation of the overall energy system (Koirala et al. 2018). In the case of LDR, however, social implications do not feature prominently in the literature. Some earlier studies, however, have highlighted the large number of coordination required from a significant number of actors, which in turn may diminish the benefits of energy-saving (Darby and McKenna, 2012), as well as lead to risks relating to implementing a level playing field among actors involved (He at al., 2013).

WIDER SOCIETAL EFFECTS

Finally, there are apparent differences when considering the wider social implications of the three configurations. Prosumage would result in very high overall demand for batteries and thus also maximize the environmental impacts associated with the production and recycling or disposal of batteries (Luthander et al. 2015; Ren et al. 2021). These impacts would be lower for community batteries (e.g., Gupta et al. 2019; Schram et al. 2020; Van Der Stelt et al. 2018) and probably even lower in the case of LDR. Based on life cycle analyses, it is clear that individual stationary battery systems are only environmentally beneficial if they contribute to the further expansion of renewable generation systems (Fares/Webber 2017). This potential contribution is controversial for Prosumage but is considerably more feasible for community batteries (Koirala et al. 2018). However, the economic and environmental benefits are the highest when no batteries are installed, and the benefits increase with the increase of onsite PV generation (Ren et al. 2021). Thus, from an environmental perspective, LDR is likely to have the lowest impact. From the energy justice viewpoint, there is moderate evidence that DR can lead to more sustainable outcomes overall by providing opportunities for greater penetration of renewables (Calver/Simcock 2021, p. 12).

In economic terms, Prosumage tends to increase the competition in the energy market, helps to mobilize "cheap" private capital for the energy transition, and reduces the size of the traditional retail market (Schill et al. 2017). However, studies also show that so far, it is mainly households with over-average incomes that benefit from Prosumage (O'Shaughnessy et al. 2018).

Several authors suggest that Prosumage and CES may positively affect the overall acceptance of the energy transition and trigger other activities in this direction (Koirala et al. 2018; Luthander et al. 2015; Schill et al. 2017; Van Der Schoor/Scholtens 2015). Indeed, beyond providing effective means for energy system integration and grid flexibility, the two storage configurations may also engender new roles and responsibilities for local community actors (Koirala et al. 2018). On the other hand, several authors show how a substantially large number of individual solutions aiming at personal self-sufficiency would likely reinforce the trend towards individualization of society, in contrast to storage systems operated by local communities (Barbour et al. 2018; Terlouw et al. 2019). Other analyses also point to broader, non-economic effects, such as community-building in the case of CES solutions, through increased engagement (Koirala et al. 2018; Roberts et al. 2019). Similar findings are also reported in the case of LDR, where several authors argue that LDR may be a reliable strategy leading to the successful integration of renewable energy sources (Carreiro et al. 2017; Lisovich et al. 2010).

In addition, there is an important difference in social perceptions between the three configurations. A recent analysis of German PV adopters investigated the preferences for different system configurations. The authors found that consumers in Germany favour ownership over use rights (Kalkbrenner 2019), indicating positive attitudes towards both Prosumage and CES solutions. On the other hand, while autarky (or independence) can be a driver of adoption (e.g., Gährs/Knoefel 2020; Gährs et al. 2015; Khalilpour/Vassallo 2015; Oberst/Madlener 2014; Oberst et al. 2019), research shows that consumers are at the same time willing to give up control to provide for their communities (Kalkbrenner 2019). CES also differs from Prosumage in this sense as total autarky would not be economical, particularly as storage systems are still expensive (Kalkbrenner 2019; Khalilpour/Vassallo 2015). User engagement is also an essential dimension in the LDR configuration. While studies highlight the importance of the role of choice and the human dimension (e.g., Rieger et al. 2016), engagement between individuals and the broader energy system is arguably lower in the LDR case compared to the two storage configurations (as we discussed above, e.g., the storage infrastructure may change socio-economic patterns and relations between individuals, communities, and energy systems).

In summary, this brief overview of available evidence already shows that there are potentially very different effects and risks associated with the three configurations. For example, financial and other risks are distributed very differently among the local actors involved. Systemic effects have not yet been sufficiently researched, but significant differences can also be assumed here. In particular, the dynamic effects of broadly rolled-out Prosumage solutions can hardly be reliably estimated but can result in technical as well as social risks. Similarly, individual solutions versus collaborative approaches clearly point in different development directions. Concerning the broader societal consequences, empirically well-founded results show that overall, CES and LDR are more environmentally friendly than Prosumage. The evidence for several effects, such as for LDR, is only moderate or uncertain and will emerge provided more research is done or after the system roll-out (Calver/Simcock 2021).

6 CONCLUSIONS

In this article, we have proposed a framework to better explore the possible side effects and risks of innovation in the energy transition context. We have argued that such a framework would be able to provide for a better knowledge base for future energy policy decisions. There is increasing evidence that the transition of the energy system is currently entering a qualitatively new phase of development, which in turn requires a better basis for comparative research. More scientifically robust knowledge about the potential consequences and risks of new practices and technologies can make a significant contribution to opening up the political discourse and reducing the threat of technological fixes and new undesirable path dependencies.

In the paper, we have outlined several key elements for such a framework. We have assumed that side effects and risks are closely related to the intended main functions of technical solutions. Consequently, we have proposed to focus on socio-technical configurations, i.e., technologies in use with emergent properties that only arise through specific combinations of elements and relations between these elements. This theoretical approach is not new, but with a research focus on technology implications in the context of transition processes, it certainly breaks new ground. To ensure that empirical research is feasible, we have proposed to identify and describe typical configurations on a semi-generic level. This is to include the important context of use into consideration without running the risk that the number of alternatives to be compared would be too large. The requirement of analysing at least two alternative configurations in each case in direct comparison corresponds to the claim that policy-relevant research should rather broaden than narrow the options for decision-making (Pielke Jr 2007). For the same reason, the framework also argues for identifying new, hitherto missing configurations and integrating them into the analysis. This has not been achieved with the example presented. However, future studies in which more empirical data is collected directly (e.g., through expert interviews or in workshops) may be able to achieve such a result.

To further structure the analysis and reflect the systemic nature of transitions, three types of effects were defined: local effects and risks that arise in immediate spatial and functional proximity to the configurations under investigation, systematic effects and risks that only unfold due to dynamic processes in infrastructures or institutions, and wider societal effects and risks that may not arise directly through application and use but can occur at any point in the life cycle of the material and social elements involved. We have also provided a few methodological considerations, but this dimension of the framework needs to be further elaborated.

To demonstrate the framework, we have chosen the example of decentralised electricity production and the associated problem of integrating large amounts of volatile generation into local distribution networks. This topic is highly relevant in the context of the envisaged energy transition and an example of the technical, social and institutional challenges that will arise in this context in the near future. Three different socio-technical configurations were described, which are considered in the literature as potentially viable solutions. The subsequent literature-based exploration of the possible consequences and risks associated with each of these three configurations clearly showed that, despite similar basic functions for the local network, the possible implications can be expected to differ significantly in many respects.

It is clear that both the framework in its current form and the empirical example presented here show a number of shortcomings. An obvious conceptual weakness relates to the description and delineation of configurations, especially in terms of the selection of key elements and the importance of interlinkages between these elements, in order to identify typical or plausible implications and risks based on these descriptions. With regard to the available empirical material that has been evaluated, it has to be said that results have been obtained in very distinct contexts that could not be traced back sufficiently, which affects the validity of the findings. Another limitation that emerged in our case study relates to the availability of empirical data. Since consequences and risks are mainly assessed by empirical research (primary and secondary data), the approach in its current version is actually particularly suitable for technologies that are already being researched well enough in the context of use. Another point relates to the thematically wide-open empirical search for feasible implications. To focus on relevant implications regarding the advisory function of this type of research, methodological strategies from the field of TA are to be integrated into the framework. This should make it possible, after an initial gross analysis, to deepen selected topics in a problem-oriented manner in a second research phase (see Decker/Fleischer 2010).

In general, however, we believe that the proposed approach has the potential to enrich the discussion in interdisciplinary technology research. The context of use of technologies is taken into account, alternatives are systematically compared, and a broad basis for the design of technologies and institutional arrangements can be created. The framework is still at an early stage of development. More theoretical as well as empirical work is needed to prove its usefulness.

There are several points of departure for future research: The theoretical basis for identifying emergent properties of socio-technical configurations can be improved. The methodological concept must be detailed, and existing empirical methods for exploring side effects and risks must be refined for analysis. And finally, more extensive case studies with configurations in other areas of the energy system (and in other areas of technology) could produce robust empirical results for the first time and also allow further conclusions to be drawn to improve the research approach.

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