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CONTESTED FUTURES: HOW SCENARIOS AND EXPECTATIONS SHAPE THE ENERGY TRANSITION

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Summary

Tackling the climate crisis creates an increasing necessity for many countries to achieve system-wide transitions from fossil fuel based energy carriers to renewable energy sources, while maintaining a secure and affordable energy supply. The decisions required for the realisation of these energy transitions are associated with deep uncertainty and a range of interdependencies. Consequently, many energy system actors require credible knowledge about plausible consequences of potential decisions. Against this background, scenarios based on sophisticated computer models are used to support long-term strategic decisions in the energy sector. Energy scenarios, which often have a techno-economic focus, can highlight feasible transition pathways to compare intended and unintended consequences associated with multiple alternative energy futures.

Despite their key function in the climate-energy nexus, empirical evidence on how and by whom energy scenarios are used is rare. This dissertation addresses this research gap with five research contributions that explore whether and how energy system actors interact with energy scenarios. Three papers study how key energy system actors (namely fossil fuel companies, utilities and researchers) select, interpret and use energy scenarios. Two papers explore the publics' energy system expectations, assessing their relevance for the acceptability of energy policy and energy infrastructure as well as evaluating their compatibility with energy scenario projections. Thereby, this dissertation provides insights on the interdependency of formal and informal conceptualisations of the energy future shaping the energy transition.

An explorative research design, which essentially consists of in-depth interviews and surveys, was applied. Paper I shows that fossil fuel companies develop and promote those energy scenarios that portray a vision of the energy future that is desirable from their perspective. This tendency to use energy scenarios that are already well aligned with the corporate strategy can also be observed among utilities, which are studied in paper V. Most utilities are more likely to refer to energy scenarios projecting incremental changes to the energy system than to scenarios outlining radically different energy futures. Overall, however, for utilities using a variety of scenarios from different actors played a larger role for the selection of scenarios, as they perceived the diversity of perspectives provided by energy scenarios to be valuable. Paper II focuses on researchers, showing that also this actor group regularly refers to energy scenarios, for example to highlight the relevance of a particular research field or by using scenarios as a data source. Accordingly, researchers have a key role in the dissemination of energy scenarios. This is important because the authority of energy scenarios ultimately depends on their uptake

by relevant actors. The more actors adhere to a certain scenario and act accordingly, the more likely its projections become. Because public support is a key requirement for various aspects related to the energy transitions, it is important to know how the expectations of the public compare to the projections of energy scenarios. Paper III found that the publics' energy system expectations influence the acceptability of the energy transition as a whole, but not the acceptability of concrete energy technology deployment options. How expectations influence opinion-formation processes has so far predominantly been analysed in transition studies focusing on expert communities. This is why paper IV studied the publics' energy system expectations in more detail, identifying different expectation clusters that represent unique combinations of promises and concerns related to the energy future. These clusters differ in varying aspects and to dissimilar degrees from the scenario projections that informed the Swiss *Energy Strategy 2050.*

This dissertation empirically demonstrates that energy scenarios are not only used to project plausible future developments, but also to gather support, mobilise investment or connect actors in the present. While the content of energy scenarios is future-oriented, their main purpose is informing and influencing present-day actors. Developed by actors with contrasting interests, energy scenarios compete to shape the perceived feasibility and desirability of energy futures. Consequently, research on energy scenarios needs to move beyond the predominant focus on their analytical capacity to project techno-economic energy system characteristics. Instead, the social context and embeddedness of their use should be at the centre of future research trying to understand the purpose of energy scenario use and its relevance for the energy transition.

Zusammenfassung

Die Bekämpfung der Klimakrise schafft für viele Länder die zunehmende Notwendigkeit von fossilen Energieträgern auf erneuerbare Energiequellen umzusteigen und gleichzeitig eine sichere und erschwingliche Energieversorgung aufrechtzuerhalten. Die für die Realisierung dieser Energiewende erforderlichen Entscheidungen sind mit grossen Unsicherheiten und einer Reihe von Abhängigkeiten verbunden. Viele Akteure des Energiesystems benötigen daher glaubwürdiges Wissen über plausible Folgen möglicher Entscheidungen. Vor diesem Hintergrund werden im Energiesektor Szenarien auf Basis ausgefeilter Computermodelle eingesetzt, um langfristige strategische Entscheidungen zu unterstützen. Energieszenarien, die oft einen technoökonomischen Fokus haben, können mögliche Wege in eine nachhaltige Energiezukunft aufzeigen, wodurch beabsichtigte und unbeabsichtigte Folgen mehrerer alternativer Energiezukünfte miteinander verglichen werden können.

Trotz ihrer Schlüsselfunktion im Grenzbereich zwischen Klima und Energie sind empirische Erkenntnisse darüber, wie und von wem Energieszenarien genutzt werden selten. Diese Dissertation befasst sich in fünf Forschungsbeiträgen mit dieser Forschungslücke und untersucht, ob und wie verschiedene Akteure mit Energieszenarien interagieren. Drei Forschungsbeiträge untersuchen jeweils wie Öl- und Kohlefirmen, Energieversorgungsunternehmen und Forscher Energieszenarien auswählen, interpretieren und nutzen. In zwei Beiträgen werden die Erwartungen der Öffentlichkeit an das Energiesystem untersucht, deren Relevanz für die Akzeptanz von Energiepolitik und Energieinfrastruktur bewertet und ihre Kompatibilität mit den Projektionen von Energieszenarien beurteilt. Dadurch liefert diese Dissertation Einblicke in die Wechselwirkung von formellen und informellen Konzeptualisierungen der Energiezukunft welche die Energiewende prägen.

Es wurde ein exploratives Forschungsdesign angewandt, das im Wesentlichen aus Interviews und Umfragen besteht. Forschungsbeitrag I zeigt, dass fossile Energieunternehmen vor allem jene Energieszenarien entwickeln und verbreiten, die eine aus ihrer Sicht wünschenswerte Vision der Energiezukunft darstellen. Diese Tendenz zur Nutzung von Energieszenarien, die bereits gut auf die Unternehmensstrategie abgestimmt sind, lässt sich auch bei Energieversorgern beobachten, welche in Forschungsbeitrag V untersucht werden. Die meisten Energieversorger beziehen sich eher auf Energieszenarien, die schrittweise Veränderungen des Energiesystems projizieren, als auf Szenarien, die radikal unterschiedliche Energiezukünfte skizzieren. Insgesamt spielt jedoch für Energieversorgungsunternehmen die Verwendung mehrerer Szenarien von verschiedenen Akteuren bei der Auswahl der Szenarien eine größere Rolle, da sie die Vielfalt der Perspektiven, welche die

Energieszenarien bieten, als wertvoll empfinden. Forschungsbeitrag II analysiert wie Forschende Energieszenarien nutzen und zeigt, dass sich auch diese Akteursgruppe regelmäßig auf Energieszenarien bezieht, beispielsweise um die Relevanz eines bestimmten Forschungsbereichs hervorzuheben oder um Szenarien als Datenquelle zu nutzen. Dementsprechend kommt Forschern eine Schlüsselrolle bei der Verbreitung von Energieszenarien zu. Dies ist wichtig, weil die Autorität von Energieszenarien letztendlich von ihrer Rezeption durch die relevanten Akteure abhängt. Je mehr Akteure sich an einem bestimmten Szenario orientieren und entsprechend handeln, desto wahrscheinlicher werden dessen Projektionen. Da die öffentliche Unterstützung eine zwingende Voraussetzung für viele Aspekte der Energiewende ist, ist es wichtig zu wissen, wie die Erwartungen der Öffentlichkeit an die Energiezukunft im Vergleich zu den Projektionen von Energieszenarien stehen. In Forschungsbeitrag III wurde festgestellt, dass die Erwartungen der Öffentlichkeit an die Energiezukunft zwar die Akzeptanz der Energiewende als Ganzes beeinflussen, nicht aber die Akzeptanz konkreter Ausbauoptionen von Energietechnologien. Inwiefern Erwartungen Meinungsbildungsprozesse beeinflussen wurde bisher überwiegend in Studien mit Fokus auf Expertengemeinschaften analysiert. Forschungsbeitrag IV untersuchte deshalb die Erwartungen der Öffentlichkeit an das Energiesystem genauer und identifizierte verschiedene Erwartungsmuster, welche ganz bestimmte Kombinationen von Versprechungen und Bedenken die im Zusammenhang mit der Energiezukunft stehen darstellen. Diese Erwartungsmuster unterscheiden sich in unterschiedlichen Aspekten und in unterschiedlichem Ausmass von den Projektionen der Energieszenarien welche der Schweizer *Energiestrategie 2050* als Basis dienten.

Diese Arbeit zeigt empirisch, dass Energieszenarien nicht nur dazu genutzt werden, plausible zukünftige Entwicklungen zu projizieren, sondern auch um in der Gegenwart Unterstützung zu gewinnen, Investitionen zu mobilisieren oder Akteure zu verbinden. Während die Inhalte von Energieszenarien zukunftsorientiert sind, geht es schlussendlich immer darum, heutige Akteure zu informieren und auch zu beeinflussen. Die von Akteuren mit unterschiedlichen Interessen entwickelten Energieszenarien konkurrieren damit um die Definition welche Energiezukunft machbar und wünschbar ist. Folglich muss die Erforschung von Energieszenarien über den vorherrschenden Fokus auf ihre analytischen Fähigkeiten zur Projektion technoökonomischer Energiesystemeigenschaften hinausgehen. Stattdessen sollte die Einbettung ihrer Nutzung in soziale Prozesse im Mittelpunkt zukünftiger Forschung stehen, um den Zweck der Nutzung von Energieszenarien und deren Relevanz für die Energiewende schlussendlich besser verstehen zu können.

Remarks

This is a cumulative dissertation consisting of five original and independent research contributions. Paper I, II and III are published in peer-reviewed journals and conference proceedings, contribution IV is under review (minor revisions) and contribution V is in preparation to be submitted. An overall introduction highlights their commonalities and introduces the reader to a broader overview of the context in which the papers are embedded. A concluding chapter wraps up the main findings. The papers were adapted in their formatting to allow consistency in numeration throughout the dissertation. The content of the publications has been included without changes. As the papers were aimed at reaching different research communities, the writing style may vary accordingly.

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1 Introduction

1.1 Context and motivation

To limit global average warming to less than 2ºC, as agreed at the 21st Conference of the Parties in Paris, many countries need to significantly reduce greenhouse gas emissions (UNFCCC, 2015). Currently, emissions resulting from energy generation and use are the biggest sectoral contributor to anthropogenic climate change, which is why achieving a sustainable energy transition is crucial for mitigating climate change (International Energy Agency, 2019). In the next few decades, the energy systems of most industrialized countries accordingly need to transition from fossil fuel based energy carriers to renewable energy sources (Berger et al., 2017; Grubler et al., 2018; Rogelj et al., 2018).

Energy is a basic requirement for the functioning of societies and many human activities are tightly interwoven with particular types of energy use and technologies, as exemplified by the mobility or heating sector (Lund, Möller, Mathiesen, & Dyrelund, 2010; Mitchell, Borroni-Bird, & Burns, 2010). The co-evolution of energy technologies and energy infrastructure with social, economic and political systems led to considerable interdependencies (Geels, 2004). Changes to the energy system thus typically involve numerous intended and unintended effects (Jenkins, McCauley, Heffron, Stephan, & Rehner, 2016; Miller, Richter, & O'Leary, 2015). This complexity is often referred to as the *Energy Trilemma*, since it is challenging to address energy security, energy equity, and environmental sustainability simultaneously (Heffron, McCauley, & Sovacool, 2015).

Investments in energy infrastructure are typically capital-intensive long-term commitments with extended periods of amortization, subject to a range of inherent uncertainties (Meijer, Koppenjan, Pruyt, Negro, & Hekkert, 2010; Pye, Sabio, & Strachan, 2015; Soroudi & Amraee, 2013). Consequently, energy system actors have developed sophisticated tools, often referred to as energy scenarios, to support decision-making processes (Söderholm, Hildingsson, Johansson, Khan, & Wilhelmsson, 2011). While no universal definition exists, Guivarch, Lempert, and Trutnevyte (2017, p. 201) have described scenarios as "plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces".

The fossil fuel company *Royal Dutch Shell* (Shell) is well known for its pioneering role in using scenarios to challenge its corporate strategy by imagining discontinuities in the global energy supply (Cornelius, Van de Putte, & Romani, 2005). The development of scenario-based strategies helped the company to manage the oil crises in the 1970s better than its relatively unprepared competitors (Jefferson, 2012). Nowadays, various energy system actors such as government agencies, research institutions, non-governmental organisations (NGOs) or utilities use scenarios to project the effects of potential decisions on the development of future energy systems or its consequences on the economy and society (see Densing, Panos, & Hirschberg, 2016 for an overview of Swiss energy scenarios). Scenarios have become the key element of future-oriented analysis in the energy sector (Carrington & Stephenson, 2018; Chiodi et al., 2015).

Although scenarios belong to the most influential policymaking tools in the energy sector, relatively little is known about their potential uptake by various energy system actors (Garb, Pulver, & VanDeveer, 2008; Hughes, 2013). This dissertation addresses this research gap by focusing on how external users, referring to users that are not involved in the scenario development process, interact with energy scenarios. Four energy system actors that have different roles in the energy system, varying competencies and hence dissimilar interests, are studied. These are fossil fuel companies, researchers, utilities and the public.

Empirically studying whether and how these actors select, interpret and use energy scenarios or are indirectly influenced by them is important because scenarios represent the multiple and sometimes contrasting actor perspectives on the energy transition. Despite their techno-economic focus, energy scenarios are not purely analytical tools used to project confined choices among technologies or fuels. Instead, energy scenarios depict what kind of sociotechnical future is both feasible and desirable (Delina & Janetos, 2018). As there is no single techno-economic truth, each scenario constitutes a different but valid actors-specific vision of the future energy system and pathways towards it (Sovacool & Brown, 2015; Trutnevyte, 2014). Energy scenarios thus implicitly or explicitly define what user practices, risks and benefits, and social behaviours are encouraged, excluded or regulated in future energy systems (Tozer & Klenk, 2018).

The authority of energy scenarios ultimately depends on their uptake by the relevant actors. The more actors adhere to a certain scenario and act accordingly, the more likely its projections become (Dieckhoff, 2015; Grunwald, 2011). In other words, scenarios are not only projecting, but also shaping the future through the expectations they create. Accordingly, the credo of looking *at* the future instead of *into* the future was the fundamental principle of this dissertation.

1.2 Dissertation structure

This dissertation is structured as follows: Section 1.3 provides background information on energy scenarios and describes what differentiates them from scenarios in other fields. Section 1.4 synthesizes the empirical evidence on the use of scenarios. Section 1.5 introduces the research framework provided by the *Sociology of Expectations*, which guides the research presented in this dissertation. Section 1.6 outlines the guiding research questions and describes how the five papers relate to them. In chapters 2 - 6, the five papers are presented. In chapter 7, the implications of the results gained from these contributions are discussed and propositions for future research are presented. A final discussion sums up the most relevant points.

1.3 History and background of energy scenarios

Scenarios as a strategic planning tool originated in the military context as *war games* during the 19th century. During the Cold War period, scenarios were taken up by the *RAND Corporation* (an acronym for Research and Development), a research group that primarily conducted defence management studies for the US Air force (Raskin et al., 2005). Herman Kahn, who left the *RAND Corporation* at the beginning of the 1960s, coined the term *scenario* in his 1967 book *The Year 2000: A Framework for Speculation on the Next Thirty-Three Years* (Kahn & Wiener, 1967). The *Limits To Growth* report, that was published by the *Club of Rome* in 1972, is often seen as counter study which further popularized scenarios as an approach to structure thinking about possible futures (Bradfield, Wright, Burt, Cairns, & Van Der Heijden, 2005; Meadows, Meadows, Randers, & Behrens, 1972).

In the business context, *Shell* was the first company to recognise that scenarios provided a more appropriate framework for engaging with the long-term future than predictive forecasts, which had repeatedly failed to enable robust strategies in the face of abrupt discontinuities (Wack, 1985a). *Shell* scenarios are often credited to have initiated the Anglo-American branch of scenario planning, which is sometimes also referred to as the *intuitive logics* scenario school (Chermack, Lynham, & Ruona, 2001; Ramírez & Selin, 2014). Since then, scenario use has spread not only to the fields of energy and climate, but also to the insurance, aviation or finance industry, as well as land use planning and environmental assessment (Bishop, Hines, & Collins, 2007; Weyant, 2017).

In the course of this diffusion, scenario techniques have continuously been adapted and occasionally merged with a plurality of related approaches, such as the French scenario school, which is usually putting a larger emphasis on trend-based extrapolation (Spaniol & Rowland, 2018). Accordingly, a heterogeneous mix of practises to explore the implications of alternative futures and develop strategies that are viable under a variety of those futures is recognised as scenario analysis today (Kosow & Gaßner, 2008; Schoemaker, 1995). Despite several attempts at differentiating the type (e.g. simulation, optimisation or backcasting) or the purpose (e.g. explorative, normative or predictive) of scenario use (see Van Notten, Rotmans, Van Asselt, & Rothman, 2003; Wilkinson & Eidinow, 2008 for an overview), the field is sometimes referred to as a methodical chaos (Bradfield et al., 2005). This is because conflicting definitions (Spaniol & Rowland, 2019 list 77 different definitions) and techniques exist (Chermack, 2019; Wright, Cairns, & Bradfield, 2013).

In the energy sector, a specific form of predominantly normative scenarios has been established. Contemporary energy scenarios are characteristically based on computer-assisted energy system models

(Keppo & Strubegger, 2010). Energy models are idealised representations of parts of the energy system, consisting of data, assumptions and code (Pfenninger, Hawkes, & Keirstead, 2014). A scenario study or report typically includes multiple scenarios that follow an identical energy model paradigm, but vary in specific assumptions. These variations enable a holistic analysis of the effects and sensitivities of the energy system towards particular developments, for example changes in energy demand or technology costs. A key contrast to probabilistic foresight methods is that scenarios do not specify likelihoods. Following a *what-if* logic, every scenario describes a unique, and often very detailed, combination of assumptions about the future.

As every energy model is designed to answer specific questions, model choices have profound impacts on the type of analyses and insights energy scenarios can provide (Wilson, Grubler, Bauer , Krey, & Riahi, 2013). One example is the distinction between bottom-up and top-down energy models (van Vuuren et al., 2009). Bottom-up models are suitable to describe technological developments, while top-down models focus on macroeconomic effects. The suitability of modelling paradigms for particular policy questions is a controversial topic, as it can directly influence what actions seem most adequate (Chiodi et al., 2015; Karjalainen, 2014). Among the energy modelling research community, there are continuous efforts to improve the accuracy of energy models and their representation of energy systems. These efforts for example concern the use of meaningful discount rates (Cochran, Mai, & Bazilian, 2014), the application of national investment costs in relation to universal costs (Egli, Steffen, & Schmidt, 2019), or downscaling from global to national or local levels (Ahn, Woo, Wagner, & Yoo, 2019).

These examples show that the efforts to improve energy scenarios are primarily directed towards their technical axis and underlying models. Due to continuous research efforts and simultaneous advances in computational power, both the capabilities and the complexity of energy models increased significantly over the last decades. For Garb et al. (2008, p. 1) this lead to a "growing imbalance between the increasing technical sophistication of the modelling elements of scenarios and the continued simplicity of our understanding of the social origins, linkages, and implications of the narratives to which they are coupled." It is only recently that research on the social aspects of scenario development and use is taking up. Ellenbeck and Lilliestam (2019), for example, have shown that many modelling choices are contingent on the perspective and subjective judgement of scenario developers. Similarly, in a retrospective analysis of UK energy scenarios, Trutnevyte, McDowall, Tomei, and Keppo (2016) highlighted that energy scenarios tend to mirror the key concerns of their time, while underestimating the possibility for radically different futures. Marvin (1988, pp. 189-190) described this as "the tendency of every age to read the future as a fancier version of the present." Hence, energy scenarios are clearly not entirely analytical constructs following completely rational modelling paradigms, but also social constructs. This is exemplified by the fact that while energy models primarily rely on insights from engineering, economics or physics, they can also integrate insights from psychology, sociology or history to varying degrees (Herbst, Toro, Reitze, & Jochem, 2012). In the following paragraph, the empirical evidence on the use of scenarios is summarized, indicating that also their uptake is deeply embedded in social settings.

1.4 Empirical evidence on the use of scenarios

Studies retrospectively analysing the performance of publicly available energy scenarios conclude that they are inevitably inaccurate as they fail to account for pivotal events. These studies mainly focus on leading scenario developers that publish reports on a regular basis, such as the International Energy Agency (IEA), the US Energy Information Administration (EIA) or the World Energy Council (WEC) and have predominantly been carried out at the beginning of the 2000s (Bezdek & Wendling, 2002; Koomey, Craig, Gadgil, & Lorenzetti, 2003; Linderoth, 2002). Since then, scenario developers have reiterated that scenarios are not forecasts and should not be treated as such. Consequently, the critique has shifted more towards the effects these scenario projections can have. For instance, there is the debate whether scenarios from the IEA, an organisation that was established to secure the fossil fuel supply to its member states during the oil crisis, systematically downplays the relevance of new renewables in their annual *World Energy Outlook* (Carrington & Stephenson, 2018; Gaede & Meadowcroft, 2016; Mohn, 2020).

However, whether the shift from predictive forecasts to the consideration of multiple futures that are equally likely is as thoroughly recognised by scenarios users as it is stressed by scenario developers, is unclear. What is evident is that this key feature of scenario analysis stands in contrast to more conventional, mostly predictive or probabilistic, decision-support mechanisms decision-makers are usually more familiar with (Moallemi & Malekpour, 2018). Nevertheless, studies focusing on the use of scenarios are rare. Schnaars (1987) provided a first review of scenarios use, concluding that little is known about how users interact with scenarios and that the available information comes from three main sources: First, case studies written by scenario practitioners that unsurprisingly tend to be biased towards successful applications praising the benefits of scenario use. Second, scenario user guides and best practice collections published by the future research literature that is assuming user needs and competencies instead of empirically testing them. Third, rare studies from researchers that do actually provide empirical evidence of scenario use. Since this assessment by Schnaars, several decades have passed and scenarios have arguably not declined in popularity (Spaniol & Rowland, 2018). Yet, empirical evidence describing the actual use of scenarios is still rare in general and even more so in the field of energy (Garb et al., 2008; Hughes, 2013; O'Brien & Meadows, 2013). This is at least partly caused by the predominantly corporate history of energy scenarios, which has limited their application to organisations that were under no obligation to share their experiences and findings (Pfenninger, 2017).

Reviewing the empirical evidence of the use of scenarios in general, across the various fields in which they have been applied, suggests that a few key principles determine the relevance and quality of scenarios from a user perspective. First, scenarios are predominantly used by large corporations and institutions active in capital-intensive industries with long planning horizons (Linneman & Klein, 1983; Malaska, 1985; Paltsev, 2016). However, connecting the use of scenarios to practical decisions is often challenging (Gordon, 2019; Parson, 2008). Analysing the public policy environment, Volkery and Ribeiro (2009) are able to show that scenarios are extremely valuable for opinion-formation processes in the early stages of policy development. Second, it has been shown that participation in the scenario development process is vital for understanding how scenario-based insights originate, what key assumptions constitute them, or what aspects have been considered to be out of scope for a particular analysis (Ernst, Biss, Shamon, Schumann, & Heinrichs, 2018; Volkery, Ribeiro, Henrichs, & Hoogeveen, 2008). This capability to contextualise scenario results is widely regarded as a key requirement for making meaningful decisions when using scenarios as a source of information. An iterative dialogue and feedback mechanisms between scenario developers and users is thus often assumed (Berkhout & Hertin, 2002; Kok, van Vliet, Bärlund, Dubel, & Sendzimir, 2011; Moallemi & Malekpour, 2018). Third, a collaboration of participants with different disciplinary backgrounds in the scenario development process is considered to be an important benefit, as it can reduce framing and overconfidence biases, and lead to the consideration of high-impact-low-probability events that are all too often neglected in settings with more homogenous participant backgrounds (D. Johnson & Fowler, 2011). Fourth, there is the idea the use of scenarios constitutes learning experiences that can lead to improvements in decision quality in the long term (Börjeson, Höjer, Dreborg, Ekvall, & Finnveden, 2006; Lempert, Hoorens, Hallworth, & Ling, 2008; Meissner & Wulf, 2013).

Hence, the available empirical evidence suggests that the social exchange that is typically associated with scenario development and use can influence the quality and relevance of scenarios just as much as the resulting scenario products. Yet, it is a typical characteristic of energy scenarios that scenario developers are not the ones using the scenarios to take decisions. This separation between energy scenario developers and users can even be traced back to the case of *Shell*, where the scenario development department was essentially providing insights to the executive board members who ultimately took the decisions (Schwartz, 2012; Wack, 1985a, 1985b). As long as scenarios primarily functioned as internal decision-making support tools, scenario developers and users were at least part of the same organisation following similar objectives, which enabled the integration of user feedback in subsequent scenario iterations (O'Brien & Meadows, 2013). However, the increasing sophistication of energy models has led to the professionalization and specialization of the experts developing and adjusting them, which are commonly referred to as *modellers*. Today, highly specialised foresight agencies, that frequently have a consulting or research background, are commissioned to develop energy scenarios for both public and private organisations (Strachan, Fais, & Daly, 2016). Therefore, many energy system actors expected to use scenario-based information are completely detached from the scenario development process, which is why Pulver and VanDeveer (2009) propose to distinguish between internal and external scenario users.

How external users select and interact with energy scenarios is largely unknown. Despite the complexity of model-based scenarios, it is commonly assumed that energy scenarios are applied in accordance with the key characteristics of scenario methodology and in acknowledgment of specific modelling choices. Furthermore, it is unclear whether the benefits linked to the social aspects of scenario use are applicable to external scenario use contexts. What is clear is that energy scenarios are no longer confined to technocratic and secretive industries taking decisions behind closed doors. To be transparent and to legitimise decisions, many countries have started to reveal the information sources of their energy system planning more generally, which in many cases results in the publication of energy scenarios (e.g. Lehr, Nitsch, Kratzat, Lutz, & Edler, 2008; Lund & Mathiesen, 2009; Prognos, 2012). Even fossil fuel companies nowadays promote their scenarios publicly, for example through webinars attracting thousands of viewers (Royal Dutch Shell, 2019). External types of scenario use can thus be assumed to become increasingly prevalent.

Because of this, there have been first attempts recently to study the interaction of the public with energy scenarios. In an experimental setting focusing on non-experts, it was found that pre-defined pathways of energy scenarios create strong framing effects that influence scenario users' energy technology mix preferences (Demski, Spence, & Pidgeon, 2017). Studies with a comparable research design observed similar framing effects, but found inconclusive evidence whether these disappear over longer time periods as the preferences sometimes revert to their initial position (Dubois, Holzer, Xexakis, Cousse, & Trutnevyte, 2019; Volken, Xexakis, & Trutnevyte, 2018). However, what kind of actors actually use scenarios in reality, for what kind of purpose they are used and in what kind of opinion-formation or decision-making context their use is embedded, are barely researched topics. The following chapter, introducing the perspective provided by the *Sociology of Expectations*, outlines why a more holistic assessment of energy scenarios and their potential influence on external users is adequate when addressing this research gap.

1.5 Contested futures and the Sociology of Expectations

Many social scientists argue that human activities are intrinsically oriented towards the future. Giddens (1998) for example claimed that a pronounced future orientation is a defining characteristic of contemporary societies. In pre-modern societies, the relationship to the future was defined by the theistic dogma of preserving the natural order of things. In the modern world, divine agency is substituted by human agency. A prominent example of this understanding is *La Prospective*, a French scenario development school founded in the late 1950s by the philosopher Gaston Berger, which is often regarded as a counterpart to the more explorative scenario development paradigms that were developed around the same time in the US. *La Prospective* intended to link scenarios to policymaking processes, such as the five year French National Plans. For *La prospective* the key purpose of scenarios is not to project possible futures, but to shape the future. The notion that scenarios and other forms how the future can be imagined take on a form of agency that affects and guides present-day actors is called *performativity* (Skjølsvold, 2014). If the future can be shaped, then actors in the present are subject to constant competitive pressures that force them to occupy favourable positions in the future. This competition for influence on future developments has been termed *contested futures* (Brown & Rappert, 2017). For Grunwald (2011), scenarios and other future-oriented products are the conflict fields of modern, pluralistic societies. which is evident in the energy sector, where the beneficiaries of the existing sociotechnical regime compete with those who seek to profit from new opportunities (Geels, 2014).

The *Sociology of Expectations*, which is a branch of Science and Technology Studies (STS), studies the role of the future in the context of transitions. The analyses are often related to technology developments and over the years a conceptual vocabulary to highlight the relevance of future-oriented products and ideas for transitions has been established (Borup, Brown, Konrad, & Van Lente, 2006; Van Lente, 2012). The key insight provided by the *Sociology of Expectations* is that for innovation to occur in relatively stable sociotechnical systems, future-oriented beliefs that are shared by relevant actors are needed. At an informal and individual level, such future-oriented beliefs are called expectations. Eames, Mcdowall, Hodson, and Marvin (2006) defined expectations as fragmented beliefs about the future that typically occur in the form of promises or concerns. Promises are optimistic expectations outlining the assumed benefits of a development or technology, whereas concerns are about potential risks and shortcomings (Te Kulve, Konrad, Palavicino, & Walhout, 2013). When expectations are shared and formalised by a selected group of stakeholders, they become a vision (McDowall & Eames, 2006). Visions are normative depictions of alternative futures explicitly intended to guide long-term action by mobilising the intellectual, financial, or political resources needed for their realisation (Trutnevyte, 2014; Uhl, 2012; Volkery et al., 2008). Visions are often the result of scenario workshops or other foresight activities that allow them to be formalised and communicated (Eames et al., 2006). This exemplifies the constructivist nature and interdependency of visions, expectations and scenarios, which is illustrated in Figure 1.

Scenarios can thus be understood as formalised, but socially constructed, expert expectations that support or reject a specific vision of the energy future. Scenarios or promises and concerns derived from scenarios can in turn influence expectations. Bakker, Van Lente, and Meeus (2011) refer to this as the *arena of expectations*. Only the most widely accepted and shared expectations, often referred to as collective expectations, become part of a generalised. but nonetheless informal, social repertoire (Konrad, 2006; Truffer, Voß, & Konrad, 2008). Individual expectations can be more or less in line with an overarching vision, which constitutes the *interpretative flexibility* of visions (Borup et al., 2006). This allows visions to encompass a range of actors with various interests. Lilliestam and Hanger (2016) have shown that even visions for a 100% renewable energy future can differ significantly, for example whether proponents expect a central or decentral energy system. Likewise, Eames et al. (2006) showed that the promises and concerns associated with the visions of the hydrogen economy diverge significantly among experts. Studies on hype and disappointment cycles have examined these dynamics between informal expectations and the content of formalised visions in more detail (Van Lente, Spitters, & Peine, 2013).

Jasanoff and Kim (2015) use the term *sociotechnical imaginaries* to highlight the interrelation between social and technological aspects of visions. Broadly speaking, the concept of *sociotechnical imaginaries* considers how visions shape policy settings, infrastructures and social norms. Understanding the functionality of visions can illuminate how technological path-dependencies or even lock-ins of the dominant sociotechnical regime can be overcome. The performative power of visions and expectations have been recognised as an important factor in processes of technological change. This is exemplified by the literature on the hydrogen economy (McDowall & Eames, 2006), nano- (Selin, 2007) or biotechnology (Tutton, 2011).

The *Sociology of Expectations* can thus provide a helpful conceptualisation of energy scenarios and their potential effects on external users that goes beyond their analytical quality of providing projections. This is in accordance with Brown and Michael (2003, p. 4) who emphasize the need "to engage with the future as an analytical object, and not simply a neutral temporal space into which objective expectations can be projected." In particular, *the Sociology of Expectations* enables assessing the influences of energy scenarios that are not immediately linked to specific actions or decisions, but frame people's conceptions and understanding of the energy system more generally.

Figure 1. The social construction and interdependency of expectations, scenarios and visions.

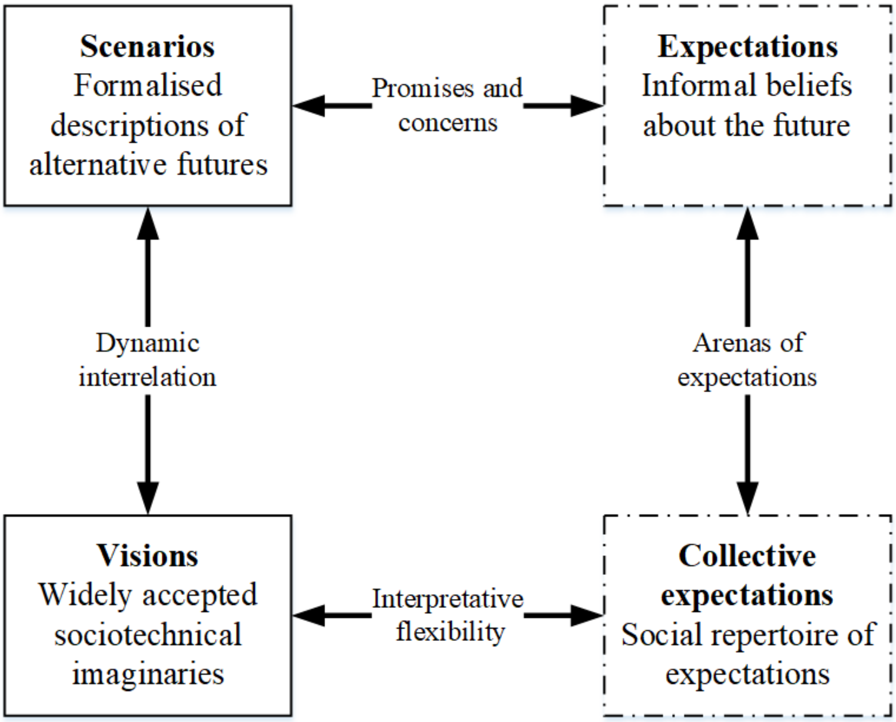

Figure 1. The relationship between informal (individual and collective expectations) and formal (scenarios and visions) conceptualisations of the future, adapted from Konrad (2006).

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1.6 Research framework

1.6.1 Research questions

As described in section 1.4, there is to date little academic literature on whether and how energy system actors interact with model-based energy scenarios. Moreover, studies that consider energy scenarios from a user perspective mostly focus on scenario use types with strong collaborations between developers and users. Against this background, this dissertation focuses on external scenario users and asks the following research questions:

1. For what purpose do actors that are not involved in the scenario development process use energy scenarios?

2. How do external users select energy scenarios from the variety of existing studies?

3. Are energy system expectations affecting opinion-formation processes and how do these expectations compare to energy scenario projections?

1.6.2 Conceptual overview

This dissertation tries to highlight the direct effects energy scenarios can have on external users as well as their more indirect effects through the framing of expectations or the formation of visions. To address the three distinct but connected research questions, an explorative approach that consists of conducting and analysing semi-structured expert interviews and surveys was chosen. Four different energy system actors, namely fossil fuel companies, researchers, utilities and the public, are studied. All these actor groups have different roles in the energy system and can thus be expected to have varying modelling competencies and interests related to the use of scenarios. Figure 2 shows how the papers relate to each other and what aspects of the scenario or expectations lifecycle, which is derived from the *Sociology of Expectations*, they address.

Figure 2. Conceptual overview of research framework and research papers.

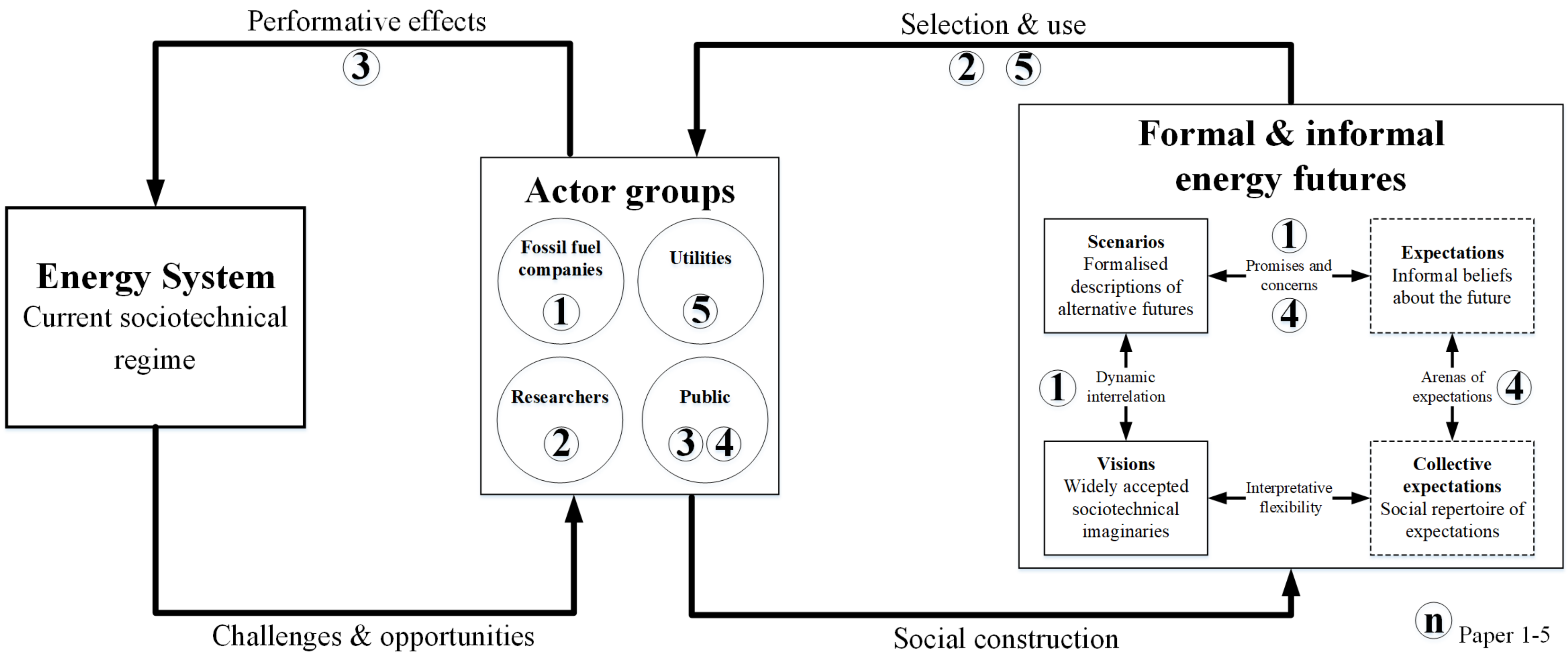

Figure 2. Conceptual overview of the social construction of energy futures and its performative effects on the energy system. Figure adapted from Grunwald (2011) and Konrad (2006). Numbers refer to the five papers, which focus on particular energy system actors and their interaction with scenarios or expectations respectively.

1.7 Research contributions

1.7.1 Paper I - Corporate CCS development perceptions

The first paper focuses on scenario use by fossil fuel companies, which do not only belong to the largest contributors to climate change, but also to the most capital-intensive organisations in the world with a lot of agency to develop and promote visions of the energy future. An interview series with high-level carbon capture and storage (CCS) experts from major multinational coal, oil and gas companies was conducted. The paper shows that fossil fuel companies strategically developed and referenced scenarios with high shares of CCS to promote the technology as a cost-efficient solution to the climate crisis. CCS enables so-called negative emissions, on which many optimisation models depend to reach climate targets. For years, unprecedented technology deployment rates were projected for CSS. Out of the 90 1.5°C-warming scenarios assessed in the latest IPCC report, 88 assume some level of net negative emissions (IPCC, 2018), indicating the relevance of CCS technology for global emissions reduction efforts. The promise of a technological fix that would leave the fossil fuel industry with its large workforce intact is attractive to policymakers, which is why many governmental institutions such as in the UK, Norway, or the EU opted to support CCS pilot- and R&D projects. However, the interviews show that the expectations of the corporate CCS representatives did not match this vision of an imminent large-scale CCS deployment. In fact, none of the interviewees expected that CCS would be deployed in accordance with scenario-based projections such as made by the IEA or even their own company. This finding is remarkable because experts are typically known to be overly optimistic regarding the field or technology they are involved in (Nemet, Anadon, & Verdolini, 2017). Instead, interviewees stressed the importance of promoting CCS as a strategic manoeuvre to weaken the link between the fossil fuel industry and climate change. Hence, contribution I exemplifies that particular scenarios can strengthen a vision of the future energy system that is desirable from a specific actors' point of view and that the uptake of energy scenarios is contingent on their compatibility with user interests.

1.7.2 Paper II - How researchers use energy scenarios

Paper II focuses on researchers, who have an important function in disseminating scenario-based insights and can thus act as filters or multiplicators for particular scenarios and associated visions of the future energy system. We show that there are two archetypical scenario users among energy researchers, which we labelled *sailors* and *divers*. *Sailors* are interested in the results of scenario studies that outline a specific vision of the energy future. Typically, *sailors* refer to these visions to highlight the relevance of personal research efforts. *Divers* mostly screen model characteristics, data and assumptions to extract them for own research or modelling activities. In contrast to what is commonly assumed, we demonstrate that the type of scenario use is not related to the disciplinary background of researchers, but rather to the specific purpose of scenarios use. Furthermore, we observe that many users use the reputation of the publishing institution as a heuristic to evaluate the credibility of a scenario study. Overall, researchers use energy scenarios similarly to how they use other sources of information, which sometimes clashes with the hypothetical nature of energy scenarios and can lead to misinterpretations of scenario content.

1.7.3 Paper III - Role of future-oriented beliefs for energy transition support

In Paper III, we studied the public acceptability of the energy transition as a whole, as well as hydropower and deep geothermal energy in particular. In addition to many factors known to be influencing technology and policy preferences, our survey among German speaking Swiss residents also included a range of items addressing the relevance of future-orientation. On the one hand, our survey included an explorative set of techno-economic energy system expectations, formulated in the form of distinct promises and concerns. These energy system expectations address issues that are typically also projected in energy scenarios. On the other hand, we included the 12-item *Consideration of Future Consequences* (CFC) scale, which measures how much relevance survey participants assign to the distant future in their present-day decisions. We are able to show that the energy system expectations as well as the CFC scores affect the acceptability of the energy transition. Hence, expectations of non-experts have performative effects on the development of the energy system. However, the relevance of future-orientation was not observed for the acceptability of energy technologies, for which more specific technology perceptions are crucial. From the perspective of the *Sociology of Expectations*, the observed importance of energy system expectations for the acceptability of an energy transition could be explained by the *interpretative flexibility* of this broad and overarching goal. Once possible technologies that are required to achieve this goal are discussed, the contrast of individual expectations with this overarching vision become more apparent.

1.7.4 Paper IV – Energy system expectation clusters

In paper IV, we analysed the energy system expectations in more detail, drawing on data form the same survey. First, a cluster analysis showed that four groups with distinct energy system expectations can be identified. Three out of the four clusters expect an energy transition in Switzerland. Even people who voted against the *Energy Strategy 2050* (ES2050) and think that an energy transition is unnecessary expect it to happen, indicating that this belief can be referred to as a collective expectation. This means that the expectation of an energy transition is so prevalent that it cannot be ignored and that both proponents and adversaries of the energy transition in Switzerland acknowledge the existence of this expectation. Furthermore, data showed that between the clusters expecting an energy transition large variations of energy system expectations exist. While one clusters expects a rather utopian (i.e. conflict free and affordable) energy future, another depicts a rather dystopian (i.e. full of energy related conflicts and high energy prices) vision of the post-transition energy system. The four energy system clusters are each more or less in line with the scenario *Energy Perspectives* that build the basis for ES2050. While it can be assumed that the public does not directly use energy scenarios, it is conceivable that the public receives particular promises and concerns that are spread by the media or political actors. These potential indirect influences of scenarios, and in particular how they frame public expectations, are not well understood to date.

1.7.5 Paper V – How utilities use energy scenarios

By conducting interviews with representatives from 20 Swiss utilities, paper 5 studies the use of scenarios in the Swiss energy industry. The paper applies the user typology developed in paper II, and additionally includes the user type of *observers* (which has been identified in a study on the use of climate scenarios, see Skelton, Fischer, Liniger, & Bresch, 2019 for details). In contrast to *sailors* and *divers*, *observers* do not actually apply the insights provided by energy scenarios. Instead, *observers* for example refer to energy scenarios to stay up to date about recent developments in the energy sector. This fits well with the functionality scenarios employ according to the *Sociology of Expectations*, as it highlights the indirect effects scenarios can have through the expectations they influence, even when they are not related to immediate decisions or actions. The paper shows that energy scenarios are perceived to be relevant by representatives from a broad spectrum of utilities, ranging from small municipal companies supplying local communities to internationally operating and vertically integrated corporations. However, they are often used to legitimize pre-existing strategies, which contrasts the consideration of multiple alternative futures that are equally plausible. In addition, we find that utilities tend to focus on relatively few scenario studies. Hence, there is an apparent discrepancy between the stated purpose why utility representatives use scenarios (considering a broad spectrum of possible futures) and the use of a limited set of scenarios (corresponding to a narrow set of possible futures). To describe how utilities select scenario studies from the variety of publicly available studies, we evaluate the relevance of the knowledge system quality criteria developed by Cash et al. (2003). While credibility and salience play a key role for how utilities select energy scenarios, legitimacy is only relevant for a small minority of users. However, also social interactions with other scenario users influence the perceived credibility and salience of scenarios, which provides an example for the social embeddedness of scenario use.

2 Paper I - The neglected importance of corporate perceptions and positions for the long-term development of CCS

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Abstract

Many companies that produce fossil fuels or fossil fuel-derived products show a strong belief in a large and continuing role for fossil fuels in the global economy up to 2050 and beyond. These companies are generally expected to be amongst the primary consumers of carbon capture and storage (CCS) technology. So far, however, fossil fuel companies have shown only moderate interest in CCS. Whilst a lot of potential operational barriers to CCS adoption have been identified in the literature, the value of CCS from a corporate strategy perspective has sometimes been assumed, but rarely explored. This paper asks the following question: What are the perceptions and positions of fossil fuel companies on CCS and how does this inform their decision making on CCS investment and advocacy? This paper addresses this issue by presenting the results of in-depth interviews with high-level CCS experts from major multinational oil and gas companies and major coal mining firms. The results indicate that CCS would require a significant change within the business strategy of fossil fuel companies. This is contrary to the common argument that CCS is attractive because the technology is regarded as not being very disruptive to the incumbent energy system as it leaves most of the existing infrastructure, actor constellations and institutions intact. While fossil fuel companies engage in CCS development, it is often to familiarise themselves with technologies that might have future value if markets for these technologies take off. In several cases, CCS engagement has served the strategic need to weaken the link between fossil fuel extraction and climate change, build up shareholder trust, and improve public perception. However, there is little evidence that these companies engage in CCS to develop a strategic insurance against climate policy risks to their core businesses.

2.1 Introduction

After COP21, there is a scientific and policy consensus on stabilizing concentrations of greenhouse gas (GHG) in the atmosphere [1]. Carbon capture and storage (CCS) regularly plays a critical role in energy scenarios, as it is the only technology that offers the possibility to significantly reduce GHG emissions while allowing the further exploitation of fossil fuels [2, 3]. The prospect of addressing climate change and the energy challenges of the twenty-first century with a single technology that is compatible with the predominantly fossil fuel based economy of today, is appealing to governmental and corporate decision-makers alike. Governments try to stimulate CCS investment by subsidizing pilot projects and developing price incentives through carbon markets [4]. Although the fossil fuel industry is promoting CCS as a panacea against climate change, most corporate activity so far has focused on participation in basic CCS related research activities and lobbying governments for subsidies [5]. As a consequence, the development of CCS has been slower than anticipated and is lagging behind what energy scenarios deem necessary to reduce CO2 emissions in time to keep climate change below 2°C warming [6].

In the literature, many barriers to CCS adoption have been identified. The common opinion is that the faith of CCS is ultimately tied to a robust carbon price, as only commercial motivations can stimulate a wide-range deployment [7]. The high costs that are associated with capturing the carbon [8], remaining technological uncertainties [9], the relatively low public acceptance of the technology [10], and missing or ineffective liability and regulatory regimes [11] have been discussed extensively. However, as Bowen [4] pointed out, "even with a strong carbon price signal, there are recognized uncertainties about the viability, affordability, effectiveness and public acceptability of CCS". Whilst much of the discussion on CCS has often focused on the technically optimal integration of CCS technologies into energy systems, corporate decision-making rationales that will determine uptake in the real world have not been thoroughly studied. The conducted in-depth interviews provide such insights. The paper shows the technology aspects that are perceived as a risk rather than a business opportunity and what parts of the CCS system corporate decision makers regard as potentially sustaining or disrupting their future value.

In particular, this paper asks the following question: What are the perceptions and positions of fossil fuel companies on CCS and how does this inform their decision-making on CCS investment and advocacy? It is argued that CCS investments are made with regard to a firm's overall corporate strategy [12]. To be able to highlight some of the prevalent complexities and interdependencies in the fossil fuel sector, oil and gas companies and coal mining companies are included in the analysis.

2.2 Methods

To capture the internal perception fossil fuel companies have towards CCS, 4 in-depth interviews with high-level CCS representatives from oil and gas companies as well as 4 interviews with high-level coal mining representatives were conducted. The interviews were part of a master thesis which the authors of this study wrote, respectively supervised. To find interview partners, a purposive sampling technique was used [13]. There are only a few companies that have the power to shape the fossil fuel sector's commitment towards CCS. The goal was to interview representatives that work for major international companies with market-leading positions in the fossil fuel business. The eight resulting interviewees have a long-lasting professional attachment to CCS and can therefore be called experts.

The interviews were conducted by telephone in August 2015 and lasted approximately one hour. A semi-structured interview technique with mostly open-ended questions was used. Open-ended questions are typically used in expert interviews because informants can provide contextual richness to their responses and are not limited by fixed choices [14, 15]. Names of interviewees and companies as well as site-specific project information have been omitted in this paper. The assured anonymity allowed the interviewees to speak freely, which was an essential part of the interview. In the result section, quotations from coal mining representatives are abbreviated "CM", respectively "OG" for oil and gas representatives. The overarching objective of the interviews was to gain a better understanding of the role fossil fuel companies assign themselves in the development of CCS. A first set of questions focused on the internal value proposition of CCS within fossil fuel companies. A second theme that is relevant for this study concerned the public presentation of CCS-related activity by the interviewed companies. The interviews were recorded and subsequently transcribed which allowed for a thematic coding of the data with the *atlas.ti* software.

The position of fossil fuel companies in the development of CCS is evaluated using publicly available documents of expert panels and policy hearings from the EU and the UK. For that purpose, the online archives of the relevant energy agencies were searched. In addition, academic literature that evaluates the role of fossil fuel companies in the development of CCS was included in the analysis.

2.3 Results

2.3.1 Oil and gas companies frame CCS as an incremental innovation

With their subsurface exploring technology, experience with injecting CO2 in geological formations for enhanced oil recovery (EOR), massive pipeline infrastructure, large workforce and investment capabilities, oil and gas companies control valuable resources that are essential for the long-term-development of CCS. These characteristics lead to an assumed compatibility of CCS with oil and gas companies which are expected to be both the drivers of CCS deployment and its primary consumers. An analysis of how oil and gas companies frame CCS in policy contributions shows that this compatibility is actively reinforced by the industry [16]. In an analysis of *Statoil's* and *Vattenfall's* media statements, for example, Buhr and Hansson [17] showed that the two companies used every opportunity to stress the benefits of CCS and the necessity to deploy the technology if the world is serious about mitigating climate change. This exemplifies a shift that most companies in the fossil fuel sector performed in the last couple of years regarding their climate change communication strategy [18]. Tjernshaugen [19] who focused the cases of *ExxonMobil*, *BP* and *Statoil,* concluded that the compatibility with CCS technology had put fossil fuel companies in a strategic dilemma as they needed to admit their influence on global emissions if they wanted to promote the technology. Correspondingly, Stephens [20] remarks that fossil fuel companies "*actively supported research and public campaigns that highlighted uncertainties and weaknesses in the theory of anthropogenic climate change*" in the past. As the scientific case for climate change strengthened, however, firms deliberately shifted their strategy towards a CCS engagement to weaken the link between fossil fuel extraction and climate change. A study that specifically focused on fossil fuel companies' role in the development of CCS argues that the industry's engagement in CCS is explained by the prospective of a prolonged extraction of fossil fuels even under severe policy restrictions that may be introduced in the future [21]. CCS enabled businesses that rely on fossil fuel extraction, production or use to accept their influence on global emissions and provided them with a possible solution where there was none before. Accordingly, the technology is often regarded as a sustaining innovation, which is interpreted as a reinforcement of the carbon lock-in by critics [22]. Before this backdrop, it might come as a surprise that the interviews show how several aspects of CCS systems are perceived as "*potentially disruptive*" (OG4) by fossil fuel companies. The following two examples are used to illustrate, however, why there are strong incentives for incumbent firms to publicly portray CCS as an incremental innovation from a technological point of view.

Whilst post-combustion capture technology is regarded as an end-of pipe solution that is generally compatible with large, centralized oil and gas firms by the interviewees, they stressed that pre-combustion technology could potentially lead to a completely different technological trajectory with unfavourable implications for their company. Consequently, although carbon capture technology has so far not developed a dominant design and several methods are conceivable, they decided to focus on the promotion of post combustion capture. Interviewees mentioned that this general approach allowed their companies to focus on CCS technologies and processes that they are familiar with from their daily business activity. Out of the 15 CCS pilot projects that are currently operating worldwide, 11 use post-combustion technology [23].

Also the second example demonstrates that firms generally look for opportunities to "*build upon their existing knowledge base*" [24] instead of considering options that are new to them when making technology decisions. A coal industry representative remarked that "u*nderstanding the subsurface geology, understanding how fluids or supercritical gases behave in the subsurface,* […] *is the bread and butter for oil and gas*" (CM1) which is why "*oil and gas* [companies] *prefer storage options they know from their core business*". Indeed, all four oil and gas interviewees stated that they prefer geological storage options over other possibilities, such as CO2-mineralisation.

The interviews suggest that oil and gas companies make optimistic public statements towards specific future CCS technology options fitting their skills and know-how. This allows them to gain access to policy processes, which is essential in this still early stage of CCS development with various potential technological pathways in the capture, transport and storage part of the CCS system. As there are very few CCS systems in operation, these policy processes and the subsequent funding mechanisms are heavily influenced by technology choices of incumbents. Another reason why oil and gas companies promote technologies or processes they are accustomed to is shareholder trust. All four oil and gas interviewees mentioned that fossil fuel companies take part in CCS projects to show a level of confidence with recent technological developments to their shareholders and demonstrate that they are prepared in case the commercialization of CCS is required to maintain or enhance competitiveness.

2.3.2 Fossil fuel companies position CCS as a crucial part of climate change mitigation

All eight interviewees assert that their company is only willing to take part in CCS projects if governmental support is attached to the commitment: "*The business model of CCS relies strongly on governmental policy. In fact, without governmental support there is no business model for CCS*" (OG1). Similarly, *Statoil* emphasized that ''*the main economic and operational responsibility for establishing CCS rests with the state*'' [17]. The following paragraph describes the arguments that are adopted by the fossil fuel industry to promote CCS to policymakers.

In 2013, the European Commission (EC) undertook a public consultation on the future of CCS in Europe [25]. Nearly all contributions from fossil fuel companies stressed the value of national and international roadmaps that outlined emission reduction pathways until 2050 and beyond. The reason for this is that contemporary national and international mitigation scenarios rely heavily on CCS. The International Energy Agency, for example, estimates that a fifth of the total emission reduction that will be needed to stabilize the CO2 concentration in the atmosphere by 2050 have to come from CCS [26]. Moreover, energy scenarios consistently find that CCS drastically reduces the overall cost of global decarbonisation [9]. The circumstance that energy modelling shows that CCS will be needed to mitigate climate change at an affordable cost is used to full capacity by the fossil fuel industry.

Because they lack the know-how of the deep-subsurface, coal producers need to employ a different strategy why they should be a key player in CCS development in general and policy processes in particular. A coal mining representative stated that his company tries to like link the supply of cheap, reliable and stable energy to economic growth and fairness towards developing countries. With this argument, the coal industry relates CCS to the longstanding environmental protection versus economic growth debate and thereby strengthens the case for CCS equipped coal-fired power plants.

According to the interviewees, CCS is the only option that would enable deep emissions reductions for many energy intensive processes such as the production of steel, cement, or chemicals. They argue that once CCS is sufficiently developed, it becomes a transferable technology that would be able to secure high-level jobs in energyintensive sectors. This argument can also be observed in various statements in the *CCS Development Forum* that was organised by the UK Department of Energy & Climate Change (DECC) between 2012 and 2015 to facilitate exchange between CCS stakeholders [27].

2.3.3 The dark side of the moon: Discrepancies between the public appraisal of CCS and the pessimistic outlooks of the interviewees

As described above, the strong association of CCS technology with fossil fuel companies can partially be attributed to the industry's engagement in promoting the technology. *Statoil*, for example, emphasized that a largescale CCS deployment is only feasible with large fossil fuel companies backing it [17]. Interviewee OG2 pointed out that the usually optimistic public framing of the technological parts of CCS serves the strategic purpose to tie CCS development to the actions of the fossil fuel industry. This can also be observed in an oral evidence session held by the House of Commons to discuss the future CCS policy in the UK. Representatives from *Shell* and other CO2-intensive companies stated that from a technical point of view, CCS is mature enough to be deployed since the industry knows how to inject CO2 into the deep subsurface since 30 years due to experiences with EOR [28]. Another example of the same argumentation is provided by an oil and gas interviewee: "*The oil and gas industry has the necessary experience with projects that cost several hundred millions of dollars or a billion dollars. That's routine for us. It is also clear that the oil and gas industry can handle the operational parts of the project. If anything goes not how it was planned, we know how to react. Because we have the experience and the engineering skills*" (OG4). Likewise, a Delphi study from the UK showed that CCS experts stressed non-technical barriers (such as regulatory frameworks and costs) rather than technological challenges as main reason for the slow CCS uptake [29].

Combined with the urgency to mitigate climate change, the assumed comparability of fossil fuel companies with CCS, leads to the expectation that a wide-scale CCS deployment is imminent. Recent energy scenarios thus project a massive CCS deployment at rates that are in some cases comparable to the expansion of the oil industry at the beginning of the century [30]. The interviewees, however, believe that these deployment projections are "*completely unrealistic* (OG2)". Whilst several studies show that experts are in general overly confident and optimistic concerning the technology they are involved in [31-33], this is not the case in this sample. In fact, none of the interviewees thinks that the deployment targets outlined by the IEA in 2015 [26] to limit global warming to 2°C can be reached. Asked about the value of CCS for the company they are working for, interviewees were not reluctant to state that CCS has little or no value to them at the moment: "*Look at the numbers. You very quickly come to the conclusion that CCS has very low value to fossil fuel companies. Otherwise, we would be investing a lot more money*" (CM1). Asked for the reasons why his company invested in CCS at all if the technology had little value to them, CM1 pointed out that "*investment is the wrong word, it is not an investment at all, it is charity*". Moreover, the interviewees question that the company they work for would take a leading role in a forthcoming CCS development, even if a global carbon price is installed.

A first reason that was supported by four oil and gas representatives and one of the coal mining representatives is that their company already uses an internal carbon price (a range of $30 to $60 dollars was named) to evaluate large engineering projects and hedge their long-term planning. This suggests that a carbon price would not trigger an immediate large-scale diffusion of CCS across the fossil fuel industry.

Secondly, whilst interviewees agreed that a carbon price would incentivise CCS deployment - "*if there is a viable business, driven by a carbon price policy, then someone will provide that storage service*" (CM1)"- they remarked that it would happen in a geographically and temporally fragmented way, with mainly spin-offs from the oil and gas sector offering transport and storage services to coal companies in an early phase. This clearly contradicts the projections of numerically-based energy scenarios that rely on input assumptions and boundary conditions to simulate CCS development and usually portray deployments paths that either do not take off at all or at a tearing pace.

A third reason for the doubtful CCS outlook that many interviewees have is the contradiction of CCS with the core business strategy of fossil fuel companies. Most interviewees were rather generic in that respect: "*We like to remain where we are the strongest as an oil and gas company. We provide energy. We are not a service company*"(OG1). However, one interviewee went into details: "*It is our culture to take a lot of risk. It is our job to invest in businesses that are risky. For example the explorations where we want to find oil or gas. So we are ready to use a lot of money in risky operations. But in return, we want to have a high profitability when we discover oil or gas. It is a high risk, high reward game. The way we frame CCS business is different. The price to store CO2 has to be as low as possible, so that it can be done worldwide. We don't see a future where a company that stores CO2 is rewarded at a high level*" (OG2). Whilst certain technological parts of CCS may indeed be compatible with fossil fuel companies and oil and gas companies in particular, organisational inertia and a strong focus on existing business models currently prevent the technology to really spark the interest of corporate decision makers. One example is that the characterisation and valorisation of geological storage capacity, which is likely to be reliant on the resources and skills that are found in today's oil and gas sector, lies outside of the oil and gas sector's current strategic value proposition.

2.4 Discussion

In contrast to the picture presented in policy contributions, the representatives of fossil fuel companies that were interviewed for the purpose of this paper indicate that CCS is perceived as much more controversial within individual firms. One key divide is between oil and gas and coal firms. Coal producers are responsible for about 40% of global CO2 emissions but lack the CCS relevant knowledge and skills the oil and gas industry has [34]. This imbalance creates interdependencies between the two competing industries. Several oil and gas representatives mentioned their fear that oil and gas companies take a deliberately unhurried stance in CCS development because coal producers are likely to be affected by carbon regulations earlier than oil and gas companies are: "*The oil and gas industry is a competitor to coal. So they are not necessarily interested in advancing the benefits of CCS more generally*". Although this tactic was denied by the oil and gas interviewees, recent U.S. carbon regulations that require new coal-fired but not natural gas or oil powered power plants to employ CCS indicate that at least the apprehension of coal producers to be affected by carbon policy first is not too far-fetched [35]. One interviewee identified this competition as the main reason for the oil and gas firms' intensive lobbying for a global price on CO2 emissions: "*The only way you're going to make gas as competitive as coal is through a carbon price. Because that will push up the price of coal more than it will the price of gas*" (CM3).

However, climate change and climate change regulation can influence the environmental and economic performance of all companies in the fossil fuel business positively or negatively.

Consequently, all of them need to make assessments of their exposure to the so-called carbon risk [36]. Several interviewees outlined that CCS is one part of a broader climate change risk mitigation strategy applied in their respective company. Other actions that are taken include virtual carbon prices to calculate investment risks (CM2; OG1-4), switch to resources with a lower calorific value whenever the cost-benefit analysis allows them to do so (CM1,2; OG1-4) various efficiency measures (CM1-4, OG1-4) and setting up a renewable technology portfolio (OG2,3). As firms have different perspectives when it comes to future energy developments [37], they are likely to attribute different levels of importance to CCS. Whilst some national fossil fuel companies, for example in the U.S. and Australia, have evolved in relatively stable and protected environments with a lot of regulation, other players have more experience with risk exposure and international project management, which also influences a company's CCS-related interests and capabilities [38]. In addition, whilst fossil fuel companies in general have a lot of experience with uncertainties, for example through options pricing, some have more than others. *Shell* for example is using scenario planning since the 1970s, which enabled them to be better prepared for the first oil crisis than any other oil company [39].

Furthermore, also the CCS system itself is highly differentiated. Whilst carbon capture can be addressed by energy equipment manufacturing firms or utilities with turbine experience, carbon transportation is probably going to rely on the pipeline infrastructure of major oil and gas companies or ocean carriers in case of a ship-based transport, whereas carbon storage is relevant for both oil and gas companies as well as oil field service providers [4]. The impression that CCS is supported and undisputed by the whole fossil fuel industry that one can get when analysing public industry statements is artificially created. The promotion of CCS allows fossil fuel companies to receive the associated public perception boosts (which seven out of eight interviewees regard as an important reason for the CCS activity of their firm) and increases the prospect of policy influence with subsequent funding opportunities [40]. To date, however, a strong and lasting interest in the commercialisation of CCS cannot be identified among fossil fuel companies. Therefore, the activity in CCS projects that almost all privately owned fossil fuel companies engage in is not a sign of an imminent wide-scale CCS diffusion, but rather a low-hanging fruit for fossil fuel companies to be invited to policy contributions, demonstrate their level of preparedness to shareholders and delay immediate or more radical emission reduction measures. In that sense, the quote "*We see CCS as a way to mitigate our emissions in cases where policy, cost and funding and other factors allow us to do so*" (OG1), strongly resembles what Meadowcroft and Langhelle [41] coined the ''*CCS when absolutely necessary; but surely it is not necessary quite yet*'' position.

2.5 Conclusion

A large gap has emerged between the technocratic discourse concerning the promise of carbon capture and storage and the de facto scale of deployment. This discrepancy has been the starting point of this study. Previous energy transitions suggest that relatively long periods of experimentation are a normal development in energy transitions. Whether CCS advocates can draw hope from these findings is doubtful. Because the technology offers no tangible value to energy producers or end-users besides lowering their exposure to climate change-related penalties, its economic value is intertwined with that of carbon pricing and thus permanently exposed to policy risk. This poses the question of whether a policy-driven (rather than policy-enabled) energy transition is comparable to historical transitions that were driven by better and ultimately cheaper energy sources and technologies. To date, fossil fuel companies regard governmental commitment and financial support as a prerequisite for own investments. Policy makers must acknowledge, however, that innovations are more likely to come from businesses at the periphery of the fossil fuel industry. While fossil fuel companies do engage in CCS development, it is often to familiarise themselves with technologies, such as CO2 injection and storage management, that might have future value if markets for these technologies take off.

The fossil fuel sector has successfully positioned CCS as a necessary emission reduction technology. By being optimistic about overcoming the technological challenges and emphasizing the scale to which CCS can contribute to climate mitigation, the fossil fuel industry builds expectations. These expectations increase the possibility to attract financial resources for CCS projects. Although fossil fuel companies use the promise of future emission reductions as an instrument to resist calls for immediate abatement measures, there is little evidence that they engage in policy process and assorted projects to develop a strategic insurance against climate policy risks to their core businesses. CCS activity is embedded in the broader corporate strategy and usually not the only carbon risk management action companies take. Being aware of corporate positions and perceptions is crucial in order to be able to interpret the actions and interests of the fossil fuel industry. It is important to move towards a better understanding of why companies engaged in CCS take their respective positions and decisions. Such understanding can inform better policy for CCS and for climate change mitigation more generally.

References

1. Schellnhuber, H.J., S. Rahmstorf, and R. Winkelmann, *Why the right climate target was agreed in Paris.*Nature Clim. Change, 2016. 6(7): p. 649-653.

2. World Energy Council, *World Energy Scenarios: Composing energy futures to 2050*. 2013, World Energy Council/Paul Scherrer Institute (PSI): London.

3. Metz, B., et al., *IPCC special report on carbon dioxide capture and storage*. 2005: Cambridge University Press, New York, NY (United States); Intergovernmental Panel on Climate Change, Geneva (Switzerland).Working Group III.

4. Bowen, F., *Carbon capture and storage as a corporate technology strategy challenge.* Energy Policy, 2011. 39(5): p. 2256-2264.

5. Stephens, J.C., et al., *Characterizing the international carbon capture and storage community.* Global Environmental Change, 2011. 21(2): p. 379-390.

6. Scott, V., et al., *Last chance for carbon capture and storage.* Nature Clim. Change, 2013. 3(2): p. 105-111.

7. Haszeldine, R.S., *Carbon Capture and Storage: How Green Can Black Be?* Science, 2009. 325(5948): p.1647-1652.

8. Azar, C., et al., *Carbon Capture and Storage From Fossil Fuels and Biomass – Costs and Potential Role in Stabilizing the Atmosphere.* Climatic Change, 2006. 74(1): p. 47-79.

9. Hansson, A. and M. Bryngelsson, *Expert opinions on carbon dioxide capture and storage—A framing of uncertainties and possibilities.* Energy Policy, 2009. 37(6): p. 2273-2282.

10. Shackley, S., et al., *The acceptability of CO2 capture and storage (CCS) in Europe: An assessment of the key determining factors: Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation.* International Journal of Greenhouse Gas Control, 2009. 3(3): p. 344-356.

11. Wilson, E.J., S.J. Friedmann, and M.F. Pollak, *Research for Deployment: Incorporating Risk, Regulation, and Liability for Carbon Capture and Sequestration.* Environmental Science & Technology, 2007. 41(17): p. 5945-5952.

12. Ahmed, P. and C.D. Shepherd, *Innovation management: Context, strategies, systems and processes*. 2010: Pearson Education Limited.

13. Tongco, M.D.C., *Purposive sampling as a tool for informant selection.* 2007.

14. Patton, M.Q., *Qualitative evaluation and research methods*. 1990: SAGE Publications.

15. Bryman, A., *Social research methods*. 2015: Oxford university press.

16. Arranz, A.M., *Carbon capture and storage: Frames and blind spots.* Energy Policy, 2015. 82: p. 249-259.

17. Buhr, K. and A. Hansson, *Capturing the stories of corporations: A comparison of media debates on carbon capture and storage in Norway and Sweden.* Global Environmental Change, 2011. 21(2): p. 336-345.

18. Pulver, S., *Making sense of corporate environmentalism an environmental contestation approach to analyzing the causes and consequences of the climate change policy split in the oil industry.* Organization & Environment, 2007. 20(1): p. 44-83.

19. Tjernshaugen, A., *Technological Power as a Strategic Dilemma: Co2 Capture and Storage in the International Oil and Gas Industry.* Global Environmental Politics, 2012. 12(1): p. 8-29.

20. Stephens, J.C., *Growing interest in carbon capture and storage (CCS) for climate change mitigation.*

Sustainability: Science, Practice, & Policy, 2006. 2(2).

21. Rubin, E.S., C. Chen, and A.B. Rao, *Cost and performance of fossil fuel power plants with CO 2 capture and storage.* Energy policy, 2007. 35(9): p. 4444-4454.

22. Rochon, E., et al., *False hope: why carbon capture and storage won't save the climate.* False hope: why carbon capture and storage won't save the climate, 2008.

23. MIT CC&ST Program. *Power Plant Carbon Dioxide Capture and Storage Projects* 2016 [07.01.2017]; Available from: https://sequestration.mit.edu/tools/projects/index_pilots.html.

24. Jacobsson, S. and A. Johnson, *The diffusion of renewable energy technology: an analytical framework and key issues for research.* Energy policy, 2000. 28(9): p. 625-640.

25. European Commission, *Report on the analysis of the responses received to the Consultative Communication on the future of Carbon Capture and Storage in Europe*. 2013.

26. IEA, *World Energy Outlook*. 2015, International Energy Agency.

27. Department of Energy & Climate Change, U.K. *CCS Development Forum*. 2015 [05.01.17]; Available from: https://www.gov.uk/government/groups/ccs-development-forum#minutes.

28. Energy and Climate Change Committee. *Oral evidence: Carbon Capture and Storage, HC 742*. 2013; [14.01.2017] Available from: http://www.publications.parliament.uk/pa/cm201314/cmselect/cmenergy/742/74202.htm

29. Gough, C., *State of the art in carbon dioxide capture and storage in the UK: An experts' review.* International Journal of Greenhouse Gas Control, 2008. 2(1): p. 155-168.

30. Grubler, A., *Energy transitions research: Insights and cautionary tales.* Energy Policy, 2012. 50: p. 8-16.

31. Stigson, P., A. Hansson, and M. Lind, *Obstacles for CCS deployment: an analysis of discrepancies of perceptions.* Mitigation and Adaptation Strategies for Global Change, 2012. 17(6): p. 601-619.

32. Markusson, N., et al., *A socio-technical framework for assessing the viability of carbon capture and storage technology.* Technological Forecasting and Social Change, 2012. 79(5): p. 903-918.

33. Van Alphen, K., M.P. Hekkert, and W.C. Turkenburg, *Accelerating the deployment of carbon capture and storage technologies by strengthening the innovation system.* International Journal of Greenhouse Gas Control, 2010. 4(2): p. 396-409.

34. de Coninck, H., J.C. Stephens, and B. Metz, *Global learning on carbon capture and storage: A call for strong international cooperation on CCS demonstration.* Energy Policy, 2009. 37(6): p. 2161-2165.

35. Clark, V., *An analysis of how climate policies and the threat of stranded fossil fuel assets incentivize CCS deployment.* 2015.

36. Branco, D.A.C., et al., *A multicriteria approach for measuring the carbon-risk of oil companies.* Energy Strategy Reviews, 2012. 1(2): p. 122-129.

37. Chang, Y. and J. Yong, *Differing perspectives of major oil firms on future energy developments: An illustrative framework.* Energy Policy, 2007. 35(11): p. 5466-5480.

38. Kolk, A. and J. Pinkse, *A perspective on multinational enterprises and climate change: Learning from "an inconvenient truth" &quest.* Journal of International Business Studies, 2008. 39(8): p. 1359-1378.

39. Cornelius, P., A. Van de Putte, and M. Romani, *Three decades of scenario planning in shell.* California management review, 2005. 48(1): p. 92-109.

40. Reiner, D., *A looming rhetorical gap: a survey of public communications activities for carbon dioxide capture and storage technologies.* Electricity Policy Research Group Working Paper, 2008.

41. Meadowcroft, J. and O. Langhelle, *The politics and policy of carbon capture and storage.* Caching the Carbon. The Politics and Policy of Carbon Capture and Storage, 2009: p. 1-21.

3 Paper II - Of sailors and divers: How researchers use energy scenarios

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Abstract

Scenarios are a key instrument to guide decision-making in the face of an uncertain future. In the field of energy, scenarios are often published to inform external stakeholders who are not part of the scenario development. This study explores how researchers, a key stakeholder group in shaping the energy future, use energy scenarios. It analyses the case of Switzerland, where several competing scenarios have been developed in reaction to the governmental decision to phase-out nuclear power. 16 structured in-depth interviews with researchers from different disciplinary backgrounds were conducted. While most interviewees use public energy scenarios, there are two contrasting user types. The first group, labelled divers, primarily uses scenarios as a data source, whereas the other group, the sailors, refers to them as plausible energy futures. We identified different interpretations of scenario content between sailors and divers, which result from the quantitative modelling on which contemporary energy scenarios are based. Due to a lack of guidance from modellers and missing qualitative information, energy scenarios are prone to misconceptions and distortions in their interpretation by external users.

3.1 Introduction

The contemporary energy system is extremely complex. The large number of relevant stakeholders, long investment horizons and structural interdependencies bring about a variety of dynamics that cannot be controlled and are difficult to predict [1]. As a consequence, policymakers and business leaders have to make decisions under deep uncertainty [2]. At the same time, the central role of energy in modern economies [3] and climate change mitigation [4], create a considerable economic and political need to characterize and cope with such uncertainties. On account of this, various influential energy system players have been using scenario-planning – a foresight method intended to support long-term decision making under volatile conditions – since the second half of the 20th century (for a review, see [5]).

The benefits and effectiveness of scenario use in the field of energy has mostly been studied in two different empirical contexts. The first is the in-house development and use of scenarios by large organisations for the purpose of risk management or strategic planning (e.g. [6–10]). Much of that research is based on case studies, *Shell* being the most prominent example: The oil and gas company is famous for using scenarios to support their decision-making processes since the 1970s [11]. The second empirical context is scenario use by public administrations. This is exemplified by the so-called La Prospective, a school of scenario building that has influenced the French government's five year planning since the 1960s [12]. Nowadays, a common characteristic is that public administrations commission highly specialised experts (hereafter referred to as "modellers") to develop scenarios [13]. Such modelling communities are often linked to public research institutes or private consultancies and have been established in many countries during the last decades [14]. In both of these scenario use contexts, the scenarios are designed for a specific target audience and purpose. Accordingly, there is typically a close collaboration between modellers who develop the scenarios and users who apply the scenarios. Users are actively guided by modellers and have access to counsel or additional information not provided in scenario reports [15]. Moreover, many users are directly involved in the scenario development process, which helps them to identify, understand and interpret the relevant information [16]. This user-modeller interaction is particularly important in the case of contemporary energy scenarios as they are based on computerized models to handle the complexities of the energy system [17]. Accordingly, many empirical studies that evaluate scenario use focus on its partly participatory development process (see [18,19]). As the scenario development provides an arena for discussion and promotes learning between different stakeholders, it is often regarded as even more relevant in supporting decision-making than a published report describing the scenarios [5]. Proximity to the scenario development process was accordingly identified as a key factor in conveying scenario-based insights effectively [20].

Nevertheless, institutions that develop or commission energy scenarios often make them available to the public. Examples include national authorities (e.g., [21], academic institutions (e.g., [22]), fossil fuel companies (e.g., [23]), environmental NGOs (e.g., [24]), as well as international institutions such as the International Energy Agency [25], the World Energy Council [26], or the EU [27]. Most scenario studies are therefore not limited to the small circle of addressees for which they are initially developed, but are made available to a wider audience. Publishing institutions, which sometimes have conflicting interests, generally claim to develop scenarios with an open outcome. Yet, they often inject their scenarios into the public discourse to convince relevant stakeholders (such as voters, shareholders or potential investors) of a specific vision of the future [28]. In that sense, the dissemination of scenarios is a way to articulate shared expectations in order to facilitate alignment around common goals, legitimize decisions, or gather support for forthcoming actions [29].

External users, such as researchers, journalists, non-governmental organizations, or voters, who have no interaction with modellers and do not participate in scenario development, may thus use scenarios as a basis for various decisions, to advance their own agenda, or simply to inform themselves [30]. In contrast to energy scenario users who are part of the development process, external users have sometimes been assumed to exist (see for example [31]), but not yet been studied empirically. To make a first step in this direction, this paper focuses on energy researchers – one potential group of external scenario users. Although devoid of direct decision-making power concerning the development of the energy system, energy research communities are catalysts for the dissemination of insights that are based on energy scenarios. Information provided by energy scenarios can directly impact research processes and results [32], which may in turn also inform decision-makers in administration and the industrial sector with the power to shape future energy systems [33].

As energy scenario use is inherently context dependent [34], we analyse one specific country and user group. We chose to focus on energy research in Switzerland, where a number of major national energy research programs have been initiated since 2011 [35]. This led to a thriving energy research community that comprises of researchers with different educational backgrounds and thematic research foci. Several of the involved research institutions, but also industry actors and NGOs, develop and publish energy scenarios. Moreover, the country is in the process of adopting a national energy strategy that is in large parts based on a scenario study [36]. As a result, the diverse energy research community can choose from a variety of publicly available energy scenarios. This makes it an interesting case to study how energy researchers understand and use energy scenarios. More specifically, this study aims to explore what role energy scenarios play in energy research, for what purposes they are used and whether there are typical use patterns. These will be first steps towards insights into the finer mechanics of how energy scenarios generate and communicate knowledge when they are used by external users who neither interact with scenario developers, nor have participated in scenario development processes.

3.2 Background

3.2.1 Energy scenarios

Scenarios are plausible descriptions of how the future might develop based on a coherent set of assumptions [37]. The scenario concept comprises of a variety of methodological approaches and techniques, but typically, there are no probabilities assigned to scenarios, which distinguishes them from forecasts or predictions. Scenarios should therefore be treated as what-if projections that can be predictive, explorative or normative [38]. Because scenarios are applied in a variety of disciplines, scenario development techniques vary greatly, and there are a large number of different methodological approaches summarized under the label ‘scenario planning’ or ‘scenarios analysis’ [39]. One aspect that differentiates energy scenarios from scenarios in other fields is their reliance on computerized models [17]. Model-based energy scenarios are widely used in many countries [14]. TIMES and MARKAL for example, which are among the most popular energy models (see [40] for a description), have been used by more than 150 institutions in 63 countries [41]. To generate energy scenarios, energy models abstract from the complex reality by integrating model inputs into the model framework. For this process model inputs describing the existing energy system and assumptions about plausible future developments are needed. While model inputs can be derived from a range of sources, such as statistical offices, assumptions are made by consulted experts or by the modellers themselves. The resulting model output, usually in the form of key figures and a report, is what is commonly referred to as a scenario. Energy models can vary in their purpose (e.g., forecasting, back-casting, simulation, or optimization), geographical scope (local, national, or global) or modelling paradigm (top-down, bottom-up, or hybrids) [42,43]. Distinctive models thus have diverging properties and apply varying levels of detail to different aspects of the energy system [44]. Most energy scenarios employ CO_2 emission reduction targets as exogenous normative constraints under which the model operates [45]. In investigating several countries, Chiodi et al. [46] showed that model choice is directly linked to both a country’s position in climate policy negotiations and its resulting policy decisions. What is more, if enough decision-makers adhere to a certain energy scenario and act accordingly, it can develop a considerable transformative power [47]. An example which regularly spurs controversial discussions in energy science and energy policy communities is the discrepancy between the antithetic paradigms of top-down (e.g., system dynamics, general equilibrium, and econometric) and bottom-up (e.g., multi-agent, optimisation, simulation, or partial equilibrium) models [37]. Top-down models try to depict the economy as a whole and assess aggregated effects of energy policies, often in terms of monetary costs. The advantage of top-down models is that they allow users to account for feedback effects concerning economic growth, employment, or welfare. These models are highly influenced by neoclassical economic theory [48]. Due to their focus on macroeconomic developments, top-down models are ineffective in assessing technological progress [49]. Bottom-up models, in contrast, focus on technological development, innovation, a cost-efficient use of investment costs from a societal perspective (including externalities), as well as inter-sectoral changes and synergies. As a consequence, bottom-up models typically indicate lower costs for climate change mitigation than top-down models [50]. Following this logic, Karjalainen [51] found it problematic that most public administrations and most economists have tended to rely on top-down models when assessing the costs and benefits of acting on climate change.

3.2.2 Empirical context: Swiss energy scenarios and energy research

In the aftermath of the Fukushima accident of 2011, Switzerland decided to phase-out domestic nuclear power production, a decision that was subsequently approved in a public referendum in May 2017. For that purpose, the Swiss Federal Office of Energy (SFOE) had commissioned a consulting company to produce a scenario study of the Swiss energy future [36]. The resulting 900-page model-based scenario study Energy Perspectives provides a normative feasibility study of the nuclear phase-out based on three different scenarios [52]. One of these scenarios served as the basis for the Swiss Energy Strategy 2050 (ES2050). This strategy aims both at a massive expansion of renewable electricity production and a reduction in energy demand in order to achieve the envisioned energy transition at minimum cost [36]. Energy Perspectives is, however, not the only long-term scenario study of the Swiss energy system. Numerous energy scenarios focusing on the Swiss energy system have been developed and published by different academic and non-academic institutions since the decision was taken to phase-out nuclear power (see Table 1). A meta-analysis comparing these scenario studies found considerable differences between them in terms of models, assumptions, and results [53].

Table 1. Overview of Swiss Energy Scenarios Developed after the Decision to Phase-out Nuclear Power in 2011.

Full Title	Acronym used in this study	Publishing institution	Modelling institution	Year
Energy Perspectives for Switzerland until 2050 (Prognos, 2012)	Energy Perspectives	Swiss Federal Office of Energy (SFOE)	Prognos AG	2012
Paths into the new electricity future (VSE, 2012)	Future paths	Association of Swiss electricity producers (VSE)	Pöyry Consulting AG	2012
Energy Future Switzerland (Andersson, Boulouchos, & Bretschger, 2011)	Energy Future	ETH Zurich, Energy Science Center	ETH Zurich	2011
Cleantech Energy Strategy (Barmettler, Beglinger, & Zeyer, 2013)	Cleantech	Renewable energy business association Swisscleantech	Foundation for Global Sustainability	2013
Transformation strategies towards a sustainable Swiss energy system (Weidmann, 2013)	PSI Energy	Paul Scherrer Institute (PSI) and ETH Zurich	PSI and ETH Zurich	2013
The Swiss TIMES Electricity Model (Kannan, Turton 2012)	PSI Electricity	PSI	PSI	2012
SCS-Energy Model (SCS, 2013)	SCS Energy	Super Computing Systems (SCS) AG	SCS	2013
energy [r]evolution (Teske & Klingler-Heiligtag, 2013)	energy [r]evolution	Greenpeace Switzerland	German Aerospace Center	2013

Together with the decision to phase-out nuclear power, the Swiss government launched a national energy research strategy. Eight Swiss Competence Centers for Energy Research (SCCER) that focus on research impact were established. The SCCERs were created with the intention to build up the required competencies and capacities to implement the national energy strategy. For that purpose, SCCERs cover different thematic foci and include a variety of researchers with various disciplinary backgrounds. In addition, there are two other major funding mechanisms. These are the National Research Programs (NRP) 70 (Energy Turnaround) and 71 (Managing Energy Consumption), which are focusing on mission-oriented research. Both NRPs and SCCERs combined received about 118 million Swiss Francs (approx. 102 million Euros) in funding between 2013 and 2016 [35]. At the end of 2016, the funding for SCCERs was extended until 2020.

3.3 Methods

To address our research questions, we conducted in-depth semi-structured qualitative interviews with Swiss energy researchers from different disciplinary backgrounds. An explorative approach was applied for all research steps (i.e., sampling, interview procedure, and data analysis) to facilitate the identification of different types of scenario use among researchers.

3.3.1 Sampling

The goal of this study was to examine a broad spectrum of energy researchers. This is due to the variety of ways in which scenarios can be used [61], and because users with different interests and perspectives are likely to attribute varying levels of credibility or relevance to particular scenarios [20]. To meet this goal, we compiled a list of all research groups funded by or associated to one of the Swiss energy research programs. In total, the list included more than 200 research groups associated to more than 30 different research institutions (see supplementary material for the full list). In order to select interview participants we applied a combination of purposive quota sampling and snowballing. We started with a purposive quota sampling based on criteria reflecting the heterogeneity of Swiss energy research (such as educational backgrounds, institutions, positions, and modelling expertise estimated through research projects and publications). However, some interviewees used energy scenarios quite differently than we had anticipated. This is why we asked interviewees for other researchers that might add a novel perspective on the topic. Eventually, we stopped interviews when we observed a saturation, meaning that there were no new understandings and use forms of energy scenarios being observed.

The researchers were contacted by email. We conducted interviews with 16 researchers from November 2015 to April 2016 (for a sample description, see supplementary material). All interviewees are associated to a major Swiss energy research program. Yet, their perspective of the energy system as well as their understanding of energy scenarios was found to vary considerably as their disciplinary backgrounds span from social sciences, such as sociology, geography, law or economics, to technical research areas such as engineering. While the sample may not be representative of the entire Swiss energy research community, it does capture a wide range of potential scenario users. For that purpose, the sample covers researchers with different thematic foci. While some concentrate on the whole energy system, others study supply and demand features, single technologies, players and their interactions, energy infrastructure, or energy law.

3.3.2 Interview procedure

The face-to-face interviews all lasted between one and two hours and were conducted either in German (10) or English (6). Most interviews were conducted in the offices of the researchers. All interviews were recorded to facilitate their transcription and analysis. The interviews followed a semi-structured interview guide (see supplementary material) that consisted of four parts.

In the first part, interviewees were informed about the goal of the study as well as the structure of the interview. Next, they were asked to describe their research interests and areas of expertise. Their answers were primarily used to verify and complement interviewee backgrounds that were the basis for sampling interview partners. The goal of the second part was to identify the relevance of energy scenarios for the respective researcher. To structure the discussion, we prepared cards referring to the most relevant public energy scenarios for Switzerland (as presented in Table 1). Participants were asked to assign the cards to one of three categories – (a) "I don't know this scenario", (b) "I have (at least partially) studied it, but did not use it in my research", and (c) "I have used the scenario for research purposes." Since "using" a scenario can have different meanings in the research context, interviewees were asked to clarify. The criterion adopted in this study to qualify as "used" was that any kind of scenario-based information was integrated into the research process. The cards aimed to help the subject to recognise the scenarios, as some have rather technical names but rather distinctive title pages and illustrations. Although the scope of the selected energy scenarios was limited to Switzerland, interviewees were also invited to name international or global energy scenarios that were of relevance to their research. In the third part, we discussed with participants how they select scenarios and for what purposes they use them in their research. The fourth part consisted of an open discussion of different attributes of model-based scenario use. Since modelling competencies and research contexts vary strongly across interviewees, this part of the interview was adjusted to the knowledge and interests of the respective interviewee.

3.3.3 Data analysis

The interviews were transcribed for further analysis. The data analysis of the transcribed interviews followed two independent manual coding steps. The first step, manifest coding, involved direct responses to particular questions on different themes, such as purpose of energy scenario use, model expertise or the relation of energy scenarios to other forms of prospective information. In accordance with the explorative nature of this study, we used an open, non-predefined analysis scheme that emerged from the interview material for the second step [62]. Following Corbin and Strauss [63] a thematic coding strategy was applied. For example, emergent codes such as “transparency” and “open-source” were grouped under a category of “user requirements”. This strategy allows thematic linkages and reoccurring themes to emerge. Other emerging categories were “understanding”, “interpretation” or “handling” of energy scenarios. This enabled the identification of typical scenario use patterns shared by multiple interviewees. In addition, we looked for contrasting opinions about these thematic categories within the sample to spot conflicting perceptions and interpretations of energy scenarios and the visions they propagate. This enabled us to capture the diversity of conceptions of energy scenarios among researchers from different scientific disciplines and highlighted conflicting and consensus statements.

3.4 Results

3.4.1 The relevance of energy scenarios in the energy research community

There is general agreement among interviewees that energy scenarios are relevant to their research. While the degree to which energy scenarios are relevant to the interviewees varies, only one researcher (#8, see supplementary material for full list) did not study a single one. Twelve of the 16 interviewees consulted at least four different public energy scenarios. Accordingly, most of them feel that they have a good overview of public energy scenarios, In fact, each scenario presented to the interviewees was studied by at least four researchers. A few of them additionally mentioned global energy scenarios as one of their references. Those were the, at the time, latest version of the World Energy Outlook (WEO) by the International Energy Agency [25] and the scenarios of the World Energy Council [26].

However, the actual use of energy scenarios is much less diverse (see Figure. 3). Energy Perspectives, commissioned by the SFOE, was the scenario study of choice for most interviewees: Of the 16 interviewees, 14 have used Energy Perspectives in their work, ten of which have not used any other energy scenario study. From their answers it became evident that of the three scenarios included in Energy Perspectives, always the scenario Political measures, which served as the basis for the national energy strategy ES2050, was used. In contrast, those four researchers who have used multiple scenario studies emphasized that the full benefit of using scenarios can only be exploited when multiple scenarios are considered simultaneously: “I think it is really important to not just focus on […] scenarios [issued] by a single institution […] of course there has to be a finite number of scenarios that we can look at, for cognitive reasons, but then I think it’s important to open up the scenarios we have to ideas that other scenarios do not cover” (#7). The importance of considering multiple scenarios by different institutions was also highlighted by another interviewee who stressed that scenarios can represent different interests: "[scenarios] can all display different expectations and interests. In that sense, a scenario is also an echo-chamber, a tool through which actors can communicate" (#2). Overall, though, no researcher effectively used more than three different scenario studies.

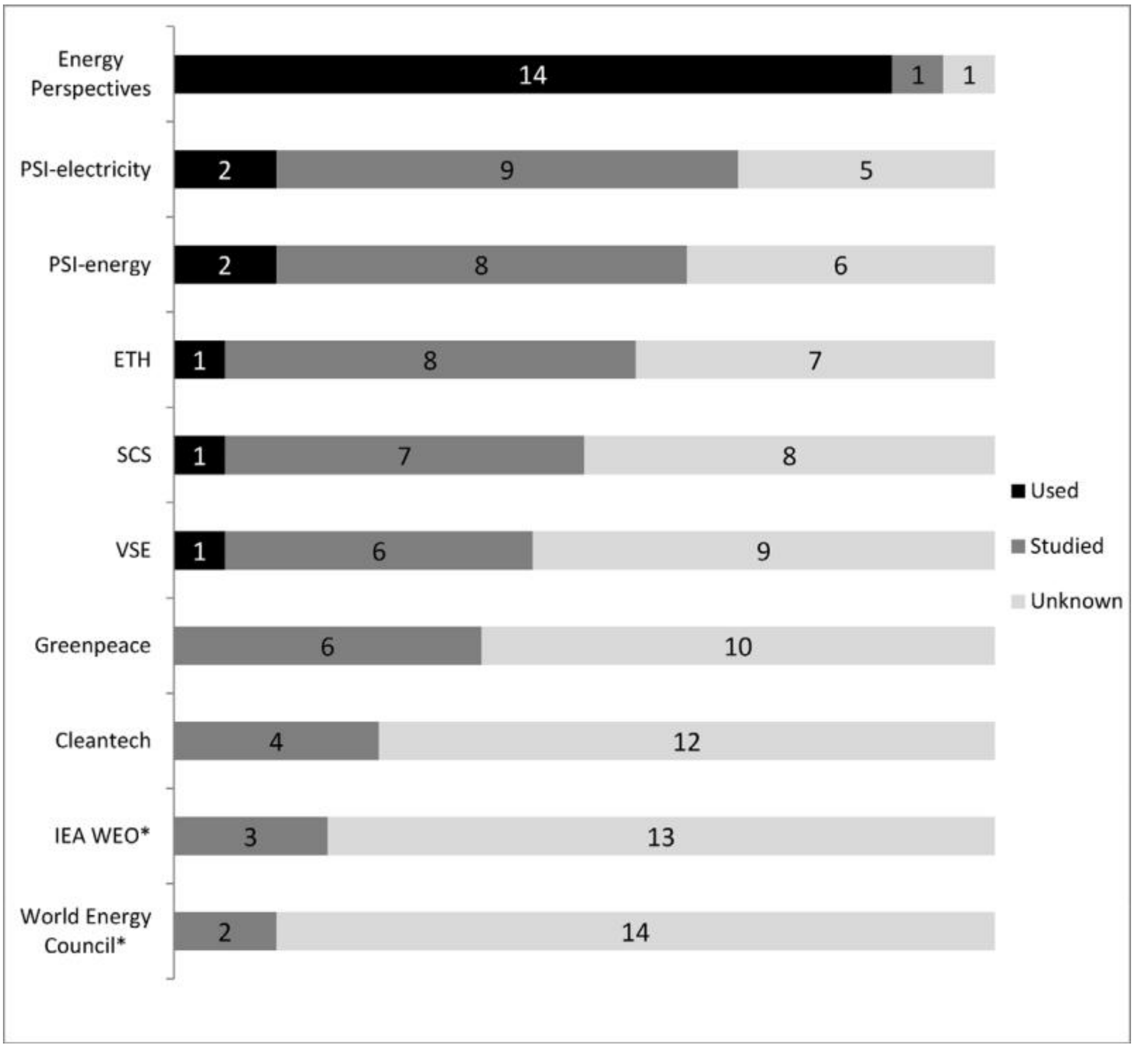

Figure. 3. Overview of energy scenarios studied and used by subjects (n=16). The criterion adopted in this study to qualify as "used" is that any kind of scenario-based information was integrated into the research process, "Studied" means that the scenarios were at least partially read. Scenarios added by Interviewees are marked with an asterisk.

3.4.2 The purpose of energy scenario use in research

In general, the interviewed researchers are interested in a variety of information provided by energy scenarios. While some variables, such as cost estimates or future demand and supply trajectories, are used by several researchers, many others were of interest only to one or two of them. The interviews also showed that the level of spatial and temporal aggregation of data that is required can vary considerably between interviewees or even between different research projects of the same researcher. Nonetheless, one key divide among interviewees with respect to their use of energy scenarios is that some are rather interested in model inputs while others focus on model outputs. In fact, different rationales for using energy scenarios tend to be associated with either using model input or output: Researchers focusing on model input use energy scenarios primarily as data source, whilst interviewees focusing on model output use energy scenarios to highlight the practical importance of a particular field of study.

More specifically, interviewees focusing on model inputs are generally looking for numerical information provided by energy scenarios, for example to feed into their own models and computations. Many of these researchers did so because accessing reliable data for certain aspects of the energy system tends to be difficult and time consuming. As energy scenarios contain a variety of data relevant for different fields of study, they serve as a validated source of information: “Some numbers, for example GDP and the population, or the heated floor space, those are key inputs that we want to have […] it is easiest for us to just take these numbers from scenarios” (#6). In contrast, interviewees focusing on model output use energy scenarios to illustrate current or future research needs by referring to scientifically validated plausible energy futures. This could, for example, be the case for researchers focusing on a particular energy technology that does not yet play an important role in the energy system, but is projected to do so in the future: “Scenarios […] confirm that we do research in a field that will be relevant in the future. It is likely that the reality will be different than the scenario, but the general direction of how the future might unfold is important to us” (#3). Also in this case energy scenarios serve as a scientifically validated source of information. However, these researchers refer to the expectations created by scenarios to illustrate important developments in the energy system. Consequently, they typically employ the results of a scenario study as holistic descriptions of low-carbon energy transitions that would be plausible in both technological and social terms. This focus on scenario results creates challenges in the interpretation of scenario-based information. Some interviewees are for example unaware that most energy scenarios do not claim to provide any kind of probability: “I would like to have more information, for example uncertainty ranges or certain statistical parameters. What is the standard deviation or which interval is the most likely?” (#4). Another interviewee said that they missed uncertainty ranges in scenario trajectories: “2050 is a fairly long time frame and the fact that it [energy demand] is always just a thin black line is really astonishing. Probably, it would have been more honest to include an uncertainty range that gets bigger and bigger” (#7).

3.4.3 Publishing institutions are key for scenario selection

Publishing institutions play a key role in the scenario selection process. Energy Perspectives provides an illustrative example that the perceived relevance of publishing institutions may even be more important than the qualities a specific scenario has. The proprietary (and therefore unpublished) model of Energy Perspectives (as mentioned by interviewee #1, #3, #4, #5, #11, #13) and the unwillingness of the responsible modellers to provide additional information on request (#4, #5, #11) were criticized by many interviewees. One interviewee additionally stated that the unusual presentation style of Energy Perspectives makes it difficult to find the relevant data: "[…] the information is mostly there in some way, but sometimes it is also in the annexes so you really have to spend hours and hours on finding the information or getting data. This not only concerns some assumptions but also basic factors that you need, for example, the efficiency of technologies, the capacity factors of a wind turbine, or the efficiency of a PV panel" (#1). Regardless of this discontent shard among many interviewees and although they are aware of the existing variety of energy scenarios, most of them use Energy Perspectives (see 4.1). The main reason is that publishing institutions function as a proxy to evaluate the relevance of a scenario. Energy Perspectives, which forms the basis of the Swiss energy strategy, is regarded as particularly relevant by interviewees: "If I take Energy Perspectives, the official government data, people usually don't ask any further questions" (1#). Similarly, another interviewee stated that "if you want to be policy-relevant, you have to use this scenario. It was commissioned by the Swiss Federal Office of Energy" (#14), while interviewee #5 concluded that "The only advantage of the Energy Perspectives is that it is endorsed by the government". That Energy Perspectives was actually developed by a private consulting company (see Table 1) did not matter for the researchers. The scenario study published by Greenpeace and developed by the German Aerospace Center, provides a contrasting example: While several interviewees highlighted its sophisticated and transparent modelling approach (#1; #5; #6; #15), they also said that they shy away from referencing a Greenpeace scenario in a scientific paper in order not to seem biased: "Their [i.e., the Greenpeace scenario study] modelling approach is pretty solid, but I will not use it for my analysis. It would just not look serious" (#6).

Another reason why publishing institutions function as a key selection criterion is that users perceive energy scenarios as very complex. In particular, many interviewees without modelling experience admitted finding it difficult to recognize differences between scenarios or identifying the factors causing these variations. Multiple interviewees referred to energy scenarios as black boxes. These users often rely on summaries or visualisations of key results to grasp the main features of scenarios. Likewise, the term black box was also used by interviewees with profound modelling competencies, albeit in a different way. Some of them criticize the often undisclosed influence of commissioning institutions and other stakeholders in the scenario development process. This, the researches claimed, limits their ability to comprehend how the scenarios materialize. For users with modelling competencies the transparency of a scenario study, i.e., the accessibility of models, data and assumptions, is thus regarded to be important. If all elements used to create scenarios are accessible, users with a certain background in energy models can at least partially reconstruct the scenario development process, which enables them to understand how the key results were developed. However, public data and models are of little use without adequate knowledge to interpret them. For example, one interviewee (#3) made the point that even with access to complete datasets and the source code of the underlying model, it would still be impossible for them to comprehend what is going on in a model-based energy scenario. In that sense, many users rely on the reputation of publishing institutions to evaluate whether an energy scenario can be used as a valid source of information.

3.4.4 Patterns of scenario use

As Sections 4.1–4.3 illustrate, there are different rationales and practices among interviewees when it comes to the use of energy scenarios. While scenario use has many different facets, such as the scenario selection, the purpose of scenario use, or the understanding, interpretation and integration of scenario-based information into research activities, these facets seem to be closely linked. In fact, among the interviewed researchers there turned out to be two relatively distinct groups of scenario users.

A first group of interviewees uses energy scenarios primarily as a source for validated data about the energy system. Many researchers that fall into this group (#1, #5, #6, #9, #11, #12, #13, #14, #15) stated that for them, the scenarios are not per se relevant. Rather, they are interested in the model inputs (i.e., data and assumptions) that were employed to develop the projections. For these users, the value of energy scenarios is that they assemble a variety of data that is otherwise hard to find or would require time-consuming data collection, validation and preparation. It is, therefore, mainly the data and assumptions of scenarios that are of interest to these researchers, rather than the future a scenario projects. To them, only a small part of the information provided by scenarios is relevant. To find the required data, a profound knowledge and intensive scrutiny of energy scenarios is needed, as the relevant variables are often buried in lengthy scenario reports or even its appendices. Sifting through this information requires a considerable expertise with respect to energy modelling and scenario methodologies. Researchers in this first group thus tend to have backgrounds in quantitative modelling, which facilitates evaluating the strengths and weaknesses of scenario studies. Publishing institutions play an important role for this user group, as they are highly interested in using data that is both scientifically validated and policy relevant.

Interviewees in the second group regard energy scenarios primarily as scientifically validated plausible energy futures that provide a context for their own research. Many of these researchers (#2, #3, #4, #7, #10, #16) have used scenarios to highlight the relevance of their field, and thereby to legitimise and contextualise their research. In contrast to the first group, they are mostly interested in the output of energy models (such as the development of energy demand or the share of different renewable energy sources over time). This kind of information is often available in syntheses and executive summaries of scenario studies. For this type of use, a less comprehensive understanding of energy models and less intensive scrutiny of scenarios is required. Often – though not always – these researchers have non-technical backgrounds and a limited understanding of the strengths and weaknesses of scenario studies. Many of them tend to perceive model-based energy scenarios as opaque. For this second group of users, publishing institutions are therefore key to evaluate the quality and relevance of a scenario.

3.5 Discussion

3.5.1 General discussion

This study analyzes how energy researchers understand and use energy scenarios. The results illustrate that energy scenarios are used by a diverse set of researchers with heterogeneous disciplinary backgrounds. This exemplifies that energy scenarios are relevant to external users who neither interact with scenario developers, nor participate in scenario development processes. Accordingly, energy scenarios are relevant beyond the small circle of addressees for which many scenario studies are initially constructed. The study also shows that energy scenarios can be used in very different ways and for different purposes: While some researchers tend to use scenarios primarily as data source, for others they serve as a reference for holistic descriptions of plausible energy futures (see Section 5.2).

In addition, this study provides empirical evidence that many potential scenario use benefits associated with user-modeller interaction [64] are inexistent in external use cases. In contrast to the typical empirical context of scenario use [65], the external user is separated from the modeller. This separation is less relevant in case the user commissioned the scenarios, as modellers can adapt the scenarios to the competencies of their target audience. However, unlike scenarios in comparable disciplines, for example climate sciences where the story and simulation approach is the dominant paradigm, energy scenarios focus strongly on quantitative modelling [66]. Non-technical factors, such as social acceptance [67], and qualitative storylines or narratives [68] are still mostly missing. Energy scenario users consequently have little indication of how the society will look like in different scenarios or what role certain actors play [69]. The absence of the broader societal environment is particularly relevant for external scenario users, as they solely depend on information published in scenario studies. The lack of guidance from modellers in combination with the absence of qualitative information strongly affects how energy scenarios generate and communicate knowledge. Occasionally, it can lead to misconceptions of scenario content, as the request to publish the probabilities related to the scenarios (see 4.2) exemplified (an analysis of common misconceptions of IPCC scenarios can be found in McMahon et al. [70]). To fill that gap, external users consider publishing institutions to be key indicators for the relevance and validity of scenarios. Publishing institutions consequently turned out to be the key scenario selection criterion for most interviewees. This finding suggests a possible bias towards scenarios issued by established and powerful institutions [71], respectively towards the models these players use and the implicit expectations their future visions entail (see 5.3).

3.5.2 Two contrasting perspectives: sailors and divers

Two contrasting perspectives on energy scenarios were identified among interviewees (see Section 4.4). They can be illustrated by the metaphor of an iceberg: The tip of the iceberg consists of key results of a scenario study that can be conveyed in an executive summary or synthesis report (e.g. energy consumption, energy supply mixes, or cost estimates). These model outputs lie above the waterline, accessible to users interested in learning about plausible energy futures. Accordingly, we labelled these users sailors. As with an iceberg, however, the larger part of the information provided by a scenario study remain below the water line, only visible to users with the determination and the expertise to scrutinize and understand the scenarios, their underlying models and their assumptions. We labelled these users who mostly use raw data divers. Interestingly, we did not find divers who use assumptions or specific modelling approaches from other energy scenarios, which might be a consequence of the limited compatibility of different energy models and, consequently, energy scenarios.

Sailors are often not able to evaluate the strengths and weaknesses of a particular scenario, as the information below the waterline is not accessible to them. Accordingly, while transparency in the sense of having access to data and model structures is an important aspect of credibility for divers, and one of the most often discussed quality criterion of energy modelling [72,73], it hardly matters for sailors. Thus, although many modellers undertake considerable efforts to make models and data publicly available with the intention of being transparent, a lot of the provided information is in fact incomprehensible for many external users. Moreover, the choice of the model structure, e.g., whether a top-down or bottom-up approach was applied, hardly plays a role for users. This is especially true for sailors, but also divers tend to be more interested in the data rather than the models. This demonstrates that the preferences, needs and behaviour of scenario users do not necessarily follow the course expected by scenario developers. To ultimately improve the accessibility and relevance of their work, modellers need to make the perspectives and constraints of different potential user groups a key factor in the development of energy scenarios, especially if they publish them with the intention of informing external stakeholders.

Sailors and divers are not principally split along the disciplinary backgrounds of interviewees (e.g. technical vs. non-technical), but rather along the purpose of scenario use that determines the understanding and degree of interaction with scenarios. Using energy scenarios as a sailor or diver is furthermore not only related to focusing on model output or model input respectively. It also affects to what degree this information is contextualised and integrated into the research process. Whereas divers process the data they use, sailors relay scientifically validated plausible energy futures and the expectations linked to them. Due to a lack of qualitative information (see 5.1), missing expertise which would be necessary to comprehend the larger parts of a scenario study, and the strong focus on model output, sailors are often constrained to using the scenario results detached from the data, assumptions and model characteristics that constitute them. Instead, sailors tend to treat energy scenarios as future visions to which they attribute their own expectations shaped by their individual background and interests. For this reason, a misplaced confidence about the information provided by energy scenarios might impact energy research and policy [74]. On a more general note, the scenario use practised by sailors could also have implications for public energy policy debates. The substantial changes that already occur in the energy sector or are expected to happen in the foreseeable future, such as the integration of renewable energy sources, climate change mitigation, public acceptance of energy technologies or smart grids spark interest across a broad range of stakeholders, including journalists, NGOs or lay people [44]. Accordingly, it can be assumed, that scenarios describing transformations in the energy sector will be increasingly recognised by external scenario users without modelling competencies or profound knowledge of energy systems. At the same time, the asymmetries in competencies and access to information on energy scenarios create a considerable interpretative flexibility [75]. Model-based energy scenarios could therefore become prone to exaggeration or distortion in public debates [76].

3.5.3 Only few energy scenarios matter

The interviews show that many users find it difficult to get a general idea of the different energy scenarios. Because of this, most interviewees select a scenario based on its publishing institution. The majority of interviewees stated that they favour scenarios issued by or associated with the federal authorities to legitimize their choice. While scenario studies in general consist of multiple scenarios, scenario sets published in a single study are usually not radically different [77]. Typically, only a few selected parameters vary. Since the core normative assumptions (e.g. the phase-out of a particular technology under cost-optimal conditions) often persist, the policy implications that can be deducted from a set of scenarios usually represent a narrow range of options. If a scenario study comprises scenario sets with major opposite directions, this is often to emphasize the possibility of undesirable outcomes (e.g., the consequences of non-acting in baseline or business-as-usual scenarios). Moreover, energy scenarios are often heavily influenced by high-level trends, such as 'consumerist' or 'community' values that lead to unrealistically uniform representation of societies in energy scenarios [45]. The observation that a single scenario is implicitly endorsed as the most suitable scenario by interviewees, therefore, contradicts the core purpose of scenario use, which is to consider a broad range of plausible developments and associated uncertainties [78]. Lund [79, p. 251] shows how critical the "awareness of the possibility to choose" was for the introduction and promotion of wind power in Denmark during the 1980's and 1990's. This demonstrates that, especially in light of the fundamental changes the energy transition is bringing about, it is vital that various alternative energy futures including their implications on the environment, security, health, justice and other affected domains are discussed [80,79]. This is in line with a more recent retrospective analysis of the predictive power of energy scenarios by Trutnevyte et al. [81, p. 5], who found that "the richest and broadest picture of uncertainty emerged when insights from multiple scenario studies by different organisations were combined." This demonstrates that the existing variety of energy models and scenarios is useful, for example to consider less expected real-world developments [82]. Considering a variety of scenarios is recommended to account for biases and missed uncertainties in individual scenarios [39].

However, considering multiple energy scenarios is extremely time-consuming and might offer no direct benefits for many users developing the evidence base for long-term policy decisions. The key role researchers have in the dissemination of scenario-based insights could, in fact, have a cascading effect if the same information source is repeatedly taken as starting point. An excessive use of a few energy scenarios could give the impression of certainty where none exists [83]. Due to the variety of ways scenarios can be constructed and the multitude of players with contrasting interest, there are no universally applicable modelling approaches; there are only more or less appropriate models for particular tasks [84]. The scenario selection process that was observed, which focuses strongly on publishing institutions rather than the qualities of a scenario, does therefore not necessarily yield the most appropriate energy scenario for external users and their varying objectives.

3.5.4 Critical reflection & further research

While this study is a first step towards understanding the external use of energy scenarios, it also has clear limitations. For one, it is important to stress that we relied on reported use of scenarios rather than actual use. Moreover, for the purpose of this research, only explicit types of energy scenario use (e.g. references, data extractions) were considered. Methodologies that are able to include implicit use (e.g. inspiration), might also be able to detect different user types. It is thus likely that the sailor and diver user perspectives are neither completely distinctive nor exclusive, as interest in scenarios and capabilities to interpret them vary gradually between potential user groups and empirical contexts. They represent two ends of a spectrum and it is likely that there are other types of energy scenario use that fall outside it, especially if we open up the scope beyond energy researchers. In addition, the scenario-based Swiss national energy strategy creates a relevance of energy scenarios that is rarely found in other countries, which makes it an interesting case but at the same time limits generalisation. The dominant policy-relevance of a single energy scenario might also limit potential user applications, which is why other user types could potentially be found in use settings with a more diverse policy-relevant scenario landscape. As scenario use is very context dependent, the situation might also be very different in countries with a longer and more extensive history of developing and using policy-relevant energy scenarios, as it is the case in the United Kingdom [32].

Furthermore, the impact of energy scenarios cannot be understood without looking at power structures, such as stated by Pulver and VanDeveer [20, p. 5] who ask for more attention from social sciences towards "the power, politics and social relations that are associated with scenarios products and processes". On account of this, we specifically advocate that the understanding and use of energy scenarios by external users, for whom they are not explicitly designed, are studied more intensively. Forthcoming studies could focus on researchers in different empirical settings, or on other potential external user groups, such as voters, politicians, planners, companies or NGOs. For example, assessing to what extent different users are aware of the dissimilar theoretical underpinnings that are associated with different models would be useful as model choices effectuate a range of major implications regarding participation, alternative awareness and policy making in general [43].

3.6 Conclusion

Historical analyses of past transitions show that socio-technical change is heavily influenced by the key players supporting different technologies, policies or infrastructures and their power gradients to opposing players. In light of the fundamental changes associated with the energy transition and the critical choices that precede these changes, energy scenarios are no longer just made for routine decisions by public administrations or energy companies, but increasingly serve as the scientifically grounded information basis for societal debates among governments, energy companies, NGOs, and the general public. At the interface of science and policy, the use of energy scenarios by external users who are not guided by the modellers thus becomes increasingly important.

This study focuses on researchers as one of many potential groups of external scenario users. The results indicate that energy scenarios are of relevance for researchers with various disciplinary backgrounds, but used very differently depending on the purpose of scenario use and the users' ability to understand model-based energy scenarios. The purpose of scenario use determines what type of information the user is interested in. Divers, who use very specific model inputs describing the existing energy system, make intensive use of scenarios. They mainly use scenarios as data source for further research. Sailors, who are mostly users without in-depth modelling competencies, use model output in an extensive way by referring to descriptions of scientifically validated plausible energy futures. Because of their lack of expertise in energy modelling and a strong focus on the future visions that the scenarios project, the data and assumptions used to develop scenarios are, thus, mostly irrelevant for sailors. Consequently, sailors tend to rely on publishing institutions to evaluate the quality of a scenario. In addition, the complexity of energy models and a general lack of qualitative information and scenario storylines could be identified as a main reason why many researchers regard energy scenarios as difficult to understand, even though they are experts in the field of energy.

It can be assumed that the share of divers who have a good knowledge and understanding of energy scenarios and the models they are based on is higher in research than in other external user groups. This suggests that the interpretation of model-based energy scenarios is even more challenging for users outside academia. To address this, modellers intending to publish their work might have to put more effort into the presentation and communication of their modelling activities to improve the explanatory power of their scenarios. Publishing institutions could provide instructions on how to use and interpret energy scenarios and highlight typical mistakes or misconceptions. Such measures could reduce the risk of misinterpretation or distortion of energy scenarios in public energy policy debates. As the various user groups have different interests in and requirements towards energy scenarios, a single scenario cannot satisfy the needs of all potential users. Institutions commissioning energy scenarios for the purpose of public policy need to be more conscious about the implications their decisions have on the usability and ultimately the decision-support functions of energy scenarios. As the choices of modelling paradigms or developing institutions are directly linked to the qualities and insights that can be provided, we advocate that these are labelled more explicitly. If such concerns are adequately addressed, energy scenarios have the potential to be powerful tools enabling open, comprehensive and inclusive societal discussions of alternative energy futures.

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References

[1] S. Pfenninger, A. Hawkes, J. Keirstead, Energy systems modeling for twenty-first century energy challenges, Renew. Sustain. Energy Rev. 33 (2014) 74–86, http://dx.doi.org/10.1016/j.rser.2014.02.003.

[2] A. Soroudi, T. Amraee, Decision making under uncertainty in energy systems: state of the art, Renew. Sustain. Energy Rev. 28 (2013) 376–384, http://dx.doi.org/10.1016/j.rser.2013.08.039.

[3] D.I. Stern, The role of energy in economic growth, Ann. N. Y. Acad. Sci. 1219 (1) (2011) 26–51, http://dx.doi.org/10.1111/j.1749-6632.2010.05921.x.

[4] G. Luderer, V. Krey, K. Calvin, J. Merrick, S. Mima, R. Pietzcker, et al., The role of renewable energy in climate stabilization: results from the EMF27 scenarios, Clim. Change 123 (3–4) (2014) 427–441, http://dx.doi.org/10.1007/s10584-013-0924-z.

[5] A. Volkery, T. Ribeiro, Scenario planning in public policy: understanding use, im-pacts and the role of institutional context factors, Technol. Forecast. Soc. Change 76 (2009) 1198–1207, http://dx.doi.org/10.1016/j.techfore.2009.07.009.

[6] K. Moyer, Scenario planning at British Airways – a case study, Long Range Plann. 29

(2) (1996) 172–181, http://dx.doi.org/10.1016/0024-6301(96)00005-2.

[7] R. Ramírez, R. Österman, D. Grönquist, Scenarios and early warnings as dynamic capabilities to frame managerial attention, Technol. Forecast. Soc. Change 80 (4) (2013) 825–838, http://dx.doi.org/10.1016/j.techfore.2012.10.029.

[8] G. Ringland, Innovation: scenarios of alternative futures can discover new opportunities for creativity, Strategy Leadersh. 36 (5) (2008) 22–27, http://dx.doi.org/10.1108/10878570810902086.

[9] S. Sondeijker, J. Geurts, J. Rotmans, A. Tukker, Imagining sustainability: the added value of transition scenarios in transition management, Foresight 8 (5) (2006) 15–30.

[10] C.A. Varum, C. Melo, Directions in scenario planning literature–a review of the past decades, Futures 42 (4) (2010) 355–369, http://dx.doi.org/10.1016/j.futures.2009. 11.021.

[11] R. Rohrbeck, J.O. Schwarz, The value contribution of strategic foresight: insights from an empirical study of large European companies, Technol. Forecast. Soc. Change 80 (8) (2013) 1593–1606, http://dx.doi.org/10.1016/j.techfore.2013.01. 004.

[12] M. Godet, F. Roubelat, Creating the future: the use and misuse of scenarios, Long Range Plann. 29 (2) (1996) 164–171.

[13] C. Dieckhoff, Modellierte Zukunft. Zur Theorie und Praxis von Energieszenarien im Kontext wissenschaftlicher Politikberatung. (Doctoral Thesis), Karlsruhe Institute of Technology (KIT), Karlsruhe, 2015.

[14] J. Cochran, T. Mai, M. Bazilian, Meta-analysis of high penetration renewable energy scenarios, Renew. Sustain. Energy Rev. 29 (2014) 246–253, http://dx.doi.org/10.1016/j.rser.2013.08.089.

[15] A. Wiek, C. Binder, R.W. Scholz, Functions of scenarios in transition processes, Futures 38 (7) (2006) 740–766, http://dx.doi.org/10.1016/j.futures.2005.12.003.

[16] F. Berkhout, J. Hertin, Foresight futures scenarios: developing and applying a participative strategic planning tool, Greener Manage. Int. (2002) 37–53.

[17] W. Weimer-Jehle, J. Buchgeister, W. Hauser, H. Kosow, T. Naegler, W.-

R. Poganietz, et al., Context scenarios and their usage for the construction of socio-technical energy scenarios, Energy 111 (2016) 956–970, http://dx.doi.org/10. 1016/j.energy.2016.05.073.

[18] L.A. Franco, M. Meadows, S.J. Armstrong, Exploring individual differences in scenario planning workshops: a cognitive style framework, Technol. Forecast. Soc. Change 80 (4) (2013) 723–734, http://dx.doi.org/10.1016/j.techfore.2012.02.008.

[19] G. Wright, R. Bradfield, G. Cairns, Does the intuitive logics method–and its recent enhancements–produce effective scenarios? Technol. Forecast. Soc. Change 80 (4) (2013) 631–642, http://dx.doi.org/10.1016/j.techfore.2012.09.003.

[20] S. Pulver, S.D. VanDeveer, Thinking about tomorrows: scenarios, global environmental politics, and social science scholarship, Glob. Environ. Polit. 9 (2) (2009) 1–13, http://dx.doi.org/10.1162/glep.2009.9.2.1.

[21] DTI UK, Energy White Paper. Our energy future? Creating a low carbon economy, Department of Trade and Industry, London, 2003.

[22] J. Nitsch, T. Pregger, T. Naegler, D. Heide, D. Luca de Tena, F. Trieb, et al., Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global, (2012).

[23] Exxon Mobil, The outlook for energy: a view to 2040, Exxon Mobil, Texas, USA, 2013.

[24] S. Teske, J. Muth, S. Sawyer, T. Pregger, S. Simon, T. Naegler, et al., Energy [r] Evolution–A Sustainable World Energy Outlook, Greenpeace International, EREC and GWEC, 2012.

[25] International Energy Agency, World Energy Outlook, International Energy Agency, Paris, France, 2015.

[26] World Energy Council, World Energy Scenarios: Composing Energy Futures to 2050, World Energy Council/Paul Scherrer Institute (PSI), London, 2013.

[27] European Commission, Energy Roadmap 2050, Publications Office of the European Union: European Commission, Luxembourg, 2012.

[28] S. Mathy, M. Fink, R. Bibas, Rethinking the role of scenarios: participatory scripting of low-carbon scenarios for France, Energy Policy 77 (2015) 176–190, http://dx. doi.org/10.1016/j.enpol.2014.11.002.

[29] Y.B. Blumer, C. Moser, A. Patt, R. Seidl, The precarious consensus on the importance of energy security: contrasting views between Swiss energy users and experts, Renew. Sustain. Energy Rev. 52 (2015) 927–936, http://dx.doi.org/10. 1016/j.rser.2015.07.081.

[30] B.K. Sovacool, B. Brossmann, Fantastic futures and three American energy transitions, Sci. Cult. 22 (2) (2013) 204–212, http://dx.doi.org/10.1080/09505431.2013.786999.

[31] J.F. DeCarolis, K. Hunter, S. Sreepathi, The case for repeatable analysis with energy economy optimization models, Energy Econ. 34 (6) (2012) 1845–1853.

[32] P.G. Taylor, P. Upham, W. McDowall, D. Christopherson, Energy model, boundary object and societal lens: 35 years of the MARKAL model in the UK, Energy Res. Soc. Sci. 4 (2014) 32–41, http://dx.doi.org/10.1016/j.erss.2014.08.007.

[33] A. Grubler, Energy transitions research: insights and cautionary tales, Energy Policy 50 (2012) 8–16, http://dx.doi.org/10.1016/j.enpol.2012.02.070.

[34] C. Selin, Trust and the illusive force of scenarios, Futures 38 (1) (2006) 1–14, http://dx.doi.org/10.1016/j.futures.2005.04.001.

[35] Swiss Federal Council, Botschaft zum Aktionsplan «Koordinierte Energieforschung Schweiz» – Massnahmen in den Jahren 2013–2016, Swiss Federal Council, Bern, 2012.

[36] Swiss Federal Council, Botschaft zum ersten Massnahmenpaket der Energiestrategie 2050, Swiss Federal Council, Bern, 2013.

[37] D.P. van Vuuren, M. Hoogwijk, T. Barker, K. Riahi, S. Boeters, J. Chateau, et al., Comparison of top-down and bottom-up estimates of sectoral and regional green-house gas emission reduction potentials, Energy Policy 37 (12) (2009) 5125–5139, http://dx.doi.org/10.1016/j.enpol.2009.07.024.

[38] L. Börjeson, M. Höjer, K.-H. Dreborg, T. Ekvall, G. Finnveden, Scenario types and techniques: towards a user's guide, Futures 38 (7) (2006) 723–739, http://dx.doi.org/10.1016/j.futures.2005.12.002.

[39] G.A. Laugs, H.C. Moll, A review of the bandwidth and environmental discourses of future energy scenarios: shades of green and gray, Renew. Sustain. Energy Rev. 67 (2017) 520–530, http://dx.doi.org/10.1016/j.rser.2016.09.053.

[40] S. Jebaraj, S. Iniyan, A review of energy models, Renew. Sustain. Energy Rev. 10 (4) (2006) 281–311, http://dx.doi.org/10.1016/j.rser.2004.09.004.

[41] U. Remme, Capacity building through energy modelling and systems analysis (slide show), IEA Experts' Group Presentation on R&D Priority-Setting and Evaluation Developments in Energy Education: Reducing Boundaries, Energy Technology Policy Division, IEA, Copenhagen, 2012.

[42] A. Herbst, F. Toro, F. Reitze, E. Jochem, Introduction to Energy Systems Modelling, Swiss J. Econ. Stat. (SJES) 148 (2) (2012), http://EconPapers.repec.org/RePEc:ses:arsjes:2012-ii-2.

[43] H. Lund, F. Arler, P. Østergaard, F. Hvelplund, D. Connolly, B. Mathiesen,

P. Karnøe, Simulation versus optimisation: theoretical positions in energy system modelling, Energies 10 (7) (2017) 840.

[44] S. Paltsev, Energy scenarios: the value and limits of scenario analysis, Wiley

Interdisciplinary Reviews: Energy and Environment, (2016), http://dx.doi.org/10.1002/wene.242.

[45] N. Hughes, N. Strachan, Methodological review of UK and international low carbon scenarios, Energy Policy 38 (10) (2010) 6056–6065, http://dx.doi.org/10.1016/j.enpol.2010.05.061.

[46] A. Chiodi, P.G. Taylor, J. Seixas, S. Simões, P. Fortes, J.P. Gouveia, et al., Energy policies influenced by energy systems modelling—case studies in UK, Ireland, Portugal and G8, in: G. Giannakidis, Maryse Labriet, Brian Ó. Gallachóir, Giancarlo Tosato (Eds.), Informing Energy and Climate Policies Using Energy Systems Models, vol. 30, 2015, pp. 15–41.

[47] N. Hughes, Towards improving the relevance of scenarios for public policy questions: a proposed methodological framework for policy relevant low carbon sce-narios, Technol. Forecast. Soc. Change 80 (4) (2013) 687–698, http://dx.doi.org/10.1016/j.techfore.2012.07.009.

[48] M. Jefferson, Closing the gap between energy research and modelling, the social sciences, and modern realities, Energy Res. Soc. Sci. 4 (2014) 42–52, http://dx.doi.org/10.1016/j.erss.2014.08.006.

[49] C. Wilson, A. Grubler, N. Bauer, V. Krey, K. Riahi, Future capacity growth of energy technologies: are scenarios consistent with historical evidence? Clim. Change 118 (2013) 381–395, http://dx.doi.org/10.1007/s10584-012-0618-y.

[50] E.P. Springfeldt, B. Tennbakk, H. Ravn, M. Havskjold, J. Niemi, T. Koljonen, et al., Coordinated use of Energy system models in energy and climate policy analysis: lessons learned from the Nordic Energy Perspectives project, in: T. Unger (Ed.), Nordic Energy Perspectives, 2010 Stockholm, Sweden.

[51] J.K.M. Karjalainen, J. Luukanen, J. Vehmas, Energy Models and Scenarios in the Era of Climate Change – Briefing Report vol. 3, University of Turku, 2014.

[52] Prognos, Die Energieperspektiven für die Schweiz bis 2050 (Energy Persepctives for Switzerland until 2050), (2012).

[53] M. Densing, E. Panos, S. Hirschberg, Meta-analysis of energy scenario studies: example of electricity scenarios for Switzerland, Energy 109 (2016) 998–1015, http://dx.doi.org/10.1016/j.energy.2016.05.020.

[54] VSE, Wege in die neue Stromzukunft (Paths into the new energy future), Verband Schweizerischer Elektrizitätsunternehmen, Aarau, 2012.

[55] G. Andersson, K. Boulouchos, L. Bretschger, Energiezukunft Schweiz (Energy Future Switzerland), Energy Science Center, ETH, Zürich, 2011.

[56] F. Barmettler, N. Beglinger, C. Zeyer, Energiestrategie–Richtig rechnen und wirtschaftlich profitieren, auf CO2-Zielkurs (Cleantech Energy Strategy), Swisscleantech, Bern, 2013.

[57] N. Weidmann, Transformation strategies towards a Sustainable Swiss Energy System–An Energy-economic Scenario Analysis. (Doctoral Thesis), ETH, Zürich, 2013.

[58] R.T.H. Kannan, The Swiss TIMES Electricity Model (STEM-E): Updates to the model input data and assumptions (Model Release 2), Paul Scherrer Institute (PSI), 2012.

[59] SCS, SCS Energiemodell (SCS Energy Model), Supercomputing Systems AG, Zürich, 2013.

[60] S. Teske, G. Klingler-Heiligtag, Energy [r]evolution, Greenpeace, Switzerland, 2013.

[61] P. Raskin, F. Monks, T. Ribeiro, V. Vuuren, M. Zurek, S.R. Carpenter, et al., Global scenarios in historical perspective, Ecosystems and Human Well-being: Scenarios vol. 2, Island Press, Washington, DC, 2005, pp. 35–44.

[62] M. Schreier, Qualitative Content Analysis in Practice, Sage Publications, 2012.

[63] J. Corbin, A. Strauss, Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory, (2008) Thousand Oaks.

[64] E. Oteros-Rozas, B. Martín-López, T. Daw, E.L. Bohensky, J. Butler, R. Hill, et al., Participatory scenario planning in place-based social-ecological research: insights and experiences from 23 case studies, Ecol. Soc. 20 (4) (2015).

[65] E. Zafeiratou, C. Spataru, Past trends for the UK energy scenarios: how close are their predictions to reality? Energy Proced. 62 (2014) 442–451, http://dx.doi.org/10.1016/j.egypro.2014.12.406.

[66] J. Alcamo, The SAS approach: combining qualitative and quantitative knowledge in environmental scenarios, Dev. Integr. Environ. Assess. 2 (2008) 123–150, http://dx.doi.org/10.1016/S1574-101X(08)00406-7.

[67] D.K.J. Schubert, S. Thuß, D. Möst, Does political and social feasibility matter in energy scenarios? Energy Res. Soc. Sci. 7 (2015) 43–54, http://dx.doi.org/10.1016/j.erss.2015.03.003.

[68] E. Trutnevyte, J. Barton, Á. O'Grady, D. Ogunkunle, D. Pudjianto, E. Robertson, Linking a storyline with multiple models: a cross-scale study of the UK power system transition, Technol. Forecast. Soc. Change 89 (2014) 26–42, http://dx.doi.org/10.1016/j.techfore.2014.08.018.

[69] P. Fortes, A. Alvarenga, J. Seixas, S. Rodrigues, Long-term energy scenarios: bridging the gap between socio-economic storylines and energy modeling, Technol. Forecast. Soc. Change 91 (2015) 161–178, http://dx.doi.org/10.1016/j.techfore.2014.02.006.

[70] R. McMahon, M. Stauffacher, R. Knutti, The unseen uncertainties in climate change: reviewing comprehension of an IPCC scenario graph, Clim. Change 133 (2) (2015) 141–154.

[71] I.F. Ballo, Imagining energy futures: sociotechnical imaginaries of the future smart grid in Norway, Energy Res. Soc. Sci. 9 (2015) 9–20, http://dx.doi.org/10.1016/j.erss.2015.08.015.

[72] S. Pfenninger, Energy scientists must show their workings, Nature 542 (7642) (2017) 393–393.

[73] N. Strachan, B. Fais, H. Daly, Reinventing the energy modelling–policy interface, Nat. Energy 1 (2016) 16012.

[74] A.T. Hermann, K. Hogl, M. Pregernig, Science–policy interactions in Austrian, Dutch, and Swiss climate policy: a comparative account, J. Environ. Policy Plann. (2016) 1–15, http://dx.doi.org/10.1080/1523908X.2016.1180238.

[75] N. Brown, M. Michael, A sociology of expectations: retrospecting prospects and prospecting retrospects, Technol. Anal. Strateg. Manage. 15 (1) (2003) 3–18, http://dx.doi.org/10.1080/0953732032000046024.

[76] C. Dieckhoff, A. Leuschner, Die Energiewende und ihre Modelle: Was uns Energieszenarien sagen können-und was nicht, transcript, Bielefeld, 2016.

[77] J.M. Vervoort, R. Bendor, A. Kelliher, O. Strik, A.E. Helfgott, Scenarios and the art of worldmaking, Futures 74 (2015) 62–70, http://dx.doi.org/10.1016/j.futures. 2015.08.009.

[78] B.P. Bryant, R.J. Lempert, Thinking inside the box: a participatory, computer-assisted approach to scenario discovery, Technol. Forecast. Soc. Change 77 (1) (2010) 34–49, http://dx.doi.org/10.1016/j.techfore.2009.08.002.

[79] H. Lund, Choice awareness: the development of technological and institutional choice in the public debate of Danish energy planning, J. Environ. Policy Plann. 2 (3) (2000) 249–259, http://dx.doi.org/10.1080/714038558.

[80] F.N. Laird, Against transitions? Uncovering conflicts in changing energy systems, Sci. Cult. 22 (2) (2013) 149–156.

[81] E. Trutnevyte, W. McDowall, J. Tomei, I. Keppo, Energy scenario choices: insights from a retrospective review of UK energy futures, Renew. Sustain. Energy Rev. 55 (2016) 326–337, http://dx.doi.org/10.1016/j.rser.2015.10.067.

[82] P.B. Berntsen, E. Trutnevyte, Ensuring diversity of national energy scenarios: bottom-up energy system model with Modeling to Generate Alternatives, Energy 126 (2017) 886–898, http://dx.doi.org/10.1016/j.energy.2017.03.043.

[83] F.G. Li, Actors behaving badly: exploring the modelling of non-optimal behaviour in energy transitions, Energy Strategy Rev. 15 (2017) 57–71.

[84] A. Grunwald, Energy futures: diversity and the need for assessment, Futures 43 (8) (2011) 820–830, http://dx.doi.org/10.1016/j.futures.2011.05.024.

4 Paper III - A two-level analysis of public support: Exploring the role of beliefs in opinions about the Swiss energy strategy

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Abstract

Energy system transitions in democracies require that national interests and central planning are reconciled with the public's preferences. This pilot study investigates public support for the Swiss national energy strategy and two specific technologies that are part of it: expansion of hydropower and deep geothermal energy. It addresses two research questions. First, how does public support for a national energy transition differ from public support for specific technologies endorsed in an energy transition strategy? Second, are there differences in the factors influencing public support for these technologies? We investigate these questions empirically with a survey (N = 640), focusing on understanding the role lay-people's expectations about the future energy system, political ideology, and future orientation play in generating support for these two levels of public support and for two technologies with different characteristics. We find that while support for an energy transition is well explained by above factors, this is true to a much lesser extent for technology support. One conclusion is that support for an energy transition and for energy technologies is politicized to varying degrees, which is why their acceptability may be less shaped by their objective characteristics, but rather by subjective perceptions and beliefs the public holds towards them.

4.1 Introduction

Many countries are under public pressure to secure their domestic energy supply while simultaneously undertaking large-scale energy system transitions (e.g., [1]). In the past, many of these decisions were made technocratically, even in democracies (e.g., [2]). However, a supportive public has come to weigh more heavily in recent energy system planning and implementation (e.g., [3,4]) — be it for siting nuclear used-fuel repositories (e.g., [5–8]) or for building wind farms [9]. Hence, enabling a complex large-scale energy system transition requires democratic governments to reconcile national interests and central planning with the public's preferences. However, the formation of public support for energy transitions is a complex process shaped by many determinants on different levels [4,10]. For instance, Dermont et al. [11] point out that actors' reactions toward a policy that shapes the overall "acceptance" of the policy differ across stages of policy-making. Moreover, depending on the specific project, technology or policy in question, the same factors may be key determinants of support or not relevant at all (see [12] for a review). This pilot study addresses the role of beliefs and future orientation as important sources of public support, and more specifically, how this role changes depending on the level of abstraction and the technology in question. Using the case of the Swiss national energy strategy, we analyze general support for an energy transition and support for two renewable energy technologies, namely hydropower (HP) and deep geothermal energy (DGE), whose capacity expansion is currently considered under the national energy strategy. Because these two technologies as well as the two levels at which public support is analyzed differ in a range of aspects, this research setting allows us to comparatively assess the differential relevance of public support determinants.

Studies on public support in the field of energy have provided insights on the categories of socio-political, market, and community acceptance [4]. Despite a high level of support for renewable energy in general (e.g., wind energy), studies highlight that specific technology infrastructures (e.g., wind farms) have attracted significant local resistance [13–16]. A long list of failed energy projects led to significant research efforts at the level of community acceptance. While the notion of Not In My Backyard (NIMBY) emerged as a possible explanation for the gap between support for renewable energy in general and concrete projects in a local context, there are also plenty of criticisms that the NIMBY framework assumes a too "simplistic relationship between proximity and objection" ([17], p. 104). In fact, further research has shown that underlying causes of public attitudes and resistance to energy infrastructure are much more nuanced and complex [3,18,19].

Indeed, there are different levels of abstraction at which public support can play a role. In addition to the above-mentioned bottom level of local support for concrete projects, there is the upper level that determines long-term energy goals, and the middle level, at which potential technologies (i.e., the practical steps to implement high-level energy transition goals) are considered. As the example of nuclear energy suggests, a technology's fit with overall national goals (e.g. low-carbon) does not necessarily equal public support [20], pointing to the important difference between public support on the upper and the middle level within the same policy domain. Notwithstanding the literature's awareness of these multiple levels, most public opinion studies have so far focused on one of these levels at a time. In other words, the interlinkages between these levels are not yet well understood. Therefore, the primary empirical goal of this paper is to identify and compare the relevant determinants of public preference between the upper and middle level.

There is also a considerable body of research investigating public preference for technologies in more detail (e.g., [21,22]). This literature concludes even those who are generally supportive of renewable energy do not support it without qualification. Accordingly, people factor in impacts of energy infrastructure developments on landscape, the environment, animals or humans [23]. Some have investigated this issue via choice experiments, measuring the effect of tangible sources of such trade-offs (e.g., costs, effects on employment, and risks) on individuals' willingness to pay [24,25]. However, in reality, public support for energy projects, technologies and policies is shaped by the interplay between social, technical, economic, and political aspects, which cannot be separated and make it a complex field of study [26–28]. In addition, acceptability may be less shaped by objective characteristics of technologies, but rather by the subjective perceptions of these characteristics held by the public (see [12]). These perceptions are shaped by various beliefs, including the intuitive assessment of the technologies themselves or how well the technology is perceived to fit into the current or future energy system. Accordingly, these perceptions are strongly dependent on knowledge, trust in institutions and socio-institutional stakeholders (see also [29], in this special issue), as well as general worldviews and political or societal discourses, which are becoming more populistic and nationalistic in many countries (see also [30], also in this special issue). The survey on which our empirical analysis is based makes it possible to account for the intertwined nature of public acceptance by focusing on the role of subjective views on energy technologies.

More specifically, the study at hand seeks to explore how public support for energy technologies depends on different aspects of individuals' broader perception of renewable energy technologies. We aim to better understand how the relevance of these aspects differ with respect to support on different levels: i.e., support for broader energy policy goals vs. for energy technologies. In addition, because perceptions can be substantially different between specific technologies, we also include the analysis of public support within the (middle) level: i.e., between two renewable energy technologies with different characteristics. This is done based on an empirical pilot study in Switzerland, which provides an ideal context to study these questions due to the current energy policy situation and also the long history of direct-democratic participation (see Section 2.2 for details). This research will enhance our understanding of how support for renewables is formed. This is not only relevant for the implementation of specific renewable energy projects, but also for the design and implementation of energy policies seeking to promote large renewable energy projects. After all, public resistance to a project is often only the manifestation of perceptions that form at a more general level due to the decisions made in the development of planning and permission procedures of energy projects [31].

4.2 Background

4.2.1 The role of beliefs in public support for energy issues

There are a number of factors that have shown to influence public acceptance of energy infrastructure and policies. They include trust in experts, operators, or authorities (see e.g., [4,12,32–34]), political ideology, which is often used as a cognitive shortcut in opinion-formation processes of complex and controversial areas [35–37], issue knowledge [38,39] and a wide range of individual psychological factors (see [12] for a review). On top of that, we know from research on mental models [40,41] that individual narratives and sets of beliefs are relevant for opinion-formation with respect to complex issues. Beliefs are statements that are presumed to be true by the holder of the belief, regardless of whether they are factually true [42]. Consequently, they are shaped by cultural, social and political dynamics [43]. For example, in this special issue, Batel and Devine-Wright [44] argue that feelings of belonging to different imaginary communities impact people's responses towards energy issues at the local, national and European level, whereas MacArthur and Matthewman [45] explore the role of indigenous ownership of energy infrastructure in New Zealand.

While beliefs are a familiar psychological concept in the energy transition literature [46], expectations, which can be defined as a reflection of beliefs about the future, are an understudied construct in research on public support for energy technologies (with Fergen and Jacquet [47] and Ryghaug and Toftaker [48], being notable exceptions). The following paragraphs describe the beliefs that are analyzed in this study.

Expectations towards the future energy system: In the field of energy research, the concept of guiding visions has received a lot of attention as a "central means of mobilizing social actors and the coordination of dispersed agency" ([49], p. 449). Both, appeal and technical feasibility, have been identified to be important components of influential visions [50]. Yet, a range of visions can be defined under a single policy goal. Lilliestam and Hanger [51] show that even among expert advocates of 100% renewable electricity systems, there can be irreconcilable differences between the energy futures they have in mind. So far, expectations of lay people have not been given much attention in energy studies. Thus, there is little empirical research on how lay people's expectations about the energy future shape their support for energy policies and technologies. However, the role of expectations and their influence on decision-making is well established in other fields, for example in transition studies (e.g., [52–55]).

Technology perception: Energy technologies have a range of specific characteristics. For example, HP dams inevitably entail environmental impacts on aquatic ecosystems or the risk of dam failures. However, research suggests that even identical energy technology characteristics are often perceived differently by people [12]. For example, Slovic et al. [56] use the concept of affect heuristic to explain how the people's risk and benefit judgments are influenced by their feelings towards a technology. Therefore, affection towards a technology leads to higher perceived benefits and lower perceived risks, and vice versa [57]. Accordingly, measuring the broad and subjective technology perceptions is important as they can be partially influenced by cultural, social and political narratives in which alternative energy technologies are embedded in Firestone et al. [58] for example showed that energy technologies can carry a range of symbolic meanings which affect their acceptability.

Future-orientation: In addition to beliefs, we also include one psychological factor in the analysis. As most energy policy proposals and energy technology planning horizons are focusing on long-term outcomes, personality traits that describe how individuals conceptualize and deal with distant future outcomes may be important in acceptability evaluations [7]. Research in other fields, such as health-related or pro-environmental behavior, have shown that not only issue-specific expectations play a role for individuals' opinions, but that also their general future orientation matters [59–61].

4.2.2 The case of Switzerland

Switzerland has a long tradition of direct democracy, meaning that voters can express their preferences about energy policies or infrastructure projects not only at the ballot box, but also through other participation channels such as consultation processes. Therefore, the Swiss government must build public support for its energy policy goals and regulations, even to a greater degree than other democracies, as it was the case in May 2017, when voters approved the new national "Energy Strategy 2050" (ES2050) by a referendum.

The key goals of ES2050 are a substantive reduction in energy demand and a drastic increase in domestic renewable energy production in order to gradually phase-out all of the operating nuclear power stations (which currently produces about a third of the countries' power [62]). A large share of this additional renewable production is supposed to come from solar and wind power. However, the ES2050 focuses on HP and DGE to partially replace the base load capacity currently provided by nuclear energy. Increasing imports of electricity and gas (in order to fuel gas-fired power plants) is not intended by the strategy [63].

Yet, while Swiss voters supported ES2050 overall, the necessary steps to implement the energy transition are neither clear nor without controversy. Although HP is a mature, well-known and well-developed technology in Switzerland [64],[1] it is highly doubtful whether HP capacity can be further expanded. An increased usage of HP resources would require compromises with respect to environmental regulations and landscape preservation [65,66]. For this reason, only few large-scale projects were built in the last decade. The only realistic options to increase HP capacity is by raising the height of existing dams, or by building new dams in locations where glaciers are retreating (periglacial hydropower).[2] DGE, in contrast, is a much less-known and trusted technology that is still in the pilot phase. While ES2050 assigns DGE a significant potential,[3] the only two DGE pilot projects so far had to be stopped, partially due to induced seismic activity in the cities of Basel and St. Gallen [67]. After the failure of these pilot projects the strength of public support for DGE is questionable.

We use this particular setting to empirically explore the relative importance of factors known or expected to influence the support for an energy transition and energy technologies. In Switzerland, public support plays a key role in reaching energy policy goals at the national, cantonal and municipal level. Accordingly, people are accustomed to concern themselves with energy related issues at varying governance levels. Additionally, the public's current ambivalent sentiments towards HP as well as DGE make Switzerland an ideal opportunity to explore support on two different levels. The striking differences between the two technologies offer a convenient basis for studying the role of individuals' perceptions and beliefs as potential determinants of public support.

4.3 Methods

4.3.1 Recruitment of survey participants

The online survey was programmed using the software package Unipark.[4] In December 2017, before being finalized, the survey was pretested.[5] For the finalized survey, German-speaking Swiss residents between the age of 18 and 70 were recruited via an online panel, Respondi.[6] The panel members received an invitation to participate in the study, with a small incentive of

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[1] In 2015, HP provided 59% of the Swiss electricity supply [62].

[2] Additional capacity due to large-scale HP plants could be up to 2500 GWh per year (7.5% additional capacity) [85].

[3] Recent estimates suggest that up to approximately 20% of the current nuclear capacity could be replaced by DGE [85].

[4] https://www.unipark.com/en/.

[5] Pretest was with a convenience sample of N=76, consisting of students and personal acquaintances of the authors.

[6] https://www.respondi.com/EN/.

0.75 Euro credited upon completion of the survey. The survey was in the field between December 13 and 20, 2017. Our sample based on the online panel is a convenience sample but approximates the characteristics of the Swiss population in terms of age and gender, as we screened participants by quota on these two dimensions at the beginning of the survey.[1]

4.3.2 Survey flow

Contingent on respondents' agreement to take part in the survey, and the clearance by the quota screening, they were randomly assigned to one of two survey flows. Half of the respondents were assigned to a flow focusing on HP whereas the other half focused on DGE. The decision for this parallel design was made based on the experiences from the pretest. On the one hand, a few pretest commentators found the combination of HP and DGE in a single survey unintuitive, which is plausible given that considerable energy system knowledge (e.g. the concepts of base- and peak load) is required to link the two. On the other hand, we aimed to keep the survey as short as possible in order to minimize negative impacts from survey fatigue on data quality [68]. Fig. 4 provides an overview of the survey flow.[2] Appendix B provides a full list of survey items verbatim. Unless specified otherwise (see 4.3), we measure all items on a 7-point Likert scale, with 1 indicating "don't agree" and 7 "agree".

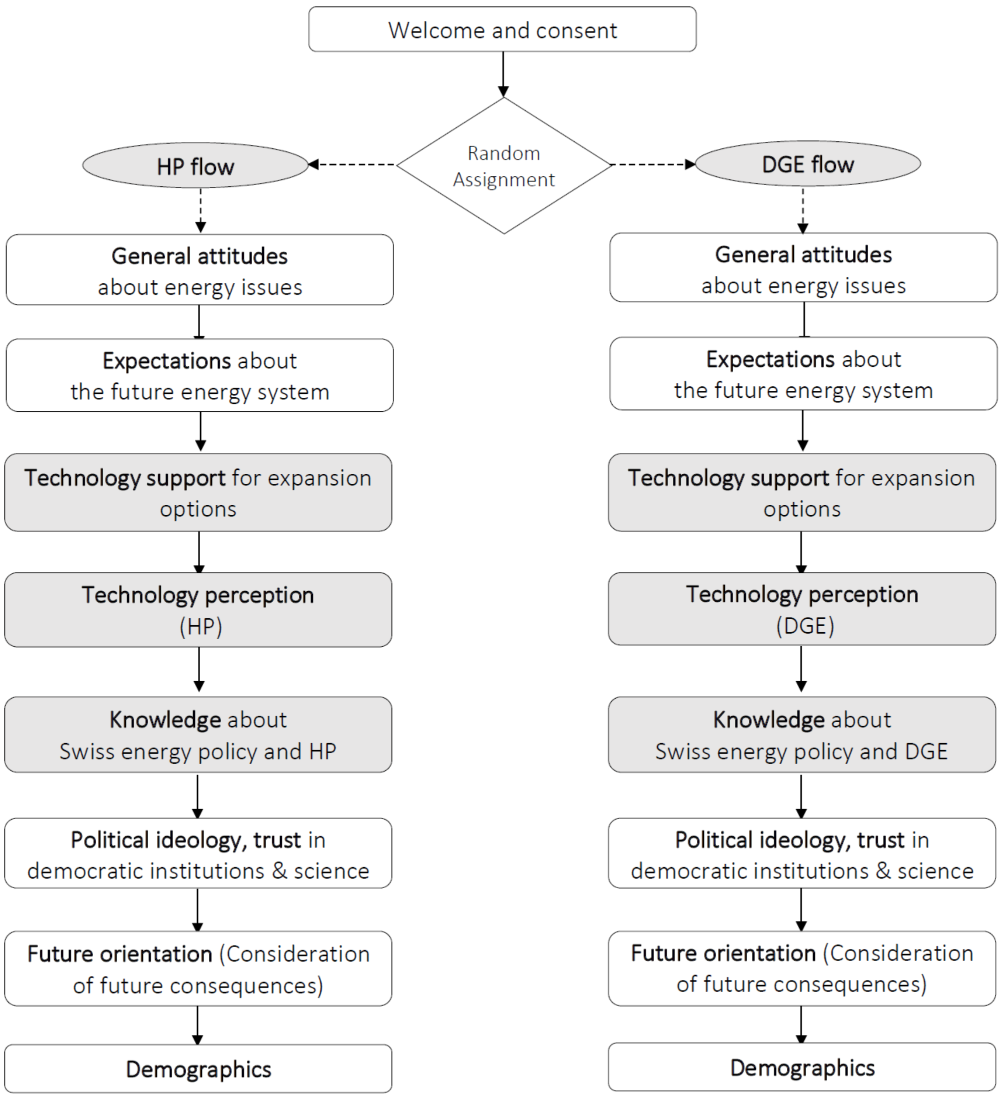
General attitudes about energy issues includes a broad battery of questions regarding participant's general attitudes on energy issues, their stance with respect to energy-related trade-offs, their preferences for different energy generation technologies, and their general support for an energy transition. Expectations about the future energy system attempts to capture respondents' vision of the energy system, i.e. whether and how they expect it to change until 2050 in comparison to today. All items refer to characteristics of the energy system that play a role in the current debate about the energy transition, some referring to continuous developments (e.g., share of renewables), while others represent changes in frequencies of events (e.g., blackouts). Technology support for either HP or DGE explored participants' general support for expanding HP or DGE production in Switzerland, as well as a number of potential qualifications for the implementation of these technologies (e.g. concerning financial compensation for host region). Technology perception measures respondents' intuitive associations towards energy technologies, using a set of bipolar semantic differential items. This should give indications towards how the technologies are perceived by the public. In the Knowledge block respondents were asked how knowledgeable they consider themselves about

[1] Five age categories were defined per gender. Once a quota was filled, additional respondents belonging to the category were screened out.

[2] Survey participants did not see survey-block labels.

the Swiss energy system and policy in general and about HP or DGE in particular. Furthermore, a set of items were included to assess participants' factual knowledge with respect to either technology. Political ideology and trust comprises of party affiliations and political leaning (left/right scale), as well as trust in different political institutions and in science. Future orientation was measured using the 12-items Consideration of Future Consequences (CFC) scale [69]. Finally, the survey ends with a set of questions on the demographics of participants.

Figure. 4. Summary of survey flows.



Note. Shaded boxes = Item blocks specific to each energy technology (HP or DGE). White boxes = Common survey items across the two implementation technologies.

4.3.3 Sample characteristics

In total, 643 respondents completed the survey,[1] out of which three observations were dropped. An observation was dropped if the following two criteria were met: the participant (i) completed the entire survey in under 5 min and (ii) clicked-to-complete, i.e., choosing the same answer for every question. The final number of observations we work with is therefore 640: 334 for HP and 306 for DGE.

The median respondent completed the survey within 16.3 min, and 90% of respondents completed within the reasonable duration of 31 min. Table 2 reports the summary statistics for some of the main demographic variables. The two survey flows are balanced; t-tests confirm that the groups are not statistically different on average over these variables. Moreover, our sample also compares very well with the Swiss population and the latest national election results, with respect to age, sex, and the distribution of partisan identification [70,71]. The share of university degree holders is slightly lower in our sample, compared to the Swiss population (22.7% in the sample, as opposed to 27% in the Swiss population).

Table 2: Summary statistics of control variables

Variable	DGE flow Mean	HP flow Mean	Mean Diff	T-Test T-Stat	P-Value
Male	0.52	0.50	0.03	0.69	0.490
	(0.50)	(0.50)	(0.04)		
Age	45.01	44.38	0.47	0.39	0.697
	(14.89)	(15.26)	(1.20)		
Votes in CH	0.64	0.67	-0.03	-0.87	0.387
	(0.48)	(0.47)	(0.04)		
Children	0.51	0.47	0.04	0.99	0.322
	(0.50)	(0.50)	(0.04)		
Political Learning	3.10	3.06	0.04	0.46	0.645
	(0.98)	(0.96)	(0.08)		
Higher Edu	4.90	5.00	-0.12	-1.06	0.287
	(1.39)	(1.41)	(0.11)		

Note. (1) P-values for 2-sided hypothesis tests, H_0: Diff = 0. (2) “Higher Edu” = The average response category of the education item. Mean values fall into category “5”, vocational school degree holders. (3) “Votes in CH” = Proportion of respondents who are granted voting rights. (4) “Children” = Share of respondents with at least one child.

[1] Completion rate of 82.5%.

4.3.4 Analyses

We analyze three types of public support, using pooled ordinary least squares (OLS) regressions. All the dependent variables (support) are measured by a single survey item, while many of the independent variables are composite indices, constructed from multiples items via confirmatory factor analyses (CFA). A detailed outline of the item selection, associated reliability scores, and factor loadings is provided in Appendix C. We further include a set of control variables, including demographic characteristics, such as age, age-squared, gender, educa-tion level, interest in energy topics, whether the person has children, and eligibility to vote in Switzerland. The following two subsections describe our dependent and independent variables.

4.3.5 Dependent variables

Three dependent variables were used in our analysis; all measured on a 7-point scale from completely disagree to completely agree. ET Support (energy transition support) indicates the support for an energy transition as a policy goal, measured with an item "I think that an energy transition is necessary for Switzerland." Although we are rather doubtful that the respondents' stated attitudes would differ significantly based on the item wording, we consciously chose the wording of "necessary" to capture their general supportive attitudes toward energy transitions, as opposed to the direct expression of "support," which might lead respondents' attention too narrowly toward the way they voted on the 2017 referendum related to the national energy transition. HP Support and DGE Support represent the level of support for the expansion of the respective technologies, which were measured with an item "Generally speaking, I support measures to increase [hydropower/deep geothermal energy] production in Switzerland."

4.3.6 Independent variables

The independent variables consist of the following determinants of public support for energy policies and technologies:

Future orientation: In line with existing research [61,72,73], we use the two-dimensional CFC scale, which distinguishes CFC Future from CFC Immediate. CFC Future consists of five items and indicates the extent to which individuals consider the potential distant outcomes of their behavior, and how strongly they are influenced by these potential outcomes. The second subscale, CFC Immediate, consists of seven items and measures to what extent respondents are influenced by immediate outcomes of decisions and actions.

Expectations: The items used to measure participants' expectations towards the future energy system were adapted from Gregorowius and Beuttler [74], but instead of 2030, the year 2050 was given as a reference to make reference to the Swiss ES2050. Participants were provided a 7-point scale on which the middle represented a situation like today (e.g., 4 = electricity prices remain the same), whereas the two endpoints would refer to a clear increase or decrease (e.g., 1/ 7 = electricity prices are considerably lower/higher than today). A factor analysis (see Appendix C) suggests that two dimensions can represent these expectations accurately. The first, expect innovation, is composed of developments related to energy transitions (improvement of the efficiency of processes, machines and gadgets; share of electric vehicles and renewable energy technologies). The second, expect shortage/conflict, consists of the items that address risks to a secure supply (i.e. likelihood of energy related conflict and power outages).

Trust in democratic institutions was constructed as a composite measure of three items: respondents' confidence in the Parliament, in the Head of the Energy Ministry, and whether they perceive that their vote matters. Trust in science, on the other hand, was measured by a single item.

Political leaning: The Swiss political landscape comprises a large number of active political parties, and hence hard to be placed on a single scale. Instead, we used a 5-point left-right scale to measure respondents' political ideology.[1]

Self-assessed knowledge: This measure uses a 10-point scale from 1 (Not At All) to 10 (Very) corresponding to a question of how knowledgeable one feels about the energy system. The item wording was intentionally kept broad, in order to avoid triggering association with any specific energy technology. In the main regression models, only the self-assessment measure was used. However, in the present survey, we also measure one's objective knowledge about each technology (see Appendix C).[2]

[1] As mentioned in Section 3.3 (Sample characteristics), the sample distribution of partisan identification is well congruent with the recent national election results.

[2] When a survey refers to hypothetical policy situations, the best one could do is to measure self-assessed knowledge about the broad issue area related to the hypothetical policy (e.g. [86,87],). As our present study analyzes currently debated energy technologies, were able to construct objective knowledge scores, using factual knowledge items, in addition to self-assessed knowledge. Eventually, we found that one's technology perception is highly correlated with his or her objective knowledge level (but not with self-assessed knowledge); therefore we decided to analyze the regression results with the technology perception but not objective knowledge scores.

Technology perception: In order to better understand the role of technology perceptions for their support, a variant of the regression models for technology support was implemented for each technology, HP and DGE. Therein, all the variables remain the same, but we add in a vector of technology perceptions, as measured by a set of bipolar semantic differentials, using contrasting word pairs. Participants were asked to place their respective energy technology (HP or DGE) on a 7-point scale between two antithetic words that can be used to characterize an energy technology. These word pairs were familiar vs. unfamiliar, Swiss vs. un-Swiss, natural vs. artificial, inexpensive vs. expensive, and safe vs. risky.

4.4 Descriptive statistics

Unless specified otherwise, (i) agreement to an issue refers to values of 5 or more on the 7-point Likert scale whereas disagreement refers to values of 3 or below (a value of 4 is interpreted as undecided) and, (ii) results refer to the full sample of 640 participants (HP and DGE flow).

4.4.1 Electricity supply preferences

Overall, there is a high agreement that there is a need for an energy transition. Almost 60% of respondents think that it is necessary and only 10% disagree. Moreover, over half of them think that whenever possible, local energy resources should be utilized and are also willing to accept changes in the landscape that may be induced by the development of renewable energy technologies. In general, there is high support for all renewable energy technologies. The most popular electricity supply options are solar, wind and hydropower. All of them are supported by more than 75% of respondents. DGE is the least supported renewable energy technology (43.2% agreement). Electricity imports (62.8% disagreement) and nuclear power (70.9% disagreement) are perceived very negatively. DGE (25.2% undecided), electricity imports (27.2% undecided) and gas (28.1% undecided) are marked by a high share of ambivalent respondents.

4.4.2 Support for energy transition, HP and DGE expansion options and corresponding technology perceptions

In line with the results in Section 4.1, over 83% of respondents generally support measures to increase HP production. For HP, the support of two specific implementation variants (heightening existing dams and building new dams in glacial retreat zones) is markedly lower (69% and 63%, agreement respectively). In case of DGE, about half of the respondents (49% agreement) generally support measures to increase production. Compared to that, DGE projects in rural areas receive stronger support (56% support), while DGE projects in urban areas receives less (34% support). Table 3 summarizes the mean support levels (on a 7-point scale) of the aforementioned items.

Furthermore, HP and DGE are also perceived differently by respondents. The technology attribute comparison (see Figure. 5) shows that HP is perceived as being more familiar, Swiss, natural, inexpensive and safe than DGE.

4.5 Results

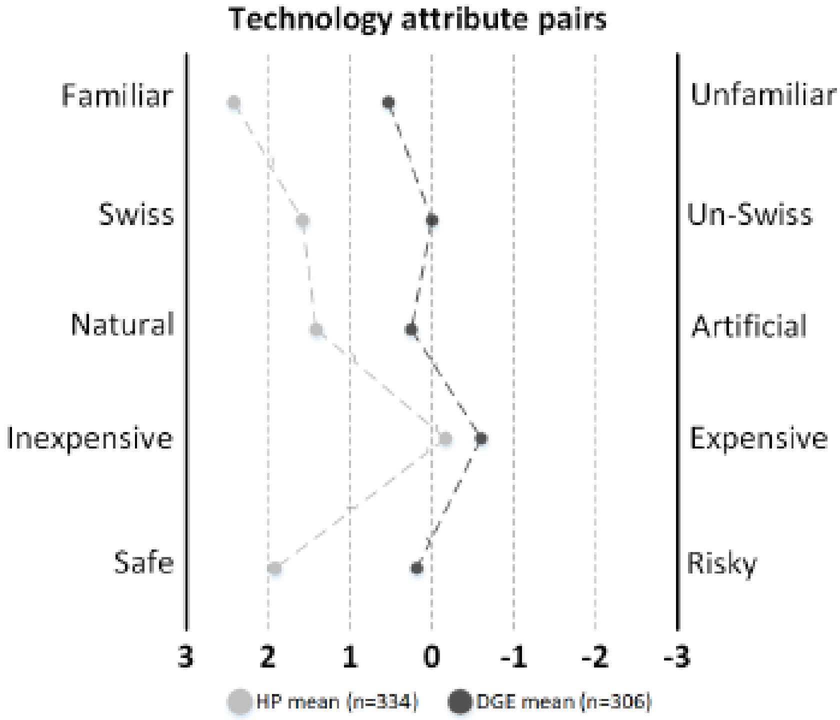
We estimate two OLS regressions to answer our empirical questions. Throughout our studies we use three different policy support outcome variables: support for (1) the national energy transition as a policy goal (ET Support) as well as support for (2) HP (HP Support) and (3) DGE (DGE Support) as measures that enable the national energy strategy. These correspond to Models 1, 2a, and 3a in the main results (see Table 3). These three models include the same set of independent variables. Model 2b and 3b additionally include Technology Perceptions to explain technology support.

Table 1: Average support for energy transition, the expansion of HP/DGE as well as for different implementation variants

Support for:		Mean	SD	N
HP	*In General	5.49	1.192	334
	Construction of New Dams	4.89	1.409	334
	Heightening Existing Dams	5.03	1.449	334
DGE	*In General	4.24	1.752	306
	Projects in Urban Areas	3.66	1.760	306
	Projects in Rural Areas	4.40	1.764	306
Energy Transition (ET)	*In General	5.11	1.485	640

Note. (1) The variables are measured on a 7-point Likert scale. (2) * indicates variables used as dependent variables of our regression analyses.

Figure 5. Intuitive assessment of technology characteristics for HP (n = 334) and DGE (n = 304), using semantic differentials (7-point scale).



4.5.1 Energy transition support compared to support for energy technologies

To grasp the overall picture, we first compare Model 1, 2a and 3a, focusing on the effects of future orientation, political ideology and the respondents' expectations on how the energy system will evolve in the future. In general, these factors help to explain a lot of the variation in support for an energy transition (Adjusted R^2 = 0.417), but are less relevant for the support of HP (Adjusted R^2 = 0.079) and DGE (Adjusted R^2 = 0.210). Particularly CFC Future scores are a significant factor positively correlated with support for the energy transition. Also Political Leaning, which indicates where the participants place themselves on the political spectrum (from left (1) to right (5)), has a significant effect on support for an energy transition. As one moves toward the right by one unit, support score decreases by 0.343. This stands in contrast to support for energy technologies (Model 2a & 3a), for which future orientation as well as political leaning are either significant on a much weaker level or not significant at all.

The respondents' expectations about the expansion of renewables, electric mobility, and technological efficiency (Expect Innovation) are positively associated with support for the energy transition (Model 1). No such effect was found for support of HP or DGE (Model 2a & 3a). In addition, we see that support for DGE increases significantly, as individuals Trust more in Science (Model 3a). No such effect was found for national transition strategies or HP. Finally, respondents' own assessment of knowledge about Swiss energy issues (Self-assessed Knowledge) is negatively associated with support for the national transition strategy and the expansion of DGE, but not HP expansion. A one unit increase in Self-assessed Knowledge leads to a decrease in support for national transition goals and DGE, respectively. In other words, the more respondents believe they know, the less they support the energy transition and DGE. As part of robustness checks, we also ran Model 1, 2a, and 3a with Income. The detailed rationale and the results are reported in Appendix A2. As in typical surveys, we lose about 25% of the observations by including income, which respondents tend not to report. Given this limitation, our robustness analysis shows that the effect of income is not statistically significantly distinguishable from 0, and the other estimates of our main focus remain mostly the same as those reported in Table 4.[1]

[1] Even though our samples between the HP and DGE flow are well balanced after random assignment of the respondents to the two flows, one might still worry that the flow assignment might be systematically correlated with the support outcome, ET Support. Therefore, as a cautious measure, we have run an additional regression for ET Support, by adding a dummy that indicates assignment to the DGE flow. (0 if assigned to HP and 1 if assigned to DGE.) As we theoretically expect from the random assignment, the dummy coefficient is statistically not significant at the conventional confidence levels, and other coefficient estimates also remain the same as the Model 1 of our main results.

Table 4. Regression results. Model 1 analyses support for the energy transition, while Model 2a and 3a analyze support for the expansion of HP and DGE. Model 2b and 3b include technology perceptions.

Dependent Variable	ET Support	HP Support		DGE Support	
	Model 1	Model 2a	Model 2b	Model 3a	Model 3b
CFC Future Std.	0.369***	0.040	0.047	-0.160*	-0.100
	(0.046)	(0.104)	(0.054)	(0.074)	(0.082)
CFC Immediate Std.	0.008	0.007	0.117*	0.034	0.020
	(0.044)	(0.053)	(0.047)	(0.082)	(0.083)
Expect Innovation Std.	0.241***	0.098	-0.010	0.001	0.067
	(0.025)	(0.064)	(0.059)	(0.101)	(0.064)
Expect Shortage/Conflict Std.	-0.047	-0.127**	-0.071	0.088	0.206**
	(0.041)	(0.042)	(0.040)	(0.145)	(0.071)
Trust Demo Institutions Std.	0.06	0.070	0.051	0.136	0.090
	(0.041)	(0.058)	(0.031)	(0.106)	(0.070)
Trust Science	-0.053	0.117	0.075	0.353**	0.309***
	(0.043)	(0.071)	(0.039)	(0.096)	(0.074)
Political Leaning	-0.343***	0.147*	0.083	0.133	0.052
	(0.073)	(0.068)	(0.066)	(0.163)	(0.084)
Knowledge measures:					
- Self-Assessment Energy	-0.128***	0.021	-0.003	-0.191***	-0.174***
	(0.025)	(0.044)	(0.036)	(0.042)	(0.025)
Technology perception					
- Swiss			0.168***		0.076*
			(0.042)		(0.031)
- Natural			0.259***		0.287***
			(0.030)		(0.048)
- Safe			0.159*		0.298***
			(0.070)		(0.036)
- Familiar			0.086		0.096*
			(0.055)		(0.046)
- Inexpensive			0.023		0.111
			(0.050)		(0.055)
Controls	Yes	Yes	Yes	Yes	Yes
Adj. R-Squared	0.417	0.079	0.343	0.210	0.545
Observations	627	329	329	298	298

Note. Standard errors are clustered at the canton level. Control variables include gender, age, age-squared, parent, whether respondent can vote in Switzerland, whether a respondent has spent a majority of time in a canton with a large share of DGE or HP, education, whether respondent is interested in energy topics,

prefers local sources of energy, and if they support importing energy. For the full set of estimates including those for control variables, see Appendix A1, Table A.4
* p < 0.05.; * * p < 0.01.; * * * p < 0.001.

4.5.2 The role of perceptions in technology support

Regression Model 2b and 3b in Table 4 add respondents' technology perceptions to the analysis of technology support. Overall, the explained total variance of both HP Support (Model 2b) and DGE Support (Model 3b) become more than twice as large compared to the previous specification, which brings them to a level comparable to that of ET Support (Model 1).[1] The technology perceptions Swiss, natural and safe are significant factors in explaining support for both technologies. The relative importance of these three characteristics differs between the technologies, but one's perception of the technology as Swiss-like and natural seems to be important for both. For both technologies (HP and DGE), the perception that the technology is more Swiss-like and natural is positively associated with an increased level of support of the respective technology. Interestingly, respondents' perceptions of safety are twice as important for supporting DGE as HP. Finally, after controlling for technology perceptions, it becomes evident that the roles of future-orientation, expectations, and trust are different between the two technologies. In fact, support for HP depends on none of the belief variables (including knowledge), except for CFC Immediate, which is weakly significant. In contrast, two types of beliefs – Expect Conflict/ Shortage and Knowledge – stand out as important drivers for support of DGE, and Trust Science remains important as well.

4.6 Discussion

4.6.1 The multi-level structure of public acceptance

A main goal of this study was to explore whether lay-people's expectations about the future energy system, future orientation and technology perceptions play a role in acceptability evaluations. The regression analysis shows that these factors do indeed function as determinants of public support, but with varying degrees of relevance, and with respect to different levels. We find that our regression, which also includes factors that are known to influence acceptability evaluations, such as self-assessed knowledge, trust and political leaning, does provide a good explanation of the variance in support for an energy transition. However, the expectations about the future energy system, future orientation and political leaning lose their

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[1] The reported values in Table 2 are *Adjusted* R^2 values, meaning that they are not necessarily inflated simply because of the larger number of included explanatory variables.

predictive power when support for energy technologies is considered. For technology support, technology perceptions were more relevant. Hence, the relative importance of the factors included in our analysis vary depending on the level public acceptance is conceptualized.[1]

Typically, the goal of a sustainable energy transition is initially formulated at a national level. At this level, broad policy goals, such as an increase of domestic renewable energy sources, are defined. Consequently, support for an energy transition pivots around the question whether these policy goals are perceived to be going in the right direction, irrespective of concrete measures to reach them and their associated consequences on a local or individual level. Construal level theory suggests that attitudes can be best explained by factors on a corresponding level of abstraction [75]. This could explain why future orientation is a relevant factor for the support of an energy transition, but not for energy technologies. In other words, desirability plays a bigger role for decisions with distant and abstract rather than near and concrete future outcomes. Accordingly, long-term perspectives might help people to make choices that are more in line with their core values [76].

It is characteristic for the situation in many countries that the debate about climate change and associated discussions about the need for an energy transition are quite polarized, often following political fault lines. Accordingly, political leaning proofed to be a significant determinant in energy transition support in this and many other studies [35–37]. However, political leaning is much less effective in explaining support for HP and DGE, whereas adding perceptions of technology characteristics to the model does improve its explanatory power considerably. This may suggest that respondents did not link these technologies to the more abstract energy transition. People evaluating a national energy transition seem to rely on a set of beliefs, which may be shaped by their political ideology, as cognitive heuristics. In contrast, evaluating energy technologies seems to be related to personal experiences and other factors influencing technology perceptions, which means that a different set of beliefs replaces those that are critical at the level of energy transition support. Accordingly, support for energy

[1] One might argue that respondents' support for the long-term general energy transition strategy (which corresponds with the dependent variable of the Energy Transition support (ET Support) equation is a strong predictor of their support for the two techno-logical measures. Therefore, as a robustness check, we have run the HP and DGE Support regressions, with ET Support (measured as perceived necessity of energy transitions) as a control variable. This control turns out statistically indistinguishable from 0, and does not influence estimation results of our variables of interest in Table 3. This suggests individuals' support for the national transition goal does not automatically lead to support for enabling technologies, and indeed, we are talking about different opinion-formation mechanisms between the two levels of energy transition discussions. Appendix B3 and Table 6 describe the analysis and results in detail.

technologies tends to be less politicized than other energy policy debates. While political leaning seems to have an overarching effect on or at least seems to be related to the factors influencing public support for energy transitions, support for local energy infrastructure tends to be shaped by contextual characteristics [26,64]. However, this dominance of political ideology at the national level and the specifics of a local context at the project level may also obscure the underlying qualifications of people towards energy technologies. Consequently, a more nuanced and critical evaluation of potential qualifications at the technology level might be the basis for aligning national energy system planning with public preferences.

In a recent literature review, Gaede and Rowlands [13] observed a shift from studies conceptualizing public acceptance as a political issue, to studies framing public acceptance as primarily a psychological issue. Our study exemplified that a combination of political and psychological factors have a varying influence depending on the level at which public acceptance is studied. Moreover, social, cultural and political aspects shape the beliefs that are relevant for acceptability evaluations, which exemplifies the intertwined nature of public acceptance. Consequently, this study follows the call for greater interdisciplinary dialogue by Devine-Wright [77].

4.6.2 Technology perceptions: a socially constructed and dynamic acceptability determinant

Our results do not only show differences between support for an energy transition and energy technologies. We also find key differences across technologies, reflecting that the perception of technology characteristics of HP and DGE differ in many respects. Our analysis shows that compared to their support for the transformation towards a more sustainable energy system in general, people use a different set of criteria to evaluate the technologies presumed to achieve this transformation. This is in line with the vast amount of public acceptance research, which concludes that support for renewable energy technologies is highest when there is little or no contextual information available [78].

Singleton et al. [79] showed that public perceptions of risk are largely based on people's subjective mental models. This suggests a social constructivist perspective of risks, which is not necessarily related to objective characteristics such as probabilities [80]. While there have been no major HP accidents for decades in Switzerland, two DGE pilot projects induced seismic activity in the cities of Basel and St. Gallen [67]. Thus, it comes as no surprise that the respondents perceive DGE to be riskier than HP, irrespective of objective probabilities, damage potentials or vulnerabilities. The comparative analysis of HP and DGE thus demonstrates the social construction of technologies [46]. Referring to pre- and post Fukushima acceptability ratings of nuclear energy, Lee and Gloaguen [81] showed that precisely because technology perceptions are anchored in cultural, social and political spheres, robust mental associations, which are resistant to change can result.

However, comparing the perceptions of HP and DGE can also exemplify the dynamic aspects of acceptability. Dreyer et al. [82] argues that energy technology acceptability depends upon the development lifecycle stage of technologies. The patterns observed in the perceptions of HP and DGE assert this. In particular, HP technology perceptions are more relevant for the explanatory power of the regression model than DGE technology perceptions. While there are clear trends and distinct evaluations identifiable in case of HP (see for example Figure 5), DGE technology perceptions suggest that people are unsure what to think of this relatively unknown technology.

While [17] calls similar findings non-attitudes or pseudo opinions, the question remains whether this is a mere consequence of the fact that there are to date no DGE plants operating in Switzerland. Instead, also the characteristics associated with DGE could have an influence. For example, it may be unintuitive for lay people to grasp the core concept of how DGE projects produce electricity, as the technology mainly operates in the subsurface [83]. In this regard, the positive effects of familiarization and habituation asserted by Joe et al. [21] could be of critical importance for DGE and other not yet widespread technologies. This is also supported by the fact that trust in science is a significant determinant in case of DGE, but not in case of HP. Accordingly, trust in science functions as a decision-making heuristics in case of DGE, whereas the public can rely more on its subjective perceptions in the case of HP.

These technology perceptions could be shaped by personal experiences, but at the same time, the results also indicate a higher level of politicization in case of HP. This finding is congruent with the Swiss energy policy context. For example, while political parties towards the right tend to oppose an energy transition and associated measures, they are known to demand subsidies for HP, which they regard as a traditional Swiss industry that needs to be protected [84]. This could explain the positive effect a political leaning towards the right has on HP support.

4.6.3 Critical reflection

We used an explorative research approach to assess a range of factors potentially influencing public support for an energy transition and for energy technologies. This approach was suitable to demonstrate that a nuanced picture of public acceptance emerges not only on a local level, but also on a general level once meaningful qualifications are considered. It would have been preferable to assess both technologies simultaneously by the same individuals in order to compare how HP and DGE support relate to each other. In addition, it would have been preferable to conduct such a study on a sample that was representative of Switzerland and its four language regions, or – even better – in several countries in parallel. Also, further studies could explore how determinants of support are differentially relevant for various ways of operationalizing public support. Specifically, in addition to the way general energy transition support was measured in this study (i.e. as the perceived necessity of an energy transition), the effect of other modes of operationalization could be tested. These may include different framings ("I support the energy transition" or "I think we as a society should strive for a 100% renewable energy system") but also additional aspects of public support, such as the difference between passive and active acceptance.

However, overall the study does provide first insights into mechanisms for support of energy policies that need to be analyzed in future studies. In particular, we advocate for more studies that look at the determinants of energy policy support on different levels, as well as their interactions.

4.7 Conclusion

Public support will be of critical importance for many of the developments necessary to develop a just, reliable and more climate friendly energy system of the future. Yet, this support has many interdependent facets that are not yet understood well enough. Based on a survey study among Swiss residents, this pilot study explores some of these facets in detail and presents some tentative empirical insights that may be relevant for directing future research but also for consideration by the decision makers involved in creating tomorrow's energy systems. While the case of Switzerland provided a good opportunity to study the varying importance of public support determinants at different levels, these determinants and their interdependencies are by no means exclusive to the situation in Switzerland. The insights presented in this study are thus relevant for energy transitions and the deployment of renewable energy technologies in many countries.

First, it is important to acknowledge that there are different levels at which public support is of critical importance and that the set of determinants that is relevant for the respective level can differ considerably. Similar to the well-studied phenomenon of local resistance towards renewable energy projects on a local level, one cannot assume that public support for the goals of an energy transition automatically translates into support for the technologies supposed to implement an energy transition. In fact, our study suggests that an individual's evaluation of national energy transition goals significantly depends on his or her political ideology and on one's future-orientation, expectations about the innovative aspects of the future energy system, and self-reported knowledge on energy-related issues. What is astonishing is that none of these seem to matter significantly when it comes to one's support for a specific energy technology. Instead, citizens tend to rely on their general perceptions of a technology, which may be informed by their own experience and familiarity with it.

Linked to that is a second insight, namely that the technology is an interesting level to study in more detail: Support on a more abstract (general energy transition support) or more specific (local energy project) level are both dominated by the general political climate or the project context, which does not allow identifying the crucial qualifications of public support. Accordingly, the technology level might be suitable middle way for gaining a better understanding for the relevant qualifications people may hold and how these qualifications form. This is relevant for developing an adequate policy framework to support a widespread deployment of renewables.

Third, while the results suggest that support is highly dependent on the level on which it is assessed, one must not conclude that these levels are independent from each other. The national energy discourse for example shapes individuals' perception of technologies. Accordingly, also the social factors that the public associates with the changes at the various levels of an energy transition need to be understood and anticipated in policy and technology developments in order to align the energy transition with public preferences.

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References

[1] K. Bruninx, D. Madzharov, E. Delarue, D. William, Impact of the German nuclear phase-out on Europe's electricity generation—a comprehensive study, Energy Policy (2013) 1–11, http://dx.doi.org/10.1016/j.enpol.2013.05.026 March 2011.

[2] F.N. Laird, Technocracy revisited: knowledge, power and the crisis in energy decision making, Organ. Environ. 4 (1) (1990) 49–61, http://dx.doi.org/10.1177/108602669000400103.

[3] P. Devine-Wright, Reconsidering public attitudes and public acceptance of renewable energy technologies: a critical review, Architecture, Working Pa, (2007) Retrieved from http://geography.exeter.ac.uk/beyond_nimbyism/deliverables/bn_ wp1_4.pdf.

[4] R. Wüstenhagen, M. Wolsink, M.J. Bürer, Social acceptance of renewable energy innovation: an introduction to the concept, Energy Policy 35 (5) (2007) 2683–2691, http://dx.doi.org/10.1016/j.enpol.2006.12.001.

[5] P. Krütli, M. Stauffacher, T. Flüeler, R.W. Scholz, Functional-dynamic public participation in technological decision-making: site selection processes of nuclear waste repositories, J. Risk Res. 13 (7) (2010) 861–875, http://dx.doi.org/10.1080/13669871003703252.

[6] H. Lund, Choice awareness: the development of technological and institutional choice in the public debate of Danish energy planning, J. Environ. Policy Plan. 2 (3) (2000) 249–259, http://dx.doi.org/10.1002/1522-7200(200007/09) 2:3<249::AID-JEPP50>3.0.CO;2-Z.

[7] C. Moser, M. Stauffacher, Y.B. Blumer, R.W. Scholz, From risk to vulnerability: the role of perceived adaptive capacity for the acceptance of contested infrastructure, J. Risk Res. 18 (5) (2015) 622–636, http://dx.doi.org/10.1080/13669877.2014.910687.

[8] M. Stauffacher, N. Muggli, A. Scolobig, C. Moser, Framing deep geothermal energy in mass media: the case of Switzerland, Technol. Forecast. Soc. Change 98 (2015) 60–70, http://dx.doi.org/10.1016/j.techfore.2015.05.018.

[9] C.R. Jones, J.R. Eiser, Understanding "local" opposition to wind development in the UK: how big is a backyard? Energy Policy 38 (6) (2010) 3106–3117, http://dx.doi.org/10.1016/j.enpol.2010.01.051.

[10] S. Batel, P. Devine-Wright, A critical and empirical analysis of the national-local "gap" in public responses to large-scale energy infrastructures, J. Environ. Plan. Manag. 58 (6) (2015) 1076–1095, http://dx.doi.org/10.1080/09640568.2014.

914020.

[11] C. Dermont, K. Ingold, L. Kammermann, I. Stadelmann-Steffen, Bringing the policy making perspective in: a political science approach to social acceptance, Energy Policy 108 (2017) 359–368, http://dx.doi.org/10.1016/j.enpol.2017.05.062.

[12] G. Perlaviciute, L. Steg, Contextual and psychological factors shaping evaluations and acceptability of energy alternatives: integrated review and research agenda, Renew. Sustain. Energy Rev. 35 (2014) 361–381, http://dx.doi.org/10.1016/j.rser. 2014.04.003.

[13] J. Gaede, I.H. Rowlands, Visualizing social acceptance research: a bibliometric review of the social acceptance literature for energy technology and fuels, Energy Res. Soc. Sci. 40 (2018) 142–158, http://dx.doi.org/10.1016/j.erss.2017.12.006 July 2017.

[14] S.K. Olson-Hazboun, R.S. Krannich, P.G. Robertson, Public views on renewable energy in the Rocky Mountain region of the United States: distinct attitudes, ex-posure, and other key predictors of wind energy, Energy Res. Soc. Sci. 21 (2016) 1–13, http://dx.doi.org/10.1016/j.erss.2016.07.002.

[15] G. Walter, Determining the local acceptance of wind energy projects in Switzerland: the importance of general attitudes and project characteristics, Energy Res. Soc. Sci. 4 (C) (2014) 78–88, http://dx.doi.org/10.1016/j.erss.2014.09.003.

[16] V. Westerberg, J.B. Jacobsen, R. Lifran, Offshore wind farms in Southern

Europe–determining tourist preference and social acceptance, Energy Res. Soc. Sci. 10 (2015) 165–179, http://dx.doi.org/10.1016/j.erss.2015.07.005.

[17] P. Upham, C. Oltra, À. Boso, Towards a cross-paradigmatic framework of the social acceptance of energy systems, Energy Res. Soc. Sci. 8 (2015) 100–112, http://dx.doi.org/10.1016/j.erss.2015.05.003.

[18] M. Wolsink, Wind power and the NIMBY-myth: institutional capacity and the limited significance of public support, Renew. Energy 21 (1) (2000) 49–64, http://dx.doi.org/10.1016/S0960-1481(99)00130-5.

[19] M. Wolsink, Invalid theory impedes our understanding: a critique on the persistence of the language of NIMBY, Trans. Inst. Br. Geogr. 31 (March (1)) (2006) 85–91, http://dx.doi.org/10.1111/j.1475-5661.2006.00191.x.

[20] K. Bickerstaff, I. Lorenzoni, N.F. Pidgeon, W. Poortinga, P. Simmons, Reframing nuclear power in the UK energy debate: nuclear power, climate change mitigation and radioactive waste, Public Underst. Sci. 17 (2) (2008) 145–168, http://dx.doi.org/10.1177/0963662506066719.

[21] J.C. Joe, K. Hendrickson, M. Wong, S.L. Kane, D. Solan, J.E. Carlisle, et al., Political efficacy and familiarity as predictors of attitudes towards electric transmission lines in the United States, Energy Res. Soc. Sci. 17 (2016) 127–134, http://dx.doi.org/10.1016/j.erss.2016.04.010.

[22] N. Pidgeon, C. Demski, C. Butler, K. Parkhill, A. Spence, Creating a national citizen engagement process for energy policy, Proc. Natl. Acad. Sci. 111 (Suppl. 4) (2014) 13606–13613, http://dx.doi.org/10.1073/pnas.1317512111.

[23] D. Bell, T. Gray, C. Haggett, The "social gap" in wind farm siting decisions: explanations and policy responses, Environ. Polit. 14 (4) (2005) 460–477, http://dx.doi.org/10.1080/09644010500175833.

[24] M. Mattmann, I. Logar, R. Brouwer, Hydropower externalities: a meta-analysis, Energy Econ. 57 (2016) 66–77.

[25] F.J. Van Rijnsoever, A. Van Mossel, K.P.F. Broecks, Public acceptance of energy technologies: the effects of labeling, time, and heterogeneity in a discrete choice

experiment, Renew. Sustain. Energy Rev. 45 (2015) 817–829, http://dx.doi.org/10.1016/j.rser.2015.02.040.

[26] S. Batel, P. Devine-Wright, T. Tangeland, Social acceptance of low carbon energy and associated infrastructures: a critical discussion, Energy Policy 58 (2013) 1–5, http://dx.doi.org/10.1016/j.enpol.2013.03.018.

[27] B.K. Sovacool, The cultural barriers to renewable energy and energy efficiency in the United States, Technol. Soc. 31 (4) (2009) 365–373, http://dx.doi.org/10.1016/j.techsoc.2009.10.009.

[28] B.K. Sovacool, S.E. Ryan, P.C. Stern, K. Janda, G. Rochlin, D. Spreng, et al., Integrating social science in energy research, Energy Res. Soc. Sci. 6 (2015) 95–99, http://dx.doi.org/10.1016/j.erss.2014.12.005.

[29] S. Gölz, O. Wedderhof, Explaining regional acceptance of the German energy transition by including trust in stakeholders and perception of fairness as socio-institutional factors, Energy Res. Soc. Sci. 43 (2018).

[30] C. Fraune, M. Knodt, Cosmopolitan, dynamic, and contested energy futures: navigating the pluralities and polarities in the energy systems of tomorrow, Energy Res. Soc. Sci. 43 (2018).

[31] K. Shaw, S.D. Hill, A.D. Boyd, L. Monk, J. Reid, E.F. Einsiedel, Conflicted or constructive? Exploring community responses to new energy developments in Canada, Energy Res. Soc. Sci. 8 (2015) 41–51, http://dx.doi.org/10.1016/j.erss.2015.04.003.

[32] Å. Boholm, Editorial: what are the new perspectives on siting controversy? J. Risk Res. 7 (2) (2004) 99–100, http://dx.doi.org/10.1080/1366987042000158677.

[33] M.R. Greenberg, Energy policy and research: the underappreciation of trust, Energy Res. Soc. Sci. 1 (2014) 152–160, http://dx.doi.org/10.1016/j.erss.2014.02.004.

[34] N. Gupta, A.R.H. Fischer, L.J. Frewer, Socio-psychological determinants of public acceptance of technologies: a review, Public Underst. Sci. 21 (7) (2012) 782–795, http://dx.doi.org/10.1177/0963662510392485.

[35] C.E. Clarke, P.S. Hart, J.P. Schuldt, D.T.N. Evensen, H.S. Boudet, J.B. Jacquet, R.C. Stedman, Public opinion on energy development: the interplay of issue framing, top-of-mind associations, and political ideology, Energy Policy 81 (2015) 131–140, http://dx.doi.org/10.1016/j.enpol.2015.02.019.

[36] E. Krick, Ensuring social acceptance of the energy transition. The German government's "consensus management" strategy, J. Environ. Policy Plan. 20 (1) (2017) 1–17, http://dx.doi.org/10.1080/1523908X.2017.1319264.

[37] J. Markard, M. Suter, K. Ingold, Socio-technical transitions and policy change–advocacy coalitions in Swiss energy policy, Environ. Innov. Soc. Transit. 18 (2016) 215–237, http://dx.doi.org/10.1016/j.eist.2015.05.003.

[38] P.M. Kellstedt, S. Zahran, A. Vedlitz, Personal efficacy, the information environment, and attitudes toward global warming and climate change in the United States, Risk Anal. 28 (1) (2008) 113–126, http://dx.doi.org/10.1111/j.1539-6924.2008. 01010.x.

[39] J.W. Stoutenborough, A. Vedlitz, The role of scientific knowledge in the public's perceptions of energy technology risks, Energy Policy 96 (2016) 206–216, http://dx.doi.org/10.1016/j.enpol.2016.05.031.

[40] W. Bruine de Bruin, A. Bostrom, Assessing what to address in science communication, Proc. Natl. Acad. Sci. 110 (Suppl._3) (2013) 14062–14068, http://dx.doi.org/10.1073/pnas.1212729110.

[41] M.G. Morgan, B. Fischhoff, A. Bostrom, C.J. Atman, Risk Communication: A Mental Models Approach, Cambridge University Press, Cambridge, UK, 2002.

[42] T.A. Heberlein, Navigating environmental attitudes, Conserv. Biol. 26 (4) (2012) 583–584, http://dx.doi.org/10.1093/acprof:oso/9780199773329.001.0001.

[43] C.R. Jones, D. Kaklamanou, L. Lazuras, Public perceptions of energy security in Greece and Turkey: exploring the relevance of pro-environmental and pro-cultural orientations, Energy Res. Soc. Sci. 28 (2017) 17–28, http://dx.doi.org/10.1016/j.erss.2017.04.002.

[44] S. Batel, P. Devine-Wright, Populism, different-level identities and responses to energy infrastructures at different scales in the UK: a post-Brexit reflection, Energy Res. Soc. Sci. 43 (2018).

[45] J.L. MacArthur, S. Matthewman, Populist resistance and alternative transitions: indigenous ownership of energy infrastructure in Aotearoa New Zealand, Energy Res. Soc. Sci. 43 (2018).

[46] P.M. Bögel, P. Upham, The role of psychology in sociotechnical transitions literature: a review and discussion in relation to consumption and technology acceptance, Environ. Innov. Soc. Transit. (2018), http://dx.doi.org/10.1016/j.eist.2018. 01.002 (in press).

[47] J. Fergen, J.B. Jacquet, Beauty in motion: expectations, attitudes, and values of wind energy development in the rural U.S, Energy Res. Soc. Sci. 11 (2016) 133–141, http://dx.doi.org/10.1016/j.erss.2015.09.003.

[48] M. Ryghaug, M. Toftaker, Creating transitions to electric road transport in Norway: the role of user imaginaries, Energy Res. Soc. Sci. 17 (2016) 119–126, http://dx.doi.org/10.1016/j.erss.2016.04.017.

[49] P. Späth, H. Rohracher, "Energy regions": the transformative power of regional discourses on socio-technical futures, Res. Policy 39 (4) (2010) 449–458, http://dx.doi.org/10.1016/j.respol.2010.01.017.

[50] E. Trutnevyte, The allure of energy visions: are some visions better than others? Energy Strategy Reviews 2 (3–4) (2014) 211–219, http://dx.doi.org/10.1016/j.esr.2013.10.001.

[51] J. Lilliestam, S. Hanger, Shades of green: centralisation, decentralisation and controversy among European renewable electricity visions, Energy Res. Soc. Sci. 17 (2016) 20–29, http://dx.doi.org/10.1016/j.erss.2016.03.011.

[52] S. Bakker, Competing Expections: The Case of the Hydrogen Car (Doctoral Dissertation), Retrieved from (2011), p. 211 https://dspace.library.uu.nl/handle/ 1874/204507.

[53] B. Budde, F. Alkemade, K.M. Weber, Expectations as a key to understanding actor strategies in the field of fuel cell and hydrogen vehicles, Technol. Forecast. Soc. Change 79 (6) (2012) 1072–1083, http://dx.doi.org/10.1016/j.techfore.2011.12. 012.

[54] B. Truffer, J.P. Voß, K. Konrad, Mapping expectations for system transformations–lessons from sustainability foresight in German utility sectors, Technol. Forecast. Soc. Change 75 (9) (2008) 1360–1372, http://dx.doi.org/10.1016/j. techfore.2008.04.001.

[55] P. Upham, P. Kivimaa, P. Mickwitz, K. Åstrand, Climate policy innovation: a sociotechnical transitions perspective, Environ. Polit. 23 (5) (2014) 774–794, http:// dx.doi.org/10.1080/09644016.2014.923632.

[56] P. Slovic, M.L. Finucane, E. Peters, D.G. MacGregor, The affect heuristic, Eur. J. Oper. Res. 177 (3) (2007) 1333–1352, http://dx.doi.org/10.1016/j.ejor.2005.04. 006.

[57] P. Lienert, B. Sütterlin, M. Siegrist, The influence of high-voltage power lines on the feelings evoked by different Swiss surroundings, Energy Res. Soc. Sci. 23 (2017) 46–59, http://dx.doi.org/10.1016/j.erss.2016.11.010.

[58] J. Firestone, D. Bidwell, M. Gardner, L. Knapp, Wind in the sails or choppy seas?: People-place relations, aesthetics and public support for the United States' first offshore wind project, Energy Res. Soc. Sci. 40 (February) (2018) 232–243, http:// dx.doi.org/10.1016/j.erss.2018.02.017.

[59] J.R. Daugherty, G.L. Brase, Taking time to be healthy: predicting health behaviors with delay discounting and time perspective, Pers. Individ. Differ. 48 (2) (2010) 202–207, http://dx.doi.org/10.1016/j.paid.2009.10.007.

[60] R.E. Hoot, H. Friedman, Connectedness and environmental behavior: sense of in-terconnectedness and pro-environmental behavior, Int. J. Transpers. Stud. 30 (1–2) (2011) 89–100.

[61] J. Joireman, D. Balliet, D. Sprott, E. Spangenberg, J. Schultz, Consideration of future consequences, ego-depletion, and self-control: support for distinguishing be-tween CFC-Immediate and CFC-Future sub-scales, Pers. Individ. Differ. 45 (1)

(2008) 15–21, http://dx.doi.org/10.1016/j.paid.2008.02.011.

[62] Bundesamt für Energie, Schweizerische Elektrizitätsstatistik 2016, Retrieved from (2017) https://www.bundespublikationen.admin.ch/cshop_mimes_bbl/8C/ 8CDCD4590EEED797FF3D9EAD3B79B3.pdf.

[63] Schweizer Bundesrat, Botschaft zum ersten Massnahmenpaket der Energiestrategie, Retrieved from (2013) https://www.admin.ch/opc/de/federal-gazette/2013/7561. pdf.

[64] A. Tabi, R. Wüstenhagen, Keep it local and fish-friendly: social acceptance of hy-dropower projects in Switzerland, Renew. Sustain. Energy Rev. 68 (2017) 763–773, http://dx.doi.org/10.1016/j.rser.2016.10.006 October 2016.

[65] M. Barry, P. Baur, L. Gaudard, G. Giuliani, W. Hediger, M. Schillinger, et al., The Future of Swiss Hydropower: A Review on Drivers and Uncertainties vol. 1, (2015), pp. 0–49 (September).

[66] A.B. Gurung, A. Borsdorf, L. Füreder, F. Kienast, P. Matt, C. Scheidegger, et al., Rethinking pumped storage hydropower in the European Alps, Mt. Res. Dev. 36 (2) (2016) 222–232, http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00069.1.

[67] J. Krummenacher, Ende der Hoffnung in St. Gallen. Neue Zürcher Zeitung, May 14. Retrieved from (2014) https://www.nzz.ch/schweiz/ende-der-hoffnung-in-stgallen-1.18302589.

[68] M. Galesic, M. Bosnjak, Effects of questionnaire length on participation and indicators of response quality in a web survey, Public Opin. Q. 73 (2) (2009) 349–360, http://dx.doi.org/10.1093/poq/nfp031.

[69] A. Strathman, F. Gleicher, D.S. Boninger, C.S. Edwards, The consideration of future consequences: weighing immediate and distant outcomes of behavior, J. Pers. Soc.Psychol. 66 (4) (1994) 742–752, http://dx.doi.org/10.1037/0022-3514.66.4.742.

[70] Parteistärke im Nationalrat, Eidgenössische Wahlen vom 18. Oktober 2015, October. Retrieved from (2015) https://www.ch.ch/de/wahlen2015/ parteienstarke-im-nationalrat.

[71] Swiss Federal Statistics Office, Switzerland's Population 2016, Retrieved from (2017) https://www.bfs.admin.ch/bfs/en/home/statistics/population.assetdetail. 3902101.html.

[72] S. Arnocky, T.L. Milfont, J.R. Nicol, Time perspective and sustainable behavior, Environ. Behav. 46 (5) (2014) 556–582, http://dx.doi.org/10.1177/ 0013916512474987.

[73] P. Wesley Schultz, The structure of environmental concern: concern for self, other people, and the biosphere, J. Environ. Psychol. 21 (4) (2001) 327–339, http://dx. doi.org/10.1006/jevp.2001.0227.

[74] D. Gregorowius, C. Beuttler, Die Stromzukunft der Schweiz: Erwartungen der Bevölkerung und Präferenzen bei Zielkonflikten, Stiftung Risiko-Dialog St.Gallen, 2015.

[75] N. Liberman, Y. Trope, The role of feasibility and desirability considerations in near and distant future decisions: a test of temporal construal theory, J. Pers. Soc. Psychol. 75 (1) (1998) 5–18, http://dx.doi.org/10.1037/0022-3514.75.1.5.

[76] A. Spence, W. Poortinga, N. Pidgeon, The psychological distance of climate change, Risk Anal. 32 (6) (2012) 957–972, http://dx.doi.org/10.1111/j.1539-6924.2011. 01695.x.

[77] P. Devine-Wright, Beyond NIMBYism: towards an integrated framework for understanding public perceptions of wind energy, Wind Energy 8 (2) (2005) 125–139, http://dx.doi.org/10.1002/we.124.

[78] C. Demski, Public Perceptions of Renewable Energy Technologies: Challenging the Notion of Widespread Support. Thesis (September). Retrieved from, (2011), p. 369 http://orca.cf.ac.uk/13562/%5Cnhttp://orca.cf.ac.uk/13562/1/ 2011demskiccphd.pdf.

[79] G. Singleton, H. Herzog, S. Ansolabehere, Public risk perspectives on the geologic storage of carbon dioxide, Int. J. Greenh. Gas Control 3 (1) (2009) 100–107, http://dx.doi.org/10.1016/j.ijggc.2008.07.006.

[80] K. Buhr, V. Wibeck, Communication approaches for carbon capture and storage: underlying assumptions of limited versus extensive public engagement, Energy Res. Soc. Sci. 3 (2014) 5–12, http://dx.doi.org/10.1016/j.erss.2014.05.004.

[81] R.P. Lee, S. Gloaguen, Path-dependence, lock-in, and student perceptions of nuclear energy in France: implications from a pilot study, Energy Res. Soc. Sci. 8 (2015) 86–99, http://dx.doi.org/10.1016/j.erss.2015.05.001.

[82] S.J. Dreyer, H.J. Polis, L.D. Jenkins, Changing tides: acceptability, support, and perceptions of tidal energy in the United States, Energy Res. Soc. Sci. 29 (2017) 72–83, http://dx.doi.org/10.1016/j.erss.2017.04.013.

[83] E. Trutnevyte, O. Ejderyan, Managing geoenergy-induced seismicity with society, J. Risk Res. 9877 (May) (2017) 1–8, http://dx.doi.org/10.1080/13669877.2017. 1304979.

[84] S. Häne, SVP und die «blödsinnige Subventionierung», April 20. Retrieved from Tages Anzeiger, 2017, https://www.tagesanzeiger.ch/schweiz/standard/die-svp-und-die-bloedsinnige-subventionierung/story/27587901.

[85] C. Bauer, Y. Bäuerle, S. Biollaz, A. Calbry-Muzyka, B. Cox, T. Heck, Potentials, Costs and Environmental Assessment of Electricity Generation Technologies, Paul Scherrer Institut, Villigen PSI, Switzerland: PSI, WSL, ETHZ, EPFL, Bern (2017).

[86] T. Bernauer, R. Gampfer, A. Kachi, European unilateralism and involuntary burden-sharing in global climate politics: a public opinion perspective from the other side, European Union Politics 15 (1) (2014) 132–151, http://dx.doi.org/10.1177/1465116513496878.

[87] A. Kachi, T. Bernauer, R. Gampfer, Climate policy in hard times: are the pessimists right? Ecol. Econ. 114 (2015) 227–241, http://dx.doi.org/10.1016/j.ecolecon.2015.03.002.

5 Paper IV - How the public imagines the energy future: Exploring and clustering non-experts' techno-economic expectations towards the future energy system

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Abstract

Various countries have pledged to carry out system-wide energy transitions to address climate change. This requires taking strategic decisions with long-term consequences under conditions of considerable uncertainty. For this reason, many actors in the energy sector develop model-based scenarios to guide debates and decision-making about plausible future energy systems. Besides being a decision support instrument for policy-makers, energy scenarios are widely recognized as a way of shaping the expectations of experts and of influencing energy policy more generally. However, relatively little is known about how energy scenarios shape preferences and expectations of the public. We use an explorative research design to assess the publics' expectations of future energy systems through an online survey among Swiss residents (N=797). We identified four significantly different clusters of people with distinct expectations about the future energy system, each seeing different implications for the acceptability of energy policies and the compatibility with projections of techno-economic energy scenarios. Cluster 1 expects a system-wide energy transition towards renewable energy sources that is similar to the policy-relevant national energy scenario. Cluster 2 also expects an energy transition, but believes it will lead to a range of technical challenges, societal conflicts and controversies with neighboring countries. Cluster 3 is the only cluster not expecting significant changes in the future energy system and thus not anticipating an energy transition. Cluster 4's expectations are between cluster 1 and 2, but it anticipates a huge increase in per capita electricity demand while prices are expected to remain low. The study at hand offers some initial insights into the interdependencies between energy transition pathways outlined in techno-economic energy scenarios and the energy system expectations of the public. These insights are essential for gaining a better understanding of whether and how energy scenarios can contribute to informed public debates about energy futures and how desirable pathways towards them might look like.

5.1 Introduction

5.1.1 Energy scenarios & public discourse

Various countries have pledged to carry out system-wide energy transitions to address climate change [1]. This requires taking strategic decisions with long-term consequences under conditions of considerable uncertainty [2]. For this reason, many countries develop or commission scenarios consisting of plausible pathways for a system change without impairing an affordable and reliable energy supply [3, 4].

Scenarios support decisions in many contexts and are typically developed and applied by academic, corporate, or governmental communities of experts [5, 6]. The energy sector has a long history of predominantly normative and proprietary scenario use [7, 8]. Today, public and private actors often publish the results of scenario studies to legitimize decisions, increase the transparency of decision-making, and to direct energy policy debate towards a particular vision of the energy future [9]. These energy scenarios exceed the typical time horizon of political processes by extending to the year 2050 and beyond, thereby implying the relevance of the socio-technical configuration of the energy system in the distant future as a basis for contemporary planning [10].

How scenarios shape understanding and support of specific policies has so far mostly been studied in the context of experts [11, 12]. At the same time, relatively little is known about the influence of energy scenarios on the public. This would, however, be important, as Demski et al. [13] have demonstrated that the pathways of energy scenarios function as powerful framing object for individual opinion formation and energy technology preferences. Some scholars, for example [14] have made first attempts to describe the influence of energy scenarios on non-experts. Recent findings by [15] furthermore suggest that interactive web-tools are not more efficient in communicating scenario content than conventional storylines. Most studies focusing on non-experts have in common that they scrutinize the influence of scenarios under experimental conditions. They test how participants react to scenario products and observe what short- and long-term effects these have on opinion formation processes. In reality, however, the public cannot be expected to actively and consciously consult or use energy scenarios. Instead, they receive scenario-based insights indirectly and in a fragmented way, for example via the media or political discussions, often in the form of specific promises and concerns. This is why our exploratory approach intends to assess the publics' energy system expectations without triggering them by scenarios or other forms of energy visions.

5.1.2 Expectations are vital for understanding individual perceptions of the future

How individuals conceptualise the future energy system outside of a lab setting is not yet understood very well. In general, individuals' views of the future can be conceptualized as expectations. Expectations are informal and often partially held beliefs about the future [16, 17]. Expectations may be entirely personal and tacit commitments to a future possibility. They can influence how people integrate new information and hence develop particular attitudes [14, 18, 19]. As [20] stated, behavior and decision-making in the present are anchored in the perception of the future.

Public acceptance studies tend to focus on stated preferences and beliefs that typically exclude expectations or perceptions of the future. This stands in contrast to the uncertainty and long-term focus inherent in the idea of an energy transition and the related goal of mitigating climate change. In fact, people differ both in their perception of long timeframes [21] as well as in their consideration of future consequences [22]. With the exception of [23], previous studies on public expectations have rarely focused on a specific socio-technical system in an in-depth way and only first attempts to create scales for assessing expectations in the energy system exist [24, 25]. Furthermore, there is no substantial body of research trying to explore and classify expectations of the future energy system among the public.

5.1.3 Collectively held expectations

If expectations are collectively held, they shape a shared understanding between actors that can ultimately become a normative force [26]. A range of case studies show that if relevant decision-makers all share the same expectations, this can impact the development and diffusion of novel technologies in otherwise relatively stable socio-technical systems [26-29]. If widely shared, expectations become publicly held visions of a desirable future [30]. At this point, expectations are no longer personal and tacit but become a performative power, influencing present-day behavior [26]. This self-fulfilling dimension can shape infrastructures and institutions, linking collectively held expectations to policy and politics, which is why the public energy system expectations matter [28, 31].

Assessing the public's collectively held energy system expectations provides insights into the potential social opportunities and constraints of techno-economic energy pathways that typically neglect societal perspectives [13]. This is important because the public is a crucial actor in energy transitions, with various roles that include accepting energy infrastructure, supporting energy policies, adapting energy demands, or adopting energy technologies [32].

The public's energy system expectations influence how likely, acceptable, or desirable alternative energy futures appear [30, 31, 33].

At the same time, an assessment of the public's energy system expectations indicates how strongly energy scenarios function as framing lenses in the energy discourse [34]. In the sense of Grunwald [9], this enables a better understanding of whether and how energy scenarios enlighten public debate by aligning their energy system expectations with the values, assumptions, and interests represented in techno-economic energy scenarios. While techno-economic energy scenarios may shape energy system expectations, techno-economic energy scenarios are, in turn, also influenced by the public's energy system expectations. Fundamentally, energy scenarios are social constructs based on assumptions and values that are contingent on the society in which they are formed. Ellenbeck & Lilliestam [35], for example, demonstrated that energy models and assumptions reflect the scenario developers' understanding of society and thus reproduce particular expert discourses.

5.1.4 Study aim

In this study, we explore public perception of a range of particular promises and concerns about the future energy system, which we refer to as expectations. To operationalize expectations, we conducted a survey among a sample of Swiss residents. In particular, we address the following research questions: i) What are the public's expectations about the techno-economic development of the energy system and how stable are they in the face of different time horizons and framings? ii) Are there different types of expectations towards the future energy system that can be identified among the public? iii) How do the public's energy system expectations relate to projections made in the policy-relevant energy scenario? In this way, our socio-scientific perspective provides empirical evidence of interdependencies between the formalized projections of techno-economic energy scenarios and the informal expectations of the energy future among the public.

5.2 Methods and procedure

5.2.1 Ethics statement

Data was collected from an online survey. Participation in the survey was voluntary. At the beginning of this survey, participants' were informed in written form that the responses they provided were going to be used for research purposes only. Furthermore, they were informed that the data was going to be analyzed and published in an anonymous form. This kind of noninvasive research does not require approval of an ethics committee according to the Swiss Federal Act on Research Involving Human Beings [36].

5.2.2 Case description: The relevance of energy scenarios to Swiss energy strategy 2050

Switzerland is an example of an industrialized country with a distinctive mix of energy sources and uses. Although not a member of the European Union, Switzerland is nevertheless very much integrated with international energy markets [37, 38]. We chose to survey residents in Switzerland because the country represents an ideal case for an empirical study of public energy system expectations and their alignment with scenario-derived energy policy. This is for a number of reasons. First, the nation's direct-democratic system allows the population to decide on a range of particular political issues, including energy policy. The most recent example was in 2017 when Swiss citizens enacted the Energy Strategy 2050 (ES2050) through a popular referendum. Hence, a significant share of the population is familiar with energy policy-related promises and concerns, and even the lengthy planning timeframes associated with an energy transition. Second, techno-economic energy scenarios were instrumental in the development of ES2050. In the aftermath of the Fukushima accident in 2011, the Swiss government decided to phase-out nuclear power gradually, although that it still generates about one-third of the nation's power supply. To identify cost-efficient and technically feasible ways of achieving this phase-out, the Swiss Federal Office of Energy (SFOE) developed a scenario study that subsequently functioned as an information basis for the development of ES2050. The respective scenario studies explores three different futures for the Swiss energy system. While scenarios ought to consider multiple futures without attaching probabilities from a methodological perspective, the policymaking processes reduced this plurality to a single pathway that ultimately was the basis for ES2050. This is why, from a voter perspective, ES2050 was presented as a single set of energy policy measures and targets. A range of scenario-based projections, for example, related to the cost of the proposed transition or its effects on the nation's reliance on electricity imports, were discussed at length in the political campaign leading up to the ES2050 referendum [38, 39].

5.2.3 Sample description

Data collection took place in December 2017. Survey participants were recruited via an online panel. Panel members received an invitation to participate in the study, with a small incentive of about 0.75 Euro credited upon completion of the survey.

The data analyzed here is part of a larger online survey covering a broad spectrum of energy-related attitudes. Detailed descriptions of the questionnaire development and participant recruitment process can be found in [18]. We applied quota sampling for the categories age and gender. In particular, five age categories (18-29; 30-39; 40-49; 50-59, 60+) were defined per gender. Once a quota was filled, additional respondents belonging to the category were screened out at the beginning of the survey. In total, 806 German-speaking respondents completed the survey of which 797 provided useful answers. 35 participants were screened out. 640 participants form the main sample, and 157 participants are part of an experimental group. The experimental group completed the same questionnaire as the main sample, but were given a different framing or time horizon for selected questions. These differences are presented in detail in section 2.3. There are no significant differences between the main sample and the experimental sample in terms of age, gender, political orientation and education. The samples is representative of the Swiss population in terms of age, gender, and political party identification (see Appendix). The share of university degree holders is slightly lower in the sample, 22.7% in the sample as opposed to 27% in the Swiss population. In addition, the assessed energy technology preferences are in line with recent attitude surveys among residents of Switzerland [40, 41].

5.2.4 Questionnaire: Items used in this study

Out Out of the longer questionnaire used for the survey, four question blocks have been analyzed in detail for this study:

The first contained questions on general energy issues: This includes the preference for renewable and non-renewable energy technologies, the perceived need for an energy transition, and the preference for locally generated electricity.

The second contained items operationalizing energy system expectations. The key rationale was to include items that in combination provide a meaningful description of the critical dimensions of the future energy system. In total, ten distinct energy system expectations were included (see Table 1). They were based on Gregorowius & Beuttler [25] and adapted by Blumer et al. [18]. In the latter study, expectation items were not explored in detail but aggregated: six of them were used in a larger regression analysis focusing on the acceptability of hydropower and deep geothermal energy. While some items describe the extent of the energy transition (for example the share of renewables), others describe the state of the energy system (for example the prevalence of power outages) or potential areas of conflict (for example related to energy infrastructure). All items describe energy system characteristics that are typically projected – be it explicit or implicit – in techno-economic energy scenarios. Survey participants were asked to indicate how they expected these characteristics to have changed in relative terms by the year 2050 (2030 for the experimental group) on a slider bar ranging from one (sharp decrease) to seven (sharp increase) with a starting position of four (same as today). The year 2050 was chosen as it is the reference year for the Swiss ES2050 as well as a standard reference year for climate and energy-related strategies. The 2030 timeframe used for the experimental group was chosen because it is far enough in the future for changes in the energy system to happen, but close enough for survey participants to imagine and significantly closer to the present than 2050.

The third block contained a task in which participants were asked to estimate the absolute share of renewables in the energy mix in 2050. For that purpose, we provided the latest historic share of 2016 (21%) as a reference point and respondents could indicate their estimation for 2050 on a slider bar from 0 to 100 percent. While the main sample got an idealistic framing ("According to your own values and preferences, how high should the share of renewables be in 2050?"), the experimental sample got a realistic framing ("Considering economic and political realities, what do you think the share of renewables will be in 2050?").

The fourth block contained a set of items to assess respondent's political ideology, trust in institutions and science, as well as their future orientation, using the 12-item Consideration of Future Consequences scale (Joireman et al., 2008).

The survey ended with a set of demographic questions. Throughout the survey, we used a seven-point Likert scale ranging from 1 (totally disagree) to 7 (totally agree), if it is not stated otherwise. On average, respondents required 16.3 minutes to complete the survey, and 90% of respondents were able to finish within 31 minutes.

5.2.5 Data analysis

Data was analyzed using the IBM SPSS software package (version 25). For research question i), descriptive statistics and a factor analysis were conducted, with the latter suggesting that two dimensions can represent the energy system expectations accurately. The first dimension, Transition Extent, is composed of three energy system expectation items describing the degree to which the energy system has transitioned (i.e. share of renewables, share of electric vehicles and the efficiency of appliances & processes). The second dimension, System State, consists of the remaining seven energy system expectations that address potential challenges and conflicts associated with the future energy system (i.e. likelihood of controversies with neighboring countries, power outages or increasing energy prices). Both dimensions have a good reliability score (for details, see appendix.

To identify patterns in the participants' energy system expectations (research question ii), a hierarchical cluster analysis (Ward method with squared Euclidian distance) [42] was applied to the main sample. Ward's minimum variance criterion minimizes the total within-cluster variance. To achieve this, at each stage, the pair of clusters that leads to a minimum increase in total within-cluster variance after merging is identified [43]. Examination of the cluster coefficients suggests that three, four, or five cluster solutions are conceivable.

Further data analysis by the authors showed that a three-cluster solution generates two almost identical clusters that makes the interpretation of the data very difficult, and a five-cluster solution creates vastly uneven cluster sizes, This is why reporting results for clustering solutions with 4 clusters was preferred. To clarify the procedure, we present the steps from the three- to the four- and five-cluster solution (see appendix). Because cluster analysis can be sensitive to the ordering of cases, several analyses with differing case sequences were conducted. While the case numbers differ slightly, the significant differences with respect to the expectation variables produce a stable pattern in all those solutions.

We then performed an analysis of variance (ANOVA) to test for significant differences between the clusters and the respondents' attitudes about energy in general and sociodemographic data, i.e. question block one and four. In general, we used Bonferroni as post hoc tests for statistical significance, which controls for the multiple number of comparisons by dividing through the total number of tests. However, because Levene's test of homogeneity of variance is significant for some of the dependent variables (both in the socio-demographic and the energy attitude ANOVA, ($p < 0.05$) and the cluster sizes are unequal, we also used Games-Howell as post hoc tests for statistical significance [43]. The ANOVA shows that the four clusters differ in their acceptance of energy technologies, support for the national energy strategy, trust in political institutions and science, future orientation, and demographic background. A second ANOVA was performed to demonstrate the relationship between the relative scores of the energy system expectations and the absolute values which respondents ascribe to renewables in the future in Part 3 of the questionnaire.

For research question iii), which relates the clusters' energy system expectations with the energy scenario "Energy Perspectives" that forms the scientific basis for ES2050, a content analysis of the 900-page scenario study was conducted [44]. For most energy system expectations used in the study, a corresponding scenario projection can be found, even though some of them are only implicitly considered. For example, acceptability is often only represented through the underlying potential ascribed to certain technologies and it is not in all cases transparent what particular assumptions were made by modellers. Exemplifying this is the case of hydropower: Switzerland has a long history of hydropower use. While the mountainous regions would offer many more opportunities with suitable geophysical properties for hydropower plants, additional reservoirs would with few exceptions require the flooding of inhabited valleys or pristine ecological environments. Hence, the limited potential ascribed to new hydropower plants in "Energy Perspectives" reflects the strong implicit assumptions about its social acceptance. After the explicit and implicit scenario projections corresponding with the public energy system expectations were identified, the authors of this paper rated their fit. A simple three part rating system was applied that labeled the fit between the scenario projection and the public's expectation either as close, average, or distant was applied. While some ratings were unequivocal (e.g. cluster expect strong increase, scenario projection a decrease), the comparison between the scenario projection (typically absolute values) and the public's expectations (relative to today) was sometimes challenging. Nevertheless, we opted for this direct way of comparison to be able to highlight both the evident similarities and the striking mismatches between the two conceptualizations of the energy future.

5.3 Results

5.3.1 The public's energy system expectations

Respondents from the main sample (n=640) overwhelmingly expect the energy system to have changed significantly by 2050 (see Table 1). The most substantial changes from the status quo (i.e., represented by a value of 4) are in the increased share of renewables (M=5.59), the increased energy efficiency of appliances and processes (M=5.63), and a larger number of electric vehicles in the passenger car fleet (M=5.54). The results also show that the public expects oil prices (M=5.21) to increase more than electricity prices (M=4.80) and the per capita consumption of electricity (M=4.61) to increase more than the share of imported electricity (M=4.18). Respondents also expect a slight increase in both domestic societal conflicts over energy infrastructure (M=4.60) and energy-related controversies with neighboring countries (M=4.44). The only energy system characteristics that survey participants expect to decrease in the future is the instance of power outages (M=3.88). Overall, the public expects the largest diversions from the present in the three *TransitionExtent* dimension items that were created using factor analyses (all items scoring >5.5). The scores of the *SystemState* dimension are more diverse, ranging from sharp increases (for example fossil fuel prices) to decreases (i.e. prevalence of power outages).

Table 5. Energy system expectations for the year 2050 of the main sample (N=640).

How do you expect [item] to change by 2050?	*M*	*SD*
TransitionExtent items		
Renewables	5.59	1.12

Energy efficiency	5.63	1.13
Electric vehicles	5.54	1.16
SystemState items		
Electricity use per capita	4.61	1.33
Oil and gas prices	5.21	1.29
Electricity prices	4.80	1.21
Imported electricity	4.18	1.20
Power outages	3.88	1.22
Societal conflicts over energy infrastructure	4.60	1.20
Energy related controversies with neighboring countries	4.44	1.09

Notes. Overview of energy system expectation of the main sample (n=640) for the year 2050. M=Mean, SD=Standard Deviation. Survey participants were provided with a seven-point scale for each item to indicate how they expect it to develop in comparison to today. The middle of the scale corresponds to a situation like today (e.g., 4=share of electric vehicles is expected to remain the same), whereas the endpoints would refer to a sharp increase (7) or decrease (1). The subdivisions *TransitionExtent,* describing the scale of the energy transition, and *SystemState*, describing the conditions of the future energy system are the result of a factor analysis (see appendix).

Our experimental design allows analyzing the sensitivity of these results towards different timeframes and framings. The energy system expectations of the experimental sample (2030 as the reference year, n=157) are very similar to those in the main sample with the reference year 2050 (see Table 2). In particular, the energy system expectations constituting the *TransitionExtent*, i.e., the three items describing the degree to which a renewable energy transition takes place are almost identical between the reference years 2030 and 2050. The T-test shows that there are statistically significant differences among four variables of the *SystemState* dimension: 1) The share of imported electricity is expected to be higher in 2030 *(M=4.6)* than in 2050 *(M=4.18); t(795)=3.93, p = 0.00.* 2) The prevalence of power outages is expected to be slightly higher than today in 2030 *(M=4.18)* and slightly lower in 2050 *(M=3.88); t(795)=2.75, p = 0.06.* 3) Controversies with neighboring countries over energy-related issues are expected to occur more frequently in 2030 (M=4.64) than in 2050 (M=4.44); t(795)=1.97, p = 0.04. 4) Electricity prices are expected to be higher in 2030 *(M=5.01)* than in 2050 *(M=4.80); t(795)=1.97, p = 0.05.* Not statistically significant are the differences between the per capita use of electricity and energy-related controversies with neighboring countries, which are both also expected to be higher in 2030 than in 2050. In contrast to the timeframe, the framing (realistic vs. idealistic) seems to produce differences in the estimated share of renewables in 2050. The realistic framing ("*Considering economic and political realities, what do you think the share of renewables will be in 2050*?") resulted in a share of 51.9% (SD 36.7). The idealistic framing ("*According to your own values and preferences, how high should the share of renewables be in 2050?"*) resulted in a share of 63.1% (SD 23.7). The difference between the two framings is significant t(795)=4.71, p = 0.00. This exemplifies that while people generally do not differentiate between the years 2030 and 2050, they do differentiate between idealistic preferences and realistic expectations in their responses regarding the future energy system.

Table 6. Energy system expectations for the year 2030 of the experimental sample (N=157) compared to 2050 main sample (N=640).

Expectation	*M*	*SD*	*Δ2050*	*t*	*p*
TransitionExtent items					
Renewables	5.59	1.10	0.00	0.00	1.00
Energy efficiency	5.62	0.95	0.01	0.10	9.19
Electric vehicles	5.54	1.00	0.00	0.00	1.00
SystemState items					
Electricity use per capita	4.52	1.31	0.09	0.76	.446
Oil and gas prices	5.26	1.34	0.05	-0.43	.667
Electricity prices	5.01	1.14	-0.21	-1.97	.049*
Imported electricity	4.60	1.20	-0.42	-3.93	.000*
Power outages	4.18	1.25	-0.30	-2.75	.060
Societal conflicts over energy infrastructure	4.62	1.14	-0.02	-0.19	.850
Energy related controversies with neighboring countries	4.64	1.06	-0.20	-2.07	.039*

Notes. Overview of energy system expectation of the subsample (*N*=157) for the year 2030 with Delta and T-test comparisons to the main sample's 2050 expectations. *M*=Mean, *SD*=Standard Deviation, Δ2050=Difference between *M*2050 and *M*2030, *t*=T-Test. *p*=significance, *p≤.05.

5.3.2 Four distinct energy system expectation clusters

The hierarchical cluster analysis resulted in four energy system expectation clusters. We start by presenting the ratings of the clusters for the ten expectations (see Table 3). Then, we present ANOVA results comparing the clusters to other items of the questionnaire. Overall, there are only very few socio-demographic differences between the clusters. Gender, age, educational level, household income or political orientation on a left-right scale are for example not significantly different among the clusters. Most differences are in the acceptance of energy technologies, the support for the national energy strategy, trust in parliament, the energy minister and science, as well as the participants' future orientation, of which we present the most relevant items. Comprehensive tables covering all questionnaire items are provided in the appendix.

Table 7. Table 3: Four energy system expectation clusters with key socio-demographics and items with significant differences (N=640).

	Cluster 1 (N=137)		Cluster 2 (N=200)		Cluster 3 (N=122)		Cluster 4 (N=181)		Overall cluster difference	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*F*	*p*
TransitionExtent items										
Renewables	$6.31^{b,c,d}$	.68	$5.62^{a,c}$	.95	$4.47^{a,b,d}$	1.26	$5.68^{a,c}$	.88	*83.65*	*.000*
Energy efficiency	$6.12^{b,c}$	.84	$5.7^{3a,c}$	.87	$4.42^{a,b,d}$	1.37	5.95^{c}	.77	*84.58*	*.000*
Electric vehicles	$6.21^{b,c,d}$	.79	$5.52^{a,c}$	1.01	$4.48^{a,b,d}$	1.12	$5.76^{a,c}$	1.07	*68.64*	*.000*
SystemState items										
Electricity use per capita	$3.23^{b,c,d}$	.99	$4.99^{a,c,d}$	1.15	$4.48^{a,b,d}$	1.15	$5.34^{a,b,c}$	1.07	*111.28*	*.000*[2]
Oil and gas prices	$5.45^{c,d}$	1.28	$5.68^{c,d}$	.94	$4.97^{a,b}$	1.02	$4.67^{a,b}$	1.55	*24.58*	*.000*
Electricity prices	$4.39^{b,c}$	1.20	$5.46^{a,c,d}$	.98	$4.79^{a,b,d}$	1.02	$4.40^{b,c}$	1.26	*37.33*	*.000*
Imported electricity	$3.48^{b,c,d}$	1.25	$4.83^{a,c,d}$	1.06	$4.24^{a,b}$	.96	$3.95^{a,b}$	1.09	*44.40*	*.000*
Power outages	$3.31^{b,d}$	1.05	$4.52^{a,c,d}$	1.14	3.52^{b}	1.13	$3.85^{a,b}$	1.18	*36.54*	*.000*[2]
Societal conflicts over energy infrastructure	$3.95^{b,d}$	1.21	$5.52^{a,c,d}$	.91	4.25^{b}	.95	$4.33^{a,b}$	1.03	*79.66*	*.000*[2]
Energy related controversies with neighboring countries	$3.78^{b,d}$	1.09	$5.23^{a,c,d}$	.93	$4.02^{b,d}$	.90	$4.35^{a,b,c}$	.83	*78.98*	*.000*
Socio-demographics										
Women (N=639)	.55	*.50*	.47	*.50*	.47	*.50*	.49	*.50*	.79	.499[1]
Age (in years)	45.33	15.1	46.72	15.0	43.65	14.5	43.13	15.4	2.12	.097

CFC 12-pt. (higher implies more future orientation)	58.6[b,c,d]	7.44	55.7[a,c]	7.80	52.2[a,b,c]	7.00	55.0a, c	7.87	15.80	.000
Political orientation and trust										
Left/right leaning on the political scale (5 pt.)	2.86[b,c]	.99	3.20[a]	.94	3.18[a]	.92	3.05	.99	3.84	.010
Self-assessed familiarity with CH politics	5.73	1.57	5.64[c]	1.72	4.81[b]	1.79	5.36	1.93	7.30	.000
Belief in value of voting (My vote makes a difference)	4.36[c]	1.78	4.04	1.63	3.72[a,d]	1.64	4.28[c]	1.73	3.86	.009
Trust in parliament	4.27[c]	1.51	3.88[d]	1.44	3.69[a,d]	1.46	4.34[b,c]	1.36	7.07	.000
Trust in energy minister	4.10	1.71	3.62d	1.70	3.62d	1.49	4.20[b,c]	1.65	5.73	.001
Trust in science	5.32[b,c]	1.19	4.89[a,c]	1.28	4.18[a,b,d]	1.43	5.05[c]	1.23	18.71	.000
Energy attitudes										
Perceived need of an energy transition	5.65 [b,c,d]	1.46	5.09 [a,c]	1.48	4.53[a,b,d]	1.46	5.14[a,c]	1.40	12.89	.000
Preference for locally produced electricity	4.80[c]	1.64	4.74[c]	1.53	4.09[a,b,d]	1.54	4.69[c]	1.45	6.01	.000
Support for Photovoltaics	6.49[b,c,d]	1.01	6.01[a,c]	1.06	5.12[a,b,d]	1.57	6.10[a,c]	1.10	30.68	.000[2]
Support for nuclear power	1.94[b,c,d]	1.35	2.79[a]	1.86	2.90[a]	1.64	2.62[a]	1.59	9.54	.000[2]
Support for natural gas	3.28	1.58	3.28	1.58	3.48	1.54	3.45	1.50	.42	.742
ES2050 yes (N=191)	.41[b,c]	.49	.26[a]	.44	.20[a]	.41	.33	.47	5.29	.001[1,2]
ES2050 no (N=100)	.08[b]	.27	.22[a]	.41	.16	.37	.14	.35	3.88	.009[1,2]

Notes. *M*=mean, *SD*=standard deviation. *F*=variance of the group means, *p*=significance. One-way ANOVA was performed to identify significant differences among the clusters. Bonferroni corrections were used for post-hoc analysis. [1] The dichotomous variables were tested with chi-square. [2] Levens homogeneity of variance is significant, which is why Games-Howell post-hoc corrections were applied. a cluster is significantly different from cluster 1 ($p \leq .05$) l. b cluster is significantly different from cluster 2 ($p \leq .05$). c cluster is significantly different from cluster 3 ($p \leq .05$). d cluster is significantly different from cluster 4 ($p \leq .05$).

5.3.3 Cluster 1

This cluster contains people that tend to expect a transition towards a sustainable energy system with much higher shares of renewable energy (M=6.31), vastly improved efficiency of appliances and processes (M=6.12) and much higher shares of electric vehicles (M=6.21) than today. It is the only cluster with values 6 in all of the *TransitionExtent* expectation variables, which is significantly different form all other clusters. Moreover, this is the only cluster expecting the per capita electricity consumption to decrease in the future (M=3.23). Consequently, they expect the prices of fossil fuels (M=5.45) to increase much more than the prices of electricity (M=4.39) and expect a decrease in electricity imports (M=3.48). Overall, this cluster expects that the energy transition will be positively associated as the prevalence of power outages (M=3.31), as well as societal conflicts over energy infrastructure (M=3.95) and energy-related controversies with neighboring countries are expected to decrease (M=3.78). Similar to the extent of the energy transition, it is thus also the cluster most expecting the challenges related to the energy transition to be resolvable.

Cluster 1 also perceives the highest need for an energy transition (M=5.65) among all clusters. In addition, the acceptance of renewable energy technologies (solar, wind, hydro) is significantly higher than in the other clusters. In contrast, nuclear energy is much less acceptable to this cluster than to any other. Consequently, this cluster also entails the highest share of people supporting ES2050 (41% voted yes) and the lowest share rejecting it (8% voted no).

Cluster 1 is the only cluster that is predominantly female (55%) and entails the respondents with the highest consideration of future consequences score and the lowest share of access to a car in the household (see appendix). Trust in the energy minister and parliament are relatively high and trust in science as well as the self-assessed familiarity with Swiss politics are the highest of all clusters.

5.3.4 Cluster 2

Cluster 2 is the biggest cluster in the sample (N=200). While this group of respondents expects the energy transition to happen (M>=5.5 in all *TransitionExten*t expectations), they expect it to be accompanied by a range of problematic developments. Most importantly, this group is characterized by the expectation that conflicts both within society over energy infrastructure (M=5.51) as well as controversies with neighboring countries over energy related issues (M=5.23) will increase strongly, which is significantly different from all other clusters. A reason for the expectation of increasing international energy-related controversies could lie in the expectation of an increasing need to import electricity (M=4.83), which is the highest of all clusters. Fear of electricity shortages could also be the reason why this is the only cluster expecting an increase in power outages (M=4.52). The pessimistic view on the energy transition is complemented by the expectation of a significant increase in per capita electricity consumption (M=4.99) as well as the highest prices for both electricity (M=5.46) and fossil fuels (M=5.68).

People belonging to this cluster were most likely to reject ES2050 (22% voted no) despite having high scores in the need for an energy transition and the preference for locally produced electricity. Moreover, renewable energy sources are perceived almost as positively as by Cluster 1. In contrast, Cluster 2 perceives nuclear power significantly more positive than all other clusters. This is the oldest (M=46.7 years) of the clusters and has rather low trust in general, particularly in the energy minister.

5.3.5 Cluster 3

Cluster 3 expects only small divergences from the present throughout all energy system expectations. For example, it expects only slight increases in the share of renewables, electric cars or the efficiency of appliances (M≥4.5). As these changes are expected to be minor, also the respective impacts on society or international relations are expected to be small. The biggest divergence from the present this cluster expects is in the price increase for electricity (M=4.79) and fossil fuels (M=4.97).

One quarter of respondents belonging to this group did not vote on ES2050, the highest share among all clusters (see appendix), while those who voted were divided (20%yes, 16% no). Similar to the energy system expectation, this cluster's energy attitudes tend not to diverge much from the "*Neither agree nor disagree*" option. Exceptions are the dislike of nuclear power, which is in line with the other clusters, and their relatively high acceptance of electricity imports.

Compared to other clusters, it is rather uninterested in energy topics and is characterized by a passiveness in political engagement (see appendix). They have the lowest values of all cluster for the trust in parliament, the energy minister and science and the lowest consideration of future consequences.

5.3.6 Cluster 4

Cluster 4's expectation patterns mostly fall between cluster 1 and 2. The key differences characterizing Cluster 4 are their expectation for a massive increase in per capita electricity consumption (M=5.34, significantly the highest score of all clusters) and their simultaneous expectation of low energy prices for both electricity (M=4.40) and fossil fuels (M=4.67).

Cluster 4 is the second largest supporter of ES2050 (33% voting yes). For nearly all energy attitudes, their scores are between Cluster 1 and Cluster 2, i.e. favorable towards renewable and locally produced electricity. Notable is the highest acceptance of deep geothermal energy of all clusters (M=4.47).

This is the youngest of all clusters (M=43.13 years), with the highest average level of education, access to a car in the household (84%), and the lowest share of homeowners. Levels of trust in parliament, the energy minister and science are high.

5.3.7 Comparison of expectations with projections of techno-economic energy scenarios

This section presents the scenario projections from the policy-relevant scenario "*Energy Perspectives*" that correspond with the energy system expectations and describes their fit with the four clusters. Cluster 1 is most closely aligned with the scenario "*Energy Perspectives*" (see Table 6). The only three expectations with only an average fit with the corresponding scenario projection are the share of electricity imports (which the cluster expects to decrease and the scenario projects the share to remain at today's level), electricity prices (which the cluster expects to increase less than the scenario) and power outages (which the cluster expects to decrease and the scenario again projects the share to remain at today's level). Cluster 1 is the only cluster where all *TransitionExtent* expectations are rated to have a close fit (massive increase in renewables, electric vehicles and energy efficiency) with the scenario. Furthermore, all other clusters expect an increase in per capita electricity consumption which is why only the expected decrease of Cluster 1 has a close fit with the scenario projection. Cluster 3 was rated to have a distant fit with the scenario projection on three occasions. Besides the electricity use per capita, it concerns the expected increase in societal and international conflicts, which is not projected by the scenario. Cluster 3 had a distant fit on four occasions. This relates to all of the *TransitionExtent* expectations (cluster expects a persistence of the status quo) and to the electricity use per capita.

Table 8. Rated fit of the four cluster's energy system expectations with the corresponding projection from the policy-relevant scenario "Energy Perspectives".

Expectation for 2050	**Energy scenario projection for 2050**	**Cluster 1 fit**	**Cluster 2 fit**	**Cluster 3 fit**	**Cluster 4 fit**
TransitionExtent items					
Renewables	From 1.38 TW/h in 2010 to 24 TW/h (excluding hydropower).	Close (M=6.31)	Average (M=5.62)	Distant (M=4.47)	Average (M=5.68)
Energy efficiency	Varying across appliances and sectors, but very significant efficiency gains are assumed overall.	Close (M=6.12)	Close (M=5.73)	Distant (M=4.42)	Close (M=5.95)
Electric vehicles	From 0.03% in 2010 to 41%.	Close (M=6.21)	Average (M=5.52)	Distant (M=4.48)	Average (M=5.76)
SystemState items					
Electricity use per capita	Minus 10% compared to 2010.	Close (M=3.23)	Distant (M=4.99)	Distant (M=4.48)	Distant (M=5.34)
Oil and gas prices	Plus 100% compared to 2010.	Close (M=5.45)	Close (M=5.68)	Average (M=4.97)	Average (M=4.67)
Electricity prices	Plus 42% compared to 2010.	Average (M=4.39)	Close (M=5.46)	Close (M=4.79)	Average (M=4.40)

Imported electricity	Larger variance throughout the year (importing during winter, exporting during summer), but stable overall.	Average (M=3.48)	Average (M=4.83)	Close (M=4.24)	Close (M=3.95)
Power outages	A highly reliable electricity system is implicitly assumed.	Average (M=3.31)	Average (M=4.52)	Close (M=3.52)	Close (M=3.85)
Societal conflicts over energy infrastructure	Social acceptance and cohesion is implicitly assumed as the whole strategy is considered to be feasible.	Close (M=3.95)	Distant (M=5.52)	Close (M=4.25)	Close (M=4.33)
Energy related controversies with neighboring countries	Implicitly regarded to be non-existent, energy imports assumed to be available at all times.	Close (M= 3.78)	Distant (M=5.23)	Close (M=4.02)	Close (M=4.35)

Notes. Fit between the scenario projection and the public's expectation as rated by the authors. Expectations rated to have a close fit to the corresponding scenario projection are shaded green. Expectations rated to have a average fit to the corresponding scenario projection are shaded grey. Expectations rated to have a distant fit to the corresponding scenario projection are shaded red. M=mean.

5.4 Discussion

5.4.1 Public energy system expectations illustrate the pervasiveness of the energy transition as an idea

The first research question of this paper asked what the public's expectations about the techno-economic aspects of the energy system are. The results suggest that the public does expect the energy system to change significantly in the future. The fact that this is also true for individuals who are critical of the Swiss energy policy indicates that the fact that a transition of some sort will take place is a widely shared and deeply rooted belief among Swiss citizens. This is remarkable because people typically tend to underestimate changes that happen over a long timescale, especially in large socio-technical systems that have been functioning and stable for decades [45]. Hence, the assessed expectations indicate "a psychological readiness to engage in the transition […]" that Vainio et al. [23] also attested to their sample in a survey assessing citizens' images of a sustainable energy transition.

The variance among the expectations of the main sample and the comparison between the main sample and the experimental sample provide insights for the interpretation of these expectations. First, the significant differences between the realistic and the idealistic framing in participants' estimation of the future share of renewables confirmed the importance of framings in attitude surveys, as it has been previously highlighted by Clarke et al. [46]. Yet, we found only a few differences between the energy system expectations for the year 2050 (main sample) and the year 2030 (experimental sample). This indicates that public energy system expectations are conceptually different from scenario projections [23]. Particularly, expectations tend to be static in the sense that they do not describe a path-to-the-end state, but rather the future end state itself. This is evident in the increased cost of fossil fuel prices and the number of electric vehicles in the passenger car fleet that often only begin to rise significantly after 2030 in energy scenarios, but are nearly identical for the time horizons 2030 and 2050 in the public expectations. As there are not many significant differences between the 2030 and the 2050 time horizons, one can question whether people differentiate between the two or whether both are perceived to be distant futures. However, there were differences in the electricity prices, the frequency of power outages, and the risk of controversies with neighboring countries over energy-related issues, which are all expected to be significantly higher in 2030 than in 2050. The expected energy future in 2050 as a whole is thus viewed more positively than the energy future in 2030 [47].

Public energy system expectations mirror the key promises and concerns associated with the energy transition [29]. Increasing energy costs and societal conflicts are, for example, clearly among the most common concerns among the expectations. However, one characteristic that is controversial and prominent both in academic literature and the political campaigns surrounding ES2050 in Switzerland, but not reflected in public expectations, is energy security [33]. The majority of respondents neither expect reliance on foreign electricity sources to increase in the future, nor power outages to become more widespread. In fact, the main sample expects a further decrease in power outages by 2050, which is astonishing considering Switzerland only experienced a cumulative total of 20 minutes without power in 2017, ten of which were due to unforeseen circumstances [48]. This suggests an expert/non-expert divide which future research could use as an interesting case to advance the understanding of how expectations influence how people integrate new and sometimes contrasting information [14]. That experts and non-experts can have different preferences for the future energy technology mix in Switzerland has recently been demonstrated by Xexakis et al. [15].

5.4.2 Relationship between expectation clusters and the acceptability of a sustainable energy transition

The variance between the clusters suggests that within the population there exist very different expectations about the energy future. Moreover, the clusters represent four different conceptualizations of the energy future consisting of distinct combinations of promises and concerns. We argue that these conceptualizations are not arbitrary. Cluster 1 focuses on the potential benefits associated with the energy transition and the respective respondents can thus be considered transition optimists. Cluster 2, in contrast, focuses on the potential risks associated with energy transitions and can thus be labelled transition pessimists. At the same time, Cluster 2 acknowledges the need for an energy transition and is not per se against renewable energy, indicating a certain ambivalence. Cluster 3 is the only one that expects the whole set of energy system characteristics to remain stable. The reason for the belief that the status quo will remain far into the future could correspond with this cluster's indifference about energy topics and their low self-assessed knowledge and activity in political processes. The rationality of Cluster 4 is defined by the assumption that there will be an abundance of various energy sources in the future. Interestingly, this cluster expects that there will be a transition towards renewable energy sources, but at the same time expects this to happen without large increases in the prices for fossil fuels.

We do not claim that these expectations a comprehensive operationalization of the complexities and interdependencies of energy systems or that they are in line with expert views on the energy future. In fact, section 4.3 shows that there are some major deviations from the formalized expert projections of the reference energy scenarios of the ES2050. While the deviations differ among the respective clusters, all clusters follow a certain logic that allows for inferring the key ideas of the energy future shaping the expectations. The clusters seem to align with the support for Switzerland's national energy strategy ES2050. There are several other significant relationships between the clusters and their related energy technology preferences and attitudes towards energy policies. However, socio-demographic differences between the clusters were less clear and seem to be of minor importance. This contrast with a lot of acceptance research on energy technologies and policies where socio-demographic variables often play a significant role [49].

In contrast, trust seems to be a key concept when it comes to why people associate the energy transition more with potential benefits or risks respectively. Trust in parliament, the energy minister and in science are significantly different between the clusters. In a review article, Huijts et al. [50] show that trust is particularly important as a heuristic when people know little about a topic. As there are many uncertainties associated with energy transitions and the effects and involved actors are manifold it seems logical that "positive expectations of the intentions or behavior of another" as trust was defined by Rousseau et al. [51] is critical.

In addition, the hierarchical cluster analysis shows that, depending on the underlying rationality of the energy system expectations, the same promises and concerns can be interpreted differently. For example, for Cluster 1, the anticipated reduction in electricity demand by 2050 seem to reflect a positive step. Possibly, it symbolizes increased efficiency and careful use of energy resources in general. In contrast, for Cluster 4, the anticipated sharp increase in electricity demand seems to be positively associated with a sustainable energy transition. This could be due to the increased degree of electrification and prevalence of "smart" appliances. Hence, the underlying conceptualizations of how an energy transition works and the different opinions about its key target (for example climate change mitigation, energy autarky or decentralization) determine the appraisal of energy technologies or policies [52]. Accordingly, promises and concerns are not universal, but contingent on personal conceptualizations of the energy future [16].

5.4.3 The varying compatibility of energy system expectation clusters and projections of the national energy scenario

The interaction of the public with energy scenarios is not comparable to the scrutiny applied by energy and modeling experts. Nevertheless, the results of this study suggest that scenario-derived promises and concerns circulated by the media and political discussions could nevertheless provide powerful reference points for the energy-related expectations of non-experts, as it has been observed under experimental conditions by Demski et al. [13]. Cluster 1, whose expectations have most expectations that are in line with the national energy scenario, exemplifies this. This cluster has the highest support rate for ES2050 and the most trust in science, indicating that this group could perceive the projections of the scientifically derived energy scenario to be credible.

At the same time, it is evident that most respondents have energy system expectations that differ significantly from the national energy strategy projections on a number of different dimensions. The largest contrast between expectations and scenario was evident in the anticipated electricity demand, which only Cluster 1 expects to decrease in line with the scenario projection. Many people associate energy with progress, which could explain why most people expect an increase in electricity demand [53]. Also, most people's personal experiences and lifestyles (i.e. more and bigger electric appliances, trends towards electrification in many jobs) could iterate the perception of more electricity use, while energy efficiency improvements are typically much less noticeable. However, the fact that most people who expect an increasing electricity demand still support ES2050 shows that the acceptability of a broader policy package is not contingent on particular promises and concerns. In contrast, a holistic view on the public's energy system expectations demonstrates a certain willingness to act or at least accept changes towards the general direction of a renewable energy transition.

Accordingly, there co-exists a range of expectations about the energy system that are more or less compatible with the scenario constituting the national energy strategy. This plurality of distinct energy system expectations could also correspond with the diversity of energy scenarios that exists. However, to date it is largely unclear what determines the uptake of scenarios and how their contested projections of future energy systems are perceived. A study among researchers showed the selection and application of energy scenarios is not determined by the users' field of study, but by the personal background and purpose of scenario use [54]. This tendency was confirmed by a study on the use of climate scenarios which found that a user's sectoral background was not a significant predictor for the type of scenario application [55]. Hence, it can be assumed that the uptake and relevance of scenario projections, for example as distinct promises and concerns proliferated by media and political discussions, is only loosely correlated with the publics' socio-demographic background. The results of this study show that trust, future-orientation and political activity are better predictors for the relationship between personal expectations and formalized scenario projections. It may well be that these attributes in turn correlate with media use patterns and affinity to follow political discussions in general.

The assessed energy system expectations can also make explicit what energy scenarios only consider implicitly, for example as ceteri paribus conditions. This includes the occurrence of societal conflicts over energy infrastructure or controversies with neighboring countries over energy related issues. The correlation between the acceptability of renewable energy technologies and the support for ES2050 shows that the reason for Cluster 2 to predominantly vote against the Swiss energy transition lies exactly in these factors that typically are outside the focus of techno-economic energy scenarios. If it is indeed these social factors determining the acceptability of an energy scenario or a corresponding energy strategy, it raises the question how relevant it is to publish energy scenarios with their traditional focus on techno-economic aspects that can be quantified. Can scenarios enable an enlightened energy discourse, as suggested by [56], when the key elements for non-experts to create meaningful and relatable storylines [15] to make sense of the energy future are missing?

5.4.4 Critical reflection and outlook

The study has some limitations. First, it is exploratory in nature, using cluster analysis of a novel set of promises and concerns as proxy for techno-economic energy system expectations. Second, the expectations were assessed over a single time period in a rather confined geographical region. As energy transition are strongly context dependent, generalizations should only be made on the basis of an analysis of the respective situation in other contexts.

Although challenging, it would be particularly interesting for future research to monitor public energy system expectations over a longer time in order to understand the formation and dynamic aspects of expectations. Longitudinal studies could shed further light on the impact of critical events, political cycles or generational effects on the persistence of expectations. For example, the study was conducted before the issue of climate change received a major boost in visibility – inter alia through the climate strike youth. Thus, comparative analyses covering multiple language regions or countries could yield interesting insights into cultural specificities, generational effects and respective expectation patterns. Third, no standardized way of comparing expectations to scenario projections exists to date, hence in this study a direct approach was chosen which worked well for many expectations, but not all. As scenario products are often distorted or simplified when they are communicated to non-expert communities, future research could use discourse analysis to identify the relevant promises and concerns in energy debates. Based on the insights presented in this study, we argue that it is worthwhile to investigate the role of expectations and their interdependence with model-based energy scenarios. As of today, it is not clear whether the public's energy system expectations or energy discourse more generally are actually influenced by scenario projections or whether scenarios basically analyze the techno-economic feasibility of expectations that are deeply rooted in society and thus also among scenario developers.

5.5 Conclusion

Energy transitions are co-evolutionary processes between social groups, their behavioral patterns and technologies. While expert perspectives tend to be well understood, the public understanding of transitions is still not. Assessing energy system expectations could be a first step in this direction. Our study used an exploratory approach to assess public expectations of the techno-economic energy system aspects for the years 2030 and 2050 with separate samples and compared them to the policy-relevant energy scenario projection. It thus provides a first attempt to assess the public's expectations about the energy system in a non-experimental setting.

We identified four clusters of energy system expectations. Each of these describes a distinct and holistic vision of the energy future. We argue that the variance between the clusters does not indicate arbitrariness, but rater variance in how the public perceives the energy future. Cluster 1 is very optimistic about the energy future, while Cluster 2 is generally more pessimistic and particularly worried about energy related conflicts. Cluster 3 is the only cluster not expecting an energy transition at all, indicating that the concept of an energy transition has become a collective expectation shared by a large majority of the public. Cluster 4 expects an increase in electricity demand and a simultaneous reduction in electricity prices, which not only stands in contrast to the expectations of the other three clusters, but also to the projection of the national energy scenario study which defined the Swiss Energy Strategy 2050. These different peculiarities of energy system expectations should be recognized by researchers and decision-makers communicating energy-related topics.

While energy system expectations tend to be static images of the future that vary only very little even between different timeframes, energy scenarios provide highly specific what-if pathways. Our analysis showed that many expectations determining the acceptability of the energy transition are only implicitly represented in energy scenarios. Scenario projections thus miss key aspects the public worries or is hopeful about in relation to the energy future. Accordingly, if the goal of publishing energy scenarios is to increase the transparency of policymaking, the scenario content also needs to be tailored at the public's interests and competencies. For example, while the timing of energy investments and technology developments is a critical aspect in energy scenarios, our analysis showed that most respondents do not differentiate between the timeframes 2030 and 2050. The strong correlations of the four clusters with the acceptability of energy technologies and support for the national energy strategy indicate that it would be worthwhile to further investigate the interdependencies between public energy system expectations and energy scenarios. Energy system expectations can function as a proxy for the range of energy futures that are attainable according to public perception

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References

Arnocky, S., Milfont, T. L., & Nicol, J. R. (2014). Time Perspective and Sustainable Behavior. *Environment and Behavior*, *46*(5), 556–582. https://doi.org/10.1177/0013916512474987

Beckert, J. (2013). Imagined futures: Fictional expectations in the economy. *Theory and Society*, *42*(3), 219–240. https://doi.org/10.1007/s11186-013-9191-2

Berkhout, F. (2006). Normative expectations in systems innovation. *Technology Analysis and Strategic Management*, *18*(3–4), 299–311. https://doi.org/10.1080/09537320600777010

Berkhout, F., & Berkhout, F. (2016). Normative expectations in systems innovation Normative Expectations in Systems Innovation, *7325*(October). https://doi.org/10.1080/09537320600777010

Bina, O., Mateus, S., Pereira, L., & Caffa, A. (2016). The future imagined: Exploring fiction as a means of reflecting on today's Grand Societal Challenges and tomorrow's options. *Futures*, *86*, 166–184. https://doi.org/10.1016/j.futures.2016.05.009

Blumer, Y.B., Braunreiter, L., Kachi, A., Lordan-Perret, R., & Oeri, F. (2018). A two-level analysis of public support: Exploring the role of beliefs in opinions about the Swiss energy strategy. *Energy Research & Social Science*, *43*, 109–118. https://doi.org/10.1016/j.erss.2018.05.024

Blumer, Yann B., Moser, C., Patt, A., & Seidl, R. (2015). The precarious consensus on the importance of energy security: Contrasting views between Swiss energy users and experts. *Renewable and Sustainable Energy Reviews*, *52*, 927–936. https://doi.org/10.1016/j.rser.2015.07.081

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures*, *38*(7), 723–739. https://doi.org/10.1016/j.futures.2005.12.002

Borup, M., Brown, N., Konrad, K., & Van Lente, H. (2006). The sociology of expectations in science and technology. *Technology Analysis and Strategic Management*, *18*(3/4), 285–298. https://doi.org/10.1080/09537320600777002

Braunreiter, L., & Blumer, Y. B. (2018). Of sailors and divers: How researchers use energy scenarios. *Energy Research and Social Science*. https://doi.org/10.1016/j.erss.2017.12.003

Brönnimann, S., Appenzeller, C., Croci-Maspoli, M., Fuhrer, J., Grosjean, M., Hohmann, R., … Thalmann, P. (2014). Climate change in Switzerland: A review of physical, institutional, and political aspects. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(4), 461–481. https://doi.org/10.1002/wcc.280

Clarke, C. E., Hart, P. S., Schuldt, J. P., Evensen, D. T. N., Boudet, H. S., Jacquet, J. B., & Stedman, R. C. (2015). Public opinion on energy development: The interplay of issue framing, top-of-mind associations, and political ideology. *Energy Policy*, *81*, 131–140. https://doi.org/10.1016/j.enpol.2015.02.019

Cousse, J., & Wüstenhagen, R. (2018). 8 th Consumer Barometer of Renewable Energy. *Good Energies Chair for Management of Renewable EnergiesInstitute for Economy and the Environment , University of St.Gallen*.

Demski, C. (2011). Public perceptions of renewable energy technologies: challenging the notion of widespread support. *Thesis*, (September), 369. Retrieved from http://orca.cf.ac.uk/13562/%5Cnhttp://orca.cf.ac.uk/13562/1/2011demskiccphd.pdf

Demski, C., Spence, A., & Pidgeon, N. (2017). Effects of exemplar scenarios on public preferences for energy futures using the my2050 scenario-building tool. Nature Energy 2 (4) Effects of exemplar scenarios on public preferences for energy futures using the my2050 scenario-building tool. *Nature Energy*, 1–26. Retrieved from http://orca.cf.ac.uk/98417/%0Ahttp://dx.doi.org/10.1038/nenergy.2017.27%0Ahttp://orca.cf.ac.uk/policies.html

Demski, C., Thomas, G., Becker, S., Evensen, D., & Pidgeon, N. (2019). Acceptance of energy transitions and policies: Public conceptualisations of energy as a need and basic right in the United Kingdom. *Energy Research and Social Science*, *48*(September 2018), 33–45. https://doi.org/10.1016/j.erss.2018.09.018

Dignum, M., Correljé, A., Groenleer, M., & Scholten, D. (2017). Governing through visions: Evaluating the performativity of the European gas target models. *Energy Research and Social Science*, *35*(October 2017), 193–204. https://doi.org/10.1016/j.erss.2017.10.016

ElCom. (2018). *Stromversorgungssicherheit der Schweiz 2018*. Retrieved from http://www.elcom.admin.ch/dokumentation/00017/index.html?lang=de&download=NHzLpZeg7t,lnp6I0NTU042l2Z6ln1acy4Zn4Z2qZpnO2Yuq2Z6gpJCDdX57hGym162epYbg2c_JjKbNoKSn6A--

Ellenbeck, S., & Lilliestam, J. (2019). How modelers construct energy costs: Discursive elements in Energy System and Integrated Assessment Models. *Energy Research and Social Science*, *47*(August 2018), 69–77. https://doi.org/10.1016/j.erss.2018.08.021

Field, A. (2013). Discovering Statistics using IBM SPSS Statistics. *Discovering Statistics Using IBM SPSS Statistics*, 297–321. https://doi.org/10.1016/B978-012691360-6/50012-4

Field, A., Miles, J., & Field, Z. (2013). *Discovering Statistics Using SPSS*. *Sage* (Vol. 81). https://doi.org/10.1111/insr.12011_21

Geels, F. W., McMeekin, A., & Pfluger, B. (2018). Socio-technical scenarios as a methodological tool to explore social and political feasibility in low-carbon transitions: Bridging computer models and the multi-level perspective in UK electricity generation (2010–2050). *Technological Forecasting and Social Change*, (January 2017). https://doi.org/10.1016/j.techfore.2018.04.001

Gregorowius, D., & Beuttler, C. (2015). *Die Stromzukunft der Schweiz: Erwartungen der Bevölkerung und Präferenzen bei Zielkonflikten*. St. Gallen.

Grunwald, A. (2011). Energy futures: Diversity and the need for assessment. *Futures*, *43*(8), 820–830. https://doi.org/10.1016/j.futures.2011.05.024

Grunwald, A. (2014). Modes of orientation provided by futures studies: making sense of diversity and divergence. *European Journal of Futures Research*, *2*, 30: 9. https://doi.org/10.1007/s40309-013-0030-5

Gupta, N., Fischer, A. R. H., & Frewer, L. J. (2012). Socio-psychological determinants of public acceptance of technologies: A review. *Public Understanding of Science*, *21*(7), 782–795. https://doi.org/10.1177/0963662510392485

Huijts, N. M. A., Molin, E. J. E., & Steg, L. (2012). Psychological factors influencing sustainable energy technology acceptance: A review-based comprehensive framework. *Renewable and Sustainable Energy Reviews*, *16*(1), 525–531. https://doi.org/10.1016/j.rser.2011.08.018

Jain, A. K., Murty, M., & Flynn, P. (1999). Data Clustering: A Review. *ACM Computing Surveys*, *31*(3), 264–323. https://doi.org/10.1192/bjp.112.483.211-a

Jasanoff, S., & Kim, S.-H. (2013). Sociotechnical Imaginaries and National Energy Policies. *Science as Culture*, *22*(2), 189–196. https://doi.org/10.1080/09505431.2013.786990

Jewell, J., Cherp, A., & Riahi, K. (2014). Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. *Energy Policy*, *65*, 743–760. https://doi.org/10.1016/j.enpol.2013.10.051

Joireman, J., Balliet, D., Sprott, D., Spangenberg, E., & Schultz, J. (2008). Consideration of future consequences, ego-depletion, and self-control: Support for distinguishing between CFC-Immediate and CFC-Future sub-scales. *Personality and Individual Differences*, *45*(1), 15–21. https://doi.org/10.1016/j.paid.2008.02.011

Konrad, K. (2006). The social dynamics of expectations: The interaction of collective and actor-specific expectations on electronic commerce and interactive television. *Technology Analysis & Strategic Management*, *18*(3–4), 429–444. https://doi.org/10.1080/09537320600777192

Mayer, L. A., Bruine De Bruin, W., & Morgan, M. G. (2014). Informed public choices for low-carbon electricity portfolios using a computer decision tool. *Environmental Science and Technology*, *48*(7), 3640–3648. https://doi.org/10.1021/es403473x

Mcdowall, W., Trutnevyte, E., Tomei, J., & Keppo, I. (2014). UKERC Energy Systems Theme Reflecting on Scenarios, (June). Retrieved from http://www.ukerc.ac.uk/publications/ukerc-energy-systems-theme-reflecting-on-scenarios.html

Moser, C., Stauffacher, M., Blumer, Y. B., & Scholz, R. W. (2015). From risk to vulnerability: The role of perceived adaptive capacity for the acceptance of contested infrastructure. *Journal of Risk Research*, *18*(5), 622–636. https://doi.org/10.1080/13669877.2014.910687

Moser, C., Stauffacher, M., Krütli, P., & Scholz, R. W. (2012). The Crucial Role of Nomothetic and Idiographic Conceptions of Time: Interdisciplinary Collaboration in Nuclear Waste Management. *Risk Analysis*, *32*(1), 138–154. https://doi.org/10.1111/j.1539-6924.2011.01639.x

Neuvonen, A., Kaskinen, T., Leppänen, J., Lähteenoja, S., Mokka, R., & Ritola, M. (2014). Low-carbon futures and sustainable lifestyles: A backcasting scenario approach. *Futures*, *58*, 66–76. https://doi.org/10.1016/j.futures.2014.01.004

Nilsson, M., Nilsson, L. J., Hildingsson, R., Stripple, J., & Eikeland, P. O. (2011). The missing link: Bringing institutions and politics into energy future studies. *Futures*, *43*(10), 1117–1128. https://doi.org/10.1016/j.futures.2011.07.010

Pfenninger, S., & Keirstead, J. (2015). Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. *Applied Energy*, *152*, 83–93. https://doi.org/10.1016/j.apenergy.2015.04.102

Prognos AG. (2012). Die Energieperspektiven für die Schweiz bis 2050. Energienachgefrage und Elektrizitätsangebot in der Schweiz 2000-2050, 842.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., … Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, *534*, 631. Retrieved from http://dx.doi.org/10.1038/nature18307

Rousseau, D. M., Sitkin, S. B., Burt, R. S., & Camerer, C. (1998). Not so different after all: A cross-discipline view of trust. *Academy of Management Review*, *23*(3), 393–404. https://doi.org/10.5465/AMR.1998.926617

Selin, C. (2008). The Sociology of the Future: Tracing Stories of Technology and Time. *Sociology Compass*, *2*(6), 1878–1895. https://doi.org/10.1111/j.1751-9020.2008.00147.x

Skelton, M., Fischer, A. M., Liniger, M. A., & Bresch, D. N. (2019). Who is 'the user' of climate services? Unpacking the use of national climate scenarios in Switzerland beyond sectors, numeracy and the research–practice binary. *Climate Services*, (July), 100113. https://doi.org/10.1016/j.cliser.2019.100113

Söderholm, P., Hildingsson, R., Johansson, B., Khan, J., & Wilhelmsson, F. (2011). Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050. *Futures*, *43*(10), 1105–1116. https://doi.org/10.1016/j.futures.2011.07.009

Soroudi, A., & Amraee, T. (2013). Decision making under uncertainty in energy systems: State of the art. *Renewable and Sustainable Energy Reviews*, *28*, 376–384. https://doi.org/10.1016/j.rser.2013.08.039

Späth, P., & Rohracher, H. (2010). "Energy regions": The transformative power of regional discourses on socio-technical futures. *Research Policy*, *39*(4), 449–458. https://doi.org/10.1016/j.respol.2010.01.017

Stauffacher, M., Muggli, N., Scolobig, A., & Moser, C. (2015). Framing deep geothermal energy in mass media: The case of Switzerland. *Technological Forecasting and Social Change*, *98*, 60–70. https://doi.org/10.1016/j.techfore.2015.05.018

Tozer, L., & Klenk, N. (2017). Discourses of carbon neutrality and imaginaries of urban futures. *Energy Research and Social Science*, *35*(October 2017), 174–181. https://doi.org/10.1016/j.erss.2017.10.017

Udris, L. (2017). *Abstimmungsmonitor zur Vorlage vom 21. Mai 2017*.

UVEK. (2017). Faktenblatt «Abstimmung Energiegesetz - Überblick», 2–5.

Vainio, A., Varho, V., Tapio, P., Pulkka, A., & Paloniemi, R. (2019). Citizens ' images of a sustainable energy transition. *Energy*, *183*, 606–616. https://doi.org/10.1016/j.energy.2019.06.134

van Notten, P. W. ., Rotmans, J., van Asselt, M. B. ., & Rothman, D. S. (2003). An updated scenario typology. *Futures*, *35*(5), 423–443. https://doi.org/10.1016/S0016-3287(02)00090-3

Volkery, A., & Ribeiro, T. (2009). Scenario planning in public policy: Understanding use, impacts and the role of institutional context factors. *Technological Forecasting and Social Change*, *76*(9), 1198–1207. https://doi.org/10.1016/j.techfore.2009.07.009

Wright, G., van der Heijden, K., Burt, G., Bradfield, R., & Cairns, G. (2008). Scenario planning interventions in organizations: An analysis of the causes of success and failure. *Futures*, *40*(3), 218–236. https://doi.org/10.1016/j.futures.2007.08.019

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy*, *35*(5), 2683–2691. https://doi.org/10.1016/j.enpol.2006.12.001

Xexakis, G., Ralph, H., Volken, S., & Trutnevyte, E. (2019). Models on the wrong track: Model-based electricity supply scenarios in Switzerland are not aligned with the perspectives of experts and the public. *Renewable and Sustainable Energy Reviews (under Review)*.

Xexakis, G., & Trutnevyte, E. (2019). Environmental Modelling & Software Are interactive web-tools for environmental scenario visualization worth the effort ? An experimental study on the Swiss electricity supply scenarios 2035. *Environmental Modelling and Software*, *119*(May), 124–134. https://doi.org/10.1016/j.envsoft.2019.05.014

6 Paper V – Same procedure as every year? The conservative use of scenarios in the Swiss energy industry

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Abstract

While the technical sophistication and methodological differentiation of energy models has been increasing for decades, it is not yet well understood how this influences their usability for key decision-makers. Here, we analyse the use of publicly available energy scenarios by utility managers, drawing from in-depth interviews with representatives from 20 Swiss utilities. The results suggest that energy scenarios are rarely part of a structured and formalized process to assist decision-making and planning processes. Instead, the selection and interpretation of scenarios is often contingent on users' perceptions of their legitimacy, credibility and salience. Due to the complexity of contemporary model-based scenarios, users tend to rely on energy scenarios that are issued by established institutions that rely on recognized methods and presentation styles. Consequently, energy scenarios risk to primarily functioning as echo chambers reinforcing existing structures instead of being explorative tools enabling a diverse consideration of plausible futures.

6.1 Introduction

The decarbonisation of energy systems is among the most important global challenges facing societies (UNFCCC, 2015). Fundamental changes to energy infrastructure, consumption patterns and related socio-technical systems are needed (International Energy Agency, 2019). Energy transitions are likely accompanied by further momentous shifts such as market liberalisation, denuclearisation, decentralisation and digitalisation that transform the way energy is produced and consumed (Moustakas, Loizidou, Rehan, & Nizami, 2020). Energy system models have the ability to assist decision-makers by developing and evaluating plausible energy system configurations and pathways towards them (Volkery & Ribeiro, 2009). The energy scenarios that are based on these models can provide multiple projections for the diffusion and integration of sustainable energy technologies, substantiate and visualise magnitudes of change, reveal fundamental trade-offs associated with particular choices, and should ultimately reduce cognitive biases (Kosow & Gaßner, 2008).

One key target groups for energy scenarios are energy utilities, as they need to make fundamental and complex strategic (investment) decisions with long term implications, while facing multifaceted uncertainties (Bolton, Foxon, & Hall, 2016). While energy sector companies are have had a pioneering role in the development and use of scenarios, empirical studies of their actual uptake and application in decision-making processes remain rare (Hughes, 2013; Pfenninger et al., 2014). There are, however theoretical considerations on what enhances the usability of a scenario, such as the framework proposed by Cash et al. (2003). According to that framework, determinants of scenario selection and applications by decision-makers are *credibility* (whether users perceive the scientific or technical evidence of scenarios to be adequate), *salience* (whether users perceive scenarios to be relevant to their needs) and *legitimacy* (whether users perceive scenarios to be fair and unbiased in their treatment of diverse views and interests).

Assessing due to which characteristics scenarios are selected is important because they are developed by a range of actors, including utilities themselves, but also fossil fuel companies, NGOs, research institutions or governmental agencies disseminate energy scenarios (Pfenninger et al., 2014). The scenarios of these actors highlight different and sometimes contrasting technology and policy options and thus compete to shape the energy future (Delina & Janetos, 2018; Grunwald, 2011). Research in Science and Technology Studies has shown that scenarios can influence expectations of individuals or contribute to the formation of shared visions that define the direction of technological change (Borup et al., 2006; Budde & Konrad, 2019; Te Kulve et al., 2013). What kind of energy future utility representatives expect, can thus guide their investment strategy, constitute the support for or rejection of corporate decisions, and, through their influence across various political and geographical scales, influence the perceived desirability of different energy transition trajectories more generally (Carrington & Stephenson, 2018; Richter, 2013). This study evaluates the circumstances and motivations of scenario selection and use among utility managers empirically through in-depth interviews with representatives from 20 Swiss utilities.

6.2 Methods

6.2.1 Case selection and context

In the Swiss energy system, the market conditions have changed significantly over the last decade. In 2011, the Federal council decided to gradually phase-out all nuclear power stations, which currently produce about a third of the countries' electricity. The techno-economic feasibility of this phase-out has been assessed in a model-based scenario study called *Energy Perspectives,* which was the basis for the *Energy Strategy 2050* (ES2050) that was enacted through a popular referendum in 2017 (Prognos, 2012). In summary, ES2050 aims to replace nuclear capacity by renewables and a significant demand reduction. Furthermore, there is a variety of newly emerging developments that, while not directly related to ES2050, are difficult to predict and potentially disruptive to the traditional business models of utilities. This includes the sudden drop of energy prices in the European market (Bublitz, Keles, & Fichtner, 2017), the incomplete liberalisation of the Swiss electricity market (Ochoa & Van Ackere, 2009), the increasing prevalence of local energy cooperatives (Noor, Yang, Guo, van Dam, & Wang, 2018), or the forthcoming re-licencing processes for hydropower operation plants with a typical lifetime of 80 years (Tonka, 2015). The resulting demand for information about plausible energy futures make the Swiss energy industry an ideal case to study the use of scenarios.

6.2.2 Sampling strategy

Switzerland counts over 600 utilities. The 15 biggest utilities cover 50% of the household electricity demand and the 200 biggest cover over 90%. The remaining 400 energy providers are very small, often only serving a few hundred customers. Our key sampling goal was to have the diversity of Swiss utilities represented in the sample, ranging from small municipal companies supplying local communities to internationally operating and vertically integrated corporations. This is because it has previously been shown that actors with a similar background can use scenarios for different purposes and accordingly refer to different parts of scenario studies (Braunreiter & Blumer, 2018).

The association of Swiss utilities (VSE), whose members cover over 90% of Swiss electricity supply, supported us in finding relevant interview partners. They provided us with an initial list of 40 representatives of utilities with demonstrated interest or background in scenario use. These representatives were identified via an email invitation sent out by VSE describing the key goals of the research project. Recipients of this invitation were able to opt-out if they did not want to appear on the list that the authors of this paper subsequently used to contact potential interview partners. The support from VSE was vital because of their overview of scenario-related competencies within the Swiss energy industry due to their regular exchange with utilities and experiences with an annual scenario development processes they organise with interested stakeholders.

Adapted from a comparative study on the financial performance of Swiss utilities conducted by Ernst & Young (2017), we grouped the utilities into five categories (see Figure 6). The criteria used to differentiate the utilities were their role in the Swiss energy system (electricity producers, electricity suppliers, transmission system operators) as well as their size (average revenues over the past five years). To increase variance within the resulting clusters, we also considered the number of employees, the size and geographical location of the supplied area, as well as ownership structures.

Figure 6. Sampling overview.

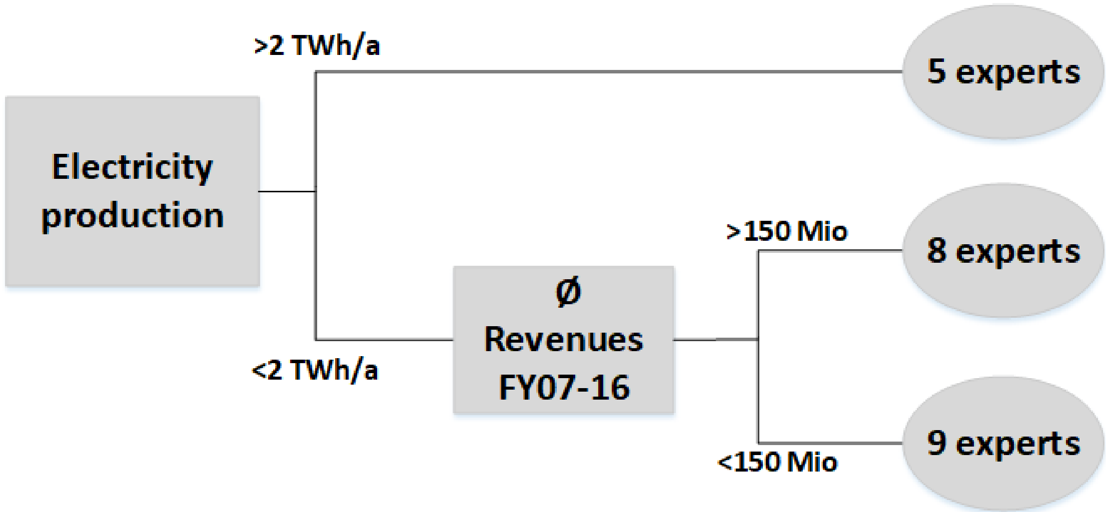

Figure 6. Anonymised overview of interview sample. Structured along the electricity production capacity and the average revenues over the past five years.

6.2.3 Sample description

Within the utilities, we intended to talk to the person(s) most suitable to talk about energy scenario use. This goal was stated in the interview invitation. With two utilities, double-interviews were held, as both representatives provided insights on scenarios use from different departments. In total, interviews with 22 industry representatives from 20 different utilities were conducted from March to May 2019. We stopped doing interviews when theoretical saturation was met (Francis et al., 2010), which meant that no new scenario use types, selection criteria and use purposes were discovered. The interviews lasted between one and two hours.

6.2.4 Interview structure and content

Because understanding the finer mechanics of scenario use requires detailed exchanges with questions that are tailored at the specific scenario user (Braunreiter & Blumer, 2018), in-depth interviews were conducted. The interview were conducted using a semi-structured interview guide consisting of four parts. At the beginning of the interview, a short description of the research project and a brief interview overview of the interview content was provided. Interview partners were assured that the data was only to be used for research purposes and that they would remain anonymous. All interviews were conducted by the lead author, with co-authors occasionally supporting.

Part 1 of the interview was about the interviewee's personal background, their current position and responsibilities within the utility as well as their experiences with scenarios. In Part 2, scenarios that were previously identified via desk research were grouped into three categories (*unknown, known, used*) by the interviewees. Scenario use encompasses all kind of use purposes, ranging from users reading parts of a scenario study to users referring to particular information for planning purposes. Then, scenario selection and use practices were discussed. This included the purpose of scenario use, what kind of scenario content is of interest, potential interactions with modellers or discussions with other users, as well as the perceived relevance and value of scenarios for the utility, the energy industry and society as a whole. Part 3 made use of six hypotheses the authors presented. Interviewees first had to state whether they generally agreed or disagreed with the statement and were subsequently asked to elaborate on their choice. The hypotheses captured different aspects of scenario methodology, for example the role of probabilities, the perceived importance of scientific scenario development practices or the contrast between forecasts and projections. Part 4 was about the interpretation of scenarios and in particular their comprehensibility. Interviewees were asked to elaborate on the perceived efficiency of different communication methods and to state their preferences how modellers could improve the comprehensibility and ultimately the relevance of scenarios for the energy industry. An English version of the interview guide can be found in the appendix.

6.2.5 Data analysis

Except for one interview where notes were taken as permission to record was not granted, all interviews were recorded. Audio files were transcribed word for word at full length (Mayring 2003). Evidence was collected in the native language of interviewees (German, Swiss German or French). Original quotations cited were translated into English. To evaluate how utilities select, interpret and use scenarios from the variety of available studies, we evaluate the relevance of the knowledge system quality criteria developed by Cash et al. (2003). They suggest that scenarios, which produce information at the interface between science and practitioners, need to balance credibility, salience, and legitimacy. Credibility refers to the perceived technical quality and scientific adequacy of scenarios, saliency to their relevance and comprehensibility and legitimacy to the perceived transparency, inclusiveness and unbiasedness of the scenario development process. (Rickards, Ison, Fünfgeld, & Wiseman, 2014) Research on climate scenarios, in which this framework has mainly been applied, claims that scenarios need to minimize conflict between these characteristics, while maintaining an adequate level of each, to be effective.(Kunseler, Tuinstra, Vasileiadou, & Petersen, 2015) To start the data analysis, the categories of the conceptual framework provided by Cash et al. (2003) were used to develop a set of main codes (legitimacy, credibility, and salience) with corresponding definitions. In a second step, a thematic coding based on the empirical material was conducted to refine the coding structure (see Table 9) and provide examples fitting the coding structure. Because of this, the code *institutional power* was added as a sub-code on legitimacy and the sub-code *presentation* to the main code credibility. We secured intercoder reliability by having different researchers coding interview transcripts independently and discussing all the coding differences with all authors. No formal intercoder reliability test was done but rather well established practice in qualitative research was followed (Gibbs, 2007). The transcripts were coded using the software package MAXQDA.

Table 9. Coding structure.

Main and sub-codes	*Definition*	*Examples*
Legitimacy		
Diversity of opinions	Whether users perceive the scenario development to be inclusive of different opinions, leading to a scenario product consisting of different values and opinions	Balance of stakeholder involvement; unbiased integration of normative values and perspectives;
Institutional bias	Regards what kind of policy goals and general interests scenario users associate with the institutions publishing scenarios	Clearly defined vision, promotion of specific business models , interests that are linked to scenario content
Institutional power	Whether users perceive scenario developers and commissioning institutions to be influential	Role and perceived influence in energy system and policymaking, recognition as longstanding scenario developer;

	organisation in energy system and related policy processes	
Credibility		
Validity	User perception on adequacy of data sources and methods used to develop scenarios	Data; assumptions; modelling framework, scientific development standards, scenario results and its broader implications
Presentation	User perception on adequacy of presentation style to convey scenario-based information	Report structure and language; visualisations; communication tools and events
Transparency	All information necessary to retrace scenario results is available to users	Documentation; open access; interaction with scenario developers
Salience		
Scope	The type of information provided by scenarios is perceived to be relevant by users	Suitability of time horizon; geographical scale; covered topics; technologies; sectoral links
Comprehensibility	Regards whether the information provided by scenarios is comprehensible and aligned with user competencies and capabilities	comprehensibility, complexity, interpretation of probabilities or lack thereof
Purpose	Analysis for what purpose interviewees consider energy scenarios and how they interact with them	Informing themselves through reading, integration off numerical data into own modelling or planning tools, formation of qualitative storylines

6.3 Results

6.3.1 Salience of energy scenarios

Salience is about whether users perceive scenarios to be relevant to their needs. On average, interviewees are aware of nine different energy scenarios and use at least one of them. This exemplifies the general relevance of energy scenarios for the energy sector and that they generally have a good overview of the variety of publicly available scenario studies. However, the interviews indicate that the usability of energy scenarios is limited by various factors, which may be independent from what makes a scenario's legitimate or credible from a user perspective.

First, utility representatives are often not aware of particular strengths, weaknesses and potential use purposes of different energy scenarios and their respective methodologies. Consequently, most interviewees describe their interaction with energy scenarios as informing themselves about recent and future developments in the energy sector, stating that this knowledge is valuable for discussions with colleagues or customers. While a scenarios' influence on individual expectations should not be undervalued, the fact that most interviewees do not have a more specific scenario use purpose is indicative of the lack of integration of scenarios in decision-making and planning process at utilities. Consequently, only few interviewees use scenarios to test the robustness of their corporate strategy by explicitly referring to a set of scenarios projecting a broad range of futures. In that sense, Interviewee #14 is an exception who described their rationality for using energy scenarios as follows: "For us, extreme scenarios are particularly relevant. We will somehow be able to master everything else. But with extreme energy futures, we will have trouble."

Second, while the complexity of contemporary model-based energy scenarios is conducive for their credibility, it also impedes their usability. About half of the interviewees think that one needs to have been part of the scenario development process to understand how the results come about, while most of the others think that at least a profound understanding how model-based scenarios operate is necessary. Interviewee #11: "No [participation is not necessary], but I would say in order to be able to understand energy scenarios, you need to have developed them yourself at least once, from start to finish, then you know where the critical levers and things that make a difference are." Only few users have the resources and competencies to engage with scenario developers to improve their comprehension of energy scenarios.

Third, many interviewees state that they would like to see scenarios that are more extensive in both their geographical and technological scope. They argue that understanding key energy system developments requires consideration of international linkages between policies and technologies. Examples include the influence of oil prices or the development of heating networks through sector coupling. Generally, users want a single scenario study to be as comprehensive as possible, providing information on all kind of developments and technologies. Furthermore, for many utilities national or even local developments are important for contextualisation with their corporate assets and strategies. Balancing requirements for breadth and depth is challenging for scenario developers, and the resulting trade-offs in modelling are hard to convey to users. Additionally, interviewees state that energy companies often have to react quickly to new developments, which scenarios often take too long to incorporate.

Fourth, the *what-if* logic applied by most energy scenarios characterising the methodological paradigm shift from predictive to explorative approaches is difficult to grasp for many users. Many users are very tentative in interpreting energy scenarios and consequently rarely use them to base decisions on their insights. This is exemplified by the question whether scenarios should provide probability assessments, which is an important issue among utility representatives. Nine interviewees consider it necessary for scenarios to provide some kind of indication on their likelihood. Interviewee #3: "I always read these [scenarios] when I need help with decisions, and help with decisions always means that things need to be quantified." Interviewee #11 provides an example that even users who do not want scenarios to specify probabilities often attach them implicitly, indicating the strong prevalence of probability-based decision-making processes: "It is my job as the reader and interpreter of the study to attribute a certain probability to it. I can only do this if I have as much transparency as possible about what happened. And then [using scenarios] generates added value for me."

6.3.2 Legitimacy of energy scenarios

According to Cash (2003), legitimacy is a key quality criterion for scenarios referring to the user perception that the scenario represents an unbiased set of values and beliefs and is impartial in its treatment of diverse views and interests. However, most interviewees consider energy scenarios as biased, as they are developed by institutions with particular interests and stakes in the energy system. Yet at the same time, this is generally not considered problematic, as the source of the scenario can be factored in in its interpretation. "*Of course I know that Shell scenarios are biased, but at least I know what I get.*" (Interviewee #4). Hence, the missions of scenario developing institutions (which can result in a normative bias), does not seem to reduce the perceived legitimacy of scenario studies. However, a key determinant of this legitimacy seem to be the reputation and power to shape policy processes of the actor commissioning or developing an energy scenario. For example, the scenarios issued by the Swiss Federal Office of Energy (SFOE) are considered the most legitimate by all interviewed decision makers. This is illustrated by the fact that all 22 interviewees use the SFOE scenarios, even despite the fact that many of them also criticize them for missing transparency, limited data availability or even question the credibility of its key findings. In contrast, scenarios developed and issued by research institutions are among the least frequently used scenarios by the interviewed energy sector representatives, even though research institutions are seen as the most independent scenario developers.

While some interviewees differentiate between commissioning institutions and modelling agencies, and occasionally even the participation of individual experts in scenario development processes is recognised, most interviewees associate the legitimacy of a scenario study with a single institution. From a user perspective, the diversity of opinions and values within scenario studies is thus rather low. As a response to this, some users try to integrate varying perspectives by comparing scenarios from different institutions. Interviewee #7: "*Of course, none of them are completely independent, all of them are affected by the interest of the organisation [publishing the scenarios]. […] But [when multiple scenario studies are used] at least the breadth of existing opinions can be represented.* "

When users make the choice to consider certain scenarios and disregard others, legitimacy is a pivotal factor. For nine utility representatives, the perceived legitimacy of the actor they associate with an energy scenario it is the most important factor for scenario selection. Generally, institutions with a substantial history of developing energy scenarios, such as the *International Energy Agency*, *Shell* or *BP* are recognised as legitimate scenario producers. Scenarios from niche actors are not only considered less, their content also tends to be scrutinized more carefully.

6.3.3 Credibility of energy scenarios

Credibility refers to whether users perceive the scientific or technical evidence of scenarios to be adequate. Credibility can thus be understood as the believability of energy scenarios and the methods used to develop them. The interviews showed that utility representatives' understanding of what constitutes a credible scenario differs considerably. One group of scenario users is focusing on the availability of data, assumptions and transparent model frameworks, because they consider it critical to be able to reproduce scenario results. This ability to reconstruct scenario results is predominantly relevant for users that have both profound modelling competencies and that work for, often larger, utilities that use numerical input from externally developed scenarios for internal models (e.g. market models). Many of these users stated that for them, the kind of energy future a scenario projects is less important than being able to identify the ingredients and rationalities used in their development.

In contrast, a second group of users tends to focusing on the believability of a scenario outcome its potential implication on the energy system. This groups includes mostly individuals working for utilities without own modelling resources. These use cases are often neither standardized nor institutionalized. Consequently, the believability of energy scenarios is mainly determined by subjective user perceptions and preferences. Many of these interviewees acknowledge that assessing the credibility of scenarios with their data sources and assumptions is challenging. Consequently, some users refer to the legitimacy of the scenario developer as a proxy for the credibility of the scenario content. For example, a study developed by a think tank not specifically known for their work in energy topics, was associated with low credibility by most interviewees. Some users also rely on credibility evaluations of other users, for example colleagues working for different utilities with demonstrated competencies in applying scenarios. An example for this is the critique of a scenario study commissioned by the SFOE, which essentially concluded that the availability of electricity imports from the EU is secured for the coming years. This finding was heavily criticized by almost all interviewees, with several interviewees stating that social exchange within the energy industry consolidated this assessment.

A key aspect for how users evaluate the credibility of energy scenarios is their assumed complexity. Users expect highly structured reports with lengthy numerical annexes describing a quantitative modelling basis: “Fancy looking graphs and so-called innovative scenario result communication approaches make me suspicious. I trust in old-school reports” stated Interviewee #9. Similarly, qualitative scenario development methodologies are often deemed unable to provide robust results. This is the case even though many users ultimately work with qualitative storylines, indicating a detachment between the perceived credibility of a scenario study and its suitability with the purpose of scenario use.

6.4 Discussion

The technical sophistication and thematic differentiation of energy models has been increasing in accordance with advances in computational power and continuous efforts by energy modelling communities (Garb et al., 2008). There exist different modelling approaches (e.g. backcasting, simulation, or optimization), foresight purposes (e.g. explorative, normative, and predictive) and scopes (time horizon, featured topics and geographical scales), offering a variety of distinctive characteristics and intended use proposes to potential scenario users. While these scenario typologies highlight the value and uniqueness of energy scenarios from a developer perspective, they are not evident from a user perspective.

For users, the complexity of contemporary energy scenarios is both an indicator of credibility as well as a limit to their usability. Our results suggest that one main reason for this might be that scenario users do not evaluate the legitimacy, credibility and salience of a scenario simultaneously. Scenario selection is often guided by their perceived legitimacy. This legitimacy tends to be, however, not related to scenario itself (system boundaries, sophistication of the model, transparency, etc.) but to the reputation of the institution that publishes and/or commissions it. Scenarios from institutions with a long history of energy scenario development are more likely to be used. In terms of credibility, many scenario users have assumptions about the superiority of quantitative scenario methodology and corresponding reporting formats, even though very few users actually use detailed numerical output. In line with what Parson (2008) found, most of the scenario use cases we observed are not institutionalized or linked to a specific purpose. Users rather report to inform themselves about the energy future in general, which is why salience is the scenario selection criterion most users are least focusing on. Similarly, corporate scenario integration processes or standards were largely absent, which risks amplifying the interpretative biases of scenario users and limits the ability of scenarios to stimulate holistic and open-minded discussions about desirable energy futures (Lilliestam & Hanger, 2016; Longhurst & Chilvers, 2019).

This hierarchical scenario selection mechanism confines the usability and, in particular, the explorative function of using scenarios to prepare for a diverse range of potential futures. Radically different futures are often neglected while scenarios from established institutions that often have strong interests in the current energy system and thus promote incremental changes (Carrington & Stephenson, 2018)) are perceived to be more plausible by many users. Only few interviewees are deliberately considering scenarios that are at odds with their corporate strategy and thus question the robustness of their business model. Against this background, scenarios mainly have a conservative instead of the commonly assumed explorative function. This not only contrasts with the key benefits associated to using scenarios, such as reducing cognitive biases and stimulating out-of-the-box thinking (Meissner & Wulf, 2013; Oteros-Rozas et al., 2015; Pfenninger et al., 2014; Van Notten et al., 2003), it also puts a question mark on the role of utilities to be a leading actor in the monumental transformation expected to take place in the energy system in the coming decades (Geels, 2014; Grubler et al., 2018).

Many of the benefits associated with scenario use stem from idealized intentions of scenario developers, which often involve unexamined assumptions about their target audience. Research is often focusing on cases of highly participatory scenario processes with iterative and time-consuming exchange between scenario developers and users, which is why these case studies might biased towards successful examples of scenario use (Mathy, Fink, & Bibas, 2015; Oteros-Rozas et al., 2015; Volkery & Ribeiro, 2009). When scenarios are published, they travel into the field of practitioners and do not bring with them a self-contained technical or scientific understanding of the scenario content. Scenarios are not ready-made “solutions”, but incorporated into pre-existing use constellations and aligned with user perspectives. For example, scenario users prefer studies from institutions with previous scenario iterations because it allows them to use the reception and feedback by the energy industry as an indication for the credibility of new studies. This shows that scenario use and. in particular, evaluations of their credibility are socially embedded activities. Strong opinions by thought leaders on the topic of using energy scenarios can create feedback loops that further exacerbate the consideration of a narrow set of energy scenarios. Research and scenario developers need to acknowledge the typical detachment between scenario developers and the recipients of scenario-based information, as suggested by Garb et al. (2008).

6.5 Limitations and further research

In this paper, we analysed the use of scenarios among Swiss utilities. Despite the large number and inherent diversity of utilities, the Swiss energy industry is a relatively small community. This might be particularly relevant for the observed importance of social exchange between scenario users. In addition, we only described reported scenario use as stated by the interviewees and have not experienced their actual use. Nevertheless, we are confident that the main results of this study, i.e. the general relevance of scenarios for utilities and the importance of social contexts for their use are valid and that future research in this regard can reveal important insights. Action research would allow following the application of scenarios more closely, which could provide particularly relevant insights for the presentation and communication of scenario products. Combining empirical scenario use analyses with actor network analyses would enable a more profound understanding of the social context of scenario use and the factors that ultimately determine their impact on energy transitions. To date, very little is known about how locally embedded and context-specific scenario use cases, be it energy industry or other fields, and the globally connected modelling and scenario development communities relate to each other. While idealized participative approaches are often assumed, they are hardly the norm, which is why we call for more research that analyses the benefits and limitations of scenario use in existing empirical settings.

6.6 Conclusion

We provide empirical evidence that while energy scenarios are an important source of prospective information in the Swiss energy industry and perceived to be relevant by representatives from a broad spectrum of utilities, their usability is limited. *Using* energy scenarios refers to all practices describing the interaction of utility representatives with energy scenarios, which are often neither institutionalized, nor standardized. User needs play only a minor role in the selection of energy scenarios, which is reflected in the few concrete use purposes identified among interviewees. Instead, the focus on established actors producing energy scenarios is likely strengthening the status quo of the energy system, because path-dependencies are hardly ever challenged. The familiarity with and expectations towards particular scenario methodologies and presentation styles further increases the risk that energy scenarios primarily function as echo-chambers reinforcing existing structures rather than being explorative tools enabling a broad and diverse consideration of possible futures.

Ultimately, the use of energy scenarios within the Swiss energy industry is not primarily indicative of the good fit between what energy scenarios provide and what scenario users need, but by the increasing need for plausible information about future developments in challenging and uncertain times. Energy scenarios could arguably become even more relevant in the future, which is why the research focus needs to shifts towards their usability for different target audiences. Since scenario use cases with close collaboration between scenario developers and users are more the exception rather than the norm, other forms of guidance and support that simultaneously match the expectations of scenario users towards scenario products are needed.

References

Borup, M., Brown, N., Konrad, K., & Van Lente, H. (2006). The sociology of expectations in science and technology. *Technology analysis & strategic management, 18*(3-4), 285-298.

Braunreiter, L., & Blumer, Y. B. (2018). Of sailors and divers: how researchers use energy scenarios. *Energy Research & Social Science, 40*, 118-126.

Bublitz, A., Keles, D., & Fichtner, W. (2017). An analysis of the decline of electricity spot prices in Europe: Who is to blame? *Energy Policy, 107*, 323-336.

Budde, B., & Konrad, K. (2019). Tentative governing of fuel cell innovation in a dynamic network of expectations. *Research policy, 48*(5), 1098-1112.

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., . . . Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the national academy of sciences, 100*(14), 8086-8091.

Delina, L., & Janetos, A. (2018). Cosmopolitan, dynamic, and contested energy futures: navigating the pluralities and polarities in the energy systems of tomorrow. *Energy Research & Social Science, 35*, 1-10.

Francis, J. J., Johnston, M., Robertson, C., Glidewell, L., Entwistle, V., Eccles, M. P., & Grimshaw, J. M. (2010). What is an adequate sample size? Operationalising data saturation for theory-based interview studies. *Psychology and Health, 25*(10), 1229-1245.

Garb, Y., Pulver, S., & VanDeveer, S. D. (2008). Scenarios in society, society in scenarios: toward a social scientific analysis of storyline-driven environmental modeling. *Environmental Research Letters, 3*(4), 045015.

Geels, F. W. (2014). Regime resistance against low-carbon transitions: Introducing politics and power into the multi-level perspective. *Theory, Culture & Society, 31*(5), 21-40.

Gibbs, G. R. (2007). Thematic coding and categorizing. *Analyzing qualitative data, 703*, 38-56.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., . . . De Stercke, S. (2018). A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. *Nature Energy, 3*(6), 515.

Grunwald, A. (2011). Energy futures: diversity and the need for assessment. *Futures, 43*(8), 820-830. doi:https://doi.org/10.1016/j.futures.2011.05.024

Hughes, N. (2013). Towards improving the relevance of scenarios for public policy questions: A proposed methodological framework for policy relevant low carbon scenarios. *Technological Forecasting and Social Change, 80*(4), 687-698. doi:http://dx.doi.org/10.1016/j.techfore.2012.07.009

International Energy Agency. (2019). *World Energy Outlook*. Retrieved from Paris, France.:

Kunseler, E.-M., Tuinstra, W., Vasileiadou, E., & Petersen, A. C. (2015). The reflective futures practitioner: Balancing salience, credibility and legitimacy in generating foresight knowledge with stakeholders. *Futures, 66*, 1-12.

Lilliestam, J., & Hanger, S. (2016). Shades of green: Centralisation, decentralisation and controversy among European renewable electricity visions. *Energy Research & Social Science, 17*, 20-29.

Longhurst, N., & Chilvers, J. (2019). Mapping diverse visions of energy transitions: co-producing sociotechnical imaginaries. *Sustainability Science*, 1-18.

Mathy, S., Fink, M., & Bibas, R. (2015). Rethinking the role of scenarios: Participatory scripting of low-carbon scenarios for France. *Energy Policy, 77*, 176-190. doi:https://doi.org/10.1016/j.enpol.2014.11.002

Meissner, P., & Wulf, T. (2013). Cognitive benefits of scenario planning: Its impact on biases and decision quality. *Technological Forecasting and Social Change, 80*(4), 801-814.

Noor, S., Yang, W., Guo, M., van Dam, K. H., & Wang, X. (2018). Energy Demand Side Management within micro-grid networks enhanced by blockchain. *Applied energy, 228*, 1385-1398.

Ochoa, P., & Van Ackere, A. (2009). Policy changes and the dynamics of capacity expansion in the Swiss electricity market. *Energy Policy, 37*(5), 1983-1998.

Oteros-Rozas, E., Martín-López, B., Daw, T., Bohensky, E. L., Butler, J., Hill, R., . . . Ruiz-Mallén, I. (2015). Participatory scenario planning in place-based social-ecological research: insights and experiences from 23 case studies. *Ecology and Society, 20*(4).

Parson, E. A. (2008). Useful global-change scenarios: current issues and challenges. *Environmental Research Letters, 3*(4), 045016.

Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews, 33*, 74-86. doi:http://dx.doi.org/10.1016/j.rser.2014.02.003

Prognos. (2012). *Die Energieperspektiven für die Schweiz bis 2050 (Energy Persepctives for Switzerland until 2050)*. Retrieved from

Pulver, S., & VanDeveer, S. D. (2009). "Thinking About Tomorrows": Scenarios, Global Environmental Politics, and Social Science Scholarship. *Global Environmental Politics, 9*(2), 1-13. doi:10.1162/glep.2009.9.2.1

Richter, M. (2013). Business model innovation for sustainable energy: German utilities and renewable energy. *Energy Policy, 62*, 1226-1237.

Rickards, L., Ison, R., Fünfgeld, H., & Wiseman, J. (2014). Opening and closing the future: climate change, adaptation, and scenario planning. *Environment and Planning C: Government and Policy, 32*(4), 587-602.

Skelton, M., Fischer, A. M., Liniger, M. A., & Bresch, D. N. (2019). Who is 'the user'of climate services? Unpacking the use of national climate scenarios in Switzerland beyond sectors, numeracy and the research–practice binary. *Climate Services*, 100113.

Strachan, N., Fais, B., & Daly, H. (2016). Reinventing the energy modelling–policy interface. *Nature Energy, 1*, 16012.

Te Kulve, H., Konrad, K., Palavicino, C. A., & Walhout, B. (2013). Context matters: promises and concerns regarding nanotechnologies for water and food applications. *Nanoethics, 7*(1), 17-27.

Tonka, L. (2015). Hydropower license renewal and environmental protection policies: a comparison between Switzerland and the USA. *Regional environmental change, 15*(3), 539-548.

UNFCCC. (2015). Adoption of the Paris Agreement.

Van Notten, P. W., Rotmans, J., Van Asselt, M. B., & Rothman, D. S. (2003). An updated scenario typology. *Futures, 35*(5), 423-443.

Volkery, A., & Ribeiro, T. (2009). Scenario planning in public policy: Understanding use, impacts and the role of institutional context factors. *Technological Forecasting and Social Change, 76*(9), 1198-1207. doi:http://dx.doi.org/10.1016/j.techfore.2009.07.009

7 Discussion

In sections 7.1.1 to 7.1.3, the key findings related to the three research questions are presented. Subsequently, sections 7.2.1 to 7.2.3 discuss the broader implications of these findings. Then, the methodological procedure of this dissertation is critically reflected in section 7.3 and future research options are outlined in section 7.4. Finally, concluding remarks are made in section 7.5.

7.1 Summary of key findings

7.1.1 Research question I: For what purpose do actors that are not involved in the scenario development use energy scenarios?

As exemplified by the papers analysing scenario use among fossil fuel companies, researchers and utilities, these three actors groups use energy scenarios as sources of prospective information. Thereby, this dissertation shows that energy scenarios are relevant for external actors who were not part of the scenario development process. This finding may seem trivial, but the use of scenarios is typically assumed to be confined to a relatively narrow set of internal users (Fortes, Alvarenga, Seixas, & Rodrigues, 2015; O'Brien & Meadows, 2013).

Corresponding with the focus on internal users in the academic literature, the purpose of scenario use is predominantly described to provide support for decision-making processes under deep uncertainty. Scenario use is thus often conceptualised as a direct knowledge transfer from scenario processes or products to scenario users (Garb et al., 2008; Koppelaar, Keirstead, Shah, & Woods, 2016; Wiek, Binder, & Scholz, 2006). This dissertation provided empirical evidence that while these textbook examples of scenario use do exist, energy scenarios use among external users is more versatile. In line with the perspective provided by the *Sociology of Expectations*, this dissertation consciously applied a very broad understanding of scenario use to be able to evaluate their influence on the energy transition more holistically.

In all five research contributions, interactions with energy scenarios could only be linked to concrete actions or decisions in a few cases, and most of them do not resemble the assumed decision-support function. Among the concrete scenario use purposes, a general differentiation between those who refer to scenario results as plausible visions of the energy future and those who are interested in particular assumptions or data constituting these results can be made. Fossil fuel companies for example deliberately endorsed energy scenarios with high shares of CCS as desirable energy futures, thereby representing their interests in policy hearings. Among researchers and utilities, both user types can be identified. Representatives of both actor groups use energy scenarios as data repositories but both also refer to the vision of the energy future provided by the scenario study. For researchers this is often related to highlighting the relevance of research topics while utilities use energy scenarios to evaluate the robustness of their corporate strategy for future developments in the energy sector. Interestingly, these two user types tend to be mutually exclusive, meaning that users are either focusing on scenario results or information constituting the results. In addition, dissimilar modelling competencies and levels of scrutiny applied to scenario studies tend to be associated with these scenario use types. Some users are unconfident about applying insights from external scenarios. The reason for this is usually their methodological complexity (see for example utility representatives in paper V).

In most cases with an immediate use of scenarios for a concrete purpose, a particular scenario instead of sets of scenarios is used. Thereby, an isolated scenarios' predictive intent is often being exaggerated, because the detachment from the scenario development process tends to shift the attention towards scenario products. Hence, from a methodological perspective, most of the observed scenario use purposes are not in line with the hypothetical nature and context-dependency of scenario results, two aspects which are often stressed to be essential for an accurate interpretation of scenario content (Börjeson et al., 2006; Van Notten et al., 2003). From the perspective of scenario developers, this means that external users are rarely using model-based scenarios as intended. A key aspect emerging form the research contributions is that the purpose of scenario use largely corresponds with their level of application, which is discussed in section 7.2.1.

7.1.2 Research question 2: How do external users select energy scenarios from the variety of existing studies?

Energy system actors can choose from a variety of publicly available energy scenarios that differ in scope (e.g. international, national or local with varying time horizons), modelling paradigms (e.g. simulation, optimisation or backcasting), purpose (e.g. explorative, normative or predictive) and thematic focus (e.g. whole energy system, electricity, energy storage, grid development). However, for most users, these specifications of energy models are not a selection criterion. In fact, users are rarely capable of evaluating the quality of energy models and whether a particular scenario is suitable for what it is being used. For external energy scenario users, the variety of unique modelling approaches often blur into an opaque mixture of highly complex models. Many actors are thus not aware of the variety of existing modelling approaches or do not recognise this diversity to be valuable. Knutti (2019), referring climate scenarios, emphasized that: "The best simulation is useless if its users don't understand it or don't know what to use it for."

Nevertheless, the popularity of energy scenarios is differing widely, which shows that users are differentiating between individual scenarios. Paper 2 and 5 in particular show that while some scenario studies are used by nearly all interviewees, other scenario studies are hardly ever used. These differences are mainly caused and reinforced by positive feedback loops. Paper 5 for example showed that salience is a key scenario selection criterion, which is mainly determined by how relevant users perceive the scenario to be for the relevant stakeholders, be it policymakers or competitors. Consequently, users are sometimes not selecting energy scenarios for particular characteristics, but feel obliged to refer to energy scenarios that other users are also using. Why particular scenarios become relevant while others are marginalized can thus only be understood if scenario use is considered to be embedded in social practices and actor networks, which is discussed in section 7.2.2. This demonstrates that also the categories of salience, credibility and legitimacy, which have thus for mostly been applied to explain evaluate the usefulness of climate scenarios, cannot be considered independent of the context in which the scenarios are being used (Cash et al., 2003; Chaudhury, Vervoort, Kristjanson, Ericksen, & Ainslie, 2013; Kunseler et al., 2015).

7.1.3 Research question 3: Are energy system expectations affecting opinion-formation processes and how do these expectations compare to energy scenario projections?

While the public cannot be expected to use scenarios directly, this dissertation provided first steps towards assessing and understanding the potential indirect effects energy scenarios can have on various actors, for example when they frame discourses and influence expectations more generally. Paper III confirmed that the publics' energy system expectations affect the acceptability of an energy transition as a whole. Expectations are thus important beyond the expert communities in which they have typically been assessed so far (see for example Budde & Konrad, 2019; Kriechbaum, Prol, & Posch, 2018). In paper IV, four different energy system expectation clusters were identified that are to varying degrees compatible with the projections of the *Energy Perspectives* scenario study. Interestingly, these energy system expectation clusters differ from the scenario projections in varying aspects. There are hardly any promises or concerns that were compatible or in contrast with all four energy system expectations clusters. In addition, the explorative research methodology also allowed making tentative assumptions about the extent to which the publics' energy system expectations differ from scenario projections. Overall, this could indicate that non-experts conceptualizations of the energy future are more nuanced and more diverse than simple and absolute “good” or “bad” associations. Nonetheless, evaluating whether and how energy scenarios indirectly influence the public is challenging because these effects are hard to quantify and causal relationships could not be detected in this dissertation. Nonetheless, some of the observed scenario use purposes inherently intend to inform actors who are not immediate users of scenarios (see e.g. Paper I). Section 7.2.3 discusses why indirect effects of energy scenarios on actors who are themselves not actively using them will become more likely and arguably also more relevant in the future.

7.2 Key implications

7.2.1 The purpose of scenario use varies according to their level of application

A key theme emerging from the papers and the existing literature on the use of energy scenarios is that the purpose of scenario use, and thereby their influence, is inherently dependent on their level of application. At the micro level, which is the most commonly studied level of scenario use, scenarios serve as participation tools enabling social exchange and open-ended discussions among individuals about possible futures that can shape and shift expectations (K. Johnson, Dana, Jordan, Draeger, & Kapuscinski, 2012). Here, scenario use has a distinct explorative purpose.

At the meso-level, referring to the institutional or organisational use of scenarios that the case studies in this dissertation examined, vested interests, pre-existing strategies and expectations that align disproportionately with certain energy futures heavily affect the selection and interpretation of scenarios. At this level, scenario use has predominantly normative purposes. This is best exemplified by researchers interviewed in contribution II. Several of them mentioned that they refrain from using the *Greenpeace* scenario study out of fear that it would be regarded to be incompatible with the scientific doctrine of using neutral information sources. Another example can be found in paper I, where representatives of fossil fuel companies promote scenarios with high shares of CCS that fit the corporate strategy but stand in stark contrast to their personal expectations. A final example is provided by the utilities in paper V, who tend to opt for scenarios confirming that the corporate strategy is on the right track.

Consequently, at the macro level, referring to the energy futures discussed in the societal energy transition discourse, only a few dominant energy futures remain. These become leading reference points with a predictive scenario use purpose. These are not necessarily representing the diversity of energy system actors and their ideas. Most societal actors are, if at all, only indirectly represented, for example through their function as energy consumers from the perspective of incumbent utilities, but not as citizens with various interests. In this way, existing social orders are reinforced (Longhurst & Chilvers, 2019).

Knutti (2018) stated that scenarios should trigger a societal debate about what is possible and what effects particular choices could have. In the democratic ideal and the demands formulated by research on climate and energy justice, such debates should involve a broad spectrum of societal actors (Walker, 2012). However, the suitability of energy scenarios for triggering societal debates about the energy future needs to be re-evaluated in light of the *arena of expectations* in which the associated energy futures are filtered. Currently, the most powerful actors of the existing sociotechnical regime largely determine which visions of the future energy system are discussed at the societal level. However, the existing configuration of the energy system is unsustainable. This is why individuals will need to adapt or completely abandon certain behaviours, and business will need to adapt or completely abandon certain business models in order to reach long-term climate targets.

Hence, the articulation of alternative energy futures should represent the interests of pluralistic societies, and not primarily resemble the perspective of incumbent actors. To overcome power asymmetries and exclusions in the development of (energy) futures, some scholars call for a politicization of futures (Knappe, Holfelder, Beer, & Nanz, 2018). One aspect of this is that foresight practices in general and scenarios in particular need to be understood beyond analytical policy contributions. In that sense, the qualities of a model-based scenario to validate the techno-economic feasibility of a particular energy system configuration needs to be differentiated from its capability to generate holistic visons of the energy future that includes a range of implications. Currently, the combination of these two aspects constitutes a main part of the attractiveness of model-based scenarios, specifically for the user type of *sailors*, who refer to the vision and its plausibility provided by scenario projections. Ultimately, public governance and planning structures need to be adapted to allow for a more versatile consideration of foresight products and ways in which the possible energy futures are discussed at a political or societal level (J. Vervoort & Gupta, 2018). In the energy industry, the restrictive focus on model-based scenarios is arguably even more challenging to overcome, because many utility representatives equate complexity with validity when it comes to the articulation of energy futures. However, the social embeddedness of scenario use and their dissemination, which are discussed in the next chapter, could also provide the opportunity for rapid adoptions of novel types and formats of energy futures.

7.2.2 The dissemination of scenario-based visions is contested

In transition studies, what kind of visions guide the actors involved in the transition is considered to be an important topic, as it can explain many long-term developments (Borup et al., 2006; Van Lente, 2012). This dissertation shows that two contrasting mechanisms can explain the uptake and dissemination of scenario-based visions in the energy sector.

The first observed dissemination mechanism is related to the perceived desirability and feasibility of an energy scenario to a wide range of actors and interests. This is exemplified by paper I, as the prominence of scenarios with high levels of CCS can only be explained by the combined appeal of the technology to fossil fuel companies, policymakers and optimisation modellers. CCS scenarios aligned these actors in a way that enabled a powerful vison of CCS as a panacea for the energy future that outweighed critical voices interpreting CCS as a prolonged carbon lock-in (Stephens, Hansson, Liu, De Coninck, & Vajjhala, 2011). The vision ultimately collapsed due to the increasing discrepancy with the real-world state of CCS. However, as described in the literature on hype and disappointment cycles, visions can re-emerge in a modified form (Dedehayir & Steinert, 2016). Therefore, it comes as no surprise that more recently, CCS has been proposed as a system to reduce emissions in industrial sectors (Bui et al., 2018). A further example for the normative selection of visions and scenarios is provided by paper V, which shows that only few utilities use scenarios to develop robust strategies that are valid for a broad range of possible futures, which is often stated to be their key purpose (Chakraborty, Kaza, Knaap, & Deal, 2011). Instead, utilities tend to refer to scenarios projecting energy futures to which their strategy is already well aligned.

The second observed dissemination mechanism is related to the authoritative power of the institutions supporting, and in many cases publishing, the energy scenario. Paper II and V showed that a small number of scenarios dominate the discourse about alternative energy futures in Switzerland. The *Energy Perspectives* scenario study, for example, is perceived to be highly relevant for subsequent policy designs, which is why nearly all researchers and utilities refer to it in one way or another. Similarly, products from powerful institutions with a lot of agency in the energy system and resources to design and promote scenarios, such as fossil fuel companies or the IEA, are more likely to be used than scenarios from NGOs or research institutions. The dissemination of scenarios can be interpreted as energy system actors competing with each other by supporting or rejecting particular energy futures in order to gain attention in a selective environment (Bakker et al., 2011). However, these effects are by no means restricted to the uptake and diffusion of scenarios. Analysing the prevalence of energy system expectations among non-experts, paper IV showed that even the adversaries of an energy transition expect it to happen. This suggests that expectations of an imminent energy transition have entered the social repertoire (Konrad, 2006). These expectations are so prominent, that also people with conflicting expectations have to acknowledge them.

What is different in these two types in which visions of the energy future can diffuse, is the circumstances under which new adherents are joining the vision. The first type of uptake is self-motivated, whereas the second type can be considered involuntary. This finding directly relates to the theme of *contested futures* (Brown & Rappert, 2017; Delina, 2018; Grunwald, 2011). A dominant vision can constrain the available set of options that actors are able to consider, irrespective of whether this vision is derived from a scenario study or constituted by collective expectations. The key actors of the existing sociotechnical regime filter and define the set of alternative energy futures. Futures that are undesirable from their perspective are continuously being erased (Delina & Janetos, 2018).

7.2.3 The relevance of scenarios for external users is increasing

During the last couple of years, the interaction of non-experts with energy scenarios became a vibrant field of study, as exemplified by Demski et al. (2017), Volken et al. (2018) as well as Xexakis and Trutnevyte (2019). These studies analyze the influence of energy scenarios in experimental settings. While this is not representative for how the public and other actors receive energy scenarios in reality, such studies are valuable as they can indicate how strong the framing effects deriving from energy scenarios are. In addition, research on how institutions can utilize unconventional foresight activities, such as computer games, to encourage participation from societal segments that are typically difficult to reach, is emerging (J. M. Vervoort, 2019). Similarly, research on arts-based scenario processes is starting to study novel forms of engagement via scenarios (Pereira, Sitas, Ravera, Jimenez-Aceituno, & Merrie, 2019). In short, research from different disciplinary backgrounds is beginning to study how foresight activities, often with a focus on scenarios, can contribute to the development of shared visions of plausible and desirable futures. Such visions are important for many technological and societal transformations, but arguably most prominent in the related fields of energy and climate.

Yet, this dissertation indicated that scenario use is often embedded in competitive social contexts that are influencing the selection of scenarios and the purpose of their use. As Sovacool and Brown (2015) noted, "Conflicts in the domain of energy and climate are not primarily due to lack of scientific facts or objective truth. Instead, they are more due to a clash of priorities, interests, and normative assumptions which create a number of subjective truths." Hence, from this perspective, energy scenarios can also advance the segmentation and polarisation that is already associated with the topic. There is for example an increasing trend among climate activists such as *Extinction Rebellion,* to refer to extreme climate scenarios to create a sense of urgency, using the precautionary principle as legitimation (Bush, 2020).

In a similar vein, climate activists across the globe are calling for actions that are in accordance with scientific evidence, demanding that until 2050, most industrialized countries need to reach net zero emissions (IPCC, 2018). In addition, the idea that the needs of the present need to be satisfied without compromising the ability of future generations to meet their own needs is becoming more and more established as a key principle of sustainability both in research and within society (Jenkins, Sovacool, & McCauley, 2018). All these examples illustrate that scenarios can be assumed to play an increasingly important role for prospective opinion-formation and decision-making processes of the public. However, in what way the interaction of the public with (energy) scenarios will be established is not yet clear. Whether scenarios will lead to enlightened public debates about the desirability of possible futures in the sense of Grunwald (2011), to a more direct integration of scientific findings in political and governance processes, or to misunderstandings related to their avoidance of probabilities remains to be seen (Alvial-Palavicino & Opazo-Bunster, 2018).

In any case, once the premise that anthropogenic climate change is a reality and that both mitigation and adaptation will be necessary is widely accepted, debates about potential measures and their implications become increasingly important. Against this background, the credo of politicians that measures need to be socially and economically acceptable could make scenarios that promise a technological fix more attractive, as it was previously described for the case of CCS. Geoengineering scenarios, for example, are often presented as so-called fall-back positions that could be used as a last resort to prevent the worst effects of climate change (Irvine et al., 2019; MacMartin, Ricke, & Keith, 2018). However, many scholars have argued that the sheer existence of geoengineering scenarios deviates the attention away from actions that would be required to find solutions that are sustainable from an economic, social and environmental perspective. This is because geoengineering scenarios often involve highly speculative interventions in natural cycles with unknown consequences for natural systems and unresolved governance issues (Talberg, Thomas, Christoff, & Karoly, 2018).

The increasing pressure to act on climate change will give further impetus to imagine sustainable energy futures. Energy scenarios are an approach seeking to make these imaginations more disciplined, transparent, and, where available, anchored in scientific knowledge. However, this should not provide scenarios a free pass from scrutiny and critique. If energy scenarios are assumed to increasingly inform external users in the future, scenario developers need to make implications deriving from particular methodologies and results much more explicit (Loftus, Cohen, Long, & Jenkins, 2015). Scenario users should be made aware that every projection entails a whole range of implicit and explicit consequences that can be biased towards particular interests, even if the scenarios are presented in a neutral and analytical manner. Hence, the presentation and communication of scenario use should be adapted towards the realities of their use contexts, which have changed dramatically since they were being proposed as internal decision-making support tools in large private corporations. Model-based energy scenarios are predestined to support the transformation of the energy system. As energy transitions do not only concern expert communities but whole societies, energy scenarios need to be adapted in order not to become dysfunctional or prone to misinterpretation in external use contexts.

7.3 Critical reflection

This dissertation clearly has a range of limitations that go beyond what is discussed in the individual papers. Many of them are related to the exploratory nature of the research and the focus on Swiss case studies. For example, paper III and IV, which focused on the publics' energy system expectations, used a novel set of questions and was only partially able to rely on standardized scales related to future-orientation. While the assessed energy system expectations are related to the projections of techno-economic energy scenarios and the relevance of expectations is a thoroughly researched topic, the concrete operationalization of how non-experts perceive the energy future is highly explorative. Also for paper II and V, which addressed the uptake of energy scenarios by external users, only few insights from the academic literature could be implemented in the research design. Nearly all of them had to be adapted from studies focusing on the use of climate scenarios, where this type of research is more advanced.

Except for paper I, which addressed multinational fossil fuel companies, the interviews and the survey were conducted with a focus on Switzerland. The advantage of this setting was that later papers were able to profit from earlier ones, as apparent in the design of paper V (the use of scenarios by utilities) which was based on insights gathered by paper II (the use of scenarios by researchers). This is because energy systems and their co-evolution with social, economic and political systems are highly context dependent and thus differ widely across nations or sectors. Nevertheless, although technology configurations and other aspects related to energy transitions are unique, many of the scenario use characteristics observed in this dissertation are applicable to other contexts. A main reason for this is that model-based energy scenarios are developed and altered by global research and foresight communities. In fact, Switzerland is an exceptionally good case to study the use and influence of energy scenarios. This is because of their relevance for the national energy strategy, the direct democratic approach that increases the public's engagement with energy policy, and the fact that Swiss energy research is one of the leading scenario development communities. While the focus on Swiss case studies limits the generalization of findings due to the uniqueness of energy systems and transitions, the general research design is suitable to be applied in many contexts. As scenario use practices seem to be contingent on many factors related to the user and not the scenario, analyzing the use of scenario by other actors, for example politicians or architects, will likely yield further distinct usage patterns.

To achieve the objectives of this dissertation, it was necessary to reach out to different scientific disciplines and energy system actors. Managing the dissimilar interests and expectations between science and practitioners was challenging. Furthermore, the key focus of what this dissertation is about was not entirely evident from the beginning. Instead, the insights provided by the early papers framed the focus for the latter contributions. In hindsight, a few adjustments in the research design of the individual papers would have allowed for a more coherent dissertation. On the other hand, many insights, for example related to the co-production of more user-friendly energy scenarios, which have not been the focus of this dissertation, would not have been possible in a more streamlined research setting. What the interviews and discussions with modellers and users showed is that a range of practices and routines that are difficult to change shape both the development as well as the use of energy scenarios. Between the corporate and the academic world, different reward systems exist that create strong incentives for particular behaviors that are not necessarily beneficial for a mutual exchange.

7.4 Further research options

The benefit of a relatively unexplored research topic is that there exist seemingly endless possibilities for further research. In general, research on the use of energy scenarios can greatly benefit from research conducted in other fields, such as climate scenarios. The capability of energy scenarios to be useful largely depends on products and services that are targeted at specific actor groups and their needs.

In addition, the *The Sociology of Expectations* offers a suitable perspective to analyse the function and relevance of scenarios in transition processes holistically. Interdisciplinary perspectives are most promising for understanding and ultimately improving the use of energy scenarios. For example, psychological phenomena are clearly instrumental when it comes to the cognitive digestion of scenario results, whereas contributions from political studies can provide insights on actor constellations and interests that are related to the use of energy scenarios.

While scenarios are inherently tied to present economic, political and societal contexts, the scrutiny of these links remains minimal. For that purpose, the gap between foresight and governance research needs to be bridged. The concept of *anticipatory governance* could provide a useful approach in that regard, as it combines the performativity of future-orientation with social scientific analyses adapted form risk governance and technology assessment (Boyd, Nykvist, Borgström, & Stacewicz, 2015; Foley, Guston, & Sarewitz, 2018).

So far, transition studies have mostly focused on more or less homogenous expert communities. Comparative studies incorporating different actors groups are largely lacking. Similarly, despite the inherent dynamic and long-term nature of transitions, longitudinal studies focusing on the perception of scenarios and the development of expectations over time are rare. Analysing the diffusion and relevance of future-oriented products in settings that are close to real-world settings is challenging, but arguably significantly different from the linear knowledge transfer typically assumed in experimental settings.

7.5 Final remarks

To prevent the worst effects of climate change, humanity needs to alter the ways energy is produced, distributed and consumed. Because of this, global energy systems are in the process of a monumental transformation from unsustainable fossil fuel dependence to renewable energy sources. In this context, model-based energy scenarios can be valuable tools to find feasible pathways towards a sustainable energy future from a techno-economic perspective. However, energy scenarios also have a distinctly normative dimension, because the most likely futures are not always the most desirable ones from the perspective of particular energy system actors. This is why this dissertation asked how energy scenarios are used by and influence energy system actors that are not involved in their development.

In particular, this dissertation tried to move beyond an often assumed but rarely empirically researched notion of scenario users. The five papers analysed whether fossil fuel companies, researchers, utilities and the public, which are all important actors in the energy transition, use energy scenarios, or are indirectly influenced by them through the expectations and visions they create. The results show that the former three actors groups directly use scenarios for various purposes, while energy system expectations play a role for the public support of the energy transition. How users select and interpret external energy scenarios is directly linked to the purpose of scenario use. A general differentiation between users that are interested in the vision provided by scenario products and users interested in particular assumptions or prices of data can be made.

A range of energy system actors, from governmental agencies to utilities, fossil fuel companies and environmental NGOs strategically feed their visions of the energy future into public discourse. When scenarios are applied by external users, they escape the control of their developers. Energy system actors select and disseminate favorable visions of a future energy system, while unfavorable visions are neglected or actively discredited. However, the relevance of a scenario is not necessarily determined by the perceived alignment with actor interests. In fact, many actors refer to scenarios that stand in contrast to their personal expectations or values because some scenario studies are widely accepted to be relevant and can thus not be ignored. Scenarios thus contribute to a continuous exchange and contestation of expectations between large numbers of actors with different interests and values. This exemplifies that the transformative power of energy scenarios is directly linked to the social characteristics of their use that have largely been neglected so far.

Due to the different interests, roles, and purposes that are associated with scenarios, contestation is an essential component of their use. Energy scenarios should be considered part of intense societal and political debates about the feasibility and desirability of energy futures. The question which energy scenarios are shaping the expectations and visions of the relevant decision-makers is directly related to how the energy future will eventually take form.

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9 References

Ahn, Y.-H., Woo, J.-H., Wagner, F., & Yoo, S. J. (2019). Downscaled energy demand projection at the local level using the Iterative Proportional Fitting procedure. *Applied energy, 238*, 384-400.

Alvial-Palavicino, C., & Opazo-Bunster, J. (2018). Looking back to go forward? The interplay between long-term futures and political expectations in sustainability transitions in Chile. *Futures, 104*, 61-74.

Andersson, G., Boulouchos, K., & Bretschger, L. (2011). *Energiezukunft Schweiz (Energy Future Switzerland)*. Retrieved from Zürich:

Bakker, S., Van Lente, H., & Meeus, M. (2011). Arenas of expectations for hydrogen technologies. *Technological Forecasting and Social Change, 78*(1), 152-162.

Barmettler, F., Beglinger, N., & Zeyer, C. (2013). *Energiestrategie – Richtig rechnen und wirtschaftlich profitieren, auf CO2-Zielkurs (Cleantech Energy Strategy)*. Retrieved from Bern:

Berger, A., Blees, T., Breon, F.-M., Brook, B. W., Deffrennes, M., Durand, B., . . . Guet, C. (2017). Nuclear energy and bio energy carbon capture and storage, keys for obtaining 1.5° C mean surface temperature limit. *International Journal of Global Energy Issues, 40*(3-4), 240-254.

Berkhout, F., & Hertin, J. (2002). Foresight futures scenarios: developing and applying a participative strategic planning tool. *Greener Management International*, 37-53.

Bezdek, R. H., & Wendling, R. M. (2002). A half century of long-range energy forecasts: errors made, lessons learned, and implications for forecasting. *Journal of Fusion Energy, 21*(3-4), 155-172.

Bishop, P., Hines, A., & Collins, T. (2007). The current state of scenario development: an overview of techniques. *foresight, 9*(1), 5-25.

Bolton, R., Foxon, T. J., & Hall, S. (2016). Energy transitions and uncertainty: Creating low carbon investment opportunities in the UK electricity sector. *Environment and Planning C: Government and Policy, 34*(8), 1387-1403.

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures, 38*(7), 723-739. doi:http://dx.doi.org/10.1016/j.futures.2005.12.002

Borup, M., Brown, N., Konrad, K., & Van Lente, H. (2006). The sociology of expectations in science and technology. *Technology analysis & strategic management, 18*(3-4), 285-298.

Boyd, E., Nykvist, B., Borgström, S., & Stacewicz, I. A. (2015). Anticipatory governance for social-ecological resilience. *Ambio, 44*(1), 149-161.

Bradfield, R., Wright, G., Burt, G., Cairns, G., & Van Der Heijden, K. (2005). The origins and evolution of scenario techniques in long range business planning. *Futures, 37*(8), 795-812.

Braunreiter, L., & Blumer, Y. B. (2018). Of sailors and divers: how researchers use energy scenarios. *Energy Research & Social Science, 40*, 118-126.

Brown, N., & Michael, M. (2003). A sociology of expectations: retrospecting prospects and prospecting retrospects. *Technology analysis & strategic management, 15*(1), 3-18. doi:http://dx.doi.org/10.1080/0953732032000046024

Brown, N., & Rappert, B. (2017). *Contested futures: A sociology of prospective techno-science*: Routledge.

Bublitz, A., Keles, D., & Fichtner, W. (2017). An analysis of the decline of electricity spot prices in Europe: Who is to blame? *Energy Policy, 107*, 323-336.
Budde, B., & Konrad, K. (2019). Tentative governing of fuel cell innovation in a dynamic network of expectations. *Research policy, 48*(5), 1098-1112.
Bui, M., Adjiman, C. S., Bardow, A., Anthony, E. J., Boston, A., Brown, S., . . . Hackett, L. A. (2018). Carbon capture and storage (CCS): the way forward. *Energy & Environmental Science, 11*(5), 1062-1176.
Bush, M. J. (2020). How to End the Climate Crisis *Climate Change and Renewable Energy* (pp. 421-475): Springer.
Carrington, G., & Stephenson, J. (2018). The politics of energy scenarios: Are International Energy Agency and other conservative projections hampering the renewable energy transition? *Energy Research & Social Science, 46*, 103-113.
Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., . . . Mitchell, R. B. (2003). Knowledge systems for sustainable development. *Proceedings of the national academy of sciences, 100*(14), 8086-8091.
Chakraborty, A., Kaza, N., Knaap, G.-J., & Deal, B. (2011). Robust plans and contingent plans: Scenario planning for an uncertain world. *Journal of the American Planning Association, 77*(3), 251-266.
Chaudhury, M., Vervoort, J., Kristjanson, P., Ericksen, P., & Ainslie, A. (2013). Participatory scenarios as a tool to link science and policy on food security under climate change in East Africa. *Regional environmental change, 13*(2), 389-398.
Chermack, T. J. (2019). Response to Spaniol and Rowland:"Defining Scenario". *Futures & Foresight Science, 1*(2), e13.
Chermack, T. J., Lynham, S. A., & Ruona, W. E. (2001). A review of scenario planning literature. *Futures Research Quarterly, 17*(2), 7-32.
Chiodi, A., Taylor, P. G., Seixas, J., Simões, S., Fortes, P., Gouveia, J. P., . . . Gallachóir, B. Ó. (2015). Energy Policies Influenced by Energy Systems Modelling—Case Studies in UK, Ireland, Portugal and G8. In G. L. Giannakidis, Maryse ; Gallachóir, Brian Ó; Tosato, GianCarlo (Ed.), *Informing Energy and Climate Policies Using Energy Systems Models* (Vol. 30, pp. 15-41).
Cochran, J., Mai, T., & Bazilian, M. (2014). Meta-analysis of high penetration renewable energy scenarios. *Renewable and Sustainable Energy Reviews, 29*, 246-253. doi:http://dx.doi.org/10.1016/j.rser.2013.08.089
Cornelius, P., Van de Putte, A., & Romani, M. (2005). Three decades of scenario planning in Shell. *California management review, 48*(1), 92-109.
Dedehayir, O., & Steinert, M. (2016). The hype cycle model: A review and future directions. *Technological Forecasting and Social Change, 108*, 28-41.
Delina, L. (2018). Whose and what futures? Navigating the contested coproduction of Thailand's energy sociotechnical imaginaries. *Energy Research & Social Science, 35*, 48-56.
Delina, L., & Janetos, A. (2018). Cosmopolitan, dynamic, and contested energy futures: navigating the pluralities and polarities in the energy systems of tomorrow. *Energy Research & Social Science, 35*, 1-10.

Demski, C., Spence, A., & Pidgeon, N. (2017). Effects of exemplar scenarios on public preferences for energy futures using the my2050 scenario-building tool. *Nature Energy, 2*(4), 17027.

Densing, M., Panos, E., & Hirschberg, S. (2016). Meta-analysis of energy scenario studies: Example of electricity scenarios for Switzerland. *Energy, 109*, 998-1015. doi:https://doi.org/10.1016/j.energy.2016.05.020

Dieckhoff, C. (2015). *Modellierte Zukunft. Zur Theorie und Praxis von Energieszenarien im Kontext wissenschaftlicher Politikberatung.* (Doctoral Thesis), Karlsruhe Institute of Technologiy (KIT), Karlsruhe.

Dubois, A., Holzer, S., Xexakis, G., Cousse, J., & Trutnevyte, E. (2019). Informed Citizen Panels on the Swiss Electricity Mix 2035: Longer-Term Evolution of Citizen Preferences and Affect in Two Cities. *Energies, 12*(22), 4231.

Eames, M., Mcdowall, W., Hodson, M., & Marvin, S. (2006). Negotiating contested visions and place-specific expectations of the hydrogen economy. *Technology analysis & strategic management, 18*(3-4), 361-374.

Egli, F., Steffen, B., & Schmidt, T. S. (2019). Bias in energy system models with uniform cost of capital assumption. *Nature communications, 10*(1), 1-3.

Ellenbeck, S., & Lilliestam, J. (2019). How modelers construct energy costs: discursive elements in energy system and integrated assessment models. *Energy Research & Social Science, 47*, 69-77.

Ernst, A., Biss, K. H., Shamon, H., Schumann, D., & Heinrichs, H. U. (2018). Benefits and challenges of participatory methods in qualitative energy scenario development. *Technological Forecasting and Social Change, 127*, 245-257.

Foley, R. W., Guston, D. H., & Sarewitz, D. (2018). Towards the anticipatory governance of geoengineering *Geoengineering our Climate?* (pp. 223-243): Routledge.

Fortes, P., Alvarenga, A., Seixas, J., & Rodrigues, S. (2015). Long-term energy scenarios: Bridging the gap between socio-economic storylines and energy modeling. *Technological Forecasting and Social Change, 91*, 161-178. doi:https://doi.org/10.1016/j.techfore.2014.02.006

Francis, J. J., Johnston, M., Robertson, C., Glidewell, L., Entwistle, V., Eccles, M. P., & Grimshaw, J. M. (2010). What is an adequate sample size? Operationalising data saturation for theory-based interview studies. *Psychology and Health, 25*(10), 1229-1245.

Gaede, J., & Meadowcroft, J. (2016). A question of authenticity: Status quo bias and the International Energy Agency's World Energy Outlook. *Journal of environmental policy & planning, 18*(5), 608-627.

Garb, Y., Pulver, S., & VanDeveer, S. D. (2008). Scenarios in society, society in scenarios: toward a social scientific analysis of storyline-driven environmental modeling. *Environmental Research Letters, 3*(4), 045015.

Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research policy, 33*(6-7), 897-920.

Geels, F. W. (2014). Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. *Theory, Culture & Society, 31*(5), 21-40.

Gibbs, G. R. (2007). Thematic coding and categorizing. *Analyzing qualitative data, 703*, 38-56.

Giddens, A. (1998). Risk society: the context of British politics. *The politics of risk society*, 23-34.
Gordon, A. V. (2019). Matrix Purpose in Scenario Planning: Implications of Congruence with Scenario Project Purpose. *Futures*, 102479.
Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., . . . De Stercke, S. (2018). A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. *Nature Energy, 3*(6), 515.
Grunwald, A. (2011). Energy futures: diversity and the need for assessment. *Futures, 43*(8), 820-830. doi:https://doi.org/10.1016/j.futures.2011.05.024
Guivarch, C., Lempert, R., & Trutnevyte, E. (2017). Scenario techniques for energy and environmental research: An overview of recent developments to broaden the capacity to deal with complexity and uncertainty. *Environmental modelling & software, 97*, 201-210.
Heffron, R. J., McCauley, D., & Sovacool, B. K. (2015). Resolving society's energy trilemma through the Energy Justice Metric. *Energy Policy, 87*, 168-176.
Herbst, A., Toro, F., Reitze, F., & Jochem, E. (2012). Introduction to Energy Systems Modelling *Swiss Journal of Economics and Statistics (SJES), 148*(2). doi:http://EconPapers.repec.org/RePEc:ses:arsjes:2012-ii-2
Hughes, N. (2013). Towards improving the relevance of scenarios for public policy questions: A proposed methodological framework for policy relevant low carbon scenarios. *Technological Forecasting and Social Change, 80*(4), 687-698. doi:http://dx.doi.org/10.1016/j.techfore.2012.07.009
International Energy Agency. (2019). *World Energy Outlook*. Retrieved from Paris, France.:
IPCC. (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Retrieved from
Irvine, P., Emanuel, K., He, J., Horowitz, L. W., Vecchi, G., & Keith, D. (2019). Halving warming with idealized solar geoengineering moderates key climate hazards. *Nature Climate Change, 9*(4), 295.
Jasanoff, S., & Kim, S.-H. (2015). *Dreamscapes of modernity: Sociotechnical imaginaries and the fabrication of power*: University of Chicago Press.
Jefferson, M. (2012). Shell scenarios: What really happened in the 1970s and what may be learned for current world prospects. *Technological Forecasting and Social Change, 79*(1), 186-197.
Jenkins, K., McCauley, D., Heffron, R., Stephan, H., & Rehner, R. (2016). Energy justice: a conceptual review. *Energy Research & Social Science, 11*, 174-182.
Jenkins, K., Sovacool, B. K., & McCauley, D. (2018). Humanizing sociotechnical transitions through energy justice: An ethical framework for global transformative change. *Energy Policy, 117*, 66-74.
Johnson, D., & Fowler, J. H. (2011). The evolution of overconfidence. *Nature, 477*(7364), 317.
Johnson, K., Dana, G., Jordan, N. R., Draeger, K. J., & Kapuscinski, A. (2012). Using participatory scenarios to stimulate social learning for collaborative sustainable development. *Ecology and Society*.

Kahn, H., & Wiener, A. J. (1967). year 2000; a framework for speculation on the next thirty-three years.

Kannan, R. T., H. (2012). *The Swiss TIMES Electricity Model (STEM-E): Updates to the model input data and assumptions (Model Release 2)*. Retrieved from

Karjalainen, J. K., M; Luukanen, J.; Vehmas, J. (2014). *Energy Models and Scenarios in the Era of Climate Change - Briefing Report*. Retrieved from

Keppo, I., & Strubegger, M. (2010). Short term decisions for long term problems–The effect of foresight on model based energy systems analysis. *Energy, 35*(5), 2033-2042.

Knappe, H., Holfelder, A.-K., Beer, D. L., & Nanz, P. (2018). The politics of making and un-making (sustainable) futures: Springer.

Knutti, R. (2018). A wider role for climate scenarios. *Nature Sustainability, 1*(5), 214.

Knutti, R. (2019). Why we need new climate models. Retrieved from https://ethz.ch/en/news-and-events/eth-news/news/2019/08/blog-knutti-klimamodelle.html

Kok, K., van Vliet, M., Bärlund, I., Dubel, A., & Sendzimir, J. (2011). Combining participative backcasting and exploratory scenario development: experiences from the SCENES project. *Technological Forecasting and Social Change, 78*(5), 835-851.

Konrad, K. (2006). The social dynamics of expectations: the interaction of collective and actor-specific expectations on electronic commerce and interactive television. *Technology analysis & strategic management, 18*(3-4), 429-444.

Koomey, J., Craig, P., Gadgil, A., & Lorenzetti, D. (2003). Improving long-range energy modeling: A plea for historical retrospectives. *The Energy Journal*, 75-92.

Koppelaar, R. H., Keirstead, J., Shah, N., & Woods, J. (2016). A review of policy analysis purpose and capabilities of electricity system models. *Renewable and Sustainable Energy Reviews, 59*, 1531-1544.

Kosow, H., & Gaßner, R. (2008). *Methods of future and scenario analysis: overview, assessment, and selection criteria* (Vol. 39): DEU.

Kriechbaum, M., Prol, J. L., & Posch, A. (2018). Looking back at the future: Dynamics of collective expectations about photovoltaic technology in Germany & Spain. *Technological Forecasting and Social Change, 129*, 76-87.

Kunseler, E.-M., Tuinstra, W., Vasileiadou, E., & Petersen, A. C. (2015). The reflective futures practitioner: Balancing salience, credibility and legitimacy in generating foresight knowledge with stakeholders. *Futures, 66*, 1-12.

Lehr, U., Nitsch, J., Kratzat, M., Lutz, C., & Edler, D. (2008). Renewable energy and employment in Germany. *Energy Policy, 36*(1), 108-117.

Lempert, R., Hoorens, S., Hallworth, M., & Ling, T. (2008). Looking back on looking forward. A review on evaluative scenario literature: Report for the European Environment Report (unpublished document).

Lilliestam, J., & Hanger, S. (2016). Shades of green: Centralisation, decentralisation and controversy among European renewable electricity visions. *Energy Research & Social Science, 17*, 20-29.

Linderoth, H. (2002). Forecast errors in IEA-countries' energy consumption. *Energy Policy, 30*(1), 53-61.

Linneman, R. E., & Klein, H. E. (1983). The use of multiple scenarios by US industrial companies: a comparison study, 1977–1981. *Long range planning, 16*(6), 94-101.

Loftus, P. J., Cohen, A. M., Long, J. C., & Jenkins, J. D. (2015). A critical review of global decarbonization scenarios: what do they tell us about feasibility? *Wiley Interdisciplinary Reviews: Climate Change, 6*(1), 93-112.

Longhurst, N., & Chilvers, J. (2019). Mapping diverse visions of energy transitions: co-producing sociotechnical imaginaries. *Sustainability Science*, 1-18.

Lund, H., & Mathiesen, B. V. (2009). Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. *Energy, 34*(5), 524-531.

Lund, H., Möller, B., Mathiesen, B. V., & Dyrelund, A. (2010). The role of district heating in future renewable energy systems. *Energy, 35*(3), 1381-1390.

MacMartin, D. G., Ricke, K. L., & Keith, D. W. (2018). Solar geoengineering as part of an overall strategy for meeting the 1.5 C Paris target. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 376*(2119), 20160454.

Malaska, P. (1985). Multiple scenario approach and strategic behaviour in European companies. *Strategic Management Journal, 6*(4), 339-355.

Marvin, C. (1988). *When old technologies were new: Thinking about electric communication in the late nineteenth century*: Oxford University Press, USA.

Mathy, S., Fink, M., & Bibas, R. (2015). Rethinking the role of scenarios: Participatory scripting of low-carbon scenarios for France. *Energy Policy, 77*, 176-190. doi:https://doi.org/10.1016/j.enpol.2014.11.002

McDowall, W., & Eames, M. (2006). Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature. *Energy Policy, 34*(11), 1236-1250.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (1972). The limits to growth. *New York, 102*, 27.

Meijer, I., Koppenjan, J., Pruyt, E., Negro, S., & Hekkert, M. (2010). The influence of perceived uncertainty on entrepreneurial action in the transition to a low-emission energy infrastructure: the case of biomass combustion in The Netherlands. *Technological Forecasting and Social Change, 77*(8), 1222-1236.

Meissner, P., & Wulf, T. (2013). Cognitive benefits of scenario planning: Its impact on biases and decision quality. *Technological Forecasting and Social Change, 80*(4), 801-814.

Miller, C. A., Richter, J., & O'Leary, J. (2015). Socio-energy systems design: a policy framework for energy transitions. *Energy Research & Social Science, 6*, 29-40.

Mitchell, W. J., Borroni-Bird, C. E., & Burns, L. D. (2010). *Reinventing the automobile: Personal urban mobility for the 21st century*: MIT press.

Moallemi, E. A., & Malekpour, S. (2018). A participatory exploratory modelling approach for long-term planning in energy transitions. *Energy Research & Social Science, 35*, 205-216.

Mohn, K. (2020). The gravity of status quo: A review of IEA's World Energy Outlook. *Economics of Energy & Environmental Policy, 9*(1).

Moustakas, K., Loizidou, M., Rehan, M., & Nizami, A. (2020). A review of recent developments in renewable and sustainable energy systems: Key challenges and future perspective: Elsevier.

Nemet, G. F., Anadon, L. D., & Verdolini, E. (2017). Quantifying the effects of expert selection and elicitation design on experts' confidence in their judgments about future energy technologies. *Risk Analysis, 37*(2), 315-330.

Noor, S., Yang, W., Guo, M., van Dam, K. H., & Wang, X. (2018). Energy Demand Side Management within micro-grid networks enhanced by blockchain. *Applied energy, 228*, 1385-1398.

O'Brien, F. A., & Meadows, M. (2013). Scenario orientation and use to support strategy development. *Technological Forecasting and Social Change, 80*(4), 643-656.

Ochoa, P., & Van Ackere, A. (2009). Policy changes and the dynamics of capacity expansion in the Swiss electricity market. *Energy Policy, 37*(5), 1983-1998.

Oteros-Rozas, E., Martín-López, B., Daw, T., Bohensky, E. L., Butler, J., Hill, R., . . . Ruiz-Mallén, I. (2015). Participatory scenario planning in place-based social-ecological research: insights and experiences from 23 case studies. *Ecology and Society, 20*(4).

Paltsev, S. (2016). Energy scenarios: the value and limits of scenario analysis. *Wiley Interdisciplinary Reviews: Energy and Environment*. doi:10.1002/wene.242

Parson, E. A. (2008). Useful global-change scenarios: current issues and challenges. *Environmental Research Letters, 3*(4), 045016.

Pereira, L., Sitas, N., Ravera, F., Jimenez-Aceituno, A., & Merrie, A. (2019). Building capacities for transformative change towards sustainability: Imagination in Intergovernmental Science-Policy Scenario Processes. *Elementa: Science of the Anthropocene, 7*(1), 35.

Pfenninger, S. (2017). Energy scientists must show their workings. *Nature, 542*(7642), 393-393.

Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews, 33*, 74-86. doi:http://dx.doi.org/10.1016/j.rser.2014.02.003

Prognos. (2012). *Die Energieperspektiven für die Schweiz bis 2050 (Energy Persepctives for Switzerland until 2050)*. Retrieved from

Pulver, S., & VanDeveer, S. D. (2009). "Thinking About Tomorrows": Scenarios, Global Environmental Politics, and Social Science Scholarship. *Global Environmental Politics, 9*(2), 1-13. doi:10.1162/glep.2009.9.2.1

Pye, S., Sabio, N., & Strachan, N. (2015). An integrated systematic analysis of uncertainties in UK energy transition pathways. *Energy Policy, 87*, 673-684.

Ramírez, R., & Selin, C. (2014). Plausibility and probability in scenario planning. *foresight, 16*(1), 54-74.

Raskin, P., Monks, F., Ribeiro, T., Vuuren, V., Zurek, M., Carpenter, S. R., . . . Zurek, M. B. (2005). Global scenarios in historical perspective *Ecosystems and Human well-being: scenarios* (Vol. 2, pp. 35-44). Washington, DC: Island Press.

Richter, M. (2013). Business model innovation for sustainable energy: German utilities and renewable energy. *Energy Policy, 62*, 1226-1237.

Rickards, L., Ison, R., Fünfgeld, H., & Wiseman, J. (2014). Opening and closing the future: climate change, adaptation, and scenario planning. *Environment and Planning C: Government and Policy, 32*(4), 587-602.

Rogelj, J., Popp, A., Calvin, K. V., Luderer, G., Emmerling, J., Gernaat, D., . . . Marangoni, G. (2018). Scenarios towards limiting global mean temperature increase below 1.5 C. *Nature Climate Change, 8*(4), 325.
Royal Dutch Shell. (2019). Shell Scenarios.
Schnaars, S. P. (1987). How to develop and use scenarios. *Long range planning, 20*(1), 105-114.
Schoemaker, P. J. (1995). Scenario planning: a tool for strategic thinking. *Sloan management review, 36*(2), 25-50.
Schwartz, P. (2012). *The art of the long view: planning for the future in an uncertain world*: Crown Business.
SCS. (2013). *SCS Energiemodell (SCS Energy Model)*. Retrieved from Zürich:
Selin, C. (2007). Expectations and the Emergence of Nanotechnology. *Science, Technology, & Human Values, 32*(2), 196-220.
Skelton, M., Fischer, A. M., Liniger, M. A., & Bresch, D. N. (2019). Who is 'the user' of climate services? Unpacking the use of national climate scenarios in Switzerland beyond sectors, numeracy and the research–practice binary. *Climate Services*, 100113.
Skjølsvold, T. M. (2014). Back to the futures: Retrospecting the prospects of smart grid technology. *Futures, 63*, 26-36.
Söderholm, P., Hildingsson, R., Johansson, B., Khan, J., & Wilhelmsson, F. (2011). Governing the transition to low-carbon futures: A critical survey of energy scenarios for 2050. *Futures, 43*(10), 1105-1116.
Soroudi, A., & Amraee, T. (2013). Decision making under uncertainty in energy systems: State of the art. *Renewable and Sustainable Energy Reviews, 28*, 376-384. doi:https://doi.org/10.1016/j.rser.2013.08.039
Sovacool, B. K., & Brown, M. A. (2015). Deconstructing facts and frames in energy research: maxims for evaluating contentious problems. *Energy Policy, 86*, 36-42.
Spaniol, M. J., & Rowland, N. J. (2018). The scenario planning paradox. *Futures, 95*, 33-43.
Spaniol, M. J., & Rowland, N. J. (2019). Defining scenario. *Futures & Foresight Science, 1*(1), e3.
Stephens, J. C., Hansson, A., Liu, Y., De Coninck, H., & Vajjhala, S. (2011). Characterizing the international carbon capture and storage community. *Global Environmental Change, 21*(2), 379-390.
Strachan, N., Fais, B., & Daly, H. (2016). Reinventing the energy modelling–policy interface. *Nature Energy, 1*, 16012.
Talberg, A., Thomas, S., Christoff, P., & Karoly, D. (2018). How geoengineering scenarios frame assumptions and create expectations. *Sustainability Science, 13*(4), 1093-1104.
Te Kulve, H., Konrad, K., Palavicino, C. A., & Walhout, B. (2013). Context matters: promises and concerns regarding nanotechnologies for water and food applications. *Nanoethics, 7*(1), 17-27.
Teske, S., & Klingler-Heiligtag, G. (2013). *energy [r]evolution*. Retrieved from
Tonka, L. (2015). Hydropower license renewal and environmental protection policies: a comparison between Switzerland and the USA. *Regional environmental change, 15*(3), 539-548.
Tozer, L., & Klenk, N. (2018). Discourses of carbon neutrality and imaginaries of urban futures. *Energy Research & Social Science, 35*, 174-181.

Truffer, B., Voß, J.-P., & Konrad, K. (2008). Mapping expectations for system transformations: Lessons from Sustainability Foresight in German utility sectors. *Technological Forecasting and Social Change, 75*(9), 1360-1372.
Trutnevyte, E. (2014). The allure of energy visions: are some visions better than others? *Energy Strategy Reviews, 2*(3-4), 211-219.
Trutnevyte, E., McDowall, W., Tomei, J., & Keppo, I. (2016). Energy scenario choices: Insights from a retrospective review of UK energy futures. *Renewable and Sustainable Energy Reviews, 55*, 326-337. doi:http://dx.doi.org/10.1016/j.rser.2015.10.067
Tutton, R. (2011). Promising pessimism: Reading the futures to be avoided in biotech. *Social studies of science, 41*(3), 411-429.
Uhl, D. (2012). *Vision assessment: shaping technology in 21st century society: towards a repertoire for technology assessment* (Vol. 4): Springer Science & Business Media.
UNFCCC. (2015). Adoption of the Paris Agreement.
Van Lente, H. (2012). Navigating foresight in a sea of expectations: lessons from the sociology of expectations. *Technology analysis & strategic management, 24*(8), 769-782.
Van Lente, H., Spitters, C., & Peine, A. (2013). Comparing technological hype cycles: Towards a theory. *Technological Forecasting and Social Change, 80*(8), 1615-1628.
Van Notten, P. W., Rotmans, J., Van Asselt, M. B., & Rothman, D. S. (2003). An updated scenario typology. *Futures, 35*(5), 423-443.
van Vuuren, D. P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., . . . Blok, K. (2009). Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy, 37*(12), 5125-5139. doi:https://doi.org/10.1016/j.enpol.2009.07.024
Vervoort, J., & Gupta, A. (2018). Anticipating climate futures in a 1.5 C era: The link between foresight and governance. *Current Opinion in Environmental Sustainability, 31*, 104-111.
Vervoort, J. M. (2019). New frontiers in futures games: leveraging game sector developments. *Futures, 105*, 174-186.
Volken, S. P., Xexakis, G., & Trutnevyte, E. (2018). Perspectives of informed citizen panel on low-carbon electricity portfolios in Switzerland and longer-term evaluation of informational materials. *Environmental science & technology, 52*(20), 11478-11489.
Volkery, A., & Ribeiro, T. (2009). Scenario planning in public policy: Understanding use, impacts and the role of institutional context factors. *Technological Forecasting and Social Change, 76*(9), 1198-1207. doi:http://dx.doi.org/10.1016/j.techfore.2009.07.009
Volkery, A., Ribeiro, T., Henrichs, T., & Hoogeveen, Y. (2008). Your vision or my model? Lessons from participatory land use scenario development on a European scale. *Systemic Practice and Action Research, 21*(6), 459-477.
VSE. (2012). *Wege in die neue Stromzukunft (Paths into the new energy future)*. Retrieved from Aarau:
Wack, P. (1985a). *Scenarios: shooting the rapids. How medium-term analysis illuminated the power of scenarios for shell management*. Retrieved from
Wack, P. (1985b). Uncharted waters ahead. *Harvard Business Review, 5*.
Walker, G. (2012). *Environmental justice: concepts, evidence and politics*: Routledge.
Weidmann, N. (2013). *Transformation strategies towards a sustainable Swiss energy system – an energy-economic scenario analysis.* (Doctoral Thesis), ETH, Zürich.

Weyant, J. (2017). Some contributions of integrated assessment models of global climate change. *Review of Environmental Economics and Policy, 11*(1), 115-137.

Wiek, A., Binder, C., & Scholz, R. W. (2006). Functions of scenarios in transition processes. *Futures, 38*(7), 740-766. doi:https://doi.org/10.1016/j.futures.2005.12.003

Wilkinson, A., & Eidinow, E. (2008). Evolving practices in environmental scenarios: a new scenario typology. *Environmental Research Letters, 3*(4), 045017.

Wilson, C., Grubler, A., Bauer , N., Krey, V., & Riahi, K. (2013). Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Climatic Change, 118*, 381–395. doi: 10.1007/s10584-012-0618-y

Wright, G., Cairns, G., & Bradfield, R. (2013). Scenario methodology: new developments in theory and practice: introduction to the special issue: Elsevier.

Xexakis, G., & Trutnevyte, E. (2019). Are interactive web-tools for scenario visualization worth the effort? An experimental study on the swiss electricity supply scenarios 2035. *Environmental modelling & software*.

10 Appendix

10.1 Appendix A: Supplementary information for paper II

This appendix provides supplementary information for paper II: *Of sailors and divers: How researchers use energy scenarios.*

A1 Interview guideline (1/2)

***Note: This sheet served as a guideline for the semi-structured interviews depending on the focus and expertise of the interviewees some interview parts were expanded whereas other parts could be only briefly covered

1. Research activities

-What are your areas of expertise (methods, topics, etc.) and ongoing research activities (within and outside SCCER)?

-Who is the main audience of your research (Which scientific community/ies, public, decision makers, etc.)?

-With which partners do you collaborate (in research, policy and industry)?

-Are decision-makers using your research (findings)? Do you know in detail how/for what they use it?

2. Scenario-specific questions

-Please describe in your own words what an (energy) scenario is and why it is (or isn't) a valuable part of your research

-Which expectations and requirements do you have on scenario-related information and insights?

-With respect to these expectations and requirements you have when working with scenarios: How are the Swiss scenarios doing? What aspects could be improved?

-Is a reference scenario a good idea? What would such a reference scenario need to provide to satisfy your research needs? Which parts (e.g. data source, assumptions, model framework, …) of the scenario would need to be consistent?

3. Relevance of Swiss energy scenarios for research

-How familiar are you with contemporary (Swiss and international) energy scenarios (list is presented)?

-Which of them do you use for the purpose of your research and what parts do you use?

-In what ways do you integrate scenario-based insights into your research?

A1 Interview guideline (2/2)

4. Use of prospective information in research

-What types of prospective information (cards with potential items is presented) is required as an input for your research? What types do you produce/calculate yourself as an output of your research?

-Are there other forms you use scenario-based information?

-What parts of scenarios are relevant to your research (e.g. results, assumptions, model, …)

-Do you treat information differently depending on what part of a scenario you work with?

5. General discussion

-How suitable was the method/card/interview layout in general for your specific research and use of energy scenarios?

-Other Suggestions/remarks about scenarios/the interview in general?

A2: Interviewee characteristics (1/2)

Table 6. Overview of interviewee's educational and professional background.

Interviewee #Nr	1	2	3	4	5	6	7	8
Educational background	Engineering	Sociology	Environmental sciences	Engineering	Physics/ Engineering	Engineering	Law	Mathematics; Geography
Thematic focus	Agent-based models	Public acceptance of energy infrastructure	Photovoltaics; micro grids; integration of renewables	Innovation; knowledge and technology transfer	Bottom-up energy system models	Sectoral energy models	Regulation of markets and land use	Technological innovation systems
Institution	*	*	*	*	*	*	*	*
Position	PhD Candidate	Professor	Professor	Professor	Group Leader	PhD Candidate	Professor	Professor

**In order to prevent interviewee identification, we omitted the institutions in the table. Overall, the sample included the following instiutions: ETH Zurich (5), EPFL Lausanne (2), Paul Scherrer Institute (2), University of Basel (2), Eawag, HSLU, Supsi and Zurich University of Applied Scienc*

A2: Interviewee characteristics (2/2)

Table 6. (continued)

Interviewee #Nr	9	10	11	12	13	14	15	16
Discipline	Engineering	Engineering	Economics	Economics	Economics; Engineering	Engineering	Physics	Environmental sciences
Thematic focus	Interactive scenario visualisation	Fuel cells; carbon capture and storage	Regional energy systems models	Electricity market models	Network Modeling; investment	Macro-economic energy system models	Climate and energy policy	Resource and waste management
Institution	*	*	*	*	*	*	*	*
Position	PhD Candidate	Post-Doc	Group Leader	PhD Candidate	Professor	Post-Doc	Post-Doc	Post-Doc

**In order to prevent interviewee identification, we omitted the institutions in the table. Overall, the sample included the following instiutions: ETH Zurich (5), EPFL Lausanne (2), Paul Scherrer Institute (2), University of Basel (2), Eawag, HSLU, Supsi and Zurich University of Applied Sciences*

A3: Individual scenario use* characteristics (1/2)

Table 7. Overview of interviewee's scenario use.

Interviewee #Nr	1	2	3	4	5	6	7	8
Energy Perspectives	1	1	1	1	1	1	2	3
SCS	2	3	3	1	2	3	2	3
ETH Zurich	2	2	2	2	2	3	2	3
Cleantech	2	3	3	2	2	3	3	3
VSE	3	3	2	1	2	2	3	3
Greenpeace	2	2	3	3	2	2	3	3
Paul Scherrer Institute (PSI) elec	3	3	1	2	1	2	3	3
Paul Scherrer Institute (PSI) energy	3	3	3	2	1	2	3	3
World Energy Counci	3	3	3	3	2	3	3	3
IEA WEO	3	3	3	3	2	3	3	3

* 1= used, 2= studied, 3=unknown

A3: Individual scenario use* characteristics (2/2)

Table 7. (continued).

Interviewee #Nr	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Energy Perspectives	1	1	1	1	1	1	1	1
SCS	3	3	2	2	2	2	3	3
ETH Zurich	3	3	3	3	3	1	2	2
Cleantech	3	3	2	3	3	3	3	3
VSE	2	3	3	3	2	3	2	3
Greenpeace	3	3	3	2	3	3	2	3
Paul Scherrer Institute (PSI) elec	2	3	2	2	2	2	2	2
Paul Scherrer Institute (PSI) energy	1	3	2	2	2	2	2	2
World Energy Counci	3	3	3	3	2	3	3	3
IEA WEO	3	3	3	3	2	3	2	3

* 1= used, 2= studied, 3=unknown

10.2 Appendix B: Supplementary information for paper III

The supplementary information for paper III: *A two-level analysis of public support: Exploring the role of beliefs in opinions about the Swiss energy strategy* is extensive and documents the survey and additional statistical analyses in a detailed manner. All this information is available at:
https://ars.els-cdn.com/content/image/1-s2.0-S2214629618305188-mmc1.pdf

10.3 Appendix C: Supplementary information for paper IV

This appendix provides supplementary information for paper 2: Expecto transitio: Exploring non-experts' techno-economic expectations of the energy future.

C1: Sample description and comparison with Swiss population

Table 8. Socio-demographic sample description and comparison with Swiss population

		Survey sample N=797	Switzerland 2017 (Swiss Federal Office of Statistics)[15] 8.54mil.
Demographics	Age (mean)	44.0	42.4
	Female	50.0%	50.4%
	University degree	22.3%	27.0%
Party preference	Swiss People's party (SVP)	27.6%	29.4%
	Social Democratic Party (SP)	16.7%	18.8%
	Liberal Democratic party (FDP)	12.5%	16.4%
	Other parties	43.2%	35.4%

C2: Overview of cluster solutions

Table 9. Different steps of cluster solutions.

3-Cluster solution	4-Cluster solution	5-Cluster solution
Cluster 1 (*N*=137)	Cluster 1 (*N*=137)	Cluster 1 (*N*=137)
Cluster 2 (*N*=200)	Cluster 2 (*N*=200)	Cluster 2 (*N*=200)
Cluster 3 (*N*=303)	Cluster 3 (*N*=122)	Cluster 3 (*N*=122)
	Cluster 4 (*N*=181)	Cluster 4 (*N*=93)
		Cluster 5 (*N*=88)

[15] Source: https://www.bfs.admin.ch/bfs/de/home/statistiken/bevoelkerung/stand-entwicklung/bevoelkerung.html [Accessed: 15.08.2019]

C3: Report of confirmatory factor analyses

We based our choice of survey items on the literature on expectations and transition studies. In order to verify the internal consistency among included survey items, we computed Cronbach's α, a measure of inter-item reliability that ranges between 0-1. The Cronbach's α values our measures are well within the conventional range of 0.6-1, indicating that the included items are reasonably clustered closely with each other as we hypothesized. Therefore, instead of empirically adjusting the included items post-hoc, we proceeded with the initial set of items as we hypothesized based on the literature. Both the TransitionExtent scale (consisting of three expectations) and the SystemState scale (consisting of seven expectations) returned only a single eigenvalue that is greater than 1, verifying that there is only one underlying factor beneath our choice of items as we hypothesized.

Table 10. Factor analysis.

TransitionExtent
Cronbach's α = 0.68
Number of eigenvalues > 1 = 1
Items included:
Renewables
Efficiency
Electric vehicles
SystemState
Cronbach's α = 0.65
Number of eigenvalues > 1 = 1
Items included:
Power outages
Fossil fuel prices
Electricity prices
Electricity use per capita
Imported electricity
Societal conflicts over energy infrastructure
Energy related international controversies

C4: Complete ANOVA tables

Table 11. Differences between the energy system expectation clusters with respect to socio-demographics, future orientation and political orientation.

	Cluster 1		Cluster 2		Cluster 3		Cluster 4		ANOVA	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*F*	*p*
Socio-demographics										
Women (N=639)	.55	*.50*	.47	*.50*	.47	*.50*	.49	*.50*	.79	.499[1]
Age (years)	45.33	15.1	46.72	15.0	43.65	14.5	43.13	15.4	2.12	.097
Children (average)	1.96	1.12	2.06	1.31	1.94	1.17	1.93	1.25	.39	.27
Education (7pt, higher equals more formal education)	4.99	1.37	5.02	1.51	4.82	1.43	5.09	1.40	.86	.460
Household income	4.53	3.36	4.91	3.53	4.49	3.51	4.58	3.37	.61	.612
Full time job (N=272)	.42	.50	.39	.49	.41	.49	.48	.50	.99	.369
Part time job (N=109)	.20	.41	.16	.36	.16	.36	.17	.38	.55	.652
Self-employed (N=47)	.07	.26	.08	.27	.07	.25	.07	.26	.08	.970
Unemployed (N=36)	.04	.19	.06	.23	.12	.33	.03	.16	4.75	.003
Retired (N=98)	.14	.35	.19	.39	.11	.31	.16	.37	1.23	.274
Student (N=)	.09	.29	.07	.26	.07	.26	.08	.27	.25	.862
Unable to work (N=)	.03	.17	.04	.20	.04	.20	.02	.13	.73	.535

Table 11. (continued)

Home owner (N=)	1.72	.50	1.71	.51	1.71	.51	1.59	.56	2.28	.078
Access to car in household	1.32	.48	1.18	.42	1.24	.43	1.16	.38	4.38	.005
Future and political orientation										
CFC 12-point (higher equals more future orientation)	58.6	7.44	55.7	7.80	52.2	7.00	55.0	7.87	15.8	.000
Left/right leaning on the political scale (5 point scale)	2.86	.99	3.20	.94	3.18	.92	3.05	.99	3.84	.010
Self-assessed familiarity with CH politics	5.73	1.57	5.64	1.72	4.81	1.79	5.36	1.93	7.30	.000
Self-assessed political activity	4.49	1.79	4.53	1.70	4.07	1.80	4.28	1.92	1.99	.114
Belief in value of voting (My vote makes a difference)	4.36	1.78	4.04	1.63	3.72	1.64	4.28	1.73	3.86	.009
Trust in parliament	4.27	1.51	3.88	1.44	3.69	1.46	4.34	1.36	7.07	0.000
Trust in energy minister	4.10	1.71	3.62	1.70	3.62	1.49	4.20	1.65	5.73	.001
Trust in science	5.32	1.19	4.89	1.28	4.18	1.43	5.05	1.23	18.71	.000

Notes. *M*=Mean, *SD*=Standard Deviation. *F*= variance of the group means, *p*=significance.

APPENDIX C

Energy attitudes

Table 12: Differences between the energy system expectation clusters with respect to energy attitudes and voting behaviour in the ES2050 referendum.

	Cluster 1		*Cluster 2*		*Cluster 3*		*Cluster 4*		*ANOVA*	
Attitudes towards energy										
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*F*	*p*
Perceived need of an energy transition	5.65	1.46	5.09	1.48	4.53	1.46	5.14	1.40	12.89	.000
Preference for locally produced electricity	4.80	1.64	4.74	1.53	4.09	1.54	4.69	1.45	6.01	.000
Willingness to sacrifice landscape aesthetics in order to place energy infrastructure	4.81	1.61	4.49	1.62	4.24	1.53	4.78	1.42	4.24	.006
My local surroundings are already impacted by energy infrastructure	2.93	1.42	3.24	1.57	3.21	1.34	3.19	1.53	1.32	.269
Energy infrastructure impacts me more than others	4.78	1.33	4.79	1.33	4.30	1.37	4.76	1.38	4.04	.007
Energy topics fascinate me	4.86	1.44	4.87	1.31	4.53	1.38	4.80	1.45	1.69	.167
Energy topics annoy me	3.98	1.53	4.46	1.48	4.25	1.41	4.04	1.45	3.85	.009
Support for photovoltaics	6.49	1.01	6.01	1.06	5.12	1.57	6.10	1.10	30.68	.000
Support for hydropower	5.88	1.46	5.73	1.11	5.25	1.32	5.62	1.28	5.61	.001
Support for wind	5.99	1.26	5.31	1.55	4.74	1.75	5.39	1.53	14.71	.000
Support for deep geothermal energy	4.22	1.87	4.01	1.85	3.80	1.53	4.47	1.60	4.20	.006
Support for gas	3.28	1.58	3.28	1.58	3.48	1.54	3.45	1.50	.42	.742

Table 12. (continued).

Support for nuclear	1.94	1.35	2.79	1.86	2.90	1.64	2.62	1.59	9.54	.000
Support for Electricity imports	2.79	1.29	2.91	1.31	3.43	1.46	2.93	1.38	5.76	.001
ES2050 yes (N=191)	.41	.49	.26	.44	.20	.41	.33	.47	5.29	.001
ES2050 no (N=100)	.08	.27	.22	.41	.16	.37	.14	.35	3.88	.009
ES2050 did not vote (N=125)	.15	.36	.21	.41	.25	.44	.17	.38	1.72	.161
ES2050 not allowed to vote (N=55)	.12	.32	.07	.25	.07	.26	.09	.29	1.05	.370
Es2050 cannot remember (N=112)	.17	.38	.18	.38	.17	.38	.18	.39	.040	.989
ES2050 do not want to disclose (N=55)	.07	.26	.07	.26	.12	.33	.08	.27	1.08	.354

Notes. *M*=Mean, *SD*=Standard Deviation. *F*= variance of the g

11 Other research activities

11.1 Peer-reviewed publications

Eschenauer, U., Braunreiter, L., Kuehn, T., Yildirim, O., Lobsiger-Kägi, E., Spiess, H., & Müller, A. W. (2017). Smart Cities in Theorie und Praxis: Szenarien, Strategien und Umsetzungsbeispiele.

Lobsiger-Kägi, E., Weiss Sampietro, T., Eschenauer, U., Carabias-Hütter, V., Braunreiter, L., & Müller, A. W. (2016). Treiber und Barrieren auf dem Weg zu einer Smart City: Erkenntnisse aus Theorie und Praxis.

Thaler, P., Hofmann, B., Abegg, A., Bornemann, B., Braunreiter, L., Burger, P., (…) & Petrovich, B. (2019). Schweizer Energiepolitik zwischen Bund, Kantonen und Gemeinden: Zentralisieren, dezentralisieren oder koordinieren?.

11.2 Publications for stakeholders (scientific reports)

Blumer, Y.B., Braunreiter, L., Cometta, C (2019). *Charting Pathways for the Swiss Energy Transition.* CREST Visions 2050 Process, Workstream 1 Report.

Braunreiter, L., Blumer, Y.B., Marchand, C. (2019). *Nutzung von Energieszenarien durch Schweizer EVU.* Short report of an interview study with representatives of Swiss utilities.

11.3 Academic conferences and meetings

14-15 June 2016: Energy systems conference 2016: 21st Century Challenges, London, United Kingdom.

14-18 November 2016: 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, Lausanne, Switzerland.

30 January – 3 February 2017: Energy Scenario Winter School, Trifels, Germany.

17-20 October 2017: Swiss Competence Centre for Energy Research School, *Shaping the energy transition* (SCCER School 2017), Engelberg, Switzerland.

5-7 September 2018: The 5th European Conference on Behaviour and Energy Efficiency (Behave 2018), Zurich, Switzerland.

3-5 April 2019: Annual conference of the Network of Early Career Researchers in Sustainability Transitions (NEST 2019), Lisbon, Portugal.

12 Curriculum Vitae

Name	Lukas Braunreiter
Date of birth	30th August 1990
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Education

2017 – today	Doctoral student at the Department of Environmental Systems Science (D-USYS) at the Transdisciplinarity lab (TdLab), ETH Zurich
2014 – 2015	Master of Science in Environmental Policy and Management, University of Bristol, UK
2010 – 2013	Bachelor of Arts in History, Geography and Political Science, University of Zurich
2003 – 2009	Kantonsschule Zug
1998 – 2003	Primarschule Oberägeri

Professional experiences

01/2017 – today	Research associate at the Institute for Innovation and Entrepreneurship, ZHAW, Winterthur
09/2015 – 12/2016	Research assistant at the Institute for Innovation and Entrepreneurship, ZHAW, Winterthur
04/2014 – 08/2014	Research associate Museum Burg Zug, Zug
07/2013 – 11/2013	Employee cantonal archaeology department, Zug
04/2010 – 09/2010	Retail employee Coop, Zug
10/2009 – 04/2010	Swiss military service