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SPECIAL FEATURE: ORIGINAL ARTICLE

The politics of making and un-making (sustainable) futures

Futurizing politics and the sustainability of real-world experiments: what role for innovation and exnovation in the German energy transition?

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Abstract
The German energy transition towards more sustainable forms of energy production has been characterized as a large-scale or real-world experiment. Whereas experiments are open-ended processes set up explicitly to allow (or even generate) surprises, by contrast sustainability implies the pursuit of clearly defined, normative ends. Whereas much of the literature on system transformation builds on the concept of innovation, our hypothesis is that focusing on the "natural" flipside of innovation—called here "exnovation," i.e., departing from unsustainable pathways—should also be seen as a valuable conceptual strategy for coping with the tension between the unavoidable indeterminacy resulting from unknown risks and the necessary amendment and redefinition of goals and rules. In this paper the German energy transition (*Energiewende*) is used to exemplify the recursive processes of experimentation that make it possible to accommodate surprise, and, thus, to conceptualize the unavoidable tension between innovation and the maintenance of older, unsustainable structures.

Keywords Futurization · Transformation · Innovation · Exnovation · Real-world experiment

Introduction

Futurizing politics by conducting real-world experiments can be a meaningful way to envision sustainable societies and to prepare policy making for a journey with unknown outcomes. One policy field well-suited to bring politics into the future is the sociotechnical system of energy production. The German energy turnaround, or energy transition (*Energiewende*), can be regarded as such a field. In this article we argue that analysis of the futurization of politics for sustainable futures implicitly builds on the idea of innovation, of novel lifestyle changes, and of novel approaches to spatial planning (cf., Felt et al. 2016; Völker 2017). This clearly entails a bias towards the new, i.e., innovation. However, as we will illustrate in this essay, the transformation towards sustainability can also be addressed in terms of what needs to be done away with to fully establish the new. Such processes have been called "exnovation" (cf. Kimberly 1981; Gross and Mautz 2015). Following this logic, the process of futurizing politics to establish sustainable futures needs to include getting rid of the old on a par with adding new ideas, practices, and technologies through experimental strategies. Therefore, not to focus on the innovation side of sustainability transformation alone and to have a concept that goes beyond the mere phasing-out of existing technologies and practices, it seems important also to develop an exnovation-focused approach to the "experimental" futurization of politics for sustainability.

Furthermore, an important part of the sustainability literature conceptualizes processes toward sustainability as based on experimental approaches (among others, see Bulkeley et al. 2016; Hodson et al. 2018). In the context here we use

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the notion of real-world experiments (Gross et al. 2003; Gross and Hoffmann-Riem 2005; van de Poel et al. 2017) since it has been established in many fields ranging from the clean-up of contaminated sites (Bleicher and Gross 2016), urban planning (Reinermann and Behr 2017), genetically modified crops (Levidow and Carr 2007), geo-engineering (Factor 2015), the gradual implementation of smart grids systems (Lösch and Schneider 2017) and waste management (Krohn 2007) to sustainability science (Caniglia et al. 2017), ecological restoration (Gross and Hoffmann-Riem 2005) and geothermal energy operations (Gross 2016).

In the present context, the notion of real-world experiments is used to frame processes of exnovation which, like many innovations, are changes to the energy production system that cannot be simulated in a scientific lab but need to be conceptualized as part of the real world. The modifier "real-world" indicates that these experiments take place in everyday social contexts, potentially including the lives of many people, plants, and animals as well as landscapes and entire ecosystems; they thus differ fundamentally from scientific experiments that are conducted in laboratories and are protected from undesired outcomes, the aim being to experience and understand an unknown process of change pursued by specific means (Gross and Hoffmann-Riem 2005). Real-world experiments are generally less controllable than experiments in a laboratory, this being mainly due to boundary conditions that may vary during the course of a given experiment or between different settings. However, they can be rendered as "real" experiments since (controlled) surprises are a crucial aspect of experimentation more generally.

The next section of this article brings together literatures on exnovation and real-world experiments to garner a better understanding of the experimental character of exnovation. Our initial understanding of exnovation builds on the definition put forward by Kimberly (1981) who focused on the organizational level of processes involving the replacement of once innovative medical equipment by new equipment and the emergence, through this, of new treatment practices. Here, we use the notion of exnovation to focus not only on organizational issues but on entire energy production systems, namely, carbon-based and nuclear energy. The question we pose is this: if innovation-oriented processes can be conceptualized as experiments to highlight the freedom to try out new technological inventions, how can exnovation be understood in similar terms?

Among other goals, the German energy transition seeks to achieve more sustainable forms of electricity production. Picking up on certain elements of this example, our framework sheds a more differentiated light on processes of energy transition by focusing not solely on the introduction of new ideas but also on strategies for getting rid of old ones. In the process we address the exnovation of nuclear power production, contrasting it with the emergence of renewable electricity production (innovation) and comparing it to developments in the exnovation of coal and lignite-based electricityproduction.

Much of the literature on energy transitions takes for granted that exnovation is a process that follows innovation. In the context of our case study this seems reasonable, as almost 40% of German electricity production is based on renewables. However, the process of winding down coal and lignite-based electricity generation seems to have stalled, with the system still operating on about 45% of coal and lignite-based power production alongside other sources (German Federal Environmental Agency 2017). This means that, even though Germany has managed to increase its rate of renewable energy production, the country will most likely fail to achieve its goal of reducing 40% of its CO_2 emissions compared to 1990 by 2020, as stated in its sustainability strategy (Cabinet of Germany 2002).

To analyze this paradoxical situation, the following sections are structured as follows. The first part focuses on nuclear energy production in Germany, introduced in post-WWII Germany to meet industry's increasing energy demands. Our account will describe how this new technology was introduced by the German government as a modernizing option and how, soon after its emergence, large parts of German civil society objected to nuclear power because they considered it too risky and unsustainable (Renn and Marshall 2016). The second part of the case study looks at renewable energy innovations introduced with the German feed-in tariff, while the third part addresses the not yet implemented exnovation of coal and lignite-based energy production in Germany. The respective outcomes are then discussed in the paper's final two sections.

Framework

Despite its strong focus on innovation, recent literature on sustainability and system transformation has sought to provide a more detailed understanding of exnovation as a process that helps us move towards more sustainable futures (e.g. Gross and Mautz 2015; Heyen et al. 2017). Central to the dominant view of the transition towards sustainability is the normative aim (contested in society) to produce knowledge that serves the creation of more sustainable futures (e.g., ISSC and UNESCO 2013). The idea is to use such knowledge to underpin the energy transition away from nuclear and carbon-based generation and towards more sustainable forms of electricity production. The concern behind this is to reduce the health-related risks and the reduction of biodiversity relating to emissions from coal and lignite-based electricity production and to avert the possibility of a nuclear meltdown and the ongoing production of radioactive waste. Alongside the introduction of innovative

technologies, this also involves processes of exnovation in a wide range of transformation-relevant arenas such as energy, climate, habitats, and social and economic policymaking (David 2017). The question that arises, then, is how best to conceptualize exnovation processes in relation to the notion of real-world experimentation (see Introduction above).

Originally, the term exnovation was used to describe the process of abandoning obsolete bureaucratic practices in public administrations (Yin 1979) and the replacement of medical equipment to enable new treatment methods (Kimberly 1981). Recent medical literature therefore refers to exnovation as a deliberate, planned organizational process of removing and replacing specific medical equipment along with the operational practices and management processes associated with the equipment (see, e.g. Bynum et al. 2018; Kaplan et al. 2018, and the liteature cited therein). Although exnovation has been associated with advances in the medical field that involve fundamental changes in medical organizations, interest has grown in viewing exnovation processes as a vital part of any transition towards sustainability, that is, away from unsustainable practices and their related technological systems. This is the aim pursued in energy transitions (among many other see Arnold et al. 2015; Heyen et al. 2017). While studies on exnovation in the medical field had an organizational focus, literature on the transformation towards sustainability looks at a more complex setting, namely, society as a whole and the various agendas and organizations of collective and individual agency which compete and interact with one another.

Some literature sees the exnovation of coal and nuclear energy as supporting future-oriented planning processes and a consensual approach toward compensating potential losers (e.g. Heyen et al. 2017; Wehnert 2017). However, for the reasons stated above, we argue that exnovations of electricity producing systems can, at least to a certain degree, be characterized as part of real-world experimentation processes. Literature on real-world experiments recognizes that experimentation is central to the transition towards sustainability. This is because the aim of experimentation is to generate knowledge and experience capable of informing the transition toward a sustainable future in a real-world context (Hopkins and Schwanen 2019; Sengers et al. 2016; Weiland et al. 2017). At a very general level, we would argue that real-world experimentation is not a sign of flawed implementation but rather an essential element of technological innovation and, as we argue here, of exnovation as well, which is perhaps just as important as the latter. In the present context, we understand real-world experiments as operations based on recursive practices that may develop, through a more or less evolutionary process, into actual strategic planning and institutionalized strategies that in turn may include the design of procedures and—of particular relevance here—the continuous adaptation, monitoring and feedback of results (cf. Gross et al. 2003). These feedback processes can be depicted as a cycle of real-world experimentation where an experimentally developed solution to a problem or the design of a new type of technology for electricity production leads to an "innovation" whose evaluation and subsequent observation is inextricably linked to the question of what has to go (see Fig. 1).

In this way, exnovation can be conceptualized as part of a recursive or iterative cycle guided by the discovery of ever new technological options. Such a cycle entails coping with knowledge gaps (brought to awareness, for example, by surprising turns of events) and accommodating new actor constellations and interests as well as new forms of knowledge production that help the actors involved become aware of the flipside of innovation. This knowledge is needed to improve processes of transition toward sustainability (see Fig. 1). Knowledge about the many different systemic functions,

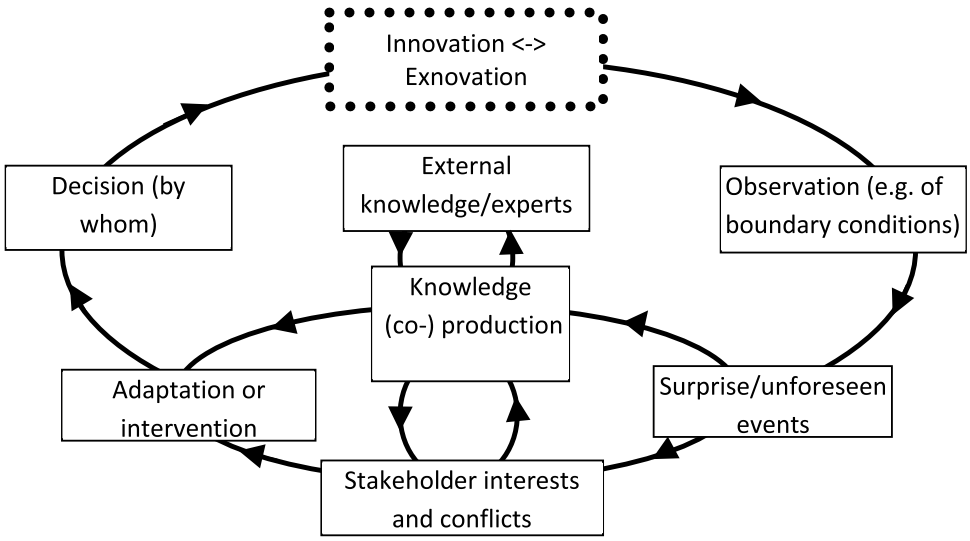

Fig. 1 A recursive design cycle of real-world experimentation developed from Gross et al. (2003). At the end of a given cycle stands a decision about whether a technology, a product or a process needs to be innovated further

causalities, and dynamics that determine the outcomes of experiments can differ from system to system.

Literature on real-world experiments has related these uncertainties to specific systemic boundary conditions. These give rise to a point at which pursuing the aim of an experiment—here, to create specific knowledge around a given innovation or exnovation—becomes a challenge due to a limited understanding of the system's dynamics. Identifying the boundary conditions of a real-world experiment, i.e., the extent to which a process such as innovation or exnovation is accepted by society, is a complicated affair: while the boundary conditions of technical systems are human-made and can be influenced, those of ecological systems can change during the experimental process (cf. Gross and Hoffmann-Riem 2005; Layzer 2008).

The embedded setting as well as the complex interplay of societal systems such as agriculture (Prové et al. 2018), built environments (Muller 2018), mobility (Akyelken et al. 2018), and energy production (Rohracher 2018) are vulnerable to the surprise of unforeseen events which might change the functional conditions of sociotechnical systems. This may occur when the boundary conditions of a given objective, which were assumed to remain stable over long periods, change, thus representing a new challenge or even making the objective obsolete. Unforeseen events might therefore change long-term planningscenarios for sociotechnical systems. Such events might be manifested in unforeseen impacts on sociotechnical systems or ecological systems or both.

However, potential conflict and controversy among stakeholders arise from the unforeseen and, especially, unintended effects generated during processes of real-world experimentation need to be understood as a normalcy. Such processes might yield new expertise and new knowledge and are incompatible with an understanding of the transition to sustainability as a specifically planned, long-term process (cf. Gross and Schulte-Römer 2019). The concept of real-world experiments also recognizes that actively envisioned processes of change can fail and that not letting go of desired goals can cause damage and loss and, as a consequence, conflict and controversy. Planned long-term processes are generally associated with external knowledge production by experts, prior existing knowledge and processes of imitation based on real-world experiments in other settings (cf. Howaldt et al. 2017).

Keeping in mind the aim of futurizing politics for sustainable futures, the above comments remind us that even though the technological resources and expert knowledge exists to place certain objectives within reach, these objectives might themselves undergo processes of adaptation through experimentally produced surprises. However, to make the best out of a surprise, it is important to be able to control the surprising event as a basis for learning. Unprecedented events in experimental processes, as Rheinberger (1997: 134) noted, "come as a surprise but nevertheless do not just happen. They are made to happen through the inner workings of the experimental machinery for making the future." After all, it often remains unclear how experimental processes may unfold over time, how unforeseen events might change the course of an experiment and, consequently, whether and how boundary conditions may change (Gross 2016). Furthermore, different ideas about possible futures might contradict one another and potentially produce not only winners but also losers, thus leading to controversy.

Nevertheless, deciding in favor of a specific exnovation pathway may represent a challenge. Potential losers might seek to inhibit or slow down innovations which endanger their specific future, as has been highlighted in the energy transition literature (e.g. Leipprant and Flachsland 2018). They might also oppose the exnovation of specific practices, infrastructures or services being adapted to the demands of a sustainable future because it means losing their job, power, business or an identity shaped by (energy) practices which become impossible to implement after exnovation (e.g. Johnstone and Stirling 2015; Heyen et al. 2017). Therefore, when looking at the following case studies, it is important to consider the conflict and controversy arising from exnovation as being related to ways of experimenting with potential sustainable futures. This means that policymaking needs to support the freedom to experiment by naming and assessing the risks that go hand in hand with futurizing new opportunities through trial processes of exnovation.

The following three sections present three case studies on the German energy system. The first deals with the development of nuclear energy and the reasons which led to the public announcement of the exnovation of nuclear energy production in Germany. The second depicts dynamics in the development of renewable energy innovations, and the third is focused on the exnovation of the coal and lignite-based energy production system. Each of these case studies seeks to shed light on how exnovation can be successfully articulated once sustainability becomes a strong narrative of an envisioned future and how policymakers might respond.

The exnovation of nuclear energy production as a failed innovation

In post-war Germany nuclear electricity generation was seen as a way out of the impending coal crisis, which occurred as a consequence of the restructuring of the country's steel and coal market. Nuclear energy was promoted by a strong coalition consisting of the federal government, leaders in the energy industry and scientists to guarantee the energy supply of a rapidly growing economy (Lauber and Jacobsson 2015). The establishment of the Federal Ministry for

Nuclear Affairs in 1955 by West Germany's chancellor Konrad Adenauer institutionalized this progressive post-war energy policy and suggested that control over nuclear technology meant control over the country's future. Committing to nuclear energy meant investing in a completely unknown technology with as yet unknown potential consequences. In this sense, it could be regarded as a real-world experiment that developed from a more evolutionary form of development to one of institutionalized design and learning (see Fig. 1).

The origins of nuclear technology lie in military-funded research conducted during WWII; as such, it was vehemently opposed by the post-war peace movement (Graichen 2003; Renn and Marshall 2016). The bias in energy technology development perceived by parts of the peace movement, combined with German policymakers' hesitation to also invest in other electricity generation technologies such as renewables to diversify electricity generation (Jacobsson and Lauber 2006) strengthened the German energy-oriented anti-nuclear movement: opposing the civil use of nuclear technology for electricity production, this part of the movement split from the main peace movement. It began to engage in intensive campaigning to oppose the planned construction of nuclear reactors (Graichen 2003; Radkau 2011). From the mid-1970s onwards, German anti-nuclear protest intensified over the nuclear controversy and at times turned violent. In 1971, for example, protests were held against plans to build nuclear power stations close to Bonn, Breisach, Esenshamm, and Neckarwestheim, and these protests reached their violent culmination in Whyl (Rucht 2008; Radkau 2011). In addition, demands were articulated towards policymakers to shift towards an ecologically safer technology as well as a more inclusive and participative mode of energy governance (Graichen 2003; Jasanoff and Kim 2013). Thus the motivation to stop the nuclear electricity experiment—at the time unwanted by a large segment of the German population—was framed within the possibility of replacement and therefore ultimately became tied to the concept of innovation.

After the unforeseen nuclear accident in Chernobyl in April 1986, itself often called a large-scale experiment (Krohn and Weingart 1987), parts of the German government and administration also began to reflect critically on the German nuclear energy program (Graichen 2003; Renn and Marshall 2016). It once more galvanized the anti-nuclear activists (e.g. Roth 1994; Lauber and Jacobsson 2015), who oriented their demands toward the exnovation of nuclear energy production, and opened up the policy arena for experimentation with renewable energies and funding schemes (Mautz et al. 2008).

In 2002 the coalition government of the SPD and the Greens elected in 1998, effected a policy shift that led to the first nuclear exnovation amendment, though it was later withdrawn by the first cabinet of Angela Merkel's (then still) conservative CDU party. The Fukushima nuclear crisis of March 11, 2011 gave rise to further intensive anti-nuclear protests and forced the second Merkel cabinet to officially declare the exnovation of nuclear electricity production by 2022. Also, the seven oldest nuclear reactors were taken off the grid. Since no blackouts occurred, as heralded in alarmist style by the nuclear industry, this can be considered a positive outcome of the real-world experiment with the exnovation of nuclear energy production, a policy decision based on experimental, real-world knowledge creation. Juridically resisted by the German nuclear energy industry, this also included the implementation of a tax on fuel rods as a means to finance its exnovation (Bartosch et al. 2014; Kungl and Geels 2018). The Federal Constitutional court ruled in June 2017, however, that industries should be given compensation for paying an unconstitutional tax (Federal Constitutional Court 2017).

Renewable energy innovations as alternatives to coal, lignite, and nuclear energy production

Although Germany's nuclear programprovoked early developments of renewable energies market regulation did not allow for the feed-in of energy generated by small scale electricity producers before 1991. Only from the 1970s onwards renewable energy groups emerged in Germany which experimented with "home-made" renewable energy solutions (Huber 1979). Although it has widely been taken for granted that renewables were developed on the basis of environmental considerations, the development of renewable energy generation during the 1970s occurred during a "latency phase" characterized by pragmatic considerations (Mautz et al. 2008: 43). For instance, in addition to environmental groups, farmers seeking decentralized energy solutions in rural, non-electrified areas also pushed this development forward, creating knowledge that was invaluable for further developments of this technology in later years (Jacobsson and Lauber 2006, Mautz et al. 2008). This demonstrates that innovations in renewable energy are based on knowledge created in different real-world experimental contexts which later formed the foundation for the narrative of renewable electricity production for a sustainable future (Mautz et al. 2008).

This experimental knowledge began to feed back into the policy cycle. In 1991 a tariff was introduced in Germany that enabled the feed-in of renewable electricity to the national grid. While this has been heralded internationally as a German success story of robust policymaking in the renewable energy sector, the origins of this law lie rather in the unfolding of unforeseen events. The draft bill was the work of two members of the German Bundestag, a member

of the Green Party and a member of the Christian Democratic Union, heavily lobbied by a coalition of renewable industry representatives (Mautz et al. 2008, Clausen 2017). As it turned out, the big energy industry groups which would have strongly opposed these developments did not pay much attention at first to this policy innovation which addressed the challenge of interlinking different energy systems because the issue of German reunification took priority at that time. As a result, they demanded its withdrawal too late and were unsuccessful (Jacobsson and Lauber 2006, Clausen 2017). In 1998 the EU directive 96/92/EG was introduced to liberalize the European energy market. It was implemented in Germany in 2000 with a modification of the existing feed-in tariff which, again, promoted renewable energy production. Consequently, smaller energy producing units were allowed to feed in. This trend towards decentralization was an important factor in the trial-and-error mode of knowledge production at the time.

Another important driver for innovation in decentralized renewable energy was the implementation of the German Co-operative Act in 2006, which allowed for a member-financed model for energy co-ops and required more transparent administration; this triggered a boom in energy co-ops in Germany (Blome-Drees et al. 2016). Whereas in 1995 Germany had 63 energy co-ops, in 2000 this number had already risen to 142 and was to grow progressively to reach 316 in 2006, 573 in 2009 and as many as 1747 in 2016 (Kahla et al. 2017). The energy industry reacted with counterstrategies, including legal challenges and diversifying into wind and gas-generated power (Kungl and Geels 2018). The introduction of the German Co-operative Act in 2006 differed to the introduction of the German feed-in tariff. It built on the experience and knowledge that innovation in small-scale renewable energy production can indeed take off when experimental regulations are implemented.

The non-exnovation of coal and lignite-based energy production in Germany

The fossil fuel supply crises of the 1970s and 1980s paradoxically established coal and lignite-based energy production in Germany even more firmly (cf. Renn and Marshall 2016) and led to rapidly rising fuel prices, which resulted in ever greater investment in lignite and coal as well as more support for nuclear energy research and development (Hatch 1986). This was to secure the provision of a cheap energy supply in the face of steadily growing energy needs worldwide (Laird and Stefes 2009). In other words, unlike in the other two case studies, in this specific case unforeseen events led to the closing down of space for experimentation for sustainable futures by the implementation of policy decisions biased towards fossil fuels and nuclear energy production regimes. To put it in a different way in reference to the illustration in Fig. 1 above, external (expert) knowledge and conflict-laden processes led to a business-as-usual approach.

Between 1979 and 1980, a roadmap was discussed in a Bundestag Enquete Commission on future nuclear energy politics, but its realization was found to be too risky from an economic standpoint (Bartosch et al. 2014). Even though this plan was rejected, and even though it relied on coal to replace nuclear, it represented the first introduction of the idea of substitution as an expression of the urge to exnovate unsustainable energy production technologies (Hennicke et al. 1985).

Ironically, while the motivation to exnovate nuclear energy production had already become established, in 1986 the Chernobyl accident additionally gave rise to a discourse of decarbonization in Germany when a statement was published by the German Society of Physics on the dangers of climate change based on worrying atmospheric observations (Beck 2012). In 1987 this issue was discussed by another Bundestag Enquete Commission on Climate Change in which the discourse that had previously focused on the reduction of nuclear energy alone was expanded to include CO_2 reduction (Laird and Stefens 2009). Even though the Kyoto Protocol came into effect at EU level in 2005 with the introduction of the European Union Emissions Trading System (EU ETS), current efforts to decarbonize the European energy system have proven to be insufficient (Leipprand and Flachsland 2018). In 2006, after an announcement of plans to construct new coal-fired plants, NGOs and civil society movements calling for the decarbonization of society started anti-coal campaigns and mounted occasional protests against coal and lignite-based energy production (Heinrich Böll-Foundation 2015; Sander 2017). This shows that although potential coal exnovation has long been debated in policy circles, unlike the anti-nuclear movement, the response from grassroots energy activists has come rather late.

After the Fukushima incident of 2011, and after publicly announcing the energy transition, the German government made plans for the construction of more coal-fired plants in the face of uncertainty over whether renewable sources would grow at a sufficient rate to fill the energy production gap left after an exnovation of nuclear energy production (Hüttl and Ossing 2011). This controversy between those favoring conventional electricity production and those opting for renewables intensified in the lead-up to COP 21 due to an emerging debate among publics, politicians and scientists about the electricity sector's contribution towards climate protection (Geels et al. 2016; Kungl and Geels 2018). Nevertheless, even though EU laws and international treaties remained a constant reminder to change national policy in favor of exnovation for sustainable futures, in 2015 an

initiative led by the Federal Ministry for Economic Affairs and Energy to cut emissions was rejected.

During the coalition negotiations between SPD and CDU the idea of a Commission on Growth, Structural Change and Employment (the so called coal commission) was established which in 2019 would consensually agree on the exact date of the coal exnovation by integrating perspectives from environmental NGOs, industries and the governing parties. In January 2019 it was decided to exnovate the last coal plant in 2038 and to compensate coal regions with 40 billion EUR This makes transparent the fact that the plan to exnovate coal and lignite-based energy production had a long way to go.

Discussion: how are exnovation and innovation related in experimental settings?

We have seen that the German government's nuclear powerful policy coalition for nuclear-generated electricity ignored the possibility of failure and the effects over time of public fears about disastrous accidents. One explanation for this behavior is that when real-world experiments bring about unexpected results, the actors involved often have little interest in exploring the reasons for what is often rendered as "failure." In real-world settings policymaking needs to be able to account for the possibility of failure and indeed to anticipate that it may happen. This is easier said than done, of course. In the case of nuclear power, this is exactly what happened, albeit only after disastrous events had occurred. In this regard, the phasing out of nuclear energy by policymakers can be regarded as the lateexnovation of a failed innovation experiment (cf. De Hoop et al. 2016).

The Chernobyl nuclear accident in 1986 led to growing societal dissent towards expert knowledge about nuclear power as well as deep-seated controversy over the future of the German energy system. Eventually, it gave rise to the idea of the exnovation of nuclear energy production. Up to now, the government's strategies for ensuring energy security in Germany have failed; the energy system has been harshly criticized publicly and continues to produce electricity in potentially life-threatening ways—and it has turned out completely different than planned. At the same time, it also reveals that unforeseen events are interpreted differently by different stakeholders of sociotechnical systems; the risk-averse pro-nuclear coalition and the risk-sensitive publics represented by the anti-nuclear movement demonstrate this. The case of nuclear exnovation thus also shows that decisions to adapt and implement energy policy that are based on experimental processes can become objects of contention. However, Fukushima seems to have had such a powerful impact that policymakers and publics alike have agreed on the exnovation of nuclear energy.

The German feed-in tariff system differed from policymaking on nuclear energy: renewable energy groups that emerged early on started applying existing experience and knowledge gained in the absence of state interventions and investment in renewables. It shaped the inclusive character of this evolving community, whose aim was to replace fossil fuels and nuclear power. The interplay of policy decisions to intervene in electricity regulation and existing knowledge enabled the generation of practical knowledge in diverse, independent local groups. The boom in decentralized energy solutions after the introduction of the feed-in tariff and its later modification might be characterized as a counter-transformation directed against centralized electricity solutions, given that they are perceived as competition by the large German energy corporations (Kungl and Geels 2018).

The turn towards decarbonization since the 1990s indicates that the significance of coal and lignite-based energy within a sustainable electricity production scenario has changed. Having initially been considered suitable for the purpose of securing energy supplies, it is now seen as an unsustainable energy source; this has enabled the idea of exnovation of unsustainable energy production to gain ground. Nevertheless, the policy coalition for coal and lignite, mentioned above, closed off policy options for climate protection by granting more certificates to emissions-intense industries including coal and lignite-based energy producers (Leipprand and Flachsland 2018). The nuclear case suggests that public protest can be understood as part of the recursive process of experimentation that may lead to exnovation. The concept of real-world experiments, as introduced above, acknowledges openly that total control and full knowledge of ecological systems and social processes are not possible and enables the development of forms of futurization that take into account knowledge gaps and uncertainties without disrupting the overall process.

While the co-production of knowledge between lay experts and accredited experts is typical for real-world experiments (see Fig. 1), it constitutes a major challenge if exnovation is viewed as a pivotal element of sustainability transformations. After all, the futurization of politics for sustainability might occur in a top-down manner, as was the case with the controversial law passed for the exnovation of nuclear energy. Even though coal and lignite-based energy production has been subject to intense debate since at least the mid-20th century, public protest has been rather insignificant compared to anti-nuclear protests (Heinrich Böll-Foundation 2015; David 2018).

But why was the public response to controversial energy policy in the coal and lignite case less influential than in the nuclear case? One explanation could be that, compared to the disasters caused by nuclear energy production, there have been no significant disasters—unforeseen or otherwise—associated with coal and lignite-based

energy production. This may, ironically, be a disadvantage, as shown by the indirect competition between nuclear and coal exnovation. Another explanation might be that the fossil fuel crises of the 1950s and 1970s further strengthened the existing path dependency on fossil fuels by triggering massive investments for the sake of supply security. Furthermore, in eastern Germany especially coal had never had the negative image of being dirty energy. It was seen as a source of wealth and a guarantee for jobs. In addition, it was mainly understood as a domestic source of energy that enabled Germany to be energy independent from sources imported from abroad (de Soto 2000).

The coal commission shows that German policy making aims for a consensual coal exnovation. Nevertheless, bearing in mind the past experience of civil society's opposition to nuclear electricity, it seems naïve to assume that coal and lignite exnovation will occur on the basis of a societal consensus. A consensual strategy was already implemented during the German nuclear energy crises since the 1980s (Graichen 2003; Mautz et al. 2008) but failed many times until Fukushima. Even though the commission shows that progress was made in the question about the exnovation of coal energy in Germany, this policy instrument is no guarantee for success as the problematic exnovation of nuclear energy showed. Any attempt at futurizing politics for a potential real-world experiment in exnovation therefore needs to include a willingness to make decisions which are opposed by specific segments of society.

What we also learn from the three cases is that their interdependence gives rise to constraints which in turn determine the options available for experimentation. Renewable energy innovations are replacing nuclear energy which itself was once the object of experimentation. Market prices for renewables have fallen dramatically and are competitive with those of fossil fuel-generated electricity—and they are expected to fall further (Couture et al. 2018). This competitive advantage might put further pressure on fossil fuels. But exnovation from nuclear energy is expected to increase innovations in renewable energy (Rogge and Johnstone 2017). The interrelationship between innovation and exnovation needs to be viewed together and understood as a mutually contingent pairing.

Paradoxically, the replacement of nuclear energy by renewables seems to be slowing down the exnovation of fossil fuel-based energy production, given that more renewable electricity production will be devoted to meeting the shortfall created by the exnovation of nuclear power production (Hüttl and Ossing 2011). This again underlines the interdependence between exnovation processes of different unsustainable energy production technologies and sustainable technologies, which one might only become aware of during crises caused by unexpected events.

Conclusion

By linking debates on exnovation with the notion of real-world experiments, we have been able to offer a framework that not only assesses the degree to which the German energy transformation can be characterized as a real-world experiment but which also shows how processes of exnovation can be conceptualized alongside processes of innovation in terms of a single recursive process. It is important to note that, in the case of nuclear energy, the initial idea was to transform the energy system and that goals to transform sociotechnical systems change over time. These changes have been framed as consecutive steps in a real-world experimental cycle (Fig. 1). Their outcomes, however, can also be interpreted in a different way. One reading is that, assisted by the feed-in tariff introduced in 1991, the co-production of knowledge regarding renewables supported the bias toward innovation in the debate about the energy transition by focusing solely on new sustainable ways of producing electricity. Another reading could be the recognition that exnovations need more time than innovations, and this for different reasons which might be embedded in cultural, technical and political path dependencies.

This reminds us that the futurization of politics is itself necessarily based on goals which might change in the course of time. To this end, exnovation can be conceptualized as a key element in experimentally coping with the tension between novel risks and conflicts between stakeholders and the amendment and redefinition of previously formulated goals. The German energy transition has served as a highly telling example to illustrate the unavoidable tension between surprise and goal orientation, but at the same time it has also drawn attention to the conflict between innovation and the maintaining of old and often unsustainable components in the current system. It is obvious that decarbonization policy lags behind actual decarbonization goals and that, to initiate a process of fossil fuel exnovation, there needs to be room for surprises (including failure) in decarbonization processes. This entails two aspects in particular. First, a vital step towards the futurization of politics might be a recognition of the importance of scenarios like exnovation to overcome the innovation bias in sustainability transformation thinking. Second, when envisioning exnovation, policymakers should seek to create co-produced knowledge and, in so doing, be more open to public sentiments and opinions. Constructively addressing controversies that develop either by not exnovating or by exnovating might be a vital asset in the futurization of politics for sustainability.

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