Energy Research & Social Science 1 (2014) 134–140

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

Rethinking the governance of energy infrastructure: Scale, decentralization and polycentrism

Andreas Goldthau [a,b,*]

[a] Belfer Center for Science and International Affairs, Harvard Kennedy School of Government, United States
[b] Department of Public Policy, Central European University, Hungary

ARTICLE INFO

Article history:
Received 22 January 2014
Received in revised form 25 February 2014
Accepted 25 February 2014
Available online 13 March 2014

Keywords:
Energy governance
Infrastructure
Polycentrism

ABSTRACT

Providing societies with reliable energy services, fighting energy poverty and mitigating climate change entail a crucial infrastructure component. Both the energy access and the low carbon challenge require more decentralized energy solutions and a change in the energy infrastructure paradigm. Yet, physical energy infrastructure co-evolves with socio-economic institutions, actors and social norms. This may produce inertia against change. The energy challenge also requires solutions at multiple scales and may entail elements of common pool resource problems. Therefore, the governance of energy infrastructure needs to be polycentric. This allows for contextualization, experimentation and innovation. The article concludes by sketching routes of further research into the energy infrastructure governance nexus in social science research.

1. Introduction

Ensuring reliable energy services, fighting energy poverty and mitigating climate change all entail a crucial infrastructure component. Across-the-board coverage requires integrated and interconnected energy infrastructure, whereas low carbon infrastructure solutions are highly localized, both in terms of energy supply and demand patterns. At the same time, energy infrastructure is characterized by the involvement of a vast number of actors, each coming with distinct and particular sets of interests; its impact on other sectors is significant due to sheer scope and scale [1]; it is subject to and interacts with a complex and multi-layered set of institutions, laws, regulations and policies; and its life span stretches across several decades. Balancing the need for large scale infrastructure with local and contextualized solutions therefore presents an unprecedented governance challenge. What is more, governance arrangement will need to remain open to learning and to adapt to changing environments, in order to keep energy infrastructure resilient. In other words, governance arrangements susceptible to facilitating energy access and low carbon transition need to be dynamic rather than static. This warrants a rethink of the governance of energy infrastructure.

This article discusses three key features in the academic literature pertaining to energy infrastructure and governance: the embeddedness of physical energy infrastructure within and its co-evolution with socio-economic institutions, regulatory agencies, incumbent market actors and social norms; multiple scales in sustainable infrastructure solutions; and elements of common pool resource problems. Therefore, as this article argues, the governance of energy infrastructure needs to be polycentric. This allows for contextualization, experimentation and innovation, which can lead to sustainable infrastructure solutions and learning across scales.

As a corollary, a polycentric approach may offer a promising way to further investigate the energy infrastructure conundrum. Given the scope and breadth of the existing literature, this article is not in a position to provide a comprehensive review of the pertinent works in this field, nor does it aspire to revolutionize energy governance research. Instead, it aims at providing pointers to crucial aspects in infrastructure governance and deliberately makes a choice in arguing that infrastructure problems should be primarily seen in the context of the energy access and low carbon challenge. This makes energy infrastructure part of the global fight against energy poverty and climate change, and hence subject to a multi-scale governance challenge.

The next section defines energy infrastructure and briefly reviews the literature on infrastructure governance. Section 3

* Correspondence to: 79 John F. Kennedy Street, Cambridge, MA 02138, United States. Tel.: +1 617 495 8739.
E-mail address: andreas@goldthau.com

http://dx.doi.org/10.1016/j.erss.2014.02.009
2214-6296/

elaborates on infrastructure as socio-technical systems, followed by a discussion of the scale dimension (Section 4) and common pool resource aspects in infrastructure (Section 5). The last section concludes by sketching routes for further research into energy infrastructure governance.

2. Defining the energy infrastructure and governance nexus

A functioning energy infrastructure – more precisely, the service it provides – is essential to modern societies. Energy infrastructure electrifies homes, heats houses, connects producers and consumers in a market, and transports energy carriers of high calorific content across countries or whole regions. In short, it is essential for the functioning of the economy and for maintaining welfare. Energy infrastructure also forms a significant part of a country's capital stock. According to a recent McKinsey study, the value of a country's overall infrastructure stock (including energy but also roads or waterways) on average amounts to 70% of its GDP [2].

As a corollary, in order to maintain or improve existing energy infrastructure, the public and private sectors need to spend considerable amounts of money. As the International Energy Agency (IEA) estimates, some USD 1.6 trillion or 1.5% of global GDP are needed per year until 2035 to meet demand and existing policy goals [3]. If additional pressing challenges such as fighting climate change and providing access to the energy poor are to be met, this number will even go up. Tackling the energy poverty challenge, which essentially consists of providing 1.3 billion people with access to modern energy services, will add an increment of USD 1 trillion in cumulative investment until 2035 [4] (see also Van de Graaf, Bazilian and Nakhooda in this special edition [5]). An additional USD 16 trillion of energy-related investment, a significant share of which into infrastructure, is required to decarbonize energy production and use, and to stabilize concentrations of greenhouse gas emissions at 450 ppm, the benchmark concentration of CO_2 for avoiding the worst consequences of climate change [3].

This article therefore focuses on key elements that characterize energy infrastructure as part of a larger energy system, and deliberately discusses the energy infrastructure and governance nexus in the context of energy access and the low carbon challenge. For the purpose of this article we define governance as the institutions, mechanisms and processes through which economic, political and administrative authority is exercised. This definition builds on an extensive literature arguing that governance has gone beyond government, and acknowledges the important role that private actors and civil society play in policy making (pars pro toto see [6–8]). Importantly, governance as an analytical concept allows studying arrangements that are non-hierarchical, multi-level or network based, and acknowledges the high degree of complexity facing modern policy problems – such as the ones surrounding energy infrastructure.

Energy infrastructure comprises the physical infrastructure required for producing, transforming, transmitting, distributing and storing energy. As a research object, energy infrastructure has received great attention, and a comprehensive review of existing works would be beyond the scope of this article (a Google Scholar search on the term produced 1,970,000 hits in January 2014).[1] By contrast, the literature referring to energy infrastructure as a governance challenge seems to be restricted to a few key themes. One strand of the available literature focuses on project governance. These works tend to center on the planning and implementation of large scale physical infrastructure. As studies show, complicated decision making processes may lead to delay or failure in energy megaprojects, such as pipelines or nuclear power plants [9,10]. Such projects involve multiple stakeholders and actors, which calls for 'effective governance' of infrastructure in order to cope with coordination problems. This literature ties back into the governance of large scale infrastructure projects (see, for instance, [11]).

A related strand of works focuses on challenges surrounding opportunistic behavior due to displaced agency. Here the emphasis is on contracting and how to properly govern public–private partnerships, and for political and regulatory risk (see, for instance [12]). Adopting yet another perspective on infrastructure, certain studies inquire into the governance of networks. These works are most interested in the distribution and transmission of (energy) infrastructure. Related, some works also conceptualize energy as systems, with infrastructure playing an important role in facilitating energy flows within the system [13,14]. Increasing attention is paid to governance for critical infrastructure protection, particularly on behalf of key energy authorities, such as the EU, which are concerned about their infrastructure's resilience against shocks or cyber attacks [15]. Energy infrastructure governance has also come to be analyzed with regard to its crucial role in disaster management and development [16]. In conceptual terms, research on critical infrastructure protection embraces the notions of diversity, resilience and interdependence among key actors [17].

In all, the existing but limited literature on energy infrastructure governance is mainly interested in managing large scale network projects, handling contractual relations between public and private parties or critical infrastructure issues. The governance of energy infrastructure, however, needs to go beyond existing agendas and include the goals of providing for comprehensive energy access and fighting climate change. Defined this way, the governance of the energy infrastructure nexus comes with the additional normative requirement of contextualizing energy infrastructure solutions so that the latter are able to contribute to global energy policy goals.

3. Socio-technical systems and the call for decentralization

Infrastructure is part of larger contexts – economic sectors (e.g. transport), national markets (e.g. for electricity) or a specific industry (e.g. photovoltaic). It is therefore important to view infrastructure as evolving with and being shaped by factors other than technology. As an important strand in innovation research has shown, technology co-evolves with institutions, societal actors and policies, eventually forming socio-technical systems (pars pro toto see [18–20]). This obviously also holds true for the physical components of technology. Conceptualizing infrastructure in general and energy infrastructure in particular as socio-technical systems is helpful in that it points to their embeddedness within the surrounding environment.

Numerous examples, such as Hughes' seminal study on the evolution of the US electricity sector, illustrate that large technological systems (LTS), such as energy networks, are deeply intertwined with the overall structure of society [21]. In fact, it is this very socio-economic and normative embeddedness that makes an LTS work properly in the first place and allows it to evolve further [22]. This, in turn, also implies that technological systems change in conjunction with changes in society and the economy, with impulses going both ways. As a corollary, the deep embeddedness of energy technology within the surrounding environment may lead to resistance

[1] There obviously exist strong differences between the types of infrastructure required for different energy fuels (such as oil, coal or biofuels) or sources (primary sources such as hydrocarbons and secondary sources such as electricity or refined energy products). This article however deliberately abstains from discussing them separately. Instead, common elements are stressed, notably scale, socio-technical systems and CPR problems.

to fundamental change, and lock-in occurs. On the one hand, lock-in may exist with regard to individual technologies [23]. For instance, as Keck has shown for the case of the nuclear sector, initial regulatory settings and policy choices solidify into lasting arrangements, favoring one technology over the other [24]. Lock-in may, however, also affect the whole system. In this case, the main patterns of the energy system persist and prove resilient to input from outside, particularly in the context of the climate change challenge [25].

To be sure, lock-in or 'stickiness' does not have to necessarily be bad. Obvious benefits include increasing returns of scale and reduced costs, along with a robustness against external shocks. Under ceteris paribus conditions, an incrementally evolved energy system may in fact offer the optimal answer to certain types of vulnerability. A case in point are strategic petroleum stocks which protect consumers against supply shocks and provide for protection against a key threat in a world relying on fossil fuels. On the other hand, however, locked-in technological systems risk becoming incapable of reacting to fundamental change. Incremental change then remains the norm and outlived technologies tend to be maintained although they no longer provide for appropriate responses to key challenges. This is, for instance, vividly demonstrated by the continuing existence of nuclear energy in Western countries despite an obvious lack of economic performance and serious human security related drawbacks.

Most important in the context of energy infrastructure, lock-in may perpetuate the centralized patterns of technology, socio-economic institutions and physical infrastructure, which co-evolved over decades. This is especially problematic in the power sector. According to IEA estimates, the sector in 2010 accounted for 38% of global primary energy demand, and relies by up to 75% on fossil fuel input [3]. This makes the power sector and its infrastructure an important target for low carbon policies. Historically, national and subnational energy infrastructure used to be built around a central converter (aka power plant), and grid networks would distribute the generated electricity (and heat) to energy end consumers. Yet, the carbon challenge requires a rethink of the centralized and by and large fossil-based approach to energy provision.

In fact, decentralized systems are believed to offer numerous advantages over centralized ones. According to the IPCC, this includes reduced costs for transmission systems, efficiency gains and lower grid loss, enhanced reliance on distributed generation involving local small scale providers, and a larger share of renewables in the local energy mix [26], 288. Decentralized energy systems are also believed to be more innovative, because of the need for producers and operators to specialize, the necessity to find solutions tailored to local contexts and the opportunity of mutual learning. This may prove particularly important in the context of rural areas with differing local endowments of wind, solar or fossil fuels. In addition, decentralized systems may come with the benefit of enhanced resilience, not the least because they are less exposed to grand or cascading failures of centralized networks [27]. In short, decentralizing energy systems, infrastructure and networks can be regarded as an essential element of low carbon transition.[2]

Conceptualizing energy as a socio-technical system suggests that there will be significant inertia against leaving established centralized patterns in energy infrastructure. This is not only because of sunk costs into building up physical facilities. It is also because the energy industry co-evolved with a centralized type of infrastructure, legislation is geared toward dealing with it, and policies have been put in place to regulate network related risks. Policy makers obviously have become aware of this [28]. Still, if the analytical assumptions presented above hold, change is unlikely to happen at the pace necessary or, indeed, at all.

How inertia in established energy infrastructure patterns can prevent change is clearly demonstrated in the context of the German *Energiewende*, the first effort of an industrialized country to comprehensively decarbonize its energy system. The infrastructure of the power sector, a key element in Germany's low carbon transition, has been designed to provide for state- (or *Laender*) level electricity coverage typically produced by coal fired or nuclear power plants. As a consequence, electricity infrastructure is both centralized and wired into sub-federal levels of regulation, where incumbent utility companies such as RWE or EnBW dominate power production and distribution. Yet, the *Energiewende* requires both decentralizing production and strengthening federal level transmission infrastructure to deal with peak load problems across states. This not only goes against the interests of key players in the energy industry, but also does not dovetail with the socio-economic characteristics of the incumbent energy system. So far, therefore, the 'sticky' character of German power infrastructure proves to be a major obstacle to implementing the country's ambitious decarbonization goals.

4. Scale

This brings us to another crucial aspect in the energy infrastructure conundrum: scale. As common discussions surrounding wind turbines, transmission lines or storage facilities suggest, energy infrastructure has a strong local component. Costs arising from allegedly spoilt natural landscapes, potential pollution or noise immission are local, often triggering local "Not in my Backyard" (NIMBY) effects. At the same time, energy infrastructure is barely restricted to the local level. To the contrary, it typically spans municipal and provincial boundaries and easily also transcends national jurisdictions. For instance, power transmission lines typically connect regions within national energy markets. Pipelines, such as the BTC which connects Caspian oil fields to Western European markets, even stretch across several countries. And because energy infrastructure by definition involves production, storage, transformation and distribution, various individual but closely interconnected elements easily scale up to complex regional infrastructure systems.

Depending on the regulatory setup, energy infrastructure may be simultaneously part of several scales. A case in point are offshore wind farms that plug into local distribution networks, which themselves form part of a bigger electricity market infrastructure regulated by national agencies. Supranational bodies such as the EU may require national transmission infrastructure to connect and integrate, which makes our offshore wind farm also part of a European network, at least for the few hours power is physically traded across national jurisdictions. This may not only raise questions regarding trading infrastructure, but also of grid stability.

Scale, therefore, becomes a key element in determining how to go about infrastructure challenges. As pointedly observed by Sovacool and Brown, "*how* we regulate something is almost as important as *what* we regulate" [29], 317. In other words, and slightly paraphrasing Butler and Macey's *Matching Principle* here, the scale of the infrastructure challenge should determine the appropriate governance level for responding to it [30], 25. Because physical energy infrastructure exhibits both a strong local dimension, and a provincial, national or even regional/supranational dimension, various scales need to be taken into account when designing regulatory answers and setting up governance arrangements.

[2] While the power sector provides for the most evident example, this also obviously holds true for individual mobility, which despite ongoing efforts keeps on relying on combustion engines (albeit more efficient ones) and the related infrastructure (roads, filling stations, etc.).

To be sure, not all pertinent energy infrastructure challenges require thinking in terms of multi-scale answers. Above mentioned decentralized energy systems, which have gained prominence both in the context of fighting climate change and of alleviating energy poverty, tend to be restricted to local scale. Green front runner cities such as Southwestern Germany's Freiburg, for instance, resume the role of regulators, providers and promoters of solar, wind, hydropower, and biomass as locally produced energy sources. Their ultimate goal is to decouple their municipal energy system from centralized infrastructure and sources (i.e. nuclear or coal) and to increase resilience (see [31–33] for more conceptual elaborations). Off-grid solutions in Developing Africa or rural India rely on local energy production and storage, involving locally available energy sources such as solar, wind, hydro but also geothermal or biofuels. Interconnectors facilitating reverse flow of natural gas between two countries primarily involve national policy levels, with the involvement of the local scale by and large being a function of the population density at the location where the infrastructure is physically constructed. And regional infrastructure such as the Nordstream pipeline transiting international waters in the Baltic Sea, primarily remained subject to international regimes such as the International Maritime Organization, besides limited involvement of adjacent countries.

Still, most challenges surrounding energy infrastructure provision and governance simultaneously involve various scales. This is because of the above mentioned interconnectivity of various crucial elements of the energy system. As a consequence, actions and governance arrangements would ideally span local, national and regional levels, and involve them simultaneously to the degree they can contribute to addressing a specific challenge and contribute to sustainable solutions.

Unsurprisingly, however, governance arrangements typically do not address all scales simultaneously. Regulatory entities often take choices without coordinating them with neighboring, higher or lower governance levels. Referring to the previous example of the *Energiewende* again, Germany's infrastructure needs are by and large seen as a national level project, without much attention being paid to Europe-level implications, or negative effects on neighboring countries. This has already led to spill-overs to adjacent provinces in Poland, the Czech Republic and the Netherlands, causing grid stability problems there [34].

A coordinated approach on the European level might alleviate some of the problems that come with a national level approach to sustainable energy infrastructure. Still, as existing studies show for the case of climate regimes, each level of intervention comes with different sets of costs and benefits. In other words, taking a choice on the regulatory level may come with severe trade-offs [29]. Whilst local intervention increases flexibility with regards to the policy answer, it may come with the downside of lacking consistency on a national or regional level. In other words, the scale component of energy infrastructure essentially points to a multi-level governance challenge.

5. Common pool problems

Finally, in addition to constituting a socio-technical system involving multiple scales, infrastructure has been described as a common pool resource (CPR). This opens up an important complementary angle for rethinking the governance of energy infrastructure. Common pool resources are goods that exhibit rivalry and non-excludability in consumption, i.e. resources to which consumers have almost unlimited access, which in turn, because these resources are ultimately limited, may lead to their destructive overuse. Typical and often-cited examples of CPRs are fish stocks, forests or the atmosphere.

Famously, Hardin coined the term 'tragedy of the commons' to describe the paradoxical situation when the rational self-interested strive for individual benefit leads to collective disaster [35]. Contemporary examples of the 'tragedy of the common' include the extinction of certain marine species due to overfishing, the disappearance of the Amazon rain forest because of large scale logging or climate change related to the 'overuse' of the global carbon sink. Challenges of CPRs, therefore, essentially center on regulating access and a fair distribution of costs and benefits among consumers of ultimately finite goods. In a joint article, Nobel prize winner Elinor Ostrom once called the effective management of CPRs "one of the most difficult tasks facing modern public policy" [36], 74. Unsurprisingly, therefore, common-pool resource problems have received wide attention in the scholarly literature [37–40].

Infrastructure can arguably also be regarded as a common-pool resource. For instance, urban infrastructure may exhibit characteristics of a CPR because it involves the central problem of renewal over consumption, and the question who pays for periodic maintenance and repair [41]. Künneke and Finger explicitly refer to energy infrastructure, which is key to delivering essential services to society, as a common pool resource [42]. They argue that whilst it is difficult to monitor access and use of, for instance, electricity infrastructure (the non-excludability criterion), power networks require load and capacity management and voltage control depending on the number of users (the rivalry criterion) [42], 6. Therefore, individual consumption and use of electricity infrastructure and its services may come with negative repercussions for the whole system if done in an unsustainable way.

Blomkvist and Larsson offer an interesting and promising addition to the concept of infrastructure as a CPR [43]. They argue that infrastructure can be simultaneously conceptualized as a common-pool resource and a large socio-technical system. They use the examples of Swedish roads to show that local infrastructure maintenance as a CPR challenge (aka the 'renewal' problem) confluences with infrastructure being composed of technology, institutions and various public or private actors. This links the CPR concept back to the socio-technical nature of infrastructure discussed above. It also reminds us of the importance of scale for the discussion of infrastructure governance.

Interestingly, changes in energy paradigms had an impact on infrastructure governance, notably, the switch from the public utility to the liberal market model during the 1980s and 1990s [44]. This has arguably made energy infrastructure even more prone to CPR problems. Whilst policies following the public utility model were designed to provide for across-the-board coverage with energy services, the push for more liberalization of the energy sector required energy services to be unbundled from infrastructure, and led to restructuring of the sector [45]. 'Traditional' energy infrastructure, i.e. vertically integrated firms covering the entire supply chain including its physical components, gave way to more "hybrid modes of organization and diffuse property rights structures" [42], 7 (for more detailed discussions see [46]).

The liberalization model has also left its mark in the development sphere. Mechanisms such as global best practice, advocated for by the EU, the World Bank or other key players in policy transfer, have introduced the principles of liberalization and unbundling to Developing Countries and have made them adopt the liberal paradigm [47]. This push toward the market model in energy has not only increased the number of involved actors and the levels of regulation; it has also enhanced the need for coordination among and between them.

6. A polycentric approach to energy infrastructure governance

Summarizing the above discussion, several key elements in the energy infrastructure nexus form a specific call on governance: scale, i.e. the existence of several regulatory levels; the need to think of solutions in context, notably with regards to decentralized energy production; the common pool issues of access and overuse; and stickiness, a function of the co-evolution of technical and institutional structures. This paper therefore advances the argument that a "polycentric" approach is an appropriate way of conceptualizing effective governance infrastructure governance.

In essence, polycentric approaches blend scales and engage multiple stakeholder groups [48], 216. A system that exhibits polycentric characteristics simultaneously comprises multiple levels and decision making bodies, which allows generating and distributing information at multiple scales. At the same time, involved regulatory units retain a certain degree of independence to make choices relevant and pertaining to the geographical area in which they operate [36]. A polycentric approach therefore goes beyond multi-level analyses of hierarchy, autonomy and accountability and incorporates the notions of inclusion and learning. Because polycentric governance systems mesh scales they may also foster policy experimentation on various levels, rendering the system overall more innovative. As Ostrom argues, this may lead to more effective and sustainable outcomes, and may reduce some problems related to the provision of collective goods [49].

Whilst polycentric approaches have initially received great attention in studies on local or regional common pool problems such as the local management of pasture or irrigation systems, they have gained prominence in research on the 'global commons', notably the oceans, the atmosphere and – strongly related – climate change (see also Pasqualetti and Brown, and Falkner in this special edition [50,51]). So far, energy infrastructure has not been extensively investigated from a polycentric angle, although it shares characteristics with global or local commons. For one, it spans across multiple scales. As discussed above, both centralized and decentralized electricity networks form part of national or regional grids. But even off-grid solutions are far from being independent of other scales, as they are part of a larger energy infrastructure ecosystem. Implementing local off-grid energy systems in, say, rural Africa crucially depends on a learning curve and experience gained in other world regions.

Moreover, advances in technology render energy systems and infrastructure increasingly complex, now comprising individual smart meters, distributed generation and various different energy sources feeding into one grid, in addition to networks becoming increasingly integrated across national borders and hence jurisdictions (at least in some world regions such as Europe). Decisions taken on the level of investment, the type of technical solution and the mode of regulation on each scale therefore matter for the stability and resilience of the overall infrastructure, and for its ability to respond to sudden changes such as shocks. Such complex systems not only call for information sharing across scales and jurisdictions as well as among involved actors (public or private) in order to provide for efficient overall solutions; they also crucially rely on mutual learning that is not based on formalized and centralized structures fostering it. The latter would simply prove inefficient to foster the type of coordination that is needed to foster learning and policy innovation.

Given their scope and scale, energy infrastructure systems comprise multiple governing authorities and actors at differing scales. Polycentrism therefore offers a promising lens to rethink the governance of energy infrastructure with a view to facilitating a low carbon future, and to successfully put in place the type of energy infrastructure that is needed to make it happen. To be sure, certain world regions already exhibit elements of polycentric energy infrastructure governance. For instance, the EU's push for integrating national energy networks has led to complex arrangements in which coordination occurs across provincial and national jurisdictions, with actors including national regulators, TSOs, interest groups or civil society associations.

What is more, a polycentric approach is not without problems. Adopting a multi-tiered approach to governing infrastructure systems may prove slow and produce less-than-optimal choices on governance levels [36], 78. Relying on overlapping levels of jurisdiction and regulation may also give rise to blame games across governance levels in the case the infrastructure fails or does not get implemented at all [48], 238. In this case, obviously, there may exist a trade-off between the accountability criterion and the goal of adopting inclusive governance arrangements.

Still, three elements are likely to further exacerbate the need for a polycentric approach to analyzing energy infrastructure. First, the more the liberal paradigm informs national or regional energy policy, the more the number of involved actors is likely to increase, and so does the complexity of regulation. Key world regions such as the EU clearly keep on pushing the liberalization agenda, and even China has started to introduce – though reluctantly – elements of liberalization in the domestic energy sector [52]. Second, decarbonizing the global energy infrastructure will imply a push for more decentralized generation. This will not only require decentralized and 'smart' infrastructure solutions, but also provide energy actors with multiple simultaneous roles as they will become both producers and consumers of energy. This in turn also raises questions of the 'buy-in' of crucial actors and the legitimacy of decisions surrounding novel infrastructure. Third, and related, the energy access agenda calls for solutions that are both tailored (i.e. contextualized and local) and work (i.e. provide for or profit from a learning curve elsewhere). Whilst many developing countries currently follow the traditional model of fossil fuel based and centralized across-the-board coverage, thinking in terms of polycentricity would open up possibilities for these countries to embrace more effective solutions at various levels, and to share their experience among peers. In all, existing trends in energy infrastructure point to the need for adopting a novel approach to governance research, and polycentrism offers a promising avenue.

7. Implications for energy research in the social sciences

What is it that a research agenda based on a polycentric approach can offer? As the above discussion has shown, three distinct elements are crucial when thinking about energy infrastructure: the deep embeddedness of energy infrastructure in larger socio-technical contexts; scale, i.e. infrastructure spanning across multiple and interconnected regulatory levels; and common pool type problems, raising the question of ownership in the use and replenishment of infrastructure. These elements need to be seen in the context of the nature of reliable energy services, the energy access challenge, the need to decarbonize the energy system (and infrastructure with it). None of this necessarily merits a theory of its own.

But research into energy infrastructure governance can certainly profit from a number of questions arising from a polycentric perspective. For one, it would be interesting to investigate how polycentric systems deal with stickiness, and whether more polycentric energy infrastructure governance provides an answer to lock-in problems. Research along these lines can possibly be informed by the rich and ongoing research on climate governance, particularly the works conceptualizing the climate challenge as multi-scale socio-ecological systems (see also Hodbod and Adger's contribution on social–ecological resilience in this special edition [5]). Empirically, countries embarking on low carbon energy transition provide rich case studies for studying changes in infrastructure governance from a polycentric angle. Cases include US states such as California but also Japan or Germany. In fact, the German *Energiewende* is one of the rare occasions when social scientists can investigate empirical phenomena in real time. It provides for an almost lab-type situation to study the emergence, success or possibly failure of various governance arrangements in energy infrastructure.

Second, an important question to investigate would be when multi-scale governance arrangements work, and under what circumstances they deliver – or not. As argued earlier, not all energy infrastructure projects are equally multilevel in terms of governance. Localized energy solutions for rural areas in developing nations, for instance, may profit from learning curves elsewhere. But adopting multi-scale governance arrangements may at the same time involve trade-offs and impact on a timely implementation of the necessary infrastructure. Interesting research may therefore evolve around comparative investigations particularly in the development context. Analyzing the energy access challenge in rural India, Developing Africa or in South East Asia promise to provide for additional insights into the factors that made (local) energy infrastructure solutions a success, and to what extent these solutions where embedded in contextualized and polycentric arrangements.

Third, energy infrastructure provides for promising case studies on how innovation and learning occurs within complex systems and across scale. Whilst existing works by and large only postulate that polycentric systems have positive effects on innovation and learning, energy infrastructure – comparably tangible and accessible research objects – offers interesting test cases for the innovation hypothesis. The same holds true for coordination among a multiplicity of actors and governance levels. Particularly large scale energy infrastructure projects such as networks spanning across jurisdictions offer a rich opportunity to better understand the processes and mechanisms of coordinating across and between governance levels – including issues related to dispersed agency. This dovetails well with CPR related problems. Investigating energy infrastructure with a view to common pool issues will therefore also add to our knowledge on whether a polycentric approach in fact helps alleviating CPR problems in more general terms.

Obviously, these are only starting points of further social science research into energy infrastructure governance. As the select avenues of research above however demonstrate, polycentrism can provide input for analyzing the complex governance of energy infrastructure which, in turn, may help generate viable policy prescriptions for implementing infrastructure projects.

References

[1] Sovacool BK. What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. Energy Res Soc Sci 2014;1:1–29.
[2] Dobbs R, Pohl H, Lin D-Y, Mischke J, Garemo N, Hexter J, et al. Infrastructure productivity: how to save $1 trillion a year. McKinsey Global Institute; 2013.
[3] IEA. World energy outlook 2012. Paris: OECD; 2012.
[4] IEA. World energy outlook 2013. Paris: OECD; 2013.
[5] Hodbod J, Adger N. Social–ecological resilience in energy systems. Energy Res Soc Sci 2014;1:226–31.
[6] Rhodes RAW. The new governance: governing without government. Polit Stud 1996;44(4):652–67.
[7] Peters BG, Pierre J. Governance without government? Rethinking public administration. J Public Adm Res Theory 1998;8(2):223–43.
[8] Rosenau J, Czempiel EO. Governance without government. Order and change in world politics. Cambridge: Cambridge University Press; 1992.
[9] Sovacool B, Cooper CJ. The governance of energy megaprojects: politics, hubris and energy security. London: Edward Elgar; 2013.
[10] Ruuska I, Ahola T, Artto K, Locatelli G, Mancini M. A new governance approach for multi-firm projects: lessons from Olkiluoto 3 and Flamanville 3 nuclear power plant projects. Int J Proj Manag 2011;29(6):647–60.
[11] Miller R, Lessard DR. The strategic management of large engineering projects: shaping institutions, risks, and governance. Cambridge, MA: MIT Press; 2000.
[12] Hodge GA, Greve C. Challenge of public–private partnerships: learning from international experience. Cheltenham: Edward Elgar; 2005.
[13] Hughes L, Ranjan A. Event-related stresses in energy systems and their effects on energy security. Energy 2013;59:413–21.
[14] Coutard O, editor. The governance of large technical systems. Oxford: Routledge; 2002.
[15] Perks J, Hyde J, Falconer A. Study on risk governance of European critical infrastructures in the ICT and energy sector. Oxfordshire: European Commission; 2009.
[16] UN ESCAP. Enhancing regional cooperation infrastructure development including that related to disaster management. New York: UN ESCAP; 2006.
[17] Farrell AE, Zerriffi H, Dowlatabadi H. Energy infrastructure and security. Annu Rev Environ Resour 2004;29(1):421–69.
[18] Geels FW. Technological transitions as evolutionary reconfiguration processes: a multi-level Perspective and a case-study. Res Policy 2002;31(8–9):1257–74.
[19] Geels FW, Kemp R. Dynamics in socio-technical systems: typology of change processes and contrasting case studies. Technol Soc 2007;29(4):441–55.
[20] Tunzelmann NV. Historical co evolution of governance and technology in the industrial revolutions. Struct Change Econ Dyn 2003;14:365–84.
[21] Hughes TP. Network of power: electrification in Western society, 1880–1930. Baltimore: Johns Hopkins University Press; 1983.
[22] The evolution of large technological systems.Hughes TP, Bijker WE, Hughes TP, Pinch TJ, editors. The social construction of technological systems: new directions in the sociology and history of technology. Cambridge, MA: MIT Press; 1987. p. 51–82.
[23] Arthur WB. Competing technologies, increasing returns, and lock-in by historical events. Econ J 1989;99(394):116–31.
[24] Keck O. Government policy and technical choice in the West German reactor programme. Res Policy 1980;9(4):302–56.
[25] Unruh GC. Understanding carbon lock-in. Energy Policy 2000;28(12):817–30.
[26] Sims REH, Schock RN, Adegbululgbe A, Fenhann J, Konstantinaviciute I, Moomaw W, et al. Energy supply. In: Metz B, et al., editors. Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge/New York: Cambridge University Press; 2007.
[27] Buldyrev SV, Parshani R, Paul G, Stanley HE, Havlin S. Catastrophic cascade of failures in interdependent networks. Nature 2010;464(7291):1025–8.
[28] Altman M, Brenninkmeijer A, Lanoix J-C, Ellison D, Crisan A, Hugyecz A, et al. Decentralized energy systems. Brussels: European Parliament, Committee on Industry, Research and Energy (ITRE); 2010.
[29] Sovacool BK, Brown MA. Scaling the policy response to climate change. Policy Soc 2009;27:317–28.
[30] Butler HH, Macey JR. Externalities and the matching principle: the case for reallocating environmental regulatory authority. Yale J Regul 1996;14:23–66.
[31] Coaffee J. Risk, resilience, and environmentally sustainable cities. Energy Policy 2008;36(12):4633–8.
[32] Pickett STA, Cadenasso ML, Grove JM. Resilient cities: meaning, models, and metaphor for integrating the ecological, socio-economic, and planning realms. Landscape Urban Plan 2004;69(4):369–84.
[33] Aber G, Kern K. Governing climate change in cities: modes of urban climate governance in multi-level systems. In: OECD, editor. Competitive cities and climate change. OECD conference proceedings. 2008.
[34] Buchan D. The Energiewende – Germany's gamble. Oxford: Oxford Institute for Energy Studies; 2012.
[35] Hardin G. The tragedy of the commons. Science 1968;1243–1248(162).
[36] Andersson KP, Ostrom E. Analyzing decentralized resource regimes from a polycentric perspective. Policy Sci 2008;41(1):71–93.
[37] Dietz T, Ostrom E, Stern P. The struggle to govern the commons. Science 2003;302(5652).
[38] Ostrom E, Burger J, Field CB, Norgaard RB, Policansky D. Revisiting the commons: local lessons, global challenges. Science 1999;284(9):278–82.
[39] Ostrom E. Governing the commons: the evolution of institutions for collective action. Cambridge: Cambridge University Press; 1990.
[40] Martin LL. Heterogeneity, linkage and commons problems. In: Keohane R, Ostrom E, editors. Local commons and global interdependence: heterogeneity and cooperation in two domains. London: Sage; 1995. p. 71–91.
[41] Little RG. Tending the infrastructure commons: ensuring the sustainability of our vital public systems. Struct Infrastruct Eng 2005;1(4):263–70.
[42] Künneke R, Finger M. The governance of infrastructures as common pool resources. In: WOW4 workshop. 2009.
[43] Blomkvist P, Larsson J. An analytical framework for common-pool resource–large technical system (CPR–LTS) constellations. Int J Commons 2013;7(1):113–39.
[44] Goldthau A. From the state to the market and back. Policy implications of changing energy paradigms. Global Policy 2012;2(S2):198–210.
[45] Hira A, Huxtable D, Leger A. Deregulation and Participation: an international survey of participation in electricity regulation. Governance 2005;18(1):53–88.

[46] Finger M, Künneke RW. International handbook of network industries. The liberalization of infrastructure. Cheltenham: Edward Elgar; 2011.
[47] Keating MF. Re-thinking EU energy security: the utility of global best practices for successful transnational energy governance. In: Kuzemko C, et al., editors. Dynamics of energy governance in Europe and Russia. Basingstoke: Palgrave Macmillan; 2012.
[48] Brown MA, Sovacool BK. Climate change and global energy security: technology and policy options. Cambridge: MIT Press; 2011.
[49] Ostrom E. Polycentric systems for coping with collective action and global environmental change. Global Environ Change 2010;20(4):550–7.
[50] Pasqualetti MJ, Brown MA. Ancient discipline, modern concern: geographers in the field of energy and society. Energy Res Soc Sci 2014;1:122–33.
[51] Falkner R. Global environmental politics and energy: mapping the research agenda. Energy Res Soc Sci 2014;1:188–97.
[52] Andrews-Speed P. Perspectives on the governance of energy in China. J Resour Ecol 2010;1(2):135–44.