



Review

Energy materiality: A conceptual review of multi-disciplinary approaches

Margarita Balmaceda^{a,*}, Per Högselius^b, Corey Johnson^c, Heiko Pleines^d, Douglas Rogers^e, Veli-Pekka Tynkkynen^f

^a School of Diplomacy and International Relations, Seton Hall University, South Orange, NJ, 07079, USA

^b Division of History of Science, Technology and Environment, KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden

^c Department of Geography, Environment, and Sustainability, UNC Greensboro, PO Box 26170, Greensboro, NC, 27403, USA

^d Research Centre for East European Studies, University of Bremen, Klagenfurter St. 8, 28359, Bremen, Germany

^e Department of Anthropology, Yale University, Box 208277, New Haven, CT, 06511, USA

^f Aleksanteri Institute, University of Helsinki, P.O. Box 42, 00014, Finland



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ABSTRACT

This jointly authored essay reviews recent scholarship in the social sciences, broadly understood, that focuses on the materiality of energy. Although this work is extraordinarily diverse in its disciplinary and interdisciplinary influences and its theoretical and methodological commitments, we discern four areas of convergence and divergence that we term the *locations*, *uses*, *relationalities*, and *analytical roles* of energy materiality. We trace these convergences and divergences through five recent scholarly conversations: materiality as a constraint on actors' behavior; historical energy systems; mobility, space and scale; discourse and power via energy materialities; and energy becoming material.

1. Introduction

Since the founding of *Energy Research and Social Science* in 2014, the journal has published more than fifty articles that include “materiality” in the title or abstract. Many more take up this topic implicitly, as in recent special issues on energy infrastructure [1] and the spatialities of energy [2]. Nearly all of these studies participate in a multidisciplinary, decades-long effort to re-materialize the concept of energy in the wake of the abstractions that accompanied the concept's nineteenth-century origins as the “the capacity to do work”—a definition that intentionally elided all manner of differences among energy sources, scales, and efficiencies [see esp. 3]. This rematerialization has, however, now come to span such a daunting range of theoretical, methodological, disciplinary, and interdisciplinary approaches to energy materiality that it defies the possibilities and conventions of a standard, single-author review essay. Our response to the massive heterogeneity surrounding what has clearly become one of the key terms in energy studies is, therefore, unconventional: a multiple-author review essay in five parts that crisscross our diverse disciplinary backgrounds (geography, anthropology, history, and political science) and our interests in material aspects of energy and energy systems (infrastructures, energy sources, human-environment relationships, and much more).

We emphasize at the outset that this article does not identify some

Archimedean point at which all of these various approaches to energy materiality converge. This is not for lack of effort on our part. As we conceived, circulated, and commented on multiple drafts of this article, we periodically stopped to ask ourselves whether we were distilling an essence of energy materiality, either in a small number of intersection points within the existing literature we were reading—published in ERSS and elsewhere—or as a single desideratum toward which we might direct future research. Instead, we came to understand energy materiality in current scholarship as a “chaotic concept,” one that, in the spirit of Andrew Sayer's formulation “cover[s] an enormous variety of activities which neither form structures nor interact causally to any significant degree” [4]. Although Sayer, some of our readers—and, in other contexts, some of us ourselves—would prefer to rationalize, distill, or otherwise decree order out of chaos, we have found it fruitful to concentrate mainly on tracing out and explaining to one another the labyrinthine paths that current scholarship on energy materiality is taking. We feel that our collaboration in this spirit has moved the rapidly proliferating conversations about energy materiality toward greater mutual intelligibility, creative recombination, and cross-fertilization. We offer this review, then, not as a distillation but as a moment to take stock of one crucial, chaotic corner of the interdisciplinary, human-centered, theoretically robust conversations engaged so centrally in *Energy Research and Social Science* [see 5].

* Corresponding author.

E-mail addresses: balmaced@fas.harvard.edu (M. Balmaceda), perho@kth.se (P. Högselius), cmjohns8@uncg.edu (C. Johnson), pleines@uni-bremen.de (H. Pleines), doug.rogers@yale.edu (D. Rogers), veli-pekka.tynkkynen@helsinki.fi (V.-P. Tynkkynen).

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After introducing four main questions that guided us and providing a concrete example to ground the subsequent discussion, our review begins in Section 2 with a range of conversations that understand the materiality of energy to be a constraint on actors' behavior. Section 3 turns to theories of technical complexity in energy systems, drawing attention to the role of history and materiality in energy-related risk, vulnerability, and security. This discussion leads us to consider theories of space, scale, and mobility in Section 4. Section 5 acknowledges the importance of discourse and power, particularly from the related points of view taken in Actor-Network Theory (ANT), assemblage, and governmentality/energopolitics approaches. Finally, Section 6 takes up a set of ways in which energy materiality can be understood as mutable, contingent, and in constant state of becoming.¹ A brief conclusion draws together the approaches we have covered.

1.1. Four questions: areas of convergence and divergence

Our conversations to date focused on four areas of convergence and divergence, phrased here as four crucial questions we asked of the literatures we read and debated.

- 1 Where is energy materiality *located*? Some perspectives look to the physical characteristics of energy sources themselves, while others see materiality in energy infrastructure such as pipelines. Still other approaches look to more broadly-defined energy infrastructures, including the roads, schools, and athletic stadiums often built by energy companies. In the widest lens we consider, all manner of semiotic connections may be relevant to understanding and theorizing the intersection of energy and materiality.
- 2 How is energy materiality *used* and *by whom*? An exceedingly wide variety of answers to this central question have been explored in recent scholarship, among them: to enable or constrain access and actions; to support—in discourse and practice—different agendas; to exercise various forms of political power or to imagine alternatives to them.
- 3 What are the *relational characteristics* of energy materiality? Energy materiality is defined in large part by relationality, at multiple spatial and temporal scales. However, we discern very different perspectives on the units that are related to each other and the nature of their relationships. Some theorists focus on objects, chains of objects, or channels through which objects move, others on spatial/territorial or temporal/historical relationships, and still others on discursive or semiotic relationships. Relationality can be highly determined or highly contingent, and it can also be considered as part of a constellation of material/immaterial relationships that define reality. This question is especially important—although not always in the same way—for scholars interested in identifying causal linkages of energy materiality.
- 4 What *analytical role* does energy materiality play in different approaches? For many scholars, energy materiality is just a scope condition—a given, constant factor that does not need to be considered in the analysis. For those who do focus their attention on energy materiality, it can be an independent variable that is a causal factor, a dependent variable that needs to be explained in its own right, or a constraint that is treated as an intervening variable impacting the object of study. For still others, material aspects of energy systems are themselves the actors or agents with which we should be concerned.

Each of the following sections notes how the scholarship it reviews is situated within these four areas of convergence and divergence.

¹ Space prohibits us from taking up still other dimensions of recent work on energy materiality, such as new approaches to energy that take a historical materialist approach [e.g. [6,7]].

1.2. Dorothe's boiler: a grounding example

Approaches to energy materiality are useful because they improve our understandings of particular, real-life situations. To supplement and ground our four primary questions, then, we begin with the thick description of a single case, a strategy that has helped us hold together our conversations. Sections 2–6 will then refer back—as our own conversations did—to this example in order to illustrate the ways in which the different approaches we outline illuminate different elements of a single, real-life experience.

Our example is drawn from the real-life experience of Dorothe Poggel, one of the staff members of the Hanse-Wissenschaftskolleg (HWK), a residential Institute for Advanced Study in Delmenhorst, Germany at which this article was initially drafted in June 2018. The context for Dorothe's experiences is as follows: the depletion of the Dutch Groningen gas fields and the increasing awareness of the environmental impact of their decades-long exploitation has sent Germany looking for replacement sources to supply Delmenhorst and the rest of the northwest. Among these new sources will be Russian gas, which has a higher energy content than Groningen gas.

Even before this transition to new gas supplies happened, however, Dorothe was forced—to the amusement of her co-workers and visiting fellows—to take showers at work for a period of weeks after the boiler in her apartment was shut off, sealed, and marked with a large red tag. She told us how her showers at work were related to the coming transition in gas supplies: “The energy provider goes around and checks every single device that runs on gas, to make sure it has a fabrication sign and fabrication number that shows the company. Mine didn't. ... Plumbers inspect the boiler for CO2 emissions and general safety every year, but they don't care about technical details.” Without the fabrication information that the additional inspection required, it was not permissible to retrofit the boiler to run on Russian gas rather than Dutch gas, so the boiler was turned off and sealed.

Dorothe's story didn't end with the red tag. The boiler looked exactly like a German Vaillant, but the lack of a fabrication number meant that it was a fake, probably built cheaply in southeastern Europe and impossible—or at least so she was told—to retrofit safely. The episode also led Dorothe into a legal dispute with her landlord, who claimed that the amount by which she had reduced her rent for having no heat or hot water was simply unpaid rent and warranted eviction. RadioBremen TV learned of the story and arrived to film a short segment that featured Dorothe boiling water in her electric kettle, the renter's legal association backing up her claims against the landlord, and a *Wesernetz* spokesperson explaining that the utility's technicians were just following safety procedures and European Union regulations when they shut off and sealed the still-working and certified-safe boiler with the transition to Russian gas still at least a year away.² “Just because something is technically possible, that doesn't mean that it's allowed. We have to pay attention to what is permissible as well as to what is technically safe,” the spokesperson emphasized.

“It's a funny story,” Dorothe concluded, “it really set a lot of things in motion.”

2. Materiality as a constraint on actors' behavior

This section takes up the scenario of Dorothe's gas boiler ordeal by focusing on contributions and perspectives emphasizing energy materiality as a constraint on actors' behavior. This is by no means a coherent, single literature, but comes from a variety of disciplines and looks at different “loci” – from “things” in general to specific characteristics of specific types of energy to their related infrastructure.

² The segment can be found at <https://www.butenunbinnen.de/videos/gasumstellung100.html> (Accessed 1 August 2018).

What these various contributions have in common, however, is an understanding of the material characteristics of natural resources as creating framework conditions for (human) actors' behavior. Attention to these issues puts it in the realm of a family of perspectives emphasizing inanimate goods' agency and ability to set constraints on human actors.

2.1. Loci of material agency

At the most basic level, we have theories (mainly coming from cultural theory, sociology and philosophy) of the agency of inanimate goods, and how these operate in social life and affect human-material interactions [8,9], how humans and things "co-constitute" each other rather than being fully separate [10], as well as raising key questions regarding the agency of both animate and inanimate beings [11–13]. A somewhat less deterministic strand of this perspective is represented by those who focus not so much on things' "agency" per se, but on how "how nonhuman actors" and infrastructures "structure the choices of human actors (...)" [14]. Although not every author discussed here makes specific reference to a theory of agency as foundational to their approach, an understanding of some level of agency of inanimate objects is a key building block for views emphasizing resources as constraints on human activity and choices.³ In this sense, this approach is related to the perspectives of ecological economists such as Cleveland and Hall who, working from a biophysical economics perspective, have emphasized the biophysical constraints on human economic activity specifically related to reliance on high- or low-entropy resources, which affects the degree to which energy sources can actually be transformed into end-use energy services such as electricity, heat, and transportation [15,16]. (In a low-entropy situation with a high degree of order, there is often a high degree of capacity to produce work, while in high-entropy situations a lot of the energy source cannot be transformed to other forms of energy.) At a higher level of specificity concerning the locus of the attention, stands the literature on natural resources as not always molding to human desires to use them for their own purposes. As shown in Bakker's [17] study of water privatization in the UK, the material qualities of a resource may complicate attempts by stakeholders to use it for their own goals. (Anand [18] takes a slightly different approach by focusing on how politics, physics, and technology shape water supplies.) In addition to the literature on water, the social sciences literature on "fugitive resources" (sometimes also called "high exclusion cost" resources [19]) makes an important contribution to this strand of thinking, as it highlights how resources such as wind and water [20], which move across jurisdictions, may complicate human actors' attempts to "capture," or monetize them.⁴

As energy *infrastructure* becomes politicized more often than the materiality of energy sources themselves, it has received more attention in the social science literature. At the same time, some of the most visible social science (especially political science) literatures dealing with energy exhibit an extreme case of taking materiality as a given constraint – by simply not addressing it at all. A key example comes from the rentier state and resource curse family of theories in the social sciences. Both approaches start from the assumption that natural resources, most prominently oil, provide a state with huge windfall profits that then have a variety of negative consequences on the domestic political system [for a summary of the related literature, see [23]].

³ Although not belonging to the same perspective, this could be related to a broader discussion on human-material interactions also including discursive and semantic aspects in the "making" of energy and nature. See Section 6 below.

⁴ The concept of "fugitive resources" has also been used by economist and property rights theorists, but in that context emphasizing the fact that these are resources that "must be captured prior to being allocated" [21, see also 22] rather than their jurisdiction-fleeing capacity.)

However, the focus is on windfall profits ("petrodollars") received, not on the conditions which are needed to make these windfall profits happen. As a result, aspects of energy materiality are ignored, as, despite their having a huge impact on the realization of large-scale exports, they do not directly affect the export revenue received once export facilities are in place.

2.2. Infrastructure and the politicization of energy materiality

At a higher level of specificity concerning the locus of attention, some perspectives within this larger trend focus their discussion of energy materiality not so much on energy resources themselves, but on the infrastructure needed to make them into energy services used by end-consumers, in particular transportation infrastructure. In this perspective, it is this infrastructure which provides key constraints on actors' behavior. In line with seeing materiality as not always molding to human desires, most of the political science literature refers to materiality as a given constraint, which either renders specific infrastructure projects unfeasible or requires political strategies to adjust to them. At the same time, the choice between different infrastructures is in many ways linked to politics and political decision-making processes. We will illustrate this by looking at two examples of how energy materiality may be politicized.

2.2.1. Politicizing energy materiality I: oil and gas pipelines

The first example concerns oil and gas pipelines. The perceived long-term relevance of Russian gas supplies to Germany, for example, which is illustrated by the change in suppliers for Dorothe's household, is the major rationale behind the decision to build the NordStream pipeline, which runs from the Russian to the German coast of the Baltic Sea. As the example of NordStream demonstrates, such links can be highly controversial. Already in 2006 the Polish defense minister compared the German-Russian pipeline agreement to the Ribbentrop-Molotov (Hitler-Stalin) pact. The US government warned in May 2018 that the construction of NordStream 2 could draw US sanctions [on the NordStream example see Ref. [24].

The (political) feasibility of different pipeline routes, for natural gas as well as oil, is an important topic in the international relations literature and especially for geopolitical approaches. In this context, pipelines are seen as international projects with at least three major functions: provision of income for exporting and transit countries, provision of energy security for importing countries, and creation of strategic partnerships between the countries involved [25]. The latter aspect also includes competition between "great powers" over these strategic partnerships and also over securing long-term access to energy resources and political influence in the respective region. This is currently visible in the academic literature on the so-called "New Great Game", which describes the rivalry among Russia, China and the US/EU over access to oil and gas resources in the Caspian region [26–28, a critical review of major books on the issue is provided by 29, for a global perspective see 30].

As the creation of links between countries is at the center of attention, the literature on pipelines and energy infrastructure has a strong spatial dimension. The advantages of competing pipeline routes in terms of technical feasibility, economic profitability, and foreign policy implications are regularly discussed in the literature. Obviously, the materiality of energy resources has a strong impact on at least the first two aspects, as Balmaceda [31] has shown in detail. Most authors would probably agree with her elaborations. However, they simply (and nearly always implicitly) treat energy materiality as given. As Sovacool [32] argues: "Many in the energy policy community, and even perhaps some geographers, treat pipelines as black boxes (or in this case, round pipes) that merely distribute hydrocarbons." Similarly, even in situations where there has been a dramatic change in how energy materiality impacts the transport options for an energy resource – for example the rise of liquid natural gas (LNG) reducing dependence

on pipelines – the literature has adjusted to focus on these new conditions as scope conditions, i.e. not as explaining factor which needs to be analyzed, but as a constant factor, a constraint. Geography, however, is more aware of the constraints territoriality creates, including how those constraints depend on different forms of materiality [see, e.g., the case of LNG in 33].

2.2.2. Politicizing energy materiality II: Nimbyism

A second example of how energy materiality may be politicized concerns opposition to large infrastructure projects from local populations (first and foremost in industrialized countries) even in cases where there are no substantial damages or risks, because they are afraid of noise from construction sites, a deterioration of landscape aesthetics, or related declines in tourism or real estate value. This phenomenon has been, since the 1980s, termed Nimbyism (from “Not In My BackYard”). While the original perception of Nimbyism was negative, it has more recently also been linked to conservationist attitudes and local patriotism. However, in the context of energy materiality the major issue is – as Wüstenhagen et al. [34] summarize – that “it is increasingly recognized that social acceptance may be a constraining factor in achieving this target [of increasing the share of renewable energy]. This is particularly apparent in the case of wind energy, which has become a subject of contested debates in several countries largely due to its visual impact on landscapes.”⁵ A Google Scholar search indicates that more than half of all publications addressing the NIMBY phenomena are related to energy infrastructure, most prominently to wind turbines [an overview of the first two decades of writing on this topic is provided by 44,45].⁶ The relevance of the energy sector for Nimbyism can be explained by its spatial dominance. In Germany, for example, land used for the energy system accounted for almost 10% of total land cover in 2012 [46].

Another focal point for opposition to energy infrastructure projects – and for the social science literature analyzing it – is environmental damage and related risks. As these damages and risks make energy infrastructure controversial, they become subject of political (as opposed to purely business) decision-making. Examples discussed in the academic literature are oil spills, most recently the Deepwater Horizon accident [e.g. [47]], the siting of nuclear waste disposals [e.g. [48,49]] or mega-dams for hydropower [50]. In the cases of hydropower dams and large-scale open-pit coal production, the materiality of energy infrastructure not only causes environmental risks, but changes whole landscapes, often with the need to resettle complete villages. In this context Mathur [51, Ch. 2] has named a book chapter “Mining coal, undermining people”. The impact of energy infrastructure projects on indigenous people living in the respective areas has been discussed broadly [on the example of Russia, where the natural gas soon to serve the home of Dorothe will come from, see e.g. 52–55].

2.3. The linguistic turn and strategic use of materiality-related frames and narratives

When energy infrastructure projects meet opposition, debates emerge in the public as well as in closed circles of decision-makers. Since the linguistic turn of the social sciences in the 1980s, such debates are seen as a major part of political decision-making. The understanding of related debates or discourses in the political science literature is

⁵ For more nuanced (but not opposed) views see e.g. Graham et al. [35], Groth and Vogt [36], Musall and Kuik [37], Thayer and Freeman [38], Warren and McFadyen [39], Swofford and Slattery [40], van der Horst [41], Zoellner et al. [42]. For a broader discussion about the spatial aspects of changes in the energy mix see Bridge et al. [43].

⁶ Search conducted on 3 February 2018 with the search function provided by <https://scholar.google.com>: 37,300 hits for NIMBY and 19,200 hits for NIMBY + energy. NIMBY + “wind turbines” alone generates 8690 hits.

mostly seen as strategic, i.e. actors are seen as employing specific frames or narratives in order to gain support for their position, whereas a structural approach to discourse, e.g. following Foucault, perceives discourses as a constraint on actors. (The structural approach will be discussed in later parts of this review.)

A prominent example for strategic discourses is securitization, which describes a “speech act” meant to move an issue beyond politics as usual by turning it into a national security concern. “Extraordinary politics” are then justified to urgently deal with the “threat”. Once the comparison of the NordStream pipeline to the Hitler-Stalin-Pact had been accepted in the Polish debate about the pipeline, for example, arguments could no longer focus on the business rationale of the project or the impact on diplomatic relations with Germany, as the issue at stake had become a much bigger security-related one [for a critical assessment of this claim see [24]]. The securitization framework developed by the Copenhagen School [56] is often applied in energy studies [for a conceptualization see 57, related empirical studies are, e.g., 58–63].

2.4. A broader perspective on supply chains and networks

By treating energy materiality as a mere scope condition, a given constraint, the focus is on narrow policy issues while the broader societal implications are often ignored. One starting point for a broader perspective could be existing work (also scattered among several disciplines) bearing, most often implicitly, on how the materiality characteristics of an energy good affect its supply chains and the dynamics and relationships within that chain. Work bearing on these issues includes discussions on the impact of power density, in the sense of the land area needed for production of a set amount of energy [15,64,65] and its consequences; the role of workers given the production (for example diffuse vs. point-source resources [66]); and the handling and transportation requirements of various types of energy. Thus, in Mitchell’s argument about coal production in the first half of the twentieth century, the more cumbersome transportation of coal (requiring direct human intervention) as compared to oil gave workers in the industry a stronger power at key transshipment nodes, a higher sense of agency, and made it possible for them to forge alliances with workers in other areas of the economy, such as “miners, railwaymen and dockworkers, allowing them unprecedented power” [67]. These factors were preconditions for the political impact of coal workers as compared to those in less labor-intensive sectors such as oil. While the Global Production Networks literature (as well as related literatures on global commodity chains and global value chains) has recently started to discuss energy more explicitly [32,68], it has not discussed materiality (in the sense used here focusing on the physical characteristics of a good) explicitly (see Gibson and Warren for a possible exception analyzing timber and musical instrument manufacturing [69]). More recent contributions have highlighted how the materiality characteristics of an energy good may constrain actors’ options not only throughout the value chain, but through the particular types of supply chain challenges that they may help create, and the responses to these challenges. Thus, for example, one of the key supply-chain challenges related to natural gas’ material characteristics, those related to its high degree of networkness and need for costly dedicated infrastructure related to the need to manage pressure, have traditionally led to a rigid contractual system seeking to allocate risk between sellers and buyers over a longer-time horizon [70,71].

The scenario provided by Dorothe’s travails with her gas boiler provides a number of possibilities for implementing such an approach, which would pay special attention to questions such as the following: (1) what are the different physical qualities of L-gas and H-gas, and what did the replacement of the first by the second mean from that perspective? (2) What does one of the most important physical characteristics of natural gas as a whole, i.e., its gaseous nature under standard conditions, add to the question and the scenario? (3) To what

extent do these physical characteristics affect they work of the system *as a whole*? How do they interact with other issues, such as the difference in caloric value between L-gas and H-gas?⁷ (4) Most importantly, such an approach would ask: in which ways and through which artifacts did these material qualities constrain or enable human choices and behavior and the range of choices by human actors? — actors including not only the end user, but also natural gas distribution companies, German and European gas regulators, and natural gas importers and exporters.

Looking at one of these questions in exemplary fashion provides a clue as to the possible contributions of such a perspective. For example, a focus on natural gas' gaseous physical state adds a lot to the scenario. While the point has been made that natural gas' gaseous nature has an important impact on transportation options, as it is most efficiently transported by pipeline [72,73], the impact is actually even more basic: as it is lighter than air, natural gas without pressure would not only not move, but would also dissipate into the air, which makes managing pressure and keeping the various parts of the system in physical balance essential for it to function safely [70].⁸ This high degree of networkness (higher than in the case of solid fuels or even oil, the functioning of whose systems does not depend so essentially on fine-tuning pressure) required by natural gas had a number of implications for the changes set in motion by the replacement of L-Gas by H-gas in Northwestern Germany. It amplified the impact of the 20% difference in caloric value between L-gas and H-gas, as each has different pressurization requirements; if pressure is not managed properly, serious accidents may happen in private residences at the end of the supply chain; if H-gas were to be used in appliances specified for L-gas, "carbon monoxide would be emitted" [74]. In terms of options open to actors, natural gas's networkness also meant that a capital intensive, complex, and highly-connected machinery has to be put in place to manage pressure, making local- and regional-level solutions to the issue unfeasible. Thus while in our scenario the only visible part of the iceberg was the change in a few ten-euro gas nozzles (*Gasdüsen*) in individual boilers, the *Gasumstellung* is one of the largest natural gas infrastructure projects in German history [75], involving not only the retrofitting of residential boilers, but the building of new pipelines, as well as the expansion of compressor stations specifically intended for H-gas. Thus, natural gas materiality made Dorothe's boiler part of a supply chain of unique characteristics *specifically related to the physical characteristics of the good it was organized around*, and which constrained not only her choices, but those of planners, distributors, importers, and exporters located in a spatial range spanning thousands of kilometers.

2.5. Four questions: constraints on actors' behavior

A key characteristic of the works reviewed in Section 2 is that energy predominantly plays the analytical role [Q4] of an independent variable that is a constraint or a causal factor in a variety of other relationships. In terms of the *location* [Q1] of energy materiality, in this perspective it is located in the energy source itself and the infrastructures built upon them. In this perspective, materiality is used [Q2] by human actors, who act within the opportunities and constraints created by the material (physical) characteristics of the good. While such a view of energy materiality does not preclude energy materiality characteristics from being used discursively and instrumentally by various actors to support their own energy agendas such as specific pipeline options, the emphasis is not so much on human actor's

⁷ "L-gas" from Dutch fields has an upper calorific value of 44.44 MJ/kg, while the level of methane (and, consequently, caloric value) of Russian H-gas was significantly higher, with an upper caloric value at 54.30 MJ/kg (INGAS 2011, 11, 76).

⁸ On this point, see also the discussion of technological lock-in and "synchronous" and "asynchronous" systems in the Large Technical Systems literature (Section 3).

discursive use of materiality as on the ability of "things" to set limits on human action. In terms of the *relational characteristics* of energy materiality [Q3] the focus is mainly on objects and their physical (or, in a broader sense, infrastructural) characteristics, and the spatial and technological relationship between them.

At the same time, the perspectives discussed in this section largely see materiality as part of a constellation of human/thing relationships (as in the human and non-human 'actant' link in Actor-Network theory; see also Section 5, below). However, even when the perspective remains restricted to materiality as a constraint on human action, the impact of the materiality of energy (infrastructure) is much more complex than most of the works quoted here account for. This is one of the major insights of the Historical Energy Systems Approach.

3. Historical energy systems approaches

The history of technology, along with Science and Technology Studies (STS), is arguably the field to which "materiality" in studies of energy comes most naturally. There has never been a "material turn" in history of technology, for the simple reason that the field has *always* been focused on the material world and, in particular, its technical constituents. For historians of technology the materiality of energy lies mainly in the technologies and technical systems that enable certain materials to be transformed into heat, light, and power.

3.1. Explaining material peculiarities

Historians of technology are primarily interested in *explaining* the specificities of energy's material nature, asking questions like: why are there two different gas systems in Europe, for low-calorific and high-calorific gas? Why do the systems span vast geographical areas rather than being locally organized? Why is the heating system in Dorothe's house based on natural gas and not on any other material substance? Why are the boilers in her house constructed in such a way that they need to undergo retrofitting just because they switch to a new source of gas? Historians of technology here criticize other scholarly communities for "black-boxing" the material characteristics of energy systems – that is, for taking them for granted [76,77]. They urge other scholars – and, even more so, policymakers and stakeholders – to critically scrutinize the technical details of new energy projects, warning them not to accept technological choices as the nature-given outcome of objective calculations of the expected effects. There was nothing "natural," for example, about petroleum-based fuels becoming dominant early on in the automotive industry; electricity and steam could also have become successful fuel bases for engine design. To understand petroleum's victory, historians of technology tell us, we must analyze the strategic manoeuvring of the involved actors, political decisions and regulations, developments in nearby activities such as oil prospecting, speculative behavior in the emerging oil market and so on [78,79]. This makes it natural for historians of technology to critically study how different actors seek to *use* or *mobilize* the material characteristics of energy (systems) for their specific purposes.

In the past, historians of technology were often criticized for being *too* obsessed with material aspects – the "nuts and bolts" – of energy, at the expense of human involvement. Since the 1980s, however, history of technology has increasingly become wound up with the human dimension and what in the literature is referred to as the "social shaping" or even "social construction" of technology [80,81, and many others]. This means that historical studies of energy systems have largely abandoned their earlier focus on the materiality of energy as such, in favor of a new focus on relationalities in terms of energy's interaction with the social world.

3.2. Messy complexity

At the same time, historians have increasingly targeted the

relational aspects of energy materiality in terms of systemic interconnectivity. Dorothe's story exemplifies what historian of technology Thomas P. Hughes has called the "messy complexity" of modern technical systems [82]. The term is used to make two points: first, that a full-blown energy system such as the European natural gas system is necessarily complex, being constituted by a myriad of material components – such as the gas fields, steel pipes, boilers, seals and red tags that came to the fore in this case – along with an equally vast range of organizational (energy companies, technicians, plumbers, landlords, gas consumers, media agencies) and institutional (laws, rules, regulations) components. Secondly, that the complexity is "messy," in the sense that no single person will ever be able to gain a perfect overview of the system in its totality and that thousands of actors have shaped the system in a way that, from a bird's eye's point of view, may appear far from logical and quite anarchic and chaotic – illustrated in our story by the curious fake boilers of unknown origin and the overall confusion about how to handle the retrofitting. While Dorothe's story attracted the attention of media and to many in the general public appeared as a strange case, the Large Technical Systems (LTS) literature in fact suggests that it is a fairly typical story. For Historical Energy Systems approaches, messy complexity in energy and materiality is not the exception. It is the rule.

3.3. Historical legacies and lock-in

Historians of technology are, naturally, interested in long-term patterns of change – and lack of change – in energy. Among other things, they are concerned with what is usually referred to as "lock-in" situations stemming from long-term processes of change, and the corresponding difficulties to "change direction" [83,84]. In the case of natural gas in Europe, many observers are surprised to hear that there is actually not a single, integrated European system based on a standard gas quality, but, as already mentioned, two standards that are only marginally connected with each other in a material sense. Dorothe's experience was one of many manifestations of a long-term plan to unify the two systems by transforming the low-calorific gas ("L-Gas") areas into high-calorific gas ("H-Gas") areas. But why did European gas system-builders not create such a unified, standardized system from the outset? If they had, the current transition problems in northwestern Germany could clearly have been avoided. Here, the relevance of a long-term historical perspective comes to the fore. Quite simply, at the time when Groningen and other L-Gas fields first started to be exploited in the 1960s, it appeared unlikely that H-Gas would ever become the dominant gas quality in Western Europe. It was in no way clear that a range of NATO member states – in the midst of the Cold War! – would want to or be able to access huge volumes of Siberian H-Gas, and it was still unknown that the North Sea rested on enormous H-gas deposits. In this situation L-Gas actors managed to mobilize sufficient support for a scheme in which L-Gas became the main standard. Later, things changed and H-Gas became more dominant. The process of European integration in natural gas became a slow process where visions of the future changed only gradually – there was no single grand plan for creating a unified pipeline grid spanning the entire continent. In the end Europe became locked into a double-standard system [85,86]. As Dorothe's experience teaches us, it is only with great pain that L-Gas areas now attempt to break this lock-in.

3.4. Technology and risk

There is close affinity between historical energy systems studies and the material and social complexity of energy supply as researched within the field of *risk studies*. Charles Perrow, for example, used the Three Mile Island nuclear disaster as his prime case when developing his "normal accidents" theory [87,88, on Fukushima], pointing to the immense material complexity of nuclear power plants as something that makes it virtually impossible to rule out the possibility of malfunctions,

accidents and disasters. Nuclear disasters, according to this view, are constantly "waiting to happen", because there is always a valve that might be accidentally left open or closed, a water pipe that has corroded and failed to attract the attention of maintenance crews or an electricity circuit that might suddenly fail due to an unexpected computer or signalling error. However, Perrow's theories have been challenged by another group of risk scholars who take as their point of departure the empirical observation that, given the messy complexity of energy and other technical systems, large-scale accidents are surprisingly rare. This is referred to as High Reliability Theory. According to this perspective, what is most astonishing about, say, today's electricity supply systems is not so much that there is a blackout from time to time, but rather how rare such events are. There are so many things that could go wrong in this monster system of millions of material components, and yet in the Western world we are so used to well-functioning electricity supply that many of us do not even keep candles or torches at home for the emergency case [cf. [89]]! There is an interesting – especially when the historical dimension is taken into account – debate still going on between these two perspectives of messy complexity and its effects [for an overview see [90]].

The notions of "risk" and "vulnerability" in the above studies are quite different from the notion of energy-related risks in geopolitical studies of energy. As Section 2 showed, students of the geopolitics of energy rarely take an interest in the technical and material details of energy supply. Instead, they have primarily focused on risk in the form of intentional, politically motivated supply disruptions and on economic risks linked to turbulence on world markets and the spectre of politically induced price shocks. Hence most studies of "energy security" to a great extent lack any reference to material aspects of the energy systems at hand. Many scholars have tried to construct elaborate "oil vulnerability indices" and the like [see, e.g., [91]], but these rarely include key material factors such as the degree of complexity of the overall material system, the degree to which technical things are kept in good shape through maintenance works, or the material strengths of electricity transmission lines, oil and gas pipelines, steam turbines, uranium centrifuges or LNG regasification facilities. Yet authors such as Högselius [86] have argued, citing historical evidence, that technical mishaps and lack of maintenance are a far more common threat to energy security than any political or economic twists and turns.

3.5. Four questions: historical energy systems

To summarize, historical energy systems studies reveal several things. First, they insist that the messy complexity of natural gas – in material and non-material terms – that became so manifest through Dorothe's story must be understood as a normal state of affairs throughout the realm of energy systems. There is nothing strange about this. Secondly, historical energy systems scholars emphasize that the material characteristics of energy supply need to be explained as the outcome of complex processes of change, rather than taken for granted. Thirdly, the analysts take great interest in how the historical shaping of energy systems creates momentum, inertia, and ultimately lock-in situations that are difficult and painful to break away from. Fourthly, historical energy systems studies conceptualize risk in material systems very differently from risk as understood in (geo)political discourses about energy.

In this analytical approach, energy materiality (Q4) is something that needs to be explained as the outcome of complex processes of change, rather than taken for granted. It is seen as embodied in (Q1) technologies and technical systems which are themselves changing and socially constructed; the material characteristics of these systems are used (Q2) by different human actors who seek to mobilize them for specific goals. In this perspective, the analytical role played by materiality (Q3) is one that focuses on relationalities in terms of energy's complex interaction with the social world.

4. Mobility, space, and scale

Dorothe's experience marks an inconvenient encounter with the complex system that provides for our energy-intensive quotidian existence. While energy use, and therefore energy's materiality, is a central feature of life for everyone, the systems put into place over the past hundred years or more in a highly urbanized place like Northwest Germany were by their very design out-of-sight and out-of-mind. Consider what came before: the pre-20th century person in Dorothe's situation would have devoted a substantial part of household time and budget to the tasks of securing access to the energy necessary to sustain life (collecting and processing biomass such as peat or firewood; starting and maintaining a fire; consuming enough calories to maintain bodily motion; feeding enough calories to animals to do necessary work; heating water to bathe; disposing of ash and waste, etc.). Dorothe, like most of us, depends on an intricate, largely hidden, technical system to do the work when we desire warmth, mobility, cooked food, or heated water. A dial is turned and a chain reaction is quietly set into motion. In the case of her shower, that reaction involved low-energy content natural gas being extracted from subterranean sinks in northern Netherlands, processed in one or more facilities to ensure a homogenized, standardized product, transported by pipeline to a storage facility somewhere near Bremen, and transported again through an underground network of pipes until the gas reaches the boiler. When someone turns the faucet on, that gas from far away is already there, waiting to be burned having its carbon and hydrogen converted to heat and CO₂, and its heat was transferred to domestic water, while the by-products of the transaction—mainly CO₂ and used water—are expelled from the household via yet another set of infrastructure.

Dorothe's travails present the energy researcher, especially one concerned with the spatial and scalar aspects of energy materiality, with a number of possible entry points. That Dorothe turning on a faucet links her body in some barely perceptible way to larger-scale processes of EU regulatory frameworks, Eurasian geopolitics, and even global trade flows of LNG, raises a number of methodological and theoretical issues that can be unearthed and offer insights into how scholars of energy have approached such topics. A number of key points, drawn largely from relevant literatures on energy materiality, can be made regarding the mobility, spatiality, and scalar characteristics of energy materiality.

4.1. Scalar and relational aspects of energy materiality

The first is that understanding energy systems requires scholars to be mindful of their innately scalar and relational aspects. The question in the Introduction of *where* energy materiality is found is not simply answered with a point on a map; rather, it is important to understand how energy materiality is constituted at multiple spatial scales. While not all questions related to energy materiality require accounting for the bodily, household, regional, national, global and other scales, being mindful of the relationships among scales—for example, how Dorothe's seemingly mundane domestic issue with a water boiler involves material contact points and networked relations between spaces ranging from the household to the global—is essential [cf. [43,92,93]]. Along these lines, and speaking to the third question in the Introduction—*what are the relational characteristics of energy materiality?*—energy materiality is by definition relational, in that the “thing,” whether it be the hydrocarbon molecule, the electrical wave, the conduit in the form of pipe or wire carrying the energy, or the contraption converting the energy into something usable, only makes sense when considering the chain of relations and motions linking human beings with things, but also linking the various spatial layouts and territorializations of infrastructure and sites of production and consumption to one another [94]. Methodologically, this may mean that a thorough accounting of energy materiality requires multiple perspectives that are able to ask questions ranging from the bodily to the global, but also synthesis that is capable

of describing and analyzing these complex scalar relationships. There is some scholarship on the micro or small scale politics of household/bodily materialities [13,95,96], as well as on the geographies of large technical systems (LTS) [97,98], but there is precious little work synthesizing the scalar linkages.

4.2. Spaces of fixity and motion

Second, energy materiality encompasses spaces of fixity and spaces of motion. Like most infrastructure, energy infrastructure is largely fixed and stable in space—indeed to the point of creating varying degrees of materially-determined path dependencies [99]—but its existence is predicated on enabling the mobility of energy from sites of production to sites of consumption. In the case above, the interface between the spatially fixed pipelines, living space, water boiler, etc., and the mobile carbon molecules, are central to Dorothe's nuisance as much as the bureaucratic, cultural, and even geopolitical dynamics that help to shape the wider contours of story. Indeed, Dorothe's story represents a *flow disruption* that falls under a much broader analytical category of research on questions such as what happens when, for example, Russia interrupts the flow of natural gas to a neighboring state [100], when a large technical system such as California's electricity grid fails [101], or when a hydroelectric dam is shut down due to low flow. Some of these flow disruptions are caused by “natural” phenomena, others by political decisions. The result to those who depend on the energy at the end of a pipe or wire is, however, largely the same.

4.3. Uneven geographies of energy materiality

The highly uneven spatialities of energy materiality present a third analytical entry point. Dorothe's brief period without domestic hot water is of course trivial when viewed against a backdrop of serious, endemic energy poverty throughout much of the world, including in parts of the Global North [93,102–104]. Here materiality means more than simply the presence or absence of the appropriate infrastructure and technologies to effectively use energy, but also in a political economic sense of how class structures may inhibit access to energy for certain groups. While energy poverty is certainly more widespread in rural areas, important scholarship looks at how the “splintered” provision of infrastructure within cities contributes to these uneven geographies as well [105,106].

A final note on thinking through the spatial and scalar aspects of energy materiality concerns the nexus of geo- and bio-politics and the various actors that shape outcomes around this nexus. The bodily scale of energy materiality could open avenues for thinking about biopolitics of energy access/provision [93,104,107], but also the role of individuals and expertise in shaping energy materiality [108].

4.4. Four questions: spatiality, mobility, and scale

A rich and growing body of literature approaches the topic of energy materiality through lenses of space, mobility, and scale. The *location* of energy materiality (Q1) is not simply a set of coordinates. It involves spaces of fixity and motion that are constituted at multiple scales, which in turn only make sense when put into conversation with the *relational characteristics* of energy materiality (Q3), such as how bodies and households are connected to, for example, territorially vast webs of physical infrastructure. Analysis of *energy use* (Q2) should not ignore the political economy of materiality that makes energy available for some, even at the expense of others, as important work on energy poverty and biopolitics shows. As for the *analytical role* (Q4), this section suggests that energy, its carriers, and users are connected through a range of actor-networks. The following section provides possibilities for theorizing energy materiality through the lenses of ANT, assemblage, and governmentality.

5. Discourse and power: ANT, assemblage, governmentality

The story of Dorothe encourages a scholar interested in the material dimensions of discourses and power to look for methodologies and theoretical approaches that explicitly elaborate these topics. All approaches, it can be argued, the ones discussed in this paper and beyond, looking at energy materialities touch the issue of political power and power-vested discourses in a way or another. Therefore, discourse and power, can be scrutinized from multiple angles. However, here we focus on three distinct methodologies: actor-network theory (or ANT), the assemblage approach, and governmentality. At first glance these analytical strategies may seem far apart from each other, but each perspective can help to elaborate a sound methodological tool-kit to ponder the agency and power of energy related materialities. What they share, when looking at energy materialities, is a socially constructed understanding of the scope and limits of those materialities. For example, all approaches can be tuned to unfold the spatial extent of the gas system, and the sub-systems with independency of a varying kind that are attached to each other to constitute the web of relations formed around natural gas, each with a distinctive set of narratives or discourses, separate but also overlapping, “attached” to them. Therefore, relationality is at the core of these approaches including both the material or contextual and the discursive or semiotic. Moreover, the networks are not fixed, but fluid. Thus, an “engineer’s approach” to energy materialities – detaching energy resources, energy transport and refining, and energy consumption infrastructures – is not important here. On the contrary, the networks are discursively held together, thus they are desired by multitude of actors that may seem unrelated to each other, and they cross these material boundaries with ease, even going beyond what is typically thought of as an energy materiality.

5.1. Actor-network theory and assemblage approach

This line of research is interested in the agency formed via interactions of the human and the material. Actor-network theory was developed initially by Latour [108], but has evolved into a large body of literature that aims to systematize the study of agency of intertwined human and non-human ‘actants.’ ANT can also be defined as a “material-semiotic” method to understand the social. Thus, the method unfolds the relationships between people and things, and the networks they maintain and renew. Rather, the networks should be understood as rhizomes, emphasizing the multi-scaled and many times non-hierarchical nature of those networks. To be more precise: the method describes relations that exist at the same time between things (the material) and between concepts (the semiotic). In our electricity-permeated societies with high energy consumption the energy related materialities and the entangled concepts are thus one avenue to unfold what the modern ‘social’ is all about. A typical criticism of ANT is that it devotes too much agency to inanimate objects, such as gas pipelines and electric appliances, yet the three components of ANT—“the socially constructed nature of technology, the process of enrollment, and the creation of socio-technic networks” [109]—if systematically operationalized, counter this critique by bringing the discursive, or semiotic, explicitly to the fore.

Assemblage as a concept was introduced by Deleuze and Guattari in their seminal 1980 book [109,110], but it took a long time for this approach to gain momentum within social theory. DeLanda [111], using the ecosystem as one metaphor, elaborated the original idea in his *Assemblage Theory*. The assemblage is performed via material, expressive, territorializing and de-territorializing as well as linguistic roles, where the material and the expressive refer to the material itself (NordStream gas pipeline with high-methane gas, household boilers etc.) and its form (e.g. gas’s path from the North Siberian subsoil to European households, and to the atmosphere in the form of CO₂ and other gases and particles). A “territorializing role” refers to the resilience of the assemblage that is maintained via linkages within the

assemblage (e.g. chain of actors and actants bound by the gas), whereas a “de-territorializing role” challenges this very resilience by introducing new elements (e.g. switch from Dutch to Russian gas) aiming or leading to replacement of parts of the assemblage. Finally, the linguistic role comes very close to the concept of discourse, as it is about maintaining or challenging the territorialized assemblage via socio-cultural practices (e.g. environmental discourses on Dutch and Russian gas).

Müller [112] argues, though, that the assemblage approach is better understood as a loose toolkit to unfold the connectedness—and, thus, agency and power of actors, human or non-human—than as an all-encompassing theory. Müller also underlines the closeness of assemblage approach and ANT, as “(B)oth assemblage thinking and ANT have much to say about the spatial dimensions of power and politics” (p. 27). In the same vein as DeLanda, he names the dimensions of assemblages: relational (parts never explain the whole), productive (new realities), heterogeneous (humans, things, ideas), de/reterritorializing (territories established and broken), and desired (coupling fragmented objects). Thus, spatiality, as in the ANT perspective, plays a central role in the assemblage approach. Therefore, many analyses using the assemblage approach lean on discussions within geography with their implicit interest in spatialities – despite its avoidance of fixation to any particular scale [113].

Therefore, the actor-networks and assemblages, formed around Dutch Groningen gas function with specific norms, discourses, and practices that tie people, institutions and (energy) materialities together. The assemblages of Russian gas are interlinked to and overlap with many sub-assemblages functioning within the Dutch gas system. Actors try to use these assemblages for their benefit, but the assemblage approach highlights implicitly that social power, as it is dynamic and dispersed, cannot be mastered by one or few actors. For example, the chemical composition of Russian gas, stemming from very different geological conditions compared to the Dutch gas, let alone the natural, infrastructural and institutional conditions along the Russian – European gas commodity chain, challenge and change the territoriality of the North German gas assemblage when the Dutch gas is being substituted. Moreover, the energy-security and environmental discourses of the Dutch and Russian gas assemblages are certainly very different, yet on the surface the gas infrastructures look very much alike. The assemblages with a smaller geographic scope, such as the one formed around household-level gas infrastructures with specific hardware (boilers, meters, stoves etc.), software, people, and institutions, are forced to transform and attach to new networks and larger scale assemblages. This change that detaches smaller scale assemblages from previous larger (host) assemblages and attaches them, possibly slightly transformed, to new ones sets people, companies, institutions, even countries in a new situation in respect to their territorial scope, political influence and power.

5.2. Governmentality

Foucault’s dynamic understanding of power and its explicit interest in discourses and practices, and the focus on the strategic thinking and action, i.e. governmentality, of those in positions of power suits well as a companion to study the entanglement of the social and the natural/material within the realm of energy. According to Moss, Becker and Gailing [114], the Foucauldian dispositive, a context where governmentality functions and can be analyzed, includes the agency of inanimate objects and artefacts, but it does it via the discursive: materiality becomes interesting only via the discourse, that is, after given meaning within the social. Foucault’s original dispositive, *dispositif*, referred to “heterogenous ensemble” brings together discourses, regulations and “architectural forms” [115]. Thus, yet the material and spatial dimension within the whole Foucauldian power-analytics field may not be central, there is a firm body of theorizing on that front [e.g. 116].

In dialogue with Foucault on the terrain of energy transitions and

governmentalities (biopolitics) is Dominic Boyer, whose terms his notion of energopower a “respectful subversion” of Foucault’s human-focused biopolitics. For Boyer [107], energopower is based on the “recognition that conditions of life today are increasingly and unstably intertwined with particular infrastructures, magnitudes, and habits of using electricity and fuel” (p. 325). Energopower, Boyer continues, is “a discourse and a truth condition to be sure, but ... one that searches out signals of the ergo-material transferences and transformations incorporated in all other sociopolitical phenomena”. To search for energopower and energopolitics, then, is to search for and historicize the contingent and shifting links between the governance of life and the energy materialities with which it is always entangled. Thus, Boyer elaborates the Foucauldian concepts of governmentality and biopolitics with an explicit energy materiality take without referring to ANT or assemblage.

5.3. Seeking common ground among ANT, assemblage, and governmentality

In energy research there is only a limited amount of studies seeking explicitly to find common ground among the ANT, assemblage, and governmentality approaches. Rutland and Aylett [117] do not focus on energy materialities as such, but analyze climate mitigation discourses and practices linked implicitly to energy materialities, such as greenhouse gas emissions. Thus, the shortcomings of both approaches – too powerful agency given to “things” in ANT and vice versa to the discursive in governmentality – enables scholars to construct methodological tool-kits that are sensitive to those human – non-human constellations in the specific context at hand.

In the field of energy studies a good example of this kind of theoretical cross-fertilization is the above-mentioned work by Moss, Becker and Gailing [114]: they use the Foucauldian dispositive, the Deleuzian assemblage and neo-Marxian metabolism as analytical tools to map networks of power within the contemporary German energy-policy scene. Leaving the Marxist approach aside, principally, both Foucauldian and Deleuzian approaches are well equipped to analyze the entanglement of energy, materiality, and power, but with a differing emphasis given to the agency of “things”. And vice versa, scholars devoted to the ANT and assemblage approaches have previously been less interested in power per se, but lately within the field there is a “growing interest in unequal relations of power” [114]. Hence, the ANT, assemblage, and governmentality methodologies seem to share a common interest in the way societal “truths” are produced. That is, despite different starting points and disciplinary traditions, there can be found fruitful confluence when these three approaches are discussed at the same tables.

Tynkkynen [118,119] has made another attempt to bridge the Foucauldian power analysis and the Latourian ANT perspective in the realm of energy via the concept of geo-governmentality. In this perspective, the goal is to understand better what kind of practical power, discursive truths, and cultural-political identities are constructed in and around energy flows and entangled materialities, and how these forms of political power condition our understanding on energy as a societal phenomenon. For example, Tynkkynen’s study of the Russian national gas programme describes how gas-based geo-governmentality is in the making via powerful discourses [117]. Following the logic of Margo Huxley [118], he asks how specific resources and spatialities, and the materialities involved, act as agents as part of the discursive-practical use of power or of governmentality. The “geo” in this approach is the deliberate use of geographical characteristics of gas when building and maintaining the desired governmentality. This approach can also challenge where the boundaries of energy materialities are. Tynkkynen [118] argues it is important to include not only energy infrastructure but also its “epiphytes” – “ancillary apparatuses and infrastructures, such as sports halls,” which “potentially serve as conduits of disciplinary power” (p. 78). Therefore, this view challenges the clear-cut

understanding of energy materiality reserved only to those linked to extraction, refining, transport and consumption of energy. He argues, in other words, that social infrastructure built and maintained by energy companies or state ministries can be understood as a materiality of energy, especially when it is linked to power-vested discourses utilizing material dimensions of the energy sector to constructing and maintaining these discourses.

Coming back to Dorothe’s case, a scholar inspired by possibility of combining the ANT, assemblage, and governmentality approaches would frame the story by highlighting the varying types of assemblages found in different networks from production sites (geological formations) to consumers (and to the atmosphere and biosphere), and how these networks and assemblages along the gas trail are territorialized and desired with the help of discourses. The North German case reminds us about the different ways the material and the discursive constitute each other, highlighting the methodological strengths and weaknesses of the three approaches: neither energy materialities are dictating the political, nor is the discursive unimpacted by the agency of the material.

First, when looking at the issue of energy via the prism of security, the gas assemblage of Germany is very different than, for example, the Finnish. In Germany households are directly part of energy-security constellations, practices, and materialities: Dorothe’s boiler is directly linked to Russian gas. Whereas in Finland the energy security practices are very different as households are linked to Russian gas only via other assemblages, such as centralized heat and power plants and urban heat-pipeline systems that partly rely on gas. In Finland the high dependence on Russian energy – half of all energy consumed is of Russian origin – is justified by maintaining a diversified energy mix. This gives room to argue that dependence is not something threatening, but instead a sign of a trustworthy neighbor that keeps energy in the realm of economics, not entangling it with issues of security [e.g. [120]]. In Germany, yet with a lower share of Russian imports, energy-security discourse leans on “consumer power” as a source of leverage vis-à-vis Russia, and therefore constructs energy as something in no need of politicizing in official accounts [e.g. [121]]. This comparison reveals that, despite very different nature of gas assemblages, the official energy-security discourses in both countries resemble each other – thus, the opportunities and risks brought about by the material and spatial constellations of energy are justified discursively in a unique way.

Second, looking at the environmental dimension of energy, the very cause—the environmental discourse on problems caused by gas extraction—that set the assemblages in motion, changing their territorial scope, is to a large extent ignored when it comes to extraction of Russian gas. The fact that in the Russian hydrocarbon-production areas the assemblages of oil and gas have been largely separated has led to excessive emissions in extracting Russian gas, for example, in the form of gas flaring [e.g. [122]]. Then again, extraction of Dutch gas is framed as an environmental problem as further use of the Groningen fields increases the risk of earthquakes that may damage infrastructures. Whereas the discourse on Russian gas is focusing on its supply – when Russian gas is discussed it is about quantity, thus about supply security, not quality incorporating environmental concerns. Hence, gas extraction both in the North Sea and Western Siberia have severe environmental consequences, but of very different nature, and the discourses on these two gas flows include issues on these materialities in a very selective way.

5.4. Four questions: discourse and power

When seeking common ground among ANT, assemblage, and governmentality approaches in analyzing energy materialities, it is important to be precise about how these takes converge and diverge. This sensitivity towards the strengths and weaknesses of these approaches, specifically the differing emphasis and power given to “things” and discourses, helps to widen the discussion on topics such as energy

security and environmental responsibility. In this case, these theories urge us to ask how environmental and security-related practices emerge within power-vested actor-networks and assemblages that enable the flow of energy from one place to another. These analytical approaches (Q4) entail taking energy materialities as phenomena in need of explanation in their own right by focusing on the agency of the material aspects of energy systems and their ability to bring about and maintain discourses. Therefore, relationality (Q3) is at the core of these approaches. They urge us to look simultaneously at spatial relationships (e.g. assemblages on different scales, such as local heat-pipeline system vis-à-vis transnational flows of energy) and discursive relationships, including how they constitute each other. The questions of location of energy materiality (Q1) and how energy materialities are used by different actors (Q2) is really the twist in this approach: energy assemblages are unique, yet may seem very much alike seen from the surface. Moreover, they are maintained via unique set of actors and their conscious and unconscious set of “truths.” Therefore, these entanglements should be questioned anew in every context [see also 120].

In sum, a certain infrastructural form or physical and economic tie does not dictate the discourses, and therefore also policies and use of power—as the comparison of German and Finnish energy-security approaches reveal. Likewise, discourses on energy materialities can reframe how we understand energy materiality, as the comparison of environmental concerns over Dutch vs. Russian gas shows. Moreover, looking at materiality-inspired energy discourses we are able to see how those materialities are utilized by those in positions of power—as the Russian energy companies do by expanding energy-transport infrastructures with the help of “epiphytes” such as sports halls. The important feature is that these (extended) energy assemblages are maintained, or their territorialized and material scope desired, in ways in which the material and the discursive constitute each other.

6. Energy becoming material

It is a fair assumption that Dorothe had thought only occasionally about her boiler, her gas supply, and Dutch vs. Russian natural gas before she was reduced to using an electric kettle. An unexpected rupture in the energy system through which she moved suddenly made the materiality of energy visible and consequential in ways that it was not just a day earlier, sending her quickly into new daily routines, unveiling a previously hidden material connection between her hot water and appliance counterfeiters, and, before long, sending her and her belongings into a new apartment altogether. If we focus on these elements of Dorothe’s story, the materiality of energy appears as mutable and contingent rather than constant or settled. It slips, sometimes rapidly, in and out of human experience, becomes enmeshed in cultural expectations and social institutions (like courts) in unpredictable ways, and varies across time and space.

This mutability and contingency make the materiality of energy an appealing location for states, corporations, and other powerful entities to insert themselves into the daily lives of citizens and consumers, as well as an arena in which alternate energy futures might be imagined. This section reviews recent scholarship on energy materiality that deals with three domains in which energy materiality can be profitably understood to be in a constant state of becoming: breakdown, transition, and visibility politics. Scholars working on these topics often have cause to draw on expansive analytical approaches to materiality, and their work situates the “wheres” of energy materiality in correspondingly expansive domains. Infrastructures have poetics and aesthetics as well as politics [123]. Images, sounds, and symbols are every bit as material as objects or technological systems [e.g. 124].

6.1. Breakdown

In her classic account of infrastructure as an object for ethnographers, Stacy Leigh Star [125] suggested that one of the major

obstacles to studying infrastructure—energy or otherwise—is that it appears “mundane to the point of boredom”: “backstage,” “embedded,” “naturalized,” and, crucially, “visible upon breakdown.” A number of studies have taken a similar approach, and the breakdowns on which they focus run from the regular and nearly routine to the rare and catastrophic. Closer to the routine end, for instance, Michael Degani [126] charts the ways in which periodic blackouts caused by Dar es Salaam’s overwhelmed electricity grid help structure urban social life in Tanzania, including the timing of meals and pervasive demand for unlicensed electrician “fixers” called *vishoka*. On the more catastrophic end, David Bond [127] shows that the Deepwater Horizon explosion and oil spill—surely one of the highest-profile breakdowns of energy infrastructure in recent memory—created new knowledge of the deep-water Gulf of Mexico as scientists and engineers were forced (and funded) to grapple with the behavior oil and water in unfamiliar ways.

Especially innovative and instructive on the topic of material breakdown is Andrew Barry’s account of the ways in which the exterior coating on a particular stretch of British Petroleum’s Baku-Tibilisi-Ceyhan pipeline became a matter of political contention in the British House of Commons. After a section of the pipeline failed, the properties of metals and the science of metallurgy—material elements of Europe’s energy infrastructure that ordinarily attract even less attention than Dorothe’s boiler—suddenly became, in Barry’s words, an “index of a much wider set of defects in corporate capitalism and its regulation” as the failure was picked up and deployed by nongovernmental organizations and, eventually, politicians [128]. This case is instructive, Barry argues, precisely because it shows that even materials assumed to be fixed and unchangeable, such as the hard metal of pipelines, are in fact mutable, subject to breakdown, and easily inserted into political struggle.

6.2. Transition

Energy transitions are the less dramatic cousins of energy breakdowns, although the two categories are not mutually exclusive. In energy transition contexts, materiality can serve as a useful lens through which to account for shifts in one or another aspect of an energy regime—from the sources of natural gas powering boilers in Delmenhorst to much larger-scale attempts to replace fossil fuels with more sustainable energy resources. Although a great deal of scholarship focuses on contemporary efforts to make a transition to renewable or sustainable energy, a rapidly expanding historical literature also discusses earlier energy transitions—from wood to coal, coal to oil, and more [see, e.g. [6,67,129]].

Studies in this vein are often adept at linking material transformations to social transformations and vice versa. In an exemplary recent study, Myles Lennon [130] focuses his attention on the “material-discursive” intersection of renewable energy technoscience and the Black Lives Matter movement in the United States. Conducting ethnographic fieldwork and interviews New York City, Lennon found that largely white and male solar technology companies were often including discussions of race and social justice in their conversations and business plans. At the same time, largely black and female activists increasingly placed renewable energy technological projects—from community-based solar installations to anaerobic digestion—at the center of their visions of a more just future. Lennon discerns, that is, a fascinating intersection at the heart of energy transition, one between “material technologies that aim to decentralize the grid and activist discourses that aim to decentralize social governance.”

Also exemplary in recent scholarship on materiality and energy transition is Stephen Collier’s study of post-Soviet Russia, *Post-Soviet Social* [14]. In this wide-ranging book, Collier shows that attempts to create what economists advising Russia on the transition from socialism saw as capitalist energy market was foiled by the entrenched materiality of the Soviet infrastructure. The communal infrastructure of heating systems that was hard-piped into entire Soviet cities meant, for

instance, that market-making instruments such as energy meters could not be fitted to individual apartments without rebuilding cities from the ground up. Collier shows that efforts to speed post-Soviet transition were confounded by material-social ties, a contrast to Lennon's case, in which such ties appear to be facilitating a more systemic agenda of transformation.⁹ Both studies, however, are usefully illustrative of a broader point made by many of the works discussed in this section: the unpredictable relationships of energy materiality cross and re-cross the social world and the material world, confounding simplistic causal or unidirectional accounts.

6.3. Visibility politics

All of this mutability and contingency in the world of energy materiality is well understood by those who occupy powerful positions in states and corporations. Indeed, the ways in which the materiality of energy sources is constantly and selectively made visible, in everything from corporate logos to national spectacles, demonstrates that Star's relegation of infrastructure to the domain of the invisible is, at best, half the story [see also [123]]. An increasing number of studies of energy follows the ways in which materiality features in state and corporate attempts to shape the experiences of citizens and consumers, often in order to defuse critiques of the environmental, social, or other negative consequences of energy use.

One significant strain of this scholarship focuses on Corporate Social Responsibility (CSR) in the energy sector, one of the chief ways in which diverse publics encounter enterprises that specialize in energy. In a study of energy-sector CSR projects in Russia, for instance, Rogers [131] pointed to the ways in which the social development projects of Gazprom and Lukoil drew heavily on the material infrastructures associated with each industry. Gazprom's imagery and rhetoric focused on the rebuilding of social connectivity in the wake of the turbulent 1990s, just as its business model sought to connect ever more towns and villages to its gas network. By contrast, Lukoil's corporate projects emphasized the relationship between the physical depths of the oil it extracted from the subsoil and the metaphorical depths of history and culture that its sponsorship of cultural revival projected.¹⁰

This is not just a corporate domain; for decades, energy producing states have assimilated representations of oil or gas infrastructure and other material forms into imaginaries of national belonging. Especially in so-called petrostates, the issue is often one of *de-materialization*: the ways in which the material qualities of oil are stripped away and re-incarnated as abstracted oil money or abstracted state power [e.g. [133,134]].¹¹ But is money—or even price—not itself material? Elizabeth Ferry's [136] recent commentary on the London Gold Fix, a consortium of London gold traders that set a daily benchmark for global gold prices, shows that prices, too, can be productively seen as material-social actors. Drawing inspiration from the social study of finance, Ferry points to these traders' material and social relationships with each other—from their habits of socializing over drinks to the electronic systems that handle bids—and from there to every corner of the global gold industry. Price, too, is an element of the energy world that is made visible through traceable material relationships.

If states and corporations are some of the main mobilizers of energy materiality, so, too, are their critics. A smaller but important line of research on visibility politics takes up political challenges to the present

energy order that also render energy's materiality visible. In a key review, Jennifer Gabrys [137] describes a number of technological and creative projects that make visible ways in which energy is constantly wasted, ranging from household electrical cords that glow in order to reinsert themselves into residents' consciousness of their energy consumption to Hanspeter Kadel and Myriel Milicevic's 2009 "Energy Harvests" project, which used innovative installations, such as a wind turbine in the Berlin metro that captured the wind generated by passing subway cars and converted it to electricity. In these projects, alternative energy futures are imagined by rendering current energy materialities more visible, more open to question and reimagination.

Scholarship on materiality and energy that focuses on visibility politics, in sum, follows the common material things of the energy world—objects, images, experiences, and much more—into much broader material, social, and semiotic fields. It tracks their movements, their unpredictable connections and disconnections with other aspects of the material and social world, and, especially, the ways in which these materializations recreate or challenge power relations.

6.4. Four questions: energy becoming material

In scholarship on energy breakdown, transition, and visibility politics, the materiality of energy is located in a constant and contested state of *becoming* (Q1). Indeed, the rapidly shifting relationships (Q3) among signs within larger semiotic and material fields are often central to these approaches. Although all manner of social and cultural groups and actors participate in the processes by which energy becomes material, recent scholarship has focused significant attention on the powerful role of states and corporations (Q2). This stance supports a wide variety of analytical approaches (Q4) within the overall rubric of energy materiality, and can therefore be combined with many of the approaches discussed in the sections above—so long as they are open to viewing both energy and materiality as anything but fixed, contained, or immutable.

7. Conclusion

The phrase "anything but fixed, contained, or immutable" might well be applied to the chaotic concept that is energy materiality, at least as our small group has encountered and wrestled with it. We have refrained from positing energy materiality as a coherent field of inquiry and consciously avoided using this review to distill an "essence" or even to gesture toward an on-the-horizon point of convergence toward which future scholarship might be vectored. However, in our view, the present chaos is neither dire nor lamentable. It is also not absolute. Table 1 presents in succinct form the ways in which Sections 2–6 have outlined answers to the four questions with which we began. Reading across the rows summarizes the main points of each section—five well-travelled paths of existing scholarship, many of them intersecting at various points; reading down the columns demonstrates the very wide variety of answers scholars have arrived at as they have contemplated basic questions about energy materiality.

A few more general reflections may also be appropriate at this stage.

First, our review seems to point to a need for an *inclusive definition* of energy materiality. This is to say that it appears fruitful to engage not only with one, but with several – often radically different – interpretations of what constitutes energy's material forms, from various geological and biological features of fuels via a diverse range of technical components that make up our human-made energy systems to semiotic systems and energy's material impacts on environments and landscapes. A perhaps surprising find in this connection is the suggestion in several of the available literatures to take into not only "star" items of energy materiality like pipelines or gas fields, but also a range of components that at first glance would seem peripheral, unimportant or simply irrelevant – such as the red tags on Dorothe's boiler and the Gazprom-sponsored stadiums.

⁹ This situation points to issues of material constraint and path dependence discussed in other sections of this article; Collier himself links the shifts in material energy structures to theories of biopolitics discussed above.

¹⁰ Other studies that take up similar themes in the study of CSR and marketing in the energy sector include Tynkynen [119] and Shever [132].

¹¹ A number of scholars who are explicit about their efforts to focus on materiality begin by critiquing studies of energy that focus largely on price or monetary abstraction rather than specific material flows or connections [67,135].

Table 1
Four questions about energy materiality.

| | [Q1] Where is energy materiality located? | [Q2] How is energy materiality used and by whom? | [Q3] What are the relational characteristics of energy materiality? | [Q4] What analytical role does energy materiality play in different approaches? |
|--|--|---|--|--|
| Materiality as a Constraint on Actors' Behavior | In energy sources themselves and the infrastructures built upon them | Used by human actors acting within the opportunities and constraints created by the material characteristics of the good. | Focus mainly on objects and their physical (or, in a broader sense, infrastructural) characteristics, and the spatial and technological relationship between them. | Largely independent variable that is a constraint or a causal factor in a variety of other relationships |
| Historical Energy Systems Approaches | In technologies and technical systems that enable certain materials to be transformed into heat, light and power. | Different human actors seek to use or mobilize the material characteristics of energy (systems) for their specific purposes | Focus on relationalities in terms of energy's interaction with the social world. | Something that needs to be explained as the outcome of complex processes of change, rather than taken for granted. |
| Mobility, Space, and Scale | Not in a particular location; energy materiality is constituted at multiple spatial scales | Political economy of energy access entails poverty for some, excess for others | Is by definition relational, only making sense when considering the chain of relations and motions linking human beings with things. | Energy, energy infrastructure, and users are connected through complex actor-networks |
| Discourse and power via Energy Materialities: ANT, Assemblage, Governmentality | In socially constructed understandings of the scope and limits of those materialities. | Actors try to use these assemblages for their benefit, but social power, as it is dynamic and dispersed, cannot be mastered by one or few actors. | Relationality is at the core of this approach including both the material or contextual and the discursive or semiotic and power. | A phenomenon in need of explanation in its own right |
| Energy Becoming Material | Materiality of energy appears as mutable and contingent rather than constant or settled; signs, symbols, and semiotic systems often central. | Various, but powerful energy companies and states often play a big role. | Relations among actors of all sorts are mediated by shifting energy materialities and processes of breakdown, transition, or visibility/invisibility politics. | Amenable to a wide variety of analytical approaches, but focus on change and power. |

Second, a majority of the approaches discussed in this article, while being rooted in totally different scholarly traditions, stress the importance of studying energy materiality in close relation to non-material aspects of energy. The material and the social world, they agree, are seamlessly interlinked and must be studied as such. The two cannot be analyzed in isolation. Hence neither the traditional obsession in a field such a history of technology with the “nuts and bolts” of energy technologies (in which the social dimension is largely ignored) nor the near-total neglect of material aspects in, say, the resource curse literature will do.

Third, our review points to a need for recognizing the ambiguities of energy materiality in terms of stability and change. On the one hand, notions such as constraints, lock-ins, path-dependencies etc. – as elaborated on in several strands of research – indicate that social actors often face great difficulties in coping with and taking on energy's materiality, sometimes to the extent that energy's material characteristics appear impossible to alter. On the other hand, finds from disparate academic fields convincingly show that energy materiality is moldable and constantly in the making – although the complexity that resides in energy's material features typically make it impossible for actors to control of such processes.

Fourth and finally, our review appears to have laid bare a number of conceptual and theoretical redundancies among the variety of available disciplinary and interdisciplinary approaches. For example, the literatures on energy systems, energy supply-chains and energy assemblages obviously have a lot in common, but the scholars studying them almost always belong to totally different academic communities. Could bringing in a unifying concept such as “energy materiality”, then, serve as a catalyst when it comes to stimulating creative interaction between different fields and literatures? This, clearly, has been an implicit hope in our review exercise.

All in all, our hope is that our review effort will be taken as an intervention that leads scholars deploying the term “energy materiality”—including the many writing for this journal—to deploy it with a greater appreciation of both its analytical purchase and its heterogeneity of usage. Indeed, the experience of drafting this article taught us more than anything else that we need to be much clearer and more intentional when we use the term energy materiality. In the short and medium term, we believe that the concept of energy materiality will likely stay productively chaotic. Our own conversations—and the new insights with which we have returned to our individual projects—suggest that there remain many possibilities for creative experimentation and cross-pollination to be gained by stepping off the well-travelled horizontal rows of Table 1 and hopscotching into less familiar analytical terrain.

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Declaration of Competing Interest

None.

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