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Tijdschrift voor economische en sociale geografie

Provided in Cooperation with:

John Wiley & Sons

Suggested Citation: Walker, Benedikt; Klagge, Britta (2024) : Infrastructure Bottlenecks as Opportunity for Local Development: The Case of Decentralized Green-Hydrogen Projects, Tijdschrift voor economische en sociale geografie, ISSN 1467-9663, Wiley Periodicals, Inc., Hoboken, NJ, Vol. 115, Iss. 5, pp. 643-659, https://doi.org/10.1111/tesg.12633

This Version is available at: https://hdl.handle.net/10419/313692

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INFRASTRUCTURE BOTTLENECKS AS OPPORTUNITY FOR LOCAL DEVELOPMENT: THE CASE OF DECENTRALIZED GREEN-HYDROGEN PROJECTS

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Received: May 2023; accepted May 2024

ABSTRACT

Energy geography has not scrutinized the role of energy infrastructures and market design for decentralized energy production and local development. The paper addresses this research gap by looking at the emerging green-hydrogen market in Germany. We argue, first, that the capacity and geography of infrastructures and associated bottlenecks determine how supply and demand can be matched at different scales. Second, market design and associated controversies over infrastructure bottlenecks are important for understanding the green-hydrogen market and its geography and financing. Conceptually, we draw on the geography-of-markets literature. Empirically, we show how infrastructure bottlenecks and market design link the green-hydrogen to the renewable-electricity market. As long as the market design requires green-hydrogen production in geographical and temporal correlation with renewable-electricity generation, the geography of green-hydrogen production follows the geography of renewable-electricity generation. Moreover, bottlenecks in transportation infrastructures offer a window of opportunity for decentralized production and local development.

Key words: energy geography; energy market; hydrogen; transportation infrastructure; market design; Germany

Article manuscript for Special Issue accepted by Tijdschrift Voor Economische en Sociale Geografie (TESG) on *Green, Alternative, or Business as Usual? Critical Geographies of Sustainable Finance*, edited by Sabine Dörry and Christian Schulz.

INTRODUCTION

Energy geographers have controversially discussed the advantages and disadvantages of centralized and decentralized renewable energy production, that is, large-scale and concentrated versus small-scale and distributed renewable-electricity generation (Naumann & Rudolph 2020). Some authors have argued that decentralized energy generation offers opportunities for local actors to contribute to economic development by substituting imported fossil fuels and using local resources (Heinbach *et al.* 2014). In addition, local energy generation offers opportunities to participate politically in the energy system and can reduce the need for grid expansion for transporting electricity from elsewhere (Schmid *et al.* 2016). However, decentralized renewable-energy generation only developed

Tijdschrift voor Economische en Sociale Geografie – 2024, DOI:10.1111/tesg.12633, Vol. 115, No. 5, pp. 643–659. © 2024 The Authors. Tijdschrift voor Economische en Sociale Geografie published by John Wiley & Sons Ltd on behalf of Royal Dutch Geographical Society / Koninklijk Nederlands Aardrijkskundig Genootschap. This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which

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in countries with early market builders (Dewald & Truffer 2011), public funding and other favourable support mechanisms (Bauwens *et al.* 2016), and/or financing by local banks (Hall *et al.* 2016). The phasingout of these support mechanisms has resulted in a shift towards more centralized, largescale renewable-energy facilities (Beermann & Tews 2017), which allow for economies of scale in financing, production and trade, and are favoured by industrial buyers as well as institutional investors (Christophers 2022).

In practice, so-called renewable-energy regions have explicitly - and often successfully taken-up decentralized renewable energy production as a development model (Späth & Rohracher 2010). However, especially renewable-electricity regions use pre-existing grid infrastructures and remain embedded in national markets. They often do not engage with electricity-grid development and energymarket regulation and, consequently, miss out on opportunities to work on (more) suitable framework conditions for decentralized energy production (Beermann & Tews 2017). Similarly, energy geography has neither conceptually nor empirically scrutinized the role of grid and pipeline infrastructures, and energymarket designs for investments in decentralized energy production and subsequent local development. Addressing this research gap is particularly important in the current situation of energy transitions in many countries worldwide. First, electricity grids in countries like Germany, the United States, Chile and South Africa face increasing difficulties in integrating renewable electricity and transport it from the places of generation to demand centers due to infrastructure bottlenecks (IEA 2023). Second, the share of renewables in the electricity sector has grown in many countries but other sectors, such as industry, heating and mobility are left behind (Markard 2018). Third, to support the defossilization¹ of those sectors, governments globally have started to promote the production of green hydrogen (van de Graaf et al. 2020). Since green hydrogen can be transported in pipelines, by ships and trucks, it has the potential to circumvent bottlenecks in electricity grids.

In this paper, we focus on the role of infrastructure bottlenecks and market design for the geography of energy markets by looking at the emerging green-hydrogen market in Germany. We argue that the capacity and geography of infrastructures and associated bottlenecks determine how supply and demand can be matched at different scales. Accordingly, we contend that the size and geography of markets evolve as the underlying infrastructure changes and that we need to analyse green-hydrogen market formation and structures from a geographical perspective. We therefore distinguish between large, centralized and small, decentralized projects as two market segments (cp. Dewald & Truffer 2011 on the German photovoltaic market), and are particularly interested in the infrastructural and regulatory conditions enabling local actors, like municipal utilities, to invest in green-hydrogen projects. We conceive energy markets as structures that enable the coordination of supply and demand according to their political regulation (Muellerleile 2018) or what, in energy policy, is called market design (Lindberg 2022). Furthermore, drawing on the geography-of-markets literature (e.g. Berndt & Boeckler 2009), we use four spatial forms of markets (Jones 2013) to conceptualize energy markets and better understand infrastructure bottlenecks. This approach leads to our research questions: How do existing infrastructure bottlenecks and the green-hydrogen market design shape the emerging geography of green-hydrogen markets in Germany, specifically the development of centralized and decentralized green-hydrogen projects in different regions? What types of actors engage in decentralized green-hydrogen projects and why, i.e. what are their motivations? And, more generally, how do infrastructure bottlenecks support or constrain the development of decentralized and/or centralized production?

The paper is structured as follows: In the next section, we develop our conceptual perspective, which focuses on how infrastructure bottlenecks and market design have an impact on the geographies of markets. Then, we explain our methodology, specifically the creation of a database on green-hydrogen projects and expert interviews. Afterwards, three analytical sections follow, in which we first analyse the emerging market design, then the geography of centralized greenhydrogen projects, and finally the geography

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of decentralized projects. In our conclusion, we discuss our conceptual approach and empirical findings and point out future research opportunities.

GEOGRAPHIES OF ENERGY MARKETS, INFRASTRUCTURE BOTTLENECKS AND LOCAL DEVELOPMENT

The role of infrastructures for energy markets and their development seems self-evident, as infrastructure bottlenecks can hamper market development (Kuzemko et al. 2018). Similarly, based on a study of financial markets, Muellerleile (2018) highlights that removing infrastructure bottlenecks can improve the conditions for accumulation and market participation. However, neither article explores the implications of bottlenecks and how they might also enable accumulation, especially in an emerging market like the one for green hydrogen. In this article, we show that when infrastructure bottlenecks constrain energy transportation and trade over long(er) distances, market development can still occur at local scale. Thereby, infrastructure bottlenecks might not lead to less accumulation but to a (more) decentralized geography of production with opportunities for local development.

There is a lack of understanding of infrastructure systems, such as power grids, and their importance for energy transitions in energy geography (Bolton & Foxon 2015; Baker & Phillips 2019). Likewise, the sociopolitical development of energy-market designs is under-researched (Lindberg 2022). In particular, energy geographers have not considered bottlenecks and spatial forms of energy infrastructures nor the importance of market design as conditions for the successful development of decentralized energy projects by local shareholders. Instead, the economic viability of decentralized energy projects is often perceived narrowly as a function of financial support (Dewald & Truffer 2012; Beermann & Tews 2017) and/or the costcompetitiveness of renewables versus fossil fuels (Christophers 2022).

In this sense, as in other fields of geographic research, "the market remains a black-box and is

simply taken as given" (Berndt & Boeckler 2009, pp. 538–539). However, as Jones (2013, p. 40) rightfully contends, "markets themselves need to be more explicitly analyzed as the spaces from which key economic outcomes emerge". For example, research has shown that the degree of centralization of national financial markets and the (non-)existence of local banks can support or constrain the development of decentralized energy projects and local ownership (Hall *et al.* 2016). In the following, we draw from the geography-of-markets literature to conceptualize how market design and energy infrastructures support or constrain decentralized energy production.

The functioning of markets depends on various infrastructures, especially to facilitate the interaction between market participants and to transport goods from one place to another (Muellerleile 2018). The transportation of electricity or gas (including hydrogen) requires specific infrastructures such as power grids, gas pipelines and specific vehicles (trucks, ships). The absence or missing capacity of these facilities can constitute infrastructure bottlenecks that prevent or limit transportation between certain places (Bridge & Bradshaw 2017). We argue that these bottlenecks, and how they are integrated into market design, have an impact on the development of energy markets. To conceptualize these impacts and their role for the development of centralized and/or decentralized energy production, we follow Jones (2013) and distinguish between four spatial forms of markets.

First, the space of markets can be conceived as contiguous territory and is equated with, e.g., regulatory territories like national states or the EU. Regarding energy markets, power grids and their territories are another example, which exist at different levels - the most important distinction being between local or regional (lower-voltage) distribution grids and supra-regional (high voltage) transmission grids. At both levels, bottlenecks can occur and need to be taken into account. To function reliably, power grids necessitate a balance of electricity fed into and sourced out of the grid. Grid management, thus, requires monitoring grid-connected electricity generation and use, as well as various types of

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storages and/or power transformers to keep the grid in balance (the latter transferring electricity between higher- and lower-voltage grids) (Estermann *et al.* 2016). As greenhydrogen production requires renewable electricity, it is important to analyse at which grid level and in which grid territory renewable electricity can be sourced in sufficient quantities, and how bottlenecks in the power grid subsequently constrain green-hydrogen production in certain territories.

Second, we understand markets as actor and infrastructural networks, which connect suppliers and buyers (Jones 2013). For new markets to emerge, actor networks of suppliers and buyers must be motivated to engage in innovative activities, take over risks, and have the capabilities to assemble the necessary financial resources, which is facilitated by geographic proximity and locally shared expertise (Dewald & Truffer 2012; Schwabe 2024). In this context, local banks contribute to the development of decentralized renewable-electricity projects by making financing available to actors that are locally bound. However, neither local banks nor institutional investors are willing to take over major project risks (Hall et al. 2016; Christophers 2022). At the same time, such networks may connect different scales by linking local actors with non-local actors like national or even international firms. Furthermore, transportation and trade can occur at different levels, depending on their infrastructure capacity and bottlenecks. For example, Bridge and Bradshaw (2017) show that natural-gas trade was limited to the continental reach of pipeline networks before the development of liquid natural gas (LNG) infrastructures (terminals, ships). In our case, decentralized and centralized green-hydrogen projects represent two segments of the emerging green-hydrogen market, which differ in their actor networks, linkages to power-grid levels and associated challenges regarding bottlenecks. Thus, they might complement or compete with each other.

Third, and closely related, we conceptualize markets and the underlying infrastructures as enabling *flows* between market participants, such as electricity or gas flows. Infrastructure bottlenecks between places of production and use, for which Muellerleile (2018) mobilizes the metaphor of traffic congestions, can limit or even prevent such flows. Hence, they can constrain market exchange and lead to fragmented markets. Our analysis shows that, as long as infrastructure bottlenecks constrain green-hydrogen transportation over longer distances, local buyers and the possibility of short-distance hydrogen flows are an important condition and motivation for both centralized and decentralized projects.

Fourth, market folds deal with connections between markets, for example, because one market provides inputs for the other, as is the case with renewable electricity and green hydrogen. To produce green hydrogen, an electrolyzer, running on renewable electricity, splits purified water into oxygen and hydrogen. Thus, the production of green hydrogen depends on the creation of market folds with electricity and water markets as well as on their networked infrastructures. As we explain later, the market fold between green-hydrogen production and renewable-electricity generation is of utmost important to understand the role of infrastructure bottlenecks for the emerging green-hydrogen market and geography - and at the center of the green-hydrogen market design.

Muellerleile and Akers define market design as "a system of technical guidelines or norms [...] concerned with economic exchange" (Muellerleile & Akers 2015, p. 1782). Market designs deal with the legal rules under which markets can develop and often include rules for the use, provision and (re-)financing of transportation infrastructures. The construction of markets through rules makes their political dimension visible, because some actors have more power to shape the market design than others (Cooper 2015). While the geography-of-markets literature has argued that "«market design» inevitably has distributional effects" (Cooper 2015, p. 1788), energy geographers, to our knowledge, have not investigated this issue, particularly not regarding the discussion about decentralized versus centralized energy production. In an emerging market like the one for green hydrogen, we expect stakeholders to be very diligent in influencing the development of rules to their advantage. We therefore argue that the development of, and controversies around, market design are

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central for understanding the emerging greenhydrogen market and its geography.

METHODOLOGY

Our conceptual framework focuses on both market design and the spatial forms of markets. Conceptually, we argue that the four spatial forms of energy markets introduced above grid and regulatory territories, actor and infrastructural networks, electricity and hydrogen flows, and market folds linking different markets related to green-hydrogen production help to better understand the implications of infrastructure bottlenecks, their role in the emerging market design and its impact on the development of centralized and decentralized green-hydrogen projects. First, we investigate how market design and infrastructural conditions at different geographical scales, and partly contiguous with regulatory territories, have an impact on the development of the two market segments and the associated market folds, by supporting or constraining electricity and hydrogen flows that both types of projects necessitate. Therefore, our empirical analysis starts with a discussion of the emerging market design and is based on 14 interviews with experts at the regional, national, and EU levels.

We understand green-hydrogen projects as actor networks of suppliers and buyers and analyse how they create market folds, react to infrastructure bottlenecks and what kind of motivations they pursue by developing decentralized projects. To get an overview of both centralized and decentralized green-hydrogen projects and their respective geographies in Germany, we created a comprehensive database of all green-hydrogen production projects in Germany. The database compiles projects listed by two public databases (dena 2022; Zukunft Gas 2023), and additional projects we discovered online and during conference visits. In total, our database lists projects in almost 100 places across Germany, most of which are in development. Figure 1 shows all green-hydrogen projects with a size indication and illustrates how, over time, average project sizes are increasing. While all already operating projects have a production capacity of <15 megawatts (MW), the majority of projects that are planned to start operation until 2030 are large-scale projects with more than 15 up to 1000 MW.

To explain the geography of greenhydrogen production in Germany, we conducted 34 expert interviews with project developers and other stakeholders. To learn more about decentralized green-hydrogen



■ - 1 MW 🛛 > 1 MW - 5 MW 🗇 > 5 MW - 15 MW 📄 > 15 MW - 50 MW 📄 > 50 MW - 100 MW 🗋 > 100 MW

Figure 1. Green-hydrogen projects in operation or in development in Germany, by the start of operation and size in MW (Source: Own database, last update April 2023).

projects, their spatial forms and underlying motivations, we employed a case study approach. We concentrated on projects, which are already operational and have a capacity of more than 1 MW up to 15 MW. We decided to not consider very small projects as the associated opportunities for local development are limited. The upper threshold of 15 MW excludes projects which lead to additional costs for power-grid management and expansions, and/or require electricity imports from other regions, thus contributing less to local value added (Schalling et al. 2022, p. 39). Based on our selection criteria, we identified seven projects that we studied in-depth. Our case-study data collection followed a mixedmethods approach, combining participatory observations of hydrogen conferences and webinars, field-site visits, website and document analyses, as well as expert interviews. We conducted interviews with 19 stakeholders who are directly involved in the seven selected projects or other projects as owners and financiers, buyers, and/or technology providers.

REGULATING THE MARKET FOLD BETWEEN GREEN-HYDROGEN AND ELECTRICITY MARKETS

The EU market design tries to make green hydrogen from wind and solar electricity an instrument to mitigate climate change by stipulating both geographical correlation and temporal correlation of renewable-electricity generation and green-hydrogen production (European Commission 2023a). By defining these two criteria, the EU market design regulates the market fold between electricity and green-hydrogen markets.² In particular, it restricts the production of one commodity (green hydrogen) based on the local nonavailability of another commodity (renewable electricity) due to infrastructure bottlenecks. As a result, green-hydrogen production needs to take place in territories offering excess or additional renewable electricity.

EU market design for green hydrogen: Geographical correlation at which level? – The European Union's market design aims at preventing the direct or indirect use of fossil electricity for green-hydrogen production. To make sure that green-hydrogen producers do not use fossil electricity, the market design stipulates that operators of electrolyzers should either commission new renewable-electricity capacities or use renewable electricity that would otherwise be curtailed (European Commission 2023b). This requirement has mixed geographical implications. Additional purpose-built – new wind or solar parks are likely to be large to offer economies of scale and, thus, incentivize large-scale electrolyzer plants and a centralized geography of hydrogen production. By contrast, curtailed renewable electricity opens opportunities for smaller plants, contingent upon a combination of volatile renewable-electricity generation, distribution-grid bottlenecks and inflexible electricity demand. In Germany, such localized opportunities will persist for some time as grid expansion, which can reduce infrastructure bottlenecks, is slower than the addition of renewable-electricity capacities, resulting in an increasing amount of curtailed electricity (Ländner et al. 2019).

The EU market design tries to take powergrid bottlenecks into account by requiring the co-location of renewable-electricity sources and electrolyzers in the same bidding zone (so-called geographical-correlation criterion). It is assumed that within a bidding zone, there are no power-grid bottlenecks and electricity can flow freely between suppliers and buyers (Lindberg 2022). However, considerable grid constraints exist within the (one!) German bidding zone, which encompasses the contiguous territories of Germany and Luxembourg. Power-grid bottlenecks in Germany affect the states of, and the industry in Southern Germany, especially Bavaria and Baden-Württemberg, most strongly, where renewable-electricity capacities are insufficient to serve large-scale electrolyzers. At the same time, bottlenecks in the transmission grid severely limit flows of renewable electricity from Northern Germany, where large off- and onshore wind capacities frequently surpass demand, to Bavaria and Baden-Württemberg. In both states, wind parks and transmission-grid expansion were met with resistance in the past, although a

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large (industrial) electricity demand exists (Deutsche Akademie *et al.* 2020).

Against this background, the two governments fear that industrial sites in Southern Germany, whose defossilization depends on green hydrogen, will face competitive disadvantages if green-hydrogen supply is uncertain. Therefore, both governments support the development of centralized electrolyzers on their territories, but have unsuccessfully lobbied the European Union to create a market design that would allow hydrogen producers to source renewable electricity across Europe, without considering grid constraints (see statements of the two governments submitted to the European Commission 2022). Since bottlenecks prevent renewable-electricity flows, electrolyzers in the South would run on locally available electricity from fossil fuels, while the operators would virtually use "green" electricity from anywhere in Europe, thereby generating "green" hydrogen with a large carbon footprint (Interview energy provider; Pototschnig 2021).

To address this problem, the EU has allowed national legislators to introduce stricter rules for geographical correlation. If the German government passes stricter rules, it would constrain the development of centralized green-hydrogen projects based on the virtual use of renewable electricity from Northern Germany in the South and leave decentralized projects as the only development option. In its updated national hydrogen strategy, the national government supports stricter geographical correlation, despite the lobbying efforts of Bavaria and Baden-Württemberg (National Government 2023, pp. 6–7). Against this background, investors have mostly shied away from developing large-scale green-hydrogen production in Southern Germany so far (see Figure 2), while it is still an open question whether and when the German government will introduce stricter rules on geographical correlation.

Temporal correlation and balancing markets – In addition to geographical correlation, the EU market design also requires a temporal correlation of renewable-electricity generation and hydrogen production (European Commission 2023b). Temporal correlation means that electrolyzers, which are connected to the power grid, can only produce hydrogen at times when the contracted renewable-electricity source generates electricity. Especially in combination with a strict geographical correlation, the temporal correlation makes it difficult to achieve a large number of full-load hours for electrolyzers, particularly in areas where renewable-electricity generation is very volatile. Since in Germany offshore-wind turbines provide electricity more hours of the year than any other renewable technology, strict geographical and temporal correlation would favour centralized green-hydrogen production in the North.

The idea of temporal correlation is not new and is part of the German electricity-market design since 2001. In so-called balancing markets, market participants do not trade electricity but rather options to dispatch electricity supply or demand (Ländner et al. 2019). Greenhydrogen producers can participate in these markets because electrolyzers can flexibly produce hydrogen depending on the local availability of renewable electricity (Ruhnau 2022). Thus, selling balancing options (dispatchable electricity demand) on balancing markets can provide an income stream for green-hydrogen producers and creates a market fold between electricity, hydrogen and balancing markets. While the transmission-grid level requires larger capacities, balancing markets also provide an incentive for small electrolyzers at the distribution-grid level. Various actors engaged in decentralized projects (e.g., Brunsbüttel, Haßfurt, Mainz, and Wunsiedel) see this as an opportunity, and either take part in these balancing markets already or plan to do so in the future (Interviews energy provider; municipal utility; Webinar municipal utility Haßfurt). Against this background, proponents of decentralized projects demand that the EU and the German government should subsidize decentralized green-hydrogen projects that contribute to distribution-grid balancing (GPE 2022; Interview project developer). Before analyzing decentralized projects in greater detail, we take a closer look at centralized hydrogen production.



Figure 2. Emerging geography of hydrogen production and pipelines in Germany (Source: Own database, last update April 2023).

FROM GREY- TO GREEN-HYDROGEN MARKETS? CHALLENGES AND THE GEOGRAPHY OF CENTRALIZED GREEN-HYDROGEN PRODUCTION

The development of a green-hydrogen market segment for centralized hydrogen production builds upon existing experiences, production facilities and – rather fragmented - infrastructures for so-called grey hydrogen. Grey hydrogen is produced from fossil fuels, usually at refineries and chemical plants, and its production emits carbon (dena 2019). In Germany, oil- and chemical-industry multinationals such as Shell, Total, Linde or Air Liquide have been producing grey hydrogen for decades (Bundesnetzagentur 2020). A few, mainly (petro-)chemical companies use most of the grey hydrogen at the respective production sites as part of local networks and with short-distance hydrogen flows. Accordingly, the grey-hydrogen market is highly centralized in few locations and offers local-development opportunities only at production sites and places served by pipelines. By now, there are only three regional hydrogen pipelines in Germany, which connect hydrogen-production facilities with places of large demand. Hydrogen transportation by truck is expensive and only demanded by customers willing to pay a higher price. Therefore, hydrogen transportation over distances only takes place for sectors in which hydrogen constitutes a minor cost factor, like the food, glass, metallurgy and electronics industries (Linde Engineering 2023). Hence, there currently does not exist a contiguous national hydrogen market, but rather multiple regional markets, which are fragmented due to the limited reach of regional pipelines that enable large-scale flows between producers and buyers.

In the next two decades, as element of policies to mitigate climate change, green hydrogen and its derivatives (ammonia, methanol) are to replace not only grey hydrogen but fossil fuels as material feedstock and energy carrier in various industries, especially cement, steel and chemicals (IEA 2019). Since green hydrogen is not yet cost-competitive with grey hydrogen or fossil fuels (IRENA 2020), reducing the costs of green-hydrogen production is key to the formation of green hydrogen markets. The most important cost components of green-hydrogen production are the investment costs for electrolyzers and electricity costs (IRENA 2020). To minimize the costs of electricity and electrolyzers by realizing economies of scale, the national government subsidizes large energy producers, such as RWE and Vattenfall, to develop largescale renewable-energy parks and centralized electrolyzers, mainly in Northern Germany (Walker 2022). Southern Germany, by contrast, lacks sufficient renewable-electricity capacities, and flows from Northern Germany are limited due to bottlenecks in the transmission grid (see above). As a result, the emerging geography of green-hydrogen production already reflects the transmission-grid

bottlenecks between Northern and Southern Germany, and centralized green-hydrogen projects are concentrated in Northern Germany (Figure 2).

The long-term idea to address transmissiongrid bottlenecks between North and South is to transport hydrogen instead of electricity to the South, since hydrogen pipelines can transport energy in larger volumes, and the existing natural-gas grid could be repurposed to this end (Interview energy provider; Semeraro 2021). Pipeline operators should gradually expand hydrogen pipelines to create one contiguous national market and enable large-scale flows of green hydrogen between centralized electrolyzers and the production sites of the steel, cement and chemical industries. Pipeline development started in 2022, and is moving from the northern sea ports to Southern Germany, but will only reach it around 2030. Against this background, the governments of Bavaria and Baden-Württemberg in Southern Germany plan to develop their own regional hydrogen pipelines to collect decentrally produced green hydrogen and channel it to demand centers (Figure 2). These plans would enable the development of regional green-hydrogen markets despite not being contiguous or networked with the North.

THE GEOGRAPHY OF DECENTRALIZED GREEN-HYDROGEN PROJECTS

Although planning for centralized greenhydrogen projects concentrates on Northern Germany, small(er), decentralized projects exist and are being developed all over Germany (Figure 2). This leads to a dual geography of large centralized projects in the North and small(er) decentralized projects across the country. The following analysis highlights how local markets, actor networks and different types of motivations are important for understanding the economics and locations of decentralized green-hydrogen projects.

The economics and actor networks of decentralized green-hydrogen projects – Economies of scale and participating in balancing markets are

not the only way to decrease green-hydrogen production costs. Both large- and small-scale operators can also reduce them by selling the byproducts of green-hydrogen production, that is, heat and oxygen. Thereby, they maximize the efficiency of electricity use and create market folds with local heat and/or oxygen markets (Schalling et al. 2022). This strategy is pursued in several of our case studies, in which actor networks include buyers of oxygen and/or heat (Table 1), for example for district heating and use in wastewater treatment plants respectively (Interview municipal utility). Since municipal utilities often operate infrastructures like heating systems and wastewater treatment plants, and know about (other) local heat and oxygen demands, they are well-positioned to integrate electrolyzers into local heat and oxygen markets (Interview VKU). Consequently, we identified a range of municipal utilities that develop decentralized green-hydrogen projects.

While selling by-products can improve the projects' economics, green-hydrogen production still requires favourable demand-side regulation and/or financial support to be economically viable. Especially important for decentralized projects are EU and national policies on clean vehicles and public transport. Such policies create demand for green hydrogen across municipal territories, which decentralized electrolyzers can supply, as for example in Brunsbüttel, Haren and Wunsiedel. Furthermore, all projects we selected as case studies received public funding by the respective regional state and/or the national government or even the EU (as in the case of Shell in Wesseling), even though the German national hydrogen strategy is strongly geared towards supporting centralized electrolyzers and large-scale imports (Schalling et al. 2022; Walker 2022). Moreover, local governments supported some projects via investment by (and ownership of) their municipal utility (Haßfurt, Mainz, Wunsiedel).³

At this early stage of the industry, project development is contingent upon public funding and equity investments. Since specialized financial products (e.g., project financing) for hydrogen projects do not exist yet, project developers usually borrow from financiers with which they have already established relations, such as local banks or banks specialized in renewable energies (Interviews Specialized Bank). However, according to our interviews, financial market actors are unwilling to act as shareholders and take over major greenhydrogen project risks (Interview Specialized Bank). They only provide debt capital up to 20 per cent of the total financing volume (Craen 2023). Hence, we found that the market fold between the green-hydrogen and the financial market is less important for project development than other market folds. Nevertheless, green-hydrogen projects provide opportunities for credit business to local banks and, thus, can contribute to local development (Interview Local Bank).

In Germany, decentralized green-hydrogen production is, according to our project database, often managed by, or in cooperation with, local actors, including utilities, project developers and operators. Six out of seven case-study projects were (co-)initiated by local investors; currently five still have local owners. Except for one project (Haren), all of these projects are joint investments with non-local actors (Table 1). There are currently only two projects without local co-owners. The first is in Werlte, which, however, was initiated in 2013 by the regional energy provider EWE together with Audi to produce synthetic gas from green hydrogen for automotive use. Meanwhile, the project produces green hydrogen as basis for climate-friendly kerosene and is owned by former Audi managers who had been in charge of the original project. The second project is integrated into Shell's refinery in Wesseling. It is the only project that started without local investors and is a special case also because it is conceived as the first step towards a large-scale centralized project with an additional capacity of 100 MW (European Commission 2023a).

Future developments, especially the expansion of energy transportation infrastructures and a growing number of centralized green-hydrogen projects, might economically challenge decentralized green-hydrogen production. However, as transregional pipeline development moves forward rather slowly, proponents of decentralized green-hydrogen production argue that at least in the coming decade, decentralized and centralized hydrogen production will not compete in many regions, since infrastructure bottlenecks will constrain

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INFRASTRUCTURE BOTTLENECKS AS OPPORTUNITY FOR LOCAL DEVELOPMENT

the emergence of transregional hydrogen markets (Interview plant manufacturer; Lundblad et al. 2023). Some interviewees even doubt that centralized green-hydrogen production, particularly in other countries, and its economies of scale will ever outweigh the additional costs of transportation (Interview energy provider; Interview project developer). In remote areas with a small hydrogen demand, it could actually remain cheaper to produce green hydrogen locally than build a hydrogen pipeline or transport hydrogen by truck. Hence, even proponents of centralized hydrogen production sometimes argue that smaller scales of hydrogen demand should be met locally with decentralized production to avoid transportation costs (Forsberg 2007).

Motivations for the development of decentralized hydrogen projects - During our empirical research, we developed a typology of four main motivations of decentralized green-hydrogen project developers. These motivations are not mutually exclusive and coincide in most projects, especially when local and non-local actors form networks to jointly realize green-hydrogen production. Both non-local and, to a lesser extent, local actors invest in green-hydrogen projects in reaction to local demand (1). Generally, however, local actors are mainly supply-driven, that is, motivated by making use of existing, or generating more, renewable electricity in their region (2). Some non-local investors also aim at developing climate-friendly consumer products (3) or new technologies (4).

First, local demand for green hydrogen is one important motivation to develop decentralized projects. Actors with a demand for green-hydrogen see decentralized production as an opportunity to become (more) climatefriendly and save transportation costs compared to centralized grey- and green-hydrogen production. In our case studies, demand for green hydrogen exists from regional industries (Haßfurt, Mainz, Wesseling, Wunsiedel) and/or mobility, mostly public transport and (hydrogen) filling stations (Brunsbüttel, Haren, planned for Wunsiedel), but also agricultural tractors (Haren). Furthermore, one project uses locally-produced green hydrogen to generate electricity and heat in a combined heat-and-power plant (Haßfurt). The case of Wunsiedel is particularly instructive regarding potential transportation-cost savings through decentralized production. Wunsiedel is located in North-East Bavaria, a region where small-scale industrial hydrogen demand has been met by truck transport from the three closest places of grey-hydrogen production in Leuna, Frankfurt am Main and Burghausen, which are more than 200 km away (Figure 2). Since the transportation costs of hydrogen by truck amount to around 1–2€ per kg of hydrogen per 100km and grey hydrogen usually costs around 10€ per kg in Germany, transportation costs can easily become a relevant part of the total costs (Interview energy provider). Saving these transportation costs motivated an industrialgas trading firm to commit to buying green hydrogen produced in Wunsiedel to supply regional industries with green instead of grey hydrogen (Interview gas trader).

Second, marketing an existing or prospective local supply of renewable electricity is another important motivation for developing decentralized green-hydrogen projects in regions characterized by distribution-grid bottlenecks. Unlike at transmission-grid level with its North/South divide, distribution-grid bottlenecks exist across Germany (Deutsche Akademie et al. 2020). Existing distributiongrid bottlenecks or concerns for future bottlenecks motivated actors such as local utilities, project developers, and/or even a wind-park company in Brunsbüttel, Haren, Haßfurt, Mainz and Wunsiedel to develop such projects (Table 1). For them, green hydrogen constitutes a way of integrating excess electricity, that would otherwise be curtailed, into non-electricity renewable-energy markets. For example, one project uses green hydrogen to generate electricity and heat in a combined heat-and-power plant (Haßfurt), while three projects feed hydrogen into the naturalgas grid (Brunsbüttel, Haßfurt, Mainz, also planned for Haren). Besides, decentralized green-hydrogen production presents an opportunity to expand renewable-electricity production in those distribution-grid territories across Germany where renewable-electricity generation already exceeds grid capacity, at least temporarily. Haßfurt and Wunsiedel have

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even endorsed renewable energies explicitly as a development model and strive to increase local generation capacities to supply electricity to decentralized green-hydrogen production. In all these supply-motivated cases, the investors see the creation of market folds between the electricity market and fuel markets for industry, mobility and heating as an opportunity to market more electricity.

The development of entirely new consumer products and markets is a third motivation for investing in decentralized green-hydrogen projects. In our case studies, such products include "green gas" by GPE (Brunsbüttel, Haßfurt) and climate-friendly fuels for aviation (Werlte). Both aim at buyers willing to pay a premium for climate-friendly products. In the case of GPE, the company created a special "green gas tariff", which allows customers to support the development of decentralized green-hydrogen projects. In return, GPE feeds green hydrogen into the natural-gas grid to create the economic conditions for a greenhydrogen consumer market, thus acting as a "market builder" (Interview energy provider). Similarly, the project in Werlte mainly produces green hydrogen for kerosene production and is financed by Atmosfair clients to compensate CO_2 emissions of their flights. Thereby, it contributes to developing the climate-friendly aviation fuels market.

Fourth, despite subsidies and supportive demand-side policies, decentralized greenhydrogen projects can often only exist because the involved actors do not expect immediate economic returns. Engineering companies such as Audi (Werlte), Fendt (Haren), Linde (Mainz) or Siemens (Mainz, Wunsiedel) primarily engage in decentralized green-hydrogen projects to participate in developing carbon-neutral technologies (Interviews Municipal Utilities). Thus, technology development constitutes an additional motivation to invest in decentralized green-hydrogen projects, which helps actors to contribute to emission savings voluntarily, to prepare for future legal requirements of carbon neutrality and/or to diversify into a new business field. However, technology-motivated (non-local) investors are usually also involved in centralized projects and view decentralized production primarily as a means of testing and developing technologies for future upscaling.

CONCLUSION

Geographers transition researchers and have argued that infrastructures (Bridge & Bradshaw 2017; Kuzemko et al. 2018) and market regulation (Lindberg 2022) can support or constrain the development of energy markets. However, there is little geographical research on this topic. Therefore, we asked how existing infrastructure bottlenecks and the evolving green-hydrogen market design shape the emerging geography of green-hydrogen markets in Germany. We analysed what types of actors engage and invest in decentralized green-hydrogen projects and their motivations. More generally, we are interested in how infrastructure bottlenecks support or constrain the development of decentralized and/or centralized green-hydrogen production. We argue that when infrastructure bottlenecks constrain transportation over long(er) distances – as is the case in Germany for both hydrogen and renewable electricity -, market development can still occur locally. Thus, infrastructure bottlenecks and a market design requiring geographical and temporal correlation might lead to a (more) decentralized production pattern, which offers opportunities for local development.

Empirically, a duality of large centralized projects in the North and small(er) decentralized projects across the country characterizes the emerging geography of green-hydrogen production in Germany. The concentration of centralized projects in Northern Germany is a result of the (local) availability of large volumes of excess or additional renewable electricity and transmission-grid bottlenecks, while the latter constrain the development of centralized projects in Southern Germany. At the same time, the non-existence of hydrogen pipelines shields decentralized projects from competition with centralized production, as transportation by truck or ship is very expensive. The current geography of decentralized green-hydrogen projects reflects four main motivations: (1) Local demand for green hydrogen, incentivized by various EU and national policies (e.g. on clean vehicles and public transport) and (financial) support mechanisms; (2) local (over)capacities of renewable electricity, which cannot be integrated into the larger energy market due to distribution-grid

bottlenecks, and the strategy of (local) renewable-electricity suppliers to enter (nonelectricity) energy markets; opportunities for (3) downstream market development, e.g. for consumer uses or climate-friendly fuels, and/ or for (4) technology development.

Overall, the geography of green-hydrogen markets is not simply a result of infrastructure bottlenecks and political support but also contingent on market folds with other, especially renewable-electricity markets, their geographies and market design. To understand the emerging dual geography of green-hydrogen production in Germany, the market cannot "remain a black-box" (Berndt & Boeckler 2009, pp. 538–539). Our conceptual framework builds on the geography-of-markets literature to explain the matching of supply and demand at different levels (Muellerleile & Akers 2015; Muellerleile 2018). We suggest conceptualizing green-hydrogen markets by looking at four spatial forms of markets (Jones 2013).

First, green-hydrogen markets are characterized by various market folds, as they connect to other markets. Folds include, first and foremost, the connection with the market for renewable electricity as largest cost factor of green-hydrogen production and focus of the EU market design, as well as connections to local markets for heat and oxygen. In comparison, the market fold with the financial market is, so far, less important. Although previous studies pointed to the important role of local banks for developing decentralized renewableenergy projects (Hall et al. 2016) and institutional investors for developing large-scale projects (Christophers 2022), neither of them plays an active role in the development of green-hydrogen markets yet, because they are unwilling to underwrite (major) project risks.

Second, the availability of renewable electricity depends on the geographies of renewable-electricity generation and grid infrastructures, which include distributionand transmission-grid territories as different *contiguous spaces*. Third, the bottlenecks in Germany's power grids so far constrain the *flows* of renewable electricity from generation sites to more distant demand centers, while hydrogen pipelines are almost entirely missing. Together with the uneven geography of renewable-electricity generation, these infrastructure bottlenecks limit the expansion of green-hydrogen markets and only allow production in territories with a sufficient local supply of renewable electricity. Fourth, in the absence of national markets, *networks* of local and non-local sellers and buyers develop decentralized green-hydrogen projects in locations where local conditions are favourable.

While infrastructure bottlenecks help to explain the geography of green-hydrogen production, the ways in which market design integrates or disregards these bottlenecks is equally important. Currently, the EU market design regulates that the geography of green-hydrogen production follows the geography of renewable-electricity generation. By stipulating rules for the use of renewable electricity (e.g. geographical and temporal correlation), market design has an impact on where and on which level production can take place. How market design defines this connection - or market fold - between greenhydrogen and renewable-electricity markets is decisive for the emerging geography of green-hydrogen projects, especially the geography of, and balance between, centralized and decentralized projects. A strict definition of both geographical and temporal correlation of renewable-electricity generation and green-hydrogen production facilitates decentralized projects across Germany and a concentration of centralized projects in the North, thus reinforcing the emerging dual geography of the two market segments.

Our findings show that market designs, in combination with infrastructure bottlenecks, are inherently political (Lindberg 2022) because they shape the geography of markets and their distributional effects (Cooper 2015), as illustrated by the scarcity of centralized projects in the states of Bavaria and Baden-Württemberg. We also show that infrastructure bottlenecks do not necessarily impede accumulation, as assumed by Muellerleile (2018). Instead, they can support more decentralized production, thereby providing opportunities for local development in more places than in the case of centralized production.

The debate on how to define green hydrogen and regulate its production is ongoing and politically contested, not only in Germany and the EU but also the United States and other countries (Chu 2023). It begs the more general question why not all forms of industrial electricity use should follow the availability of renewable electricity. In other words, the question of how to regulate and govern the geographical and temporal relationship between industrial activities and their supply with renewable energy is an important future research question for economic geography and sustainability studies.

Acknowledgement

Open Access funding enabled and organized by Projekt DEAL.

Endnotes

- ¹We speak of defossilization instead of decarbonization because in a climate-neutral economy carbon from renewable resources will still be required by various industries. Hence, not the use of carbon per se but the use of carbon of fossil origin should be abandoned (Falcone *et al.* 2021).
- ²The EU market design, passed in February 2023, does not cover projects in operation. In addition, it grants projects that were to be developed before 2028 an exception from the additionality rule (see Article 11) and weakens the temporal correlation criteria until 2030 (see Article 6) (European Commission 2023b). However, hydrogen projects (especially large-scale) typically contract renewable energy sources for 10-15 years and have even longer refinancing timelines, so the exceptions for early projects granted by the European Commission do not match the timelines of project development (Hydrogen Europe 2023). In addition, project developers expect to only receive the necessary subsidies if they adhere to the market design, even before it is binding. Hence, the market design is reflected in the planning of hydrogen projects, even though it is technically not binding yet.
- ³While we acknowledge the importance of financial support for the development of the German green-hydrogen market, we do not explore the funding landscape in more detail (to this end, see Walker 2022; Schwabe 2024).

REFERENCES

BAKER, L. & J. PHILLIPS (2019), Tensions in the Transition: The politics of Electricity Distribution in South Africa. Environment and Planning C: Politics and Space 37, pp. 177–196. https://doi. org/10.1177/2399654418778590.

- BAUWENS, T., B. GOTCHEV & L. HOLSTENKAMP (2016), What Drives the Development of Community Energy in Europe? The Case of Wind Power Cooperatives. *Energy Research & Social Science* 13, pp. 136–147. https://doi.org/10. 1016/j.erss.2015.12.016.
- BEERMANN, J. & K. TEWS (2017), Decentralised Laboratories in the German Energy Transition. Why Local Renewable Energy Initiatives Must Reinvent Themselves. *Journal of Cleaner Production* 169, pp. 125–134. https://doi.org/10.1016/j. jclepro.2016.08.130.
- BERNDT, C. & M. BOECKLER (2009), Geographies of Circulation and Exchange: Constructions of Markets. *Progress in Human Geography* 33, pp. 535– 551. https://doi.org/10.1177/0309132509104805.
- BOLTON, R. & T.J. FOXON (2015), Infrastructure Transformation as a Socio-Technical Process – Implications for the Governance of Energy Distribution Networks in the UK. *Technological Forecasting and Social Change* 90, pp. 538–550. https://doi.org/10.1016/j.techfore.2014.02.017.
- BRIDGE, G. & M. BRADSHAW (2017), Making a Global Gas Market: Territoriality and Production Networks in Liquefied Natural Gas. *Economic Geography* 93, pp. 215–240. https://doi.org/10. 1080/00130095.2017.1283212.
- BUNDESNETZAGENTUR. (2020), Regulierung von Wasserstoffnetzen Bestandsaufnahme. Available at <https://www.bundesnetzagentur.de/Share dDocs/Downloads/DE/Sachgebiete/Energie/ Unternehmen_Institutionen/Netzentwicklung UndSmartGrid/Wasserstoff/Wasserstoffpapi er.pdf?__blob=publicationFile&v=2> (accessed 03.04.23).
- CHRISTOPHERS, B. (2022), Fossilised Capital: Price and Profit in the Energy Transition. *New Political Economy* 27, pp. 146–159. https://doi.org/10. 1080/13563467.2021.1926957.
- CHU, A. (2023), Energy Groups Mount Campaign Against Tough US Clean Hydrogen Rules. *Financial Times*. Available at <<u>https://www.ft.com/content/b8815253-64c6-4509-ac33-06d47</u> 45a6caa> (accessed 11.10.23).
- COOPER, M.H. (2015), Measure for Measure? Commensuration, Commodification, and Metrology in Emissions Markets and Beyond. *Environment and Planning A* 47, pp. 1787–1804. https://doi.org/10.1068/a130275p.

- CRAEN, S. (2023), Financing a World Scale Hydrogen Export Project. Available at <<u>https://ora.ox.ac.</u> uk/objects/uuid:bd3de91d-dfae-45e1-91c0-a818e b55a8a6> (accessed 03.11.23).
- DENA. (2019), Erdölraffinerie, Einsatzgebiete für Power Fuels. Available at <<u>https://www.dena.</u> de/fileadmin/dena/Publikationen/PDFs/2019/ Factsheet_PowerFuels_Erdoelraffinerie.pdf> (accessed 03.04.23).
- DENA. (2022), Wasserstoffprojekte in Deutschland. Available at <https://www.dena.de/fileadmin/dena/ Dokumente/Pdf/20220816_dena_Wasserstoffproj ekte_Deutschland.pdf> (accessed 03.04.23).
- DEUTSCHE AKADEMIE DER NATURFORSCHER LEOPOLDINA, UNION DER DEUTSCHEN AKADEMIEN DER WISSENSCHAFTEN, DEUTSCHE AKADEMIE DER TECHNIKWISSENSCHAFTEN. (2020), Netzengpässe als Herausforderung für das Stromversorgungssystem: Optionen zur Weiterentwicklung des Marktdesigns, Schriftenreihe zur wissenschaftsbasierten Politikberatung. Available at <https://www.leopoldina. org/uploads/tx_leopublication/2020_SN_ESYS_ Netzengpaesse.pdf> (accessed 03.04.23).
- DEWALD, U. & B. TRUFFER (2011), Market Formation in Technological Innovation Systems – Diffusion of Photovoltaic Applications in Germany. *Industry* and Innovation 18, pp. 285–300. https://doi.org/ 10.1080/13662716.2011.561028.
- DEWALD, U. & B. TRUFFER (2012), The Local Sources of Market Formation: Explaining Regional Growth Differentials in German Photovoltaic Markets. *European Planning Studies* 20, pp. 397–420. https:// doi.org/10.1080/09654313.2012.651803.
- ESTERMANN, T., M. NEWBOROUGH & M. STERNER (2016), Power-to-Gas Systems for Absorbing Excess Solar Power in Electricity Distribution Networks. *International Journal of Hydrogen Energy* 41, pp. 13950–13959. https://doi.org/10.1016/j. ijhydene.2016.05.278.
- EUROPEAN COMMISSION. (2022), Production of Renewable Transport Fuels – Share of Renewable Electricity (Requirements). Available at <<u>https://</u> ec.europa.eu/info/law/better-regulation/haveyour-say/initiatives/7046068-Production-of-renew able-transport-fuels-share-of-renewable-electricit y-requirements-/feedback_en?p_id=30819715> (accessed 04.03.23).
- EUROPEAN COMMISSION. (2023a), Clean Refinery Hydrogen for Europe II | REFHYNE II Project. Available at https://cordis.europa.eu/project/id/101036970/de> (accessed 03.04.23).

- EUROPEAN COMMISSION. (2023b), Commission Sets out Rules for Renewable Hydrogen. European Commission. Available at https://ec.europa.eu/ commission/presscorner/detail/en/ip_23_594 (accessed 03.04.23).
- FALCONE, P.M., M. HIETE & A. SAPIO (2021), Hydrogen Economy and Sustainable Development Goals: Review and Policy Insights. *Current Opinion* in Green and Sustainable Chemistry 31, 100506. https://doi.org/10.1016/j.cogsc.2021.100506.
- FORSBERG, C.W. (2007), Future Hydrogen Markets for Large-Scale Hydrogen Production Systems. International Journal of Hydrogen Energy, Path Forward to a Hydrogen Economy 32, pp. 431–439. https://doi.org/10.1016/j.ijhydene.2006.06.059.
- GREEN PLANET ENERGY. (2022), Neue Studie zeigt Vorteile dezentraler Elektrolyseure. Available at <https://green-planet-energy.de/presse/artikel/ neue-studie-zeigt-vorteile-dezentraler-elektrolys eure> (accessed 03.04.23).
- HALL, S., T.J. FOXON & R. BOLTON (2016), Financing the Civic Energy Sector: How Financial Institutions Affect Ownership Models in Germany and the United Kingdom. *Energy Research & Social Science* 12, pp. 5–15. https://doi.org/10.1016/j. erss.2015.11.004.
- HEINBACH, K., A. ARETZ, B. HIRSCHL, A. PRAHL & S. SALECKI (2014), Renewable Energies and their Impact on Local Value Added and Employment. *Energy, Sustainability and Society* 4, pp. 1–10. https://doi.org/10.1186/2192-0567-4-1.
- HYDROGEN EUROPE. (2023), Impact Assessment of the RED II Delegated Acts on RFNBO and GHG Accounting. Available at <<u>https://hydrogeneurope.</u> eu/wp-content/uploads/2023/07/Impact-Asses sment-on-the-RED-II-DAs.pdf> (accessed 11.04.24).
- IEA. (2019), The Future of Hydrogen. Available at <<u>https://www.iea.org/reports/the-future-of-hy-drogen></u> (accessed 03.04.23).
- IEA. (2023), Electricity Grids and Secure Energy Transitions. Available at <<u>https://www.iea.org/</u> reports/electricity-grids-and-secure-energy-trans itions> (accessed 1.22.24).
- IRENA. (2020), Green Hydrogen Cost Reduction. Available at <<u>https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reductions</u> (accessed 03.04.23).
- JONES, A. (2013), (Re)Conceptualising the Space of Markets: The Case of the 2007–9 Global Financial Crisis. *Geoforum* 50, pp. 31–42. https://doi.org/ 10.1016/j.geoforum.2013.07.010.

- KUZEMKO, C., M.F. KEATING & A. GOLDTHAU (2018), Nexus-Thinking in International Political Economy: What Energy and Natural Resource Scholarship can Offer International Political Economy. *In*: A. Goldthau, M. Keating & C. Kuzemko, (eds.), *Handbook of the International Political Economy of Energy and Natural Resources*, pp. 1–20. Cheltenham: Edward Elgar Publishing. https://doi.org/10.4337/ 9781783475636.00007.
- LÄNDNER, E.-M., A. MÄRTZ, M. SCHÖPF & M. WEIBELZAHL (2019), From Energy Legislation to Investment Determination: Shaping Future Electricity Markets with Different Flexibility Options. *Energy Policy* 129, pp. 1100–1110. https:// doi.org/10.1016/j.enpol.2019.02.012.
- LINDBERG, M.B. (2022), The Power of Power Markets: Zonal Market Designs in Advancing Energy Transitions. *Environmental Innovation and Societal Transitions* 45, pp. 132–153. https://doi. org/10.1016/j.eist.2022.08.004.
- LINDE ENGINEERING. (2023), Think Hydrogen. Available at <https://www.linde-engineering.com/ en/hydrogen/index.html> (accessed 03.04.23).
- LUNDBLAD, T., M. TALJEGARD & F. JOHNSSON (2023), Centralized and Decentralized Electrolysis-Based Hydrogen Supply Systems for Road Transportation – A Modeling Study of Current and Future Costs. *International Journal of Hydrogen Energy* 48, pp. 4830–4844. https://doi.org/10.1016/j.ijhydene. 2022.10.242.
- MARKARD, J. (2018), The Next Phase of the Energy Transition and Its Implications for Research and Policy. *Nature Energy* 3, pp. 628–633. https://doi. org/10.1038/s41560-018-0171-7.
- MUELLERLEILE, C. (2018), Calming Speculative Traffic: An Infrastructural Theory of Financial Markets. *Economic Geography* 94, pp. 279–298. https://doi.org/10.1080/00130095.2017. 1307100.
- MUELLERLEILE, C. & J. AKERS (2015), Making Market Rule(s). *Environment and Planning A* 47, pp. 1781–1786. https://doi.org/10.1177/03085 18X15610950.
- NATIONAL GOVERNMENT. (2023), Fortschreibung Der Nationalen Wasserstoffstrategie. Available at <https://www.bmbf.de/SharedDocs/Downloads/ de/2023/230726-fortschreibung-nws.pdf?__blob= publicationFile&v=1> (accessed 15.01.24).
- NAUMANN, M. & D. RUDOLPH (2020), Conceptualizing Rural Energy Transitions: Energizing Rural Studies,

Ruralizing Energy Research. *Journal of Rural Studies* 73, pp. 97–104. https://doi.org/10.1016/j.jrurs tud.2019.12.011.

- POTOTSCHNIG, A. (2021), Renewable Hydrogen and the "Additionality" Requirement: Why Making It More Complex than Is Needed? EUI Policy Briefs 2021/36. https://doi.org/10.2870/201657
- RUHNAU, O. (2022), How Flexible Electricity Demand Stabilizes Wind and Solar Market Values: The Case of Hydrogen Electrolyzers. *Applied Energy* 307, 118194. https://doi.org/10.1016/j. apenergy.2021.118194.
- SCHALLING, A., O. ARNHOLD, K. HELFENBEIN, T. RÖPCKE & A. BACKHAUS (2022), Netzdienliche Wasserstofferzeugung. Available at <<u>https://reine r-lemoine-institut.de/wp-content/uploads/2022/ 03/2022-03-10_Abschlussbericht_Netzdienliche_</u> Wasserstofferzeugung.pdf> (accessed 03.04.23).
- SCHMID, E., B. KNOPF & A. PECHAN (2016), Putting an Energy System Transformation into Practice: The Case of the German Energiewende. *Energy Research & Social Science* 11, pp. 263–275. https:// doi.org/10.1016/j.erss.2015.11.002.
- SCHWABE, J. (2024), Regime-Driven Niches and Institutional Entrepreneurs: Adding Hydrogen to Regional Energy Systems in Germany. *Energy Research & Social Science* 108, 103357. https://doi. org/10.1016/j.erss.2023.103357.
- SEMERARO, M.A. (2021), Renewable Energy Transport via Hydrogen Pipelines and HVDC Transmission Lines. *Energy Strategy Reviews* 35, 100658. https://doi.org/10.1016/j.esr.2021. 100658.
- SPÄTH, P. & H. ROHRACHER (2010), 'Energy Regions': The Transformative Power of Regional Discourses on Socio-Technical Futures. *Research Policy, Special Section on Innovation and Sustainability Transitions* 39, pp. 449–458. https://doi.org/10. 1016/j.respol.2010.01.017.
- VAN DE GRAAF, T., I. OVERLAND, D. SCHOLTEN & K. WESTPHAL (2020), The New Oil? The Geopolitics and International Governance of Hydrogen. *Energy Research & Social Science* 70, 101667. https:// doi.org/10.1016/j.erss.2020.101667.
- WALKER, B. (2022), Governance der deutschen Wasserstoffwirtschaft. Standort 46, pp. 265–270. https://doi.org/10.1007/s00548-022-00789-z.
- ZUKUNFT GAS. (2023), Hersteller Grünes Gas Karte. Available at <<u>https://gas.info/energie-gas/gas-infrastruktur/hersteller-gruenes-gas-karte></u> (accessed 03.04.23).