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POLICY BRIEF

SPATIAL HETEROGENEITY – CHALLENGE AND OPPORTUNITY FOR NET-ZERO GERMANY

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SPATIAL HETEROGENEITY – CHALLENGE AND OPPORTUNITY FOR NET-ZERO GERMANY

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3 GEOMAR

4 Helmholtz-Zentrum hereon

5 GFZ Helmholtz Centre Potsdam

6 GERICS Climate Service Center Germany — An institution of Helmholtz-Zentrum Hereon

7 UFZ Helmholtz Centre for Environmental Research

8 DBFZ

SPATIAL HETEROGENEITY – CHALLENGE AND OPPORTUNITY FOR NET-ZERO GERMANY

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ABSTRACT:

The energy system transformation in Germany is a challenge for society, economy and politics and has several impacts on multiple scales. This paper investigates the effects of the trajectories towards net zero emissions by 2050 through focusing on the spatial dimension of impacts, benefits, and losses for different stakeholders and technologies. Spatial heterogeneity in the energy transition means that regions enjoying benefits from decarbonization might diverge from regions experiencing losses, and that there are different geographical potentials and challenges. The question arising is one of the need for redistribution between benefits and losses, whilst ensuring that all stakeholders remain willing to act as frontrunners in the transformation of the energy system. Inclusion and participation in the process, together with a carefully targeted mixed set of regional energy policy, combining tax solutions and incentives for acceptance of required measures could facilitate a successful, efficient policy-supported energy transition.

1 INTRODUCTION

It is clear that a transformation of the energy system will involve extensive societal and economic changes. Discussions on the extension of the electricity grid, the siting of pipeline and storage options and resistance against the phasing out of coal-fired power plants in some regions show that there can be a stark difference between the acceptance of the decarbonization of the German energy system on a national and local level. In particular, a lack of acceptance on the local level could restrict the speed of decarbonization. Spatial heterogeneity means that there are regions that may suffer from decarbonization whereas others might benefit from the transition process – through, for example, attracting energy-intensive industries thanks to their local renewable energy resources and/or their development of hydrogen or carbon storage in their region. Hence, some regions are even interested in becoming front-runners in the transition, whereas others might be more reluctant. Thus, to ensure climate action in Germany at the necessary speed, taking into account the remaining carbon budget from 2021 onward, the question arises as to how benefits and losses of decarbonization could be distributed among the actors and regions without them losing interest in being front-runners.

This paper aims to identify possible challenges and opportunities resulting from spatial heterogeneity to provide policy makers with information on actors' support of transformation pathways. In particular, we take a closer look at spatial heterogeneity across five particular topics: heterogeneity in the availability of energy resources, storage capacities, the allocation of stakeholders, energy intensive industries, and the impact of decarbonization on individual households. For each of the topics, we investigate spatial relations, the extent, and the importance of spatial heterogeneity. In the concluding section, effects on transformation pathways are examined and contrasted with one another, comparing positive and negative economic, social, and environmental effects.

The structure of the paper is as follows: chapter two presents the five topics in detail. We first provide a hypothesis for each of the topics that introduces the direction of spatial relevance. Second, this hypothesis is illustrated and analyzed. In a third step, a conclusion on the spatial dimension of the topic is formed. In chapter three, the conclusions of all topics are used to generate implications for spatial energy policy and energy policy in general. At the end of the paper, we conduct a summary and outlook on matters raised in the preceding chapters.

2 SPATIAL STATEMENTS

2.1 TOPIC I: DISTRIBUTION OF ENERGY RESOURCES

Hypothesis

A transition of the German energy system will strengthen regions which feature high wind, solar, or biomass potential. In contrast, previous and current coal regions will suffer from the transition. Beyond that, the distribution of energy sources will also have an indirect impact on regions affected by the co-evolution of infrastructures, such as grids and storage facilities. Thus, the transition of the energy supply system will be linked with a spatial redistribution of positive and negative effects (e.g. creation or losses of jobs) which might affect the acceptance of the transformation processes.

Discussion

It is a well-known fact that the photovoltaic (PV) potential is higher across the South and high wind power potentials are located in the North of Germany, which is also reflected in the absorption of these potentials as locally generated electricity [Lehneis et al., 2020, Lehneis et al., 2021]. The imbalance is further increased by offshore wind potential, which specifically affects the coastal regions [Scholz, 2012, Stetter, 2014], which is illustrated in Figure 1. Since current installations follow this distribution of potential [AEE, 2021], their impacts can be attributed to these regions as well. Both technologies will have a leading role in the energy transformation and it is projected that there will be a proliferation of installed units in the coming years [Pregger et al., 2013, Günther et al., 2017, Gerbert et al., 2018, Robinius et al., 2020]. Therefore, it is envisaged that new regional inequalities will be enhanced or created in the near-term, as long as the regions with higher wind and PV potential are the focus of the renewables expansion. In the long term, when potentials of lower quality need to be exploited, this regional disparity might decrease again.

The fact that this potential gradient is overlapped by other renewable resources, such as the exploitable geothermal potential available predominantly in northern and southern Germany, but not in central Germany is less prominent. Biomass is also spatially unevenly distributed. Focal points of current biomass use are found primarily in areas dominated by agriculture and forestry in Bavaria, Baden-Württemberg, and generally, in Lower Saxony and North Rhine-Westphalia, which have high potentials and installed capacities [AEE, 2021]. Even though biomass is considered transportable, potentials tend to be exploited near the source, especially residues and wastes.

While northern and southern Germany are influenced strongly by the expansion of renewable energy installations, central Germany will be affected by the additional infrastructure needed to balance renewable energy generation. This concerns not only electricity grids, whose expansion planning is already widely discussed [Drees et al., 2021], but also storage and grid capacities needed in the future for hydrogen or other electricity-based synthetic energy carriers [Fette et al., 2020].

For new technology concepts, it is not yet possible to foresee the regional distribution, as their dissemination cannot yet be estimated. For example, the use of algae biomass could affect coastal regions, or the use of

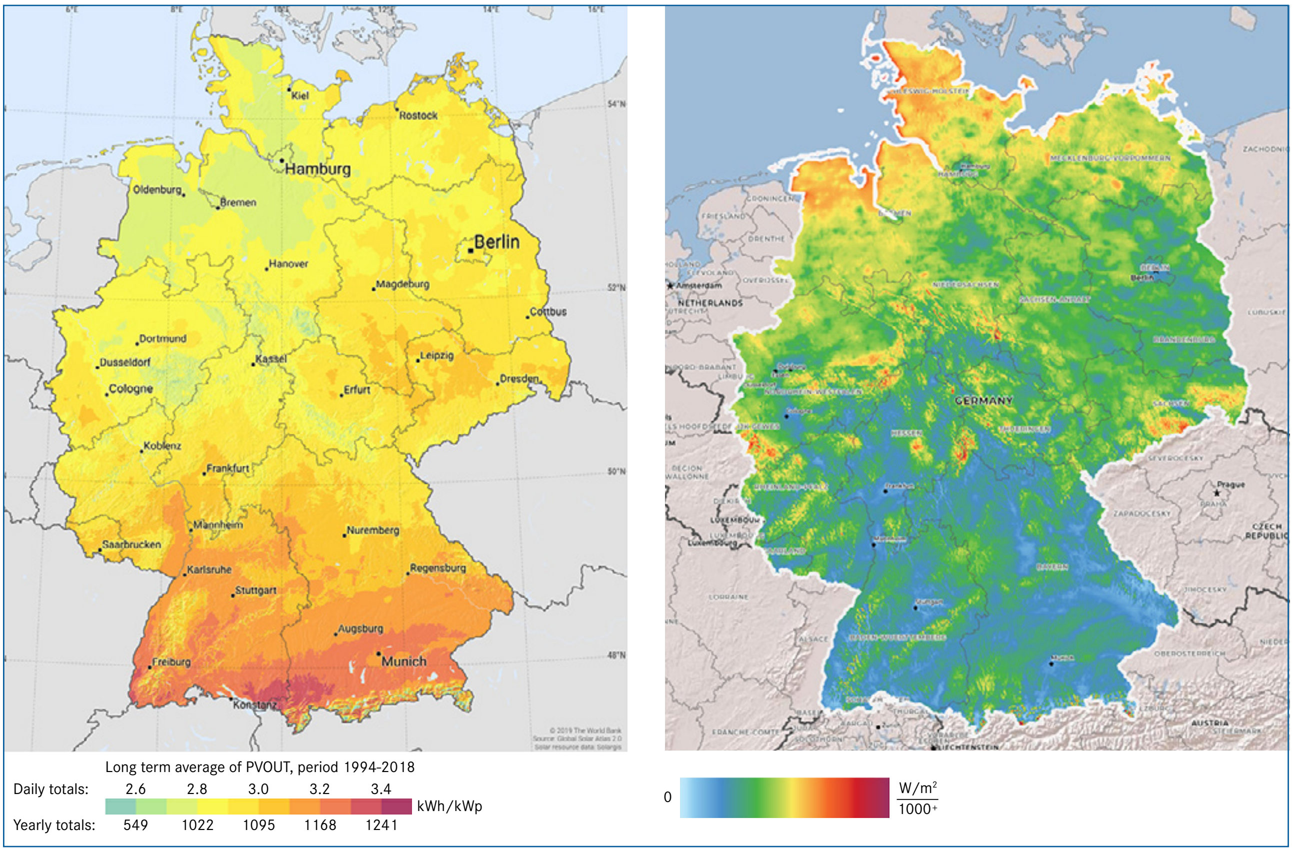

Figure 1: ***Left:*** *Photovoltaic Power Potential in Germany [The World Bank, 2019],* ***right:*** *Mean Wind Power Density [DTU Wind Energy, 2021].*

BECCS could take place at the already established biomethane and bioethanol sites, in regions with reasonable unused biomass potentials [Brosowski et al., 2019] or regions with access to international shipping, as this is the case with the formal coal power plants in Bremen, Hamburg or Rostock. However, promotion of new technology fields needs to consider spatial redistribution aspects – especially if a massive expansion is expected as it is for hydrogen applications [Robinius et al., 2020].

On the one hand, the expansion of renewable energies has positive economic effects for the regions in terms of jobs for the construction and operation of the plants and infrastructure [Aniello et al., 2019], which needs, on the other hand, the consideration of local environmental and neighbor-related concerns [Liebe & Dobers, 2019]. Although increasing use of renewable energies will lead to overall higher positive environmental effects, it is not clear whether regionalization will increase or rather balance out effects in the long term.

In contrast to these large-scale imbalances, the energy turnaround with regard to fossil energies is more selective. While large parts of Germany are hardly affected by the phase out of coal use, some hotspots are substantially affected: specifically the Lausitz, as well as the Mitteldeutsches and Rheinisches Revier (coalfields) [BMWi, 2019], e.g. through job losses and infrastructure dismantling. This leads locally to extremely high resistance from some clearly defined stakeholders – companies and employees as well as the affected communities [Geels, 2014]. Solutions for areas like these are urgently needed and approaches as well as new concepts are highly promoted, e.g. as the bio-economy model region of the Rheinisches Revier.

In the renewable energy sector, the range of stakeholders affected positively or negatively is much broader and thus more difficult to address, as they range from employees to companies to citizens and farmers, who may be negatively affected as landscape and land users, or positively affected as prosumers. This also highlights regional differences between urban and rural regions, which are structurally distinct and thus offer different potentials for application of technologies and their benefits and costs [Binz et al., 2020].

Some approaches to mitigate the aforementioned negative regional effects of the energy transformation can be based on a conversion of fossil fuel-based infrastructure to renewable technologies, e.g. by converting existing infrastructures – examples are the use of existing gas grid structures for hydrogen, conversion of coal power plants into storage sites or towards biomass-powered sites [enervis, 2021], or the use of fossil power plant sites for electrolysers for hydrogen production [BUKEA, 2021]. Abandoned lignite mines could, in future, provide areas for open-space PV plants [Jenniches & Worrell, 2019] or wind turbines – which, at the same time, can achieve a cautious approach to land consumption and a reallocation of jobs within the energy sector [Aniello et al., 2019].

Conclusion

The concentration of energy structure in certain regions with high resources could lead to multiple conflicts on a social and environmental level, as the spatial distribution of renewable energy infrastructure is not evenly dispersed which leads to inequalities. This gives rise to winners and losers, with states with more abundant renewable resources benefiting from a greater share of investment, whereas states with more limited resources having to bear a greater share of the costs of expansion.

2.2 TOPIC II: CENTRALIZED ENERGY STORAGE IN 2050

Hypothesis

The decarbonization of the energy system requires radical changes in the storage supply system. Despite electricity storage systems (e.g. batteries, pump-storage), less storage capacity will be necessary for natural gas. In contrast, huge capacities for synthetic gases as well as hydrogen will be necessary. With the decarbonization of the heat supply system, new heat storage will gain in importance. Candidates for such storage systems are high-temperature geothermal energy storage systems, which enable the transfer of large amounts of excess heat from summer to winter. New requirements for storage systems as well as new storage options will impact attitudes of actors towards the energy system transition.

Discussion

A decarbonization of the German energy system requires a drop in the demand for natural gas. Accordingly, less storage capacity for natural gas will be necessary. Currently, 17 cavern storage facilities (capacity: 134 TWh), 16 pore storage facilities (124 TWh) and 1 other storage facility (22 TWh) are in operation [Bundesnetzagentur, 2019]. The pore storage facilities are mainly located in the Southern part of Germany, whereas, in other regions, natural gas is mainly stored in caverns [Kabuth et al., 2017, Uniper SE, 2021]. The existing storage facilities are well integrated in the existing gas transmission network. For the next decade, natural gas will still be a key pillar of the German energy system. However, with increasing progress in the transformation process, other gases will become more important. It is expected that, in particular, hydrogen and synthetic methane (produced by using hydrogen and carbon dioxide as feedstocks) will become key elements in the system.

With increasing use of variable renewable energy sources, the meaning of energy storage options will rise. In principle, storage facilities that are no longer required for storing natural gas can gain new importance. Since the characteristics of hydrogen differ from natural gas, there are concerns regarding the unrestricted retrofitting of existing underground storage systems. In particular, there are great uncertainties regarding the possibilities for storing hydrogen in porous systems [Heinemann et al., 2021]. The storage of hydrogen in caverns seems to be no problem, so the current caverns used for natural gas will be turned into hydrogen storage facilities, while the current pore storage facilities in use will probably serve as storage units for synthetic methane or CO_2. Since underground caverns can also be an option for storing CO_2, it could be that, for economic (i.e. high prices for CO_2 allowances) and safety reasons, the underground storage capacities will be limited. With respect to jobs, the use of underground storage capacities is less relevant. However, with increasing fluctuating electricity supply the meaning of them for local, regional, and national energy systems will rise.

The decarbonization of the energy system (linked with phasing out of natural gas at least to a very great extent) will not only foster the use of hydrogen but also the development of new heat supply options. One novel approach is seasonal thermal energy storage. Depleted oil reservoirs, in particular, located in the Upper Rhine Basin, are suitable for storing heat in great amounts [Stricker et al., 2020], compare Figure 2.

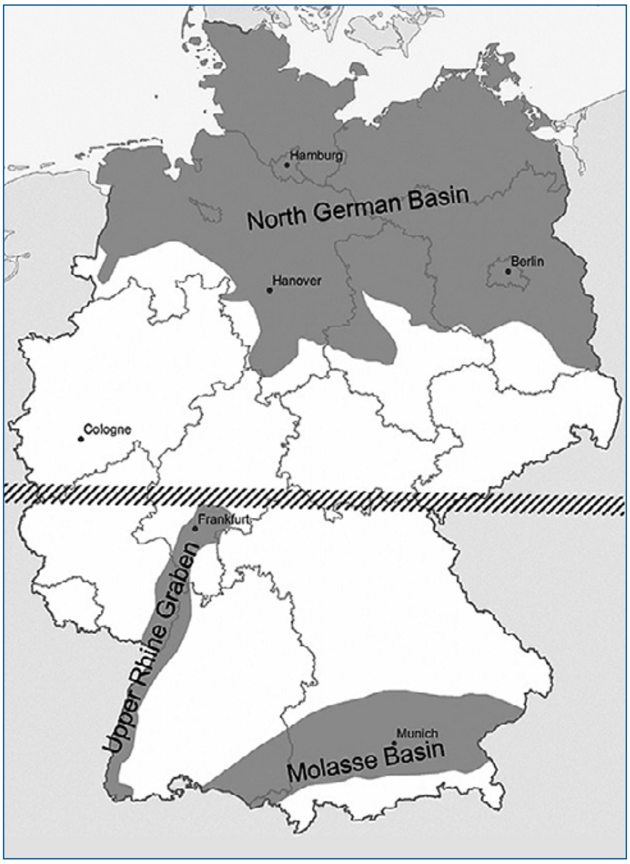

Figure 2: *Suitable regions for geothermal exploitation (shaded, based on two merged temperature models at the hatched line) [Agemar et al., 2012].*

High-temperature aquifer thermal energy storage systems enable the shift of large amounts of excess heat from summer to winter. The possibility of dealing with high-temperature systems can be interesting, for instance, for industries with high heat demand (at moderate temperature level).

On a local level, the option to store excess heat for a longer period as well as the option to use geothermal energy on a comparable high temperature level can play an important role for a transition of the energy system towards climate neutrality. In contrast to deep geothermal projects, which face resistance because of possible earthquakes caused by drilling and operation, fear with respect to possible contamination of groundwater, the use of depleted reservoirs might be linked with less opposition. However, geothermal heat storage technology still has to prove its feasibility. A key characteristic of geothermal systems is that cost (including impacts on environment) and benefits (i.e. supply of energy) are greatly restricted to the local level. On a local level, the actor can benefit from having geothermal energy or heat storage reservoirs as options in order to transform their energy system, in particular since these options can be part of a greater heat supply system (e.g. as a substitute for conventional district heating systems).

Conclusion

Although natural gas will lose its meaning as the decarbonization of the energy system progresses, new gases will gain importance. Even if the existing gas storage options are not suitable for each of the "new" gases, the storage infrastructure will retain its functions. Partially, there will be a competition between gases with respect to existing storage options. Depleted oil reservoirs cannot only be used for storing gases but are also an option for heat storage. With respect to the decarbonization of the heating system, high temperature heat storage, in particular, could become a favored option for the regions located close to depleted oil reservoirs. It can be expected that, as far as the use of existing infrastructure is concerned, there will be no great resistance by the public to the reuse of storage options.

2.3 TOPIC III: CO_2 STORAGE OPTIONS

Hypothesis

It is unlikely that the net zero target can be reached without permanent CO_2 storage. In Germany, CO_2 storage options are distributed unevenly and partly far away from current emission sources. Since some regions might perceive that they will suffer, as they have to store the captured CO_2, others will benefit from their CO_2 emissions being captured and stored elsewhere; opposition to CO_2 storage can be expected.

Discussion

As mentioned in Chapter 2.2, underground gas storage options are divided between porous aquifers, salt disused oil and gas fields, and salt caverns. While all options offer storage space for permanent CO_2 disposal, the cost and high potential for recoverable storage in salt caverns renders them more suitable for high-value energy carriers such as Hydrogen or Methane. Permanent CO_2 storage potential in porous aquifers in Germany is found in the northern and far southern parts of Germany, as well as in the German corridor of the North Sea. Porous aquifer storage relies on the combined existence of low permeability barrier rock overlaying a high porosity rock for the storage itself. This storage-barrier complex (SBC) ensures long-term safe CO_2 disposal. Geological characterization of underground layers allows the establishment of storage potential maps in which storage-barrier complexes of sufficient thickness can be identified [Müller & Reinhold, 2011]. Due to the stratigraphic nature of the underground, multiple storage-barrier complexes of varying depth can be found in the same map coordinates. We represent storage potential as zones displaying storage-barrier complexes in Figure 3.

While not represented here, a considerable amount of porous aquifer storage is also found in the German North Sea subsurface [Knopf & May, 2017]. Such off-shore stores might represent a stepping stone in underground CO_2 storage as there are fewer barriers to implementation (interaction with other subsurface uses, public acceptance). Furthermore, large-scale offshore storage is either ongoing or planned in North Sea domains of other countries [Chadwick, 2013, Porthos, 2021].

Despite the large identified potential storage areas, a significant fraction of German territory does not offer viable storage locations. Specifically, the highly industrialized state of North Rhine-Westphalia does not present direct porous aquifer storage options in its locality. In this regard, we display average CO_2

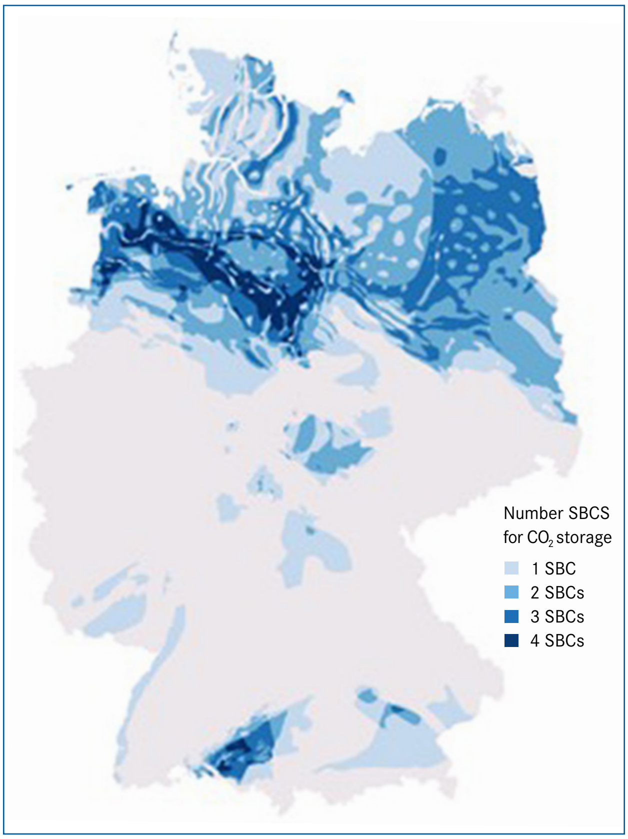

Figure 3: Summary of the Storage Barrier Complexes' (SBC) coverage inside Germany [Müller & Reinhold, 2011].

emission quantities for industry sources in Figure 4. Emissions related to primary energy production are not displayed as the planned phase out of coal power plants will significantly modify the expected emissions landscape in 2050 and are therefore not deemed relevant here.

The discrepancy between emissions locations of hard-to-abate industry CO_2 sources and storage options is expected to be dealt with via national CO_2 transportation networks, either via shipping, or dedicated pipelines. These solutions in effect overcome the heterogeneity and low overlap between storage and emission landscapes.

For the case of pipeline networks, technical prerequisites for CO_2 transport require an overhaul of gas pipeline characteristics, and furthermore projected CO_2 pipeline widths are not expected to match current gas pipeline capacities as they transport a different commodity all together. Development of a new network altogether is therefore required. Planning, construction and maintenance of the new CO_2 network will create a vast amount of job opportunities nationally. The ultimate fate of CO_2 storage in Germany (local onshore, offshore, or even international trans-border transport), will decide the specifics of the pipeline network as pipeline widths of a combined network (and the minimum-cost network layout itself) will be highly dependent on the final output location [Yeates et al., 2021]). In any case, the chosen pipeline layout is expected to adhere to current gas pipeline corridors as much as possible for legal and social acceptance reasons.

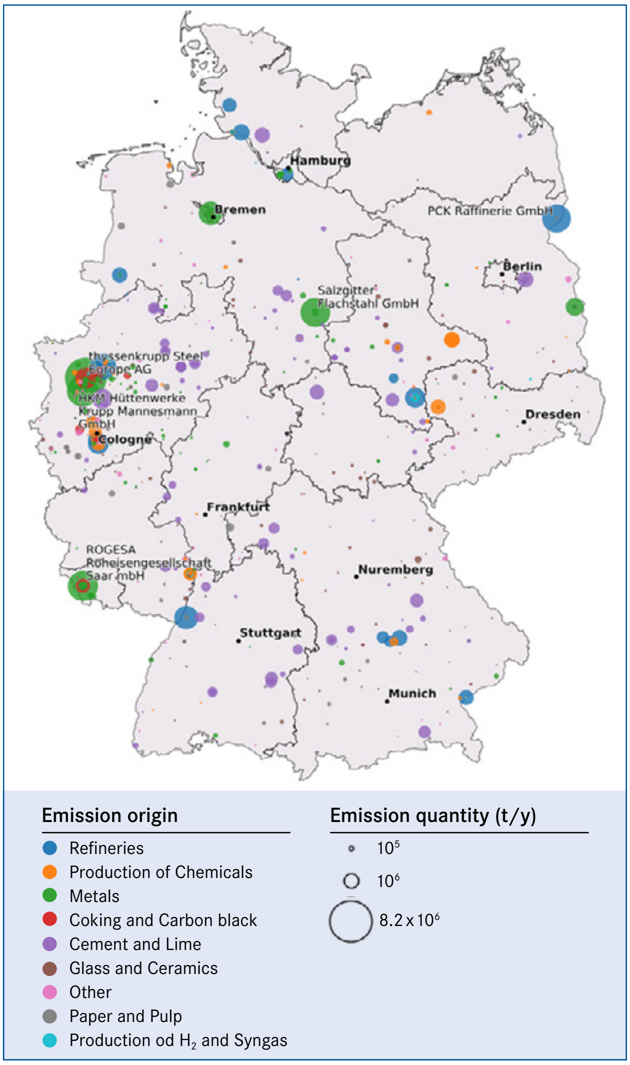

Figure 4: Point source average emissions > 10 000 t/y in Germany for 2015-2018 from all sources excluding (primary) energy production [Emissionshandelsstelle, 2018].

Potential regional discrepancies could be increased as some federal states feel that they need to dispose of other states' emissions. Looking to the future however, a large-scale CO_2 network is expected to provide incentives for highly emitting industries to relocate near the nodes of the pipeline system to simplify CO_2 abatement. Planning of the pipeline network must then be done in a strategic manner and offers crucial opportunities to reinvigorate less industry-intensive states. At the final storage site, whether on- or offshore, employment opportunities are projected for skilled technical workers within monitoring of the underground storage system.

The understood barriers to CO_2 storage are well documented for the German case, with a known lack of social acceptance for CO_2 storage in most of its forms [Ruhr-Universität Bochum, 2020]. Social science research, however, shows that more important reasons for such resistance might be basic value conflicts, distributive concerns, and failures of trust in governing institutions such as regulatory authorities and technical advice bodies [Waller et al., 2020, Markusson et al., 2020]. A successful public outreach concept was proven for the

Ketzin CO_2 pilot storage project, where an open and transparent dialogue with all stakeholders was present from the very beginning [Martens et al., 2015]. The German approach is based on experiences from public attitudes and preferences towards emerging technologies and shows the need for a close collaboration between social science research, energy scenario research and political decision makers in order to initiate a fair discourse with public participation [Scheer et al., 2017].

Conclusion

Underground storage options for long-term CO_2 storage exist in abundance in Germany. However, most are located in areas of relatively low emissions and, therefore, transport options are required to overcome this mismatch. This raises some potential issues regarding the responsibilities or incentives less-emitting states have to dispose of emissions of highly industrialized states. A notable lack of social acceptance regarding underground CO_2 storage technologies in Germany highlights this difficulty. A thorough public outreach effort is required to first open up areas of high storage potential to this prospect and should perhaps be aided by financial incentives for storage. One way out might be communicating the strategic importance for industry to be located near CO_2 pipelines or storage sites in a 2050 Net Zero emission landscape.

2.4 TOPIC IV: ENERGY INTENSIVE INDUSTRIES

Hypothesis

Ambitious climate change policies will challenge particularly energy intensive industries and vehicle manufacturers. International competition might lower their interest in supporting such policies. Since these industries are unevenly disrupted, regions will show resistance against climate change policy in order to avoid an economic decline.

Discussion

In Germany, closeness to resources and customers have been the main drivers for an uneven distribution of industries. The iron and steel industry can serve as a prominent example; this industry is mainly located in North Rhine-Westphalia, Lower Saxony, Saarland, Bremen, Hamburg, and Brandenburg. In particular, the availability of access to coal mines and transport infrastructure led to the decision to choose these sites for production. Since supply industries favor closeness to their customers, usually agglomerations of companies are located on production sites. Hence, on a local level, the number of jobs, which depends directly and indirectly on production of industrial goods, can be very high. In Saarland for instance, 11,700 jobs depend directly and 21,900 indirectly on steel production [Verband der Saarhütten & Isoplan Marktforschung, 2020]. Assuming the same direct/indirect relation for North Rhine-Westphalia, the 46,000 direct jobs are linked with more than 86,000 indirect jobs.

The chemical industry, which also comes under the energy intensive industries facing challenges from ambitious climate change policies, is also located in North Rhine-Westphalia (about 97,000 direct jobs). Other larger production sites are in Bavaria (56,000 jobs) and Rhineland-Palatinate (47,000 jobs) [Statistische Ämter des Bundes und der Länder, 2021]. The cement industry and the paper industry are other examples of energy intensive industries that are sited mainly in North Rhine-Westphalia, Bavaria and Baden-Wuerttemberg, or Lower Saxony. In the Eastern part of Germany, fewer people are employed in energy-intensive industries. However, on a local level, the meaning for economic activity could be very high (e.g. in Leuna) [IMG Sachsen-Anhalt, 2021]

Energy intensive industries like the ones mentioned above are characterized by a high share of energy costs in their overall costs. Currently, the production process of these industries mentioned above is mainly based on the use of fossil energy carriers. Thus, a decarbonization of the energy system (resulting e.g. in increases in the cost for fossil fuels) requires strong efforts by these industries. It is very likely that incremental improvements in energy efficiency will be insufficient for reaching the target set by the German government. In particular, the iron and steel industry faces high international competition [OECD, 2020]. Hence, decisions to modify production routes or to switch to new routes (e.g. hydrogen-direct reduction) should be considered carefully. The European Commission recognized that, in particular, the cost for CO_2 allowances can weaken the competitiveness of industries and put them on a carbon leakage list [European Commission, 2018]. Being on this list offers opportunities for getting a limited number of free CO_2 allowances. To become CO_2-neutral in the long term, new options have to be identified and specified if avoiding the relocation of industries is desired[1].

Due to the current importance of energy intensive industries, a scale-down of their production will be linked with a greater need for structural changes. In comparison to the financial support for the phase out of coal-fired power plants, which amounts to more than 40,000 Mio. Euro [BMWi, 2020] for cushioning losses of about 30.000 jobs, a conversion or overhaul of energy intensive industries may require significantly more effort.

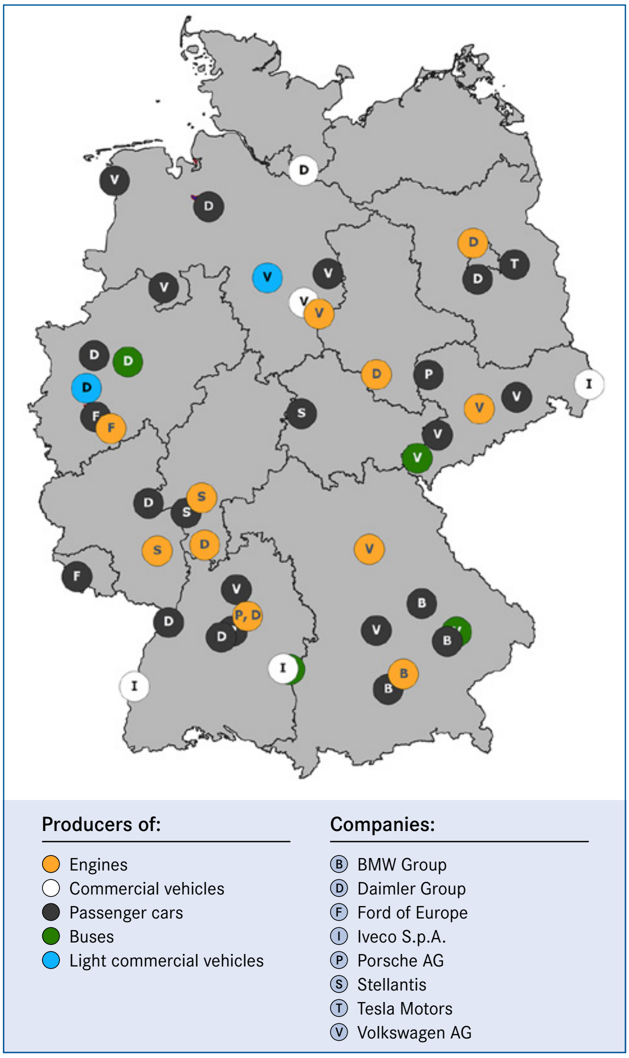

Figure 5: Automotive industry in Germany (incl. key suppliers), source: [ACEA, 2021].

The vehicle manufacturers face similar problems as the energy intensive industries. In particular, the envisaged phase out of cars with internal combustion engines will be a challenge for the German car industry since the transformation of the mobility sector requires significant changes in value chains and production activities. Currently, the vehicle manufacturers and their suppliers are mainly located in Baden-Wuerttemberg (about 233,000 direct jobs), Bavaria (207,000 jobs) and Lower Saxony (120,000 jobs) [bw-invest.de, 2021, Invest in Niedersachsen, 2021, Bayern innovativ, 2021], compare Figure 5. It is expected that the car suppliers, in particular, will suffer from the transformation of the mobility sector [Arbeitsgemeinschaft der Zulieferindustrie, 2020].

Conclusion

It can be expected that car industry suppliers, vehicle manufactures and energy intensive industries, in general, will show resistance towards ambitious climate change policies and ask for strong financial support for the transformation process. Considering the relevance of these industries on a regional and national level, it is likely that their resistance will be supported by political decision makers who are interested in conserving existing

1 Contract for Difference (CfD) und Carbon Border Adjustment Mechanism (CBAM) could serve as examples for such options.

economic structures [Bauer et al., 2018]. However, broadly based climate change policies, which include e.g. support of the transformation process by providing public R&D infrastructure, measures on the demand side (e.g. "green labeling") as well as on the supply side can help to ensure competitiveness for the long term. Examples like the implementation of hydrogen in industrial steel production [ArcelorMittal, 2020] show that more and more industries recognize that the transformation of the energy system can be a chance to strengthen their market position in the long term. Even if a first mover advantage is not guaranteed – since for reaching climate change targets on an international level, a transformation of the energy system is inevitable – it would be better to be prepared well in advance rather than to "wait and see" what happens in other countries.

2.5 TOPIC V: POPULATION AND PRIVATE HOUSEHOLDS

Hypothesis

Private households are especially important, as the acceptance of the population is crucial for a successful energy transition. Thus, depending on the geographical allocation of the population, energy system possibilities, changes to the energy system, and the effects of GHG reduction measures affect the population differently on multiple scales. Regions with a high population density are expected to be impacted more than regions where the population density is relatively lower. The benefits and challenges on the road to Net Zero are, therefore, unevenly distributed across the population.

Discussion

A successful energy transition is in need of the support of the population. Private households have a high importance, as they are not only a major consumer of energy, in general, but also own a significant share of renewable energy producing infrastructure [AEE, 2019]. A change in energy systems also goes hand in hand with infrastructural changes, changes to the economy and can e.g. influence the household income through energy price changes. The transition poses a major challenge to households, as centralized decisions may not be able to take local specificities into account and the population is unevenly distributed [Coenen et al., 2012].

There exist major agglomeration regions, e.g. in the Rhine-Ruhr-Area, surrounding capital cities like Hamburg, Munich, or Berlin. The center of Germany and parts of the Northeast are more sparsely populated [Destatis, 2021].

Several factors can regionally determine population density. Some regions or some households may be more feasible to live in than others. Major agglomerations/cities have different possibilities than rural areas and there is a distinction between West-East, which results from the historical division of Germany, which is reinforced by inner-German migration, leading to a demographic structure significantly distorted towards older people in the East. This could be attributed to the availability of jobs and further social and economic infrastructure that is lacking in more rural regions of the East and often determines where households choose to settle [Destatis, 2021].

Studies show that accounting for regional characteristics like the distinction between urban and rural regions is important for energy systems. Their allocation differs regionally based on the characteristics of renewable energy sources.

This differentiation may still not be extensive enough, as there are visible differences for example in energy consumption between the regions, based on their geographic location, not the extent of their urban development. In addition, there are differences in living space and typical heating systems between rural and urban regions. This is illustrated also in the study by the BMU [BMU, 2016], where the differentiation between East Germany and the rest of the country is revealed. The actual geographic location of the population seems to be very relevant.

Moreover, if the distribution of other important population criteria like income or the growth of population, and correlated, their age, are taken into account, even more distinctions appear. The distribution of the population across the country is uneven, but the characteristics are also not spread evenly, as the maps of BBSR [BBSR, 2021] show, compare Figure 6. Population growth is positive in the South, in Northwest Germany and near highly agglomerated regions like Hamburg or Berlin. In the center, the population growth is negative, thus, energy consumption will likely decrease in those regions in line with ongoing trends. Additionally, the income distribution is highly differentiated, illustrating the South and West of Germany as hotspots of high per capita income.

In research, the population is often considered undifferentiated, but as consumers of energy are one of the most important factors to consider when addressing Net Zero, households have to be center stage [Wells & Nieuwenhuis, 2012]. The consideration of household size, age, if they have children, their employment status, or income provides valuable information on their characteristics. These social factors can approximate the behavior of the households as actors in the energy transition, so they should be explicitly represented [Bergantino & Catalano, 2016].

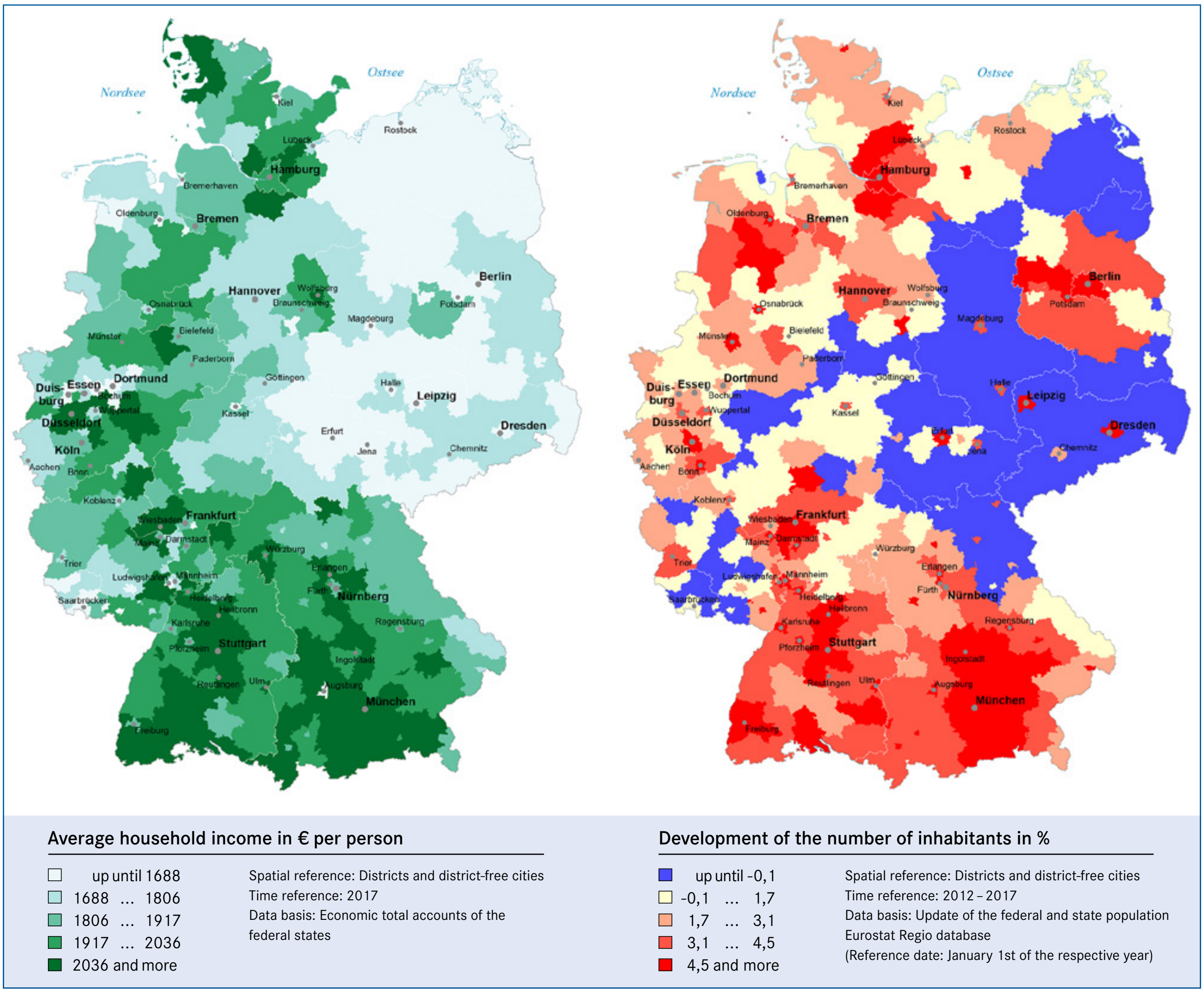

*Figure 6: Geographical Differences of Population Characteristics (**left:** household income per capita in 2017, **right:** population growth from 2012 to 2017) [BBSR, 2021].*

The variation regarding energy use is most relevant and scientifically proven for income, as the standard of living rises with incomes and, thus, households can afford more energy con-sumption [BMU, 2016, DEFRA, 2007]. The measures necessary to reduce the GHGs, their impacts on households, and the households' ability to stomach possible negative effects are mostly positively related to the income of a household [Büchs & Schnepf, 2013]. Thus, this relation is investigated more specifically with regard to the impacts of GHG reduction measures.

It is crucial to consider that households with different incomes can be affected unequally by possible adverse effects. Furthermore, this provokes financial misalignment and can impair the fairness and effectiveness of policies, giving rise to an unfair burden for some households [Büchs & Schnepf, 2013]. This is especially relevant if policy disregards the potential for households to stomach the transition, as lower income households would e.g. be most adversely affected by a general consumption tax as a measure to reduce GHG emissions. Households with higher incomes are probably not as adversely affected.

CO_2 emissions of households seem to follow energy consumption – as supported by the findings of Büchs and Schnepf [Büchs & Schnepf, 2013]. This points to the decoupling of energy consumption and emissions as an important topic in the energy transition. This would need incentives to increase the share of carbon-free energy carriers.

Household characteristics vary geographically, but there is no distinct pattern in the variations as would be expected with urban-rural contrasts, for instance. This is a major factor when considering the effects of GHG reduction measures. Benefits or adverse effects may always affect the population in general, regardless of where it is geographically located in Germany. The acceptance of the transition and the ability to adapt to the changes of the energy transition varies with that, as well. A point to address this could be the consideration of the strong regional variation of income per capita, as there exists a significant gap between East and West regions in Germany. If a spatial policy approach is desired, this could possibly approximate the diverging household characteristics, albeit this approach is not recommended based on our research.

Conclusion

The spatial dimension for private households is not as relevant as the characteristics of the households themselves. The population is allocated unevenly in Germany, but its characteristics like household income, household size, and age seem to have a more relevant impact on a successful transition. The spatial effects relevant to the energy transition are reduced to the existence of the population, but the characteristics of households are the determining factors of acceptance and success, not the place of residence of that population.

3 POLICY IMPLICATIONS

Regions with high potentials for successful implementation of renewable energy resources will be able to benefit from increased RES deployment, irrespective if based on state subsidies or market-driven state subsidies. This may lead to disadvantages in other regions. A reorientation from purely economically optimal locations for wind and PV to ecological-economic and social co-optimization may also lead to a cushioning of regional differences. The use of agro-PV above arable land or the use of building-integrated PV can help balance regional focal points in terms of land use and landscape impacts [Fraunhofer ISE, 2021].

In the future, geological storage capacities will be needed for gases other than natural gas. Depending on the time horizon, there will be partial competition for using the existing capacities for hydrogen, synthetic gas and CO_2. From the perspective of actors, it is important that the storage options can be used dynamically e.g. for balancing gas production and gas demand or as a permanent storage device for CO_2. Since gas storage will still be a key pillar of the future energy system, having access to the storage option will be of interest for actors like utilities, gas suppliers, and energy intensive industries close to and far away from storage sites. A coordinated strategy on possible use of this storage option would be helpful. The use of depleted oil reservoirs for storing heat should be included in such a strategy. In such a strategy the need for additional infrastructure e.g. heat grid, gas pipelines, or connection to electrolyzers should be taken into consideration.

A decarbonization of the energy system implies significant changes in industrial processes. In particular, energy intensive sectors will be impacted. In principle, in the next decades there will still be a high demand for products of these industries. High competition on national and international markets restricts the possibility of passing on additional cost resulting from environmental constraints. Hence, the future of the existing production sites strongly depends on the development of their cost. For avoiding carbon leakage and to strengthen a greening of industries, measures which help to develop and improve novel production processes in a protective space are necessary [Geels, 2002]. An example of such measures is an implementation of carbon-cross border adjustment in combination with a support of research, development and demonstration (RD&D) activities. Of course, there is no guarantee that the number of jobs will remain at the current level or that there will be no relocation of industries. Access to resources (e.g. wind for hydrogen production or closeness to customers) can influence decisions on relocations.

Since energy intensive industries as well as the car industry are unevenly distributed, some regions may suffer more than others. On the one hand, there are broad examples of regions that suffered from structural change for longer periods. On the other hand, structural change can be seen as a window of opportunity or as a starting point for "creative destruction" [Schumpeter, 2016].

In principle, federal states as well as national governments are experienced in measures to minimize negative effects of structural changes. However, it is likely the regions such as North Rhine-Westphalia, Bremen and parts in Eastern Germany that suffered in the past from structural change will again be negatively affected. Hence, there will be a need for new adjustments of the redistribution of cost and benefits between federal states.

Concerning private households, the spatial dimension seems to be less relevant compared to the different characteristics of households. Household income seems to be the factor most important for households' ability to counterbalance negative effects of policy measures from the energy transition. A possible solution could be a CO_2 consumption tax in combination with a redistribution mechanism. This way, adverse effects on lower income households can be held low, as they do not have high energy consumption and thus high emissions. As energy consumption and emissions of households increase with income, those who consume more energy can also face policy regulation targeted at CO_2 reduction better. Additionally, incentives are needed to raise awareness among the population and lead to higher intrinsic GHG reduction. This could be executed by providing more information and generally more environmentally friendly consumption options; emissions would likely decrease with energy consumption [Gordon et al., 2018, Frame & Newton, 2007]. Acceptance of the energy transition could increase through this as well. Still, it is most important that social segregation is avoided to build trust in the transition process which can ensure the successful transformation of pathways.

4 CONCLUSION & OUTLOOK

In this paper, five different topics with high relevance to the energy transition and towards achieving net zero have been investigated with regard to the importance of spatial heterogeneity. First, energy resources that are differently distributed across Germany are especially relevant for the change towards renewable energy. Second, centralized energy and CO_2 storage possibilities to secure energy requirements and to deposit CO_2 are a non-negligible factor in achieving net zero and keeping future emissions to a minimum. Additionally, energy intensive industries, especially that locate in particular regions with geographical proximity to abundant energy sources, should be considered when analyzing where the highest energy consumption is to be expected. This also holds for private households that settle mostly – but, importantly, not exclusively – in dense urban areas of the country. It is vital to include their location, as public acceptance of transition measures and infrastructure is a key element for a successful transformation of the energy system towards net zero 2050.

Innovative ways of engaging stakeholders could help to increase acceptance of local energy projects. In Karlsruhe, for instance, co-creation processes, involving the participation of stakeholders and citizens through workshops and interviews, was implemented to reduce the risk of rejection of a geothermal heat project [Schill et al., 2021]. Furthermore, participatory processes are essential to inform society and build trust that can counter the regime resistance often present in relation to fundamental changes like the energy transition [Halbe et al., 2020]. Still, considering another recent development as an example, the Covid-19 pandemic has highlighted the extent to which society is vulnerable to damage to the ecosystem and this may lead to greater public attention on environmental issues and greater willingness to embrace radical social innovations that are required [EEA, 2021].

Considering spatial differences of energy types, storage and industry needs, whilst paying attention to household characteristics like income or household age/size, a mixed portfolio of measures seems to be most sensible. A mixed set of place-based regional policy and incentivizing acceptance by households through CO_2 consumption taxes could be an option for a successful, efficient policy-supported energy transition.

Overall, the spatial dimension of the energy transition is neither only a challenge nor an opportunity; it is characterized by a mixture of both. It is necessary to take into account the different resource potentials, diverging storage capacities and energy needs across the country, and the various stakeholders of the energy transition. Geographically differentiated regional energy policy, often with strong disparities in the balancing of needs and losses, with a focus on the stakeholders, could provide essential guidelines for a sustainable, successful energy transition across all scales, resources, and technologies.

REFERENCES

- ACEA (2021) Interactive map – Automobile assembly and production plants in Europe. https://www.acea.auto/figure/interactive-map-automobile-assembly-and-production-plants-in-europe. Accessed 21.10.2021
- AEE (2019) *Eigentümerstruktur der Erneuerbaren Energien*. Agentur für Erneuerbare Energien. https://www.unendlich-viel-energie.de/mediathek/grafiken/eigentuemerstruktur-erneuerbare-energien. 22.07.2021.
- AEE (2021) *Föderal Erneuerbar.*, Agentur für Erneuerbare Energien. https://www.foederal-erneuerbar.de/uebersicht/bundeslaender/. 01.02.2021.
- AGEMAR, T., SCHELLSCHMIDT, R., SCHULZ, R. (2012) Subsurface temperature distribution in Germany. *Geothermics,* 44, 65-77.
- ANIELLO, G., TÖBBEN, J., KUCKSHINRICHS, W. (2019) The Transition to Renewable Energy Technologies—Impact on Economic Performance of North Rhine-Westphalia. *Applied Sciences,* 9:18, 3783.
- ARBEITSGEMEINSCHAFT DER ZULIEFERINDUSTRIE (2020) *Für einen Neustart der deutschen Industrie*.
- ARCELORMITTAL (2020) *Umwelt und grüner Stahl aus Hamburg*. https://hamburg.arcelormittal.com/icc/arcelor-hamburg-de/broker.jsp?uMen=f0e10ffc-365a-0e51-a18f-7ff407d7b2f2&uCon=5b850257-935e-c571-919d-a7e30cab71d8&uTem=aaaaaaaa-aaaa-aaaa-aaaa-000000000042. 09.06.2021.
- BAUER, N., MCGLADE, C., HILAIRE, J., EKINS, P. (2018) Divestment prevails over the green paradox when anticipating strong future climate policies. *Nature Climate Change,* 8:2, 130-134.
- BAYERN INNOVATIV (2021) *Bedeutung der Automobilindustrie in Bayern*. https://www.bayern-innovativ.de/seite/bedeutung-der-automobilindustrie-in-bayern. 22.07.2021.
- BBSR (2021) *INKAR – Indikatoren und Karten zur Raum- und Stadtentwicklung*. Bundesinstitut für Bau-, Stadt- und Raumforschung. https://www.inkar.de/.
- BERGANTINO, A.S., CATALANO, M. (2016) Individual's Psychological Traits and Urban Travel Behaviour. *International Journal of Transport Economics,* 43:3.
- BINZ, C., COENEN, L., MURPHY, J. T., TRUFFER, B. (2020) Geographies of transition—From topical concerns to theoretical engagement: A comment on the transitions research agenda. *Environmental Innovation and Societal Transitions,* 34, 1-3.
- BMU (2016) *Repräsentative Erhebung von Pro-Kopf- Verbräuchen natürlicher Ressourcen in Deutschland (nach Bevölkerungsgruppen)*.
- BMWI (2019) *Kommission „Wachstum, Strukturwandel und Beschäftigung" Abschlussbericht*.
- BMWI (2020) *Kerninhalte Kohleausstiegsgesetz und Strukturstärkungsgesetz.* Bonn.
- BROSOWSKI, A., et al. (2019) How to measure the impact of biogenic residues, wastes and by-products: Development of a national resource monitoring based on the example of Germany. *Biomass and Bioenergy,* 127, 105275.
- BÜCHS, M., SCHNEPF, S.V. (2013) Who emits most? Associations between socio-economic factors and UK households' home energy, transport, indirect and total CO_2 emissions. *Ecological Economics,* 90, 114-123.
- BUKEA (2021) *Energy transition: Shell, Mitsubishi Heavy Industries, Vattenfall and Wärme Hamburg Sign Letter of Intent for 100MW Hydrogen Project in Hamburg*. Behörde für Umwelt, Klima, Energie und Agrarwirtschaft. https://www.hamburg.de/pressearchiv-fhh/14847344/2021-01-22-hydrogen-project-hamburg-moorburg/. 09.06.2021.
- BUNDESNETZAGENTUR (2019) *Monitoring report 2019.* Bonn.
- BW-INVEST.DE (2021) *Automobilwirtschaft*. https://www.bw-invest.de/standort/branchen-cluster/automobilwirtschaft. 22.07.2021.
- CHADWICK, R. (2013) *Offshore CO_2 storage: Sleipner natural gas field beneath the North Sea. Geological Storage of Carbon Dioxide (CO_2).* 227-253e, Elsevier.
- COENEN, L., BENNEWORTH, P., TRUFFER, B. (2012) Toward a spatial perspective on sustainability transitions. *Research policy,* 41:6, 968-979.
- DEFRA (2007) *Distributional Impacts of Personal Carbon Trading.* Department for Environment, Food and Rural Affairs.

- DESTATIS (2021) *Bevölkerungsentwicklung in Ost- und Westdeutschland zwischen 1990 und 2019: Angleichung oder Verfestigung der Unterschiede?* https://www.destatis.de/DE/Themen/Querschnitt/Demografischer-Wandel/Aspekte/demografie-bevoelkerungsentwicklung-ost-west.html. 09.06.2021.
- DREES, T., MEDERT, H., MEINECKE, M., HALICI, C. (2021) *Netzentwicklungsplan Strom 2035*.
- DTU WIND ENERGY, T. W. B., VORTEX, (2021) *Global Wind Atlas*. https://globalwindatlas.info/area/Germany. 09.06.2021.
- EEA (2021) *Covid-19 and Europe's environment: impacts of a global pandemic*. Copenhagen, European Environment Agency. https://www.eea.europa.eu/publications/covid-19-and-europe-s/covid-19-and-europes-environment. 09.06.2021.
- EMISSIONSHANDELSSTELLE (2018) *Installations covered by ETS in Germany 2018*.
- ENERVIS (2021) *Conversion of coal power plants to biomass*. https://enervis.de/leistung/foerderbedarf-fuer-die-umstellung-von-kohlekraftwerken-auf-biomasse/. 09.06.2021.
- EUROPEAN COMMISSION (2018) *Commission Notice, Preliminary Carbon Leakage List, 2021-2030 (2018/C 162/01).* Brussels, European Commission.
- FETTE, M., BRANDSTÄTT, C., GILS, H. C., GARDIAN, H., PREGGER, T., SCHAFFERT, J., TALI, E., N., B. (2020) *Multi-Sektor-Kopplung-Modellbasierte Analyse der Integration erneuerbarer Stromerzeugung durch die Kopplung der Stromversorgung mit dem Wärme-, Gas-und Verkehrssektor.*
- FRAME, B., NEWTON, B. (2007) Promoting sustainability through social marketing: examples from New Zealand. *International Journal of Consumer Studies,* 31:6, 571-581.
- FRAUNHOFER ISE (2021) *Agrivoltaics*. https://www.ise.fraunhofer.de/en/key-topics/integrated-photovoltaics/agrivoltaics.html. 22.07.2021.
- GEELS, F. W. (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy,* 31:8-9, 1257-1274.
- GEELS, F. W. (2014) Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective. *Theory, Culture & Society,* 31:5, 21-40.
- GERBERT, P., HERHOLD, P., BURCHARDT, J., SCHÖNBERGER, S., RECHENMACHER, F., KIRCHNER, A., KEMMLER, A., WÜNSCH, M. (2018) *Klimapfade für Deutschland*, BCG, The Boston Consulting Group.
- GORDON, R., WAITT, G., COOPER, P., BUTLER, K. (2018) Storying energy consumption: Collective video storytelling in energy efficiency social marketing. *Journal of Environmental Management,* 213, 1-10.
- GÜNTHER, J., LEHMANN, H., LORENZ, U., PURR, K., GRIMM, F. (2017) *Den Weg zu einem treibhausgasneutralen Deutschland ressourcenschonend gestalten*. Umweltbundesamt.
- HALBE, J., HOLTZ, G., RUUTU, S. (2020) Participatory modeling for transition governance: Linking methods to process phases. *Environmental Innovation and Societal Transitions,* 35, 60-76.
- HEINEMANN, N., et al. (2021) Enabling large-scale hydrogen storage in porous media – the scientific challenges. *Energy & Environmental Science,* 2021:14, 853-864.
- IMG SACHSEN-ANHALT (2021) *ZUKUNFTSORT Chemiestandort Leuna*. IMG Investitions- und Marketinggesellschaft Sachsen-Anhalt mbH. https://www.investieren-in-sachsen-anhalt.de/zukunftsort-chemiestandort-leuna. 22.07.2021.
- INVEST IN NIEDERSACHSEN (2021) *Weltspitze – die Automobilwirtschaft*. https://www.nds.de/de/branchen/mobilitaet/automobilwirtschaft. 22.07.2021.
- JENNICHES, S., WORRELL, E. (2019) Regional economic and environmental impacts of renewable energy developments: Solar PV in the Aachen Region. *Energy for Sustainable Development,* 48, 11-24.
- KABUTH, A., et al. (2017) Energy storage in the geological subsurface: dimensioning, risk analysis and spatial planning: the ANGUS+ project. *Environmental Earth Sciences,* 76:1, 1-17.
- KNOPF, S., MAY, F. (2017) Comparing methods for the estimation of CO_2 storage capacity in saline aquifers in Germany: Regional aquifer based vs. structural trap based assessments. *Energy Procedia,* 114, 4710-4721.
- LEHNEIS, R., MANSKE, D., THRÄN, D. (2020) Generation of Spatiotemporally Resolved Power Production Data of PV Systems in Germany. *ISPRS International Journal of Geo-Information,* 9:11, 621.

- LEHNEIS, R., MANSKE, D., THRÄN, D. (2021) Modeling of the German Wind Power Production with High Spatiotemporal Resolution. *ISPRS International Journal of Geo-Information,* 10:2, 104.
- LIEBE, U., DOBERS, G. M. (2019) Decomposing public support for energy policy: what drives acceptance of and intentions to protest against renewable energy expansion in Germany? *Energy Research & Social Science,* 47, 247-260.
- MARKUSSON, N., BALTA-OZKAN, N., CHILVERS, J., HEALEY, P., REINER, D., MCLAREN, D. (2020) Social science sequestered. *Frontiers in Climate,* 2, 2.
- MARTENS, S., KEMPKA, T., LIEBSCHER, A., MÖLLER, F., SCHMIDT-HATTENBERGER, C., STREIBEL, M., SZIZYBALSKI, A., ZIMMER, M. (2015) Field experiment on CO_2 back-production at the Ketzin pilot site. *Energy Procedia,* 76, 519-527.
- MÜLLER, C., REINHOLD, K. (2011) Geologische Charakterisierung tiefliegender Speicher- und Barrierehorizonte in Deutschland – Speicher-Kataster Deutschland. *Schriftenr. dt. Ges. Geowiss.*: Heft 74.
- OECD (2020) *Latest developments in steelmaking capacity.* Paris.
- PORTHOS (2021) *CO_2 reduction through storage beneath the North Sea*. https://www.porthosco2.nl/en/. 22.06.2021.
- PREGGER, T., NITSCH, J., NAEGLER, T. (2013) Long-term scenarios and strategies for the deployment of renewable energies in Germany. *Energy Policy,* 59, 350-360.
- ROBINIUS, M., et al. (2020) *Wege für die Energiewende: kosteneffiziente und klimagerechte Transformationsstrategien für das deutsche Energiesystem bis zum Jahr 2050*, Forschungszentrum Jülich GmbH Zentralbibliothek, Verlag.
- RUHR-UNIVERSITÄT BOCHUM (2020) *ELEGANCY – Enabling a Low-Carbon Economy via Hydrogen and CCS*.
- SCHEER, D., KONRAD, W., CLASS, H., KISSINGER, A., KNOPF, S., NOACK, V. (2017) Regional-scale brine migration along vertical pathways due to CO_2 injection–Part 1: The participatory modeling approach. *Hydrology and Earth System Sciences,* 21:6, 2739-2750.
- SCHILL, E., BAUER, F., SCHÄTZLER, K., RÖSCH, C., MBAH, M., BENIGHAUS, C., KUPPLER, S., KROHN, J. (2021) *Coproduction of knowledge: towards a co-design of geothermal heat utilization*. EGU General Assembly Conference Abstracts.
- SCHOLZ, Y. (2012) Renewable energy based electricity supply at low costs: development of the REMix model and application for Europe.
- SCHUMPETER, J. A. (2016) *49. Capitalism, Socialism and Democracy*, Columbia University Press.
- STATISTISCHE ÄMTER DES BUNDES UND DER LÄNDER (2021) *Betriebe und Beschäftigte nach Wirtschaftszweigen (WZ 2008)*. 20/04/2021.
- STETTER, D. (2014) *Enhancement of the REMix energy system model: Global renewable energy potentials, optimized power plant siting and scenario validation*. Universtität Stuttgart.
- STRICKER, K., GRIMMER, J. C., EGERT, R., BREMER, J., KORZANI, M. G., SCHILL, E., KOHL, T. (2020) The Potential of Depleted Oil Reservoirs for High-Temperature Storage Systems. *Energies,* 13:24, 6510.
- THE WORLD BANK (2019) *Global Solar Atlas 2.0, Solar resource data: Solargis*. https://solargis.com/maps-and-gis-data/download/germany. 09.06.2021.
- UNIPER SE (2021) *Germany: Our Storage Facilities in Germany*. https://www.uniper.energy/storage/what-we-do/where-we-operate/germany. 09.06.2021.
- VERBAND DER SAARHÜTTEN, ISOPLAN MARKTFORSCHUNG (2020) *Die Zukunft der saarländischen Stahlindustrie – Chancen und Risiken unter kritischen Rahmenbedingungen*.
- WALLER, L., RAYNER, T., CHILVERS, J., GOUGH, C. A., LORENZONI, I., JORDAN, A., VAUGHAN, N. (2020) Contested framings of greenhouse gas removal and its feasibility: Social and political dimensions. *Wiley Interdisciplinary Reviews: Climate Change,* 11:4, e649.
- WELLS, P., NIEUWENHUIS, P. (2012) Transition failure: Understanding continuity in the automotive industry. *Technological Forecasting and Social Change,* 79:9, 1681-1692.
- YEATES, C., SCHMIDT-HATTENBERGER, C., BRUHN, D. (2021) *A method for simultaneous minimal-cost supply node location and network design in pipelined infrastructure*. EGU General Assembly Conference Abstracts.

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S.V. conceived the idea of the paper, which was then developed together with C.B. and I.R. S.V. drafted the paper's structure. All co-authors contributed to the text and to editing. S.S. drafted chapter 2.1, C.Y. drafted chapter 2.3, N.M. contributed to 2.3. S.V. drafted chapter 2.2 and 2.4, I.R. drafted chapter 2.5. B.S. provided insights for chapter 4. L.B. contributed to 2.1 and 2.3, D.T provided insights to 2.1 and 2.5, D.M. contributed to 2.1

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