nature communications

Article

https://doi.org/10.1038/s41467-026-76500-9

How sovereign control, decarbonization and energy costs shape public support for data centers

Received: 2 December 2025

Accepted: 28 July 2026

Published online: 10 August 2026

Check for updates

Jonas Heering [1] & Erik Voeten [1,2]

The rapid expansion of data centers has created new political challenges. Governments want to build more data centers to reap the benefits from the artificial intelligence (AI) economy and achieve their digital sovereignty agendas. However, data centers require enormous amounts of electricity and water, threaten emission-reduction targets, and often raise local electricity prices. As a result, local communities increasingly mobilize against data center construction. We use a vignette and conjoint survey experiment in Germany to evaluate how publics think about the environmental, economic, and (geo) political tradeoffs that data centers entail. We find that directly priming people with digital sovereignty concerns only marginally increases support for building more data centers. Yet, support varies substantially based on characteristics that people do have strong views about: decarbonization, geopolitics, and local environmental and economic impact. Geopolitical concerns are particularly salient: people strongly favor data centers operated by German or European firms over US or Chinese operators. These nationality effects are large even when compared to the effects of electricity price increases and variation in energy sources. Our findings suggest that public opposition to data centers depends on pre-existing political cleavages and that sovereignty concerns loom large.

The digital revolution requires an enormous expansion in the number and capacity of data centers. These facilities provide the backbone of the digital economy, housing the physical infrastructure necessary to store and process data—computer servers, storage drives, and network equipment—used to develop artificial intelligence (AI) and operate social media, e-commerce, and cloud computing. As governments are eager to reap the benefits from the digital economy, they have pledged hundreds of billions of dollars of public investment into data center construction[1], often offering attractive tax, land, and electricity rate deals to data center operators[2].

Building more data centers is also a geopolitical imperative: under the umbrella of 'digital sovereignty,' states promote local data infrastructure to retain control over data, maintain regulatory authority, boost the competitiveness of their national digital economy, and reduce dependence on foreign technologies[3–5]. A growing web of national laws and bilateral agreements places restrictions on what types of data can be stored and processed outside of a country's jurisdiction[6–8]. And, amidst geopolitical competition over AI, governments promote the development of 'sovereign AI'—large-language models and AI applications that are tailored to a country's cultural and linguistic needs and ensure the competitiveness of the local AI industry by training AI models on local datasets and in domestically-located data centers[9]. As such, governments have strong incentives to build more data centers within their national boundaries.

Yet, the construction of new data centers increasingly elicits public backlash. Data centers' energy demands conflict with climate

[1]Department of Government, Georgetown University, Washington DC, USA. [2]School of Foreign Service, Georgetown University, Washington DC, USA.
e-mail: jh2176@georgetown.edu

objectives and may increase local electricity prices. Already by 2026, global data center electricity demand is expected to equal that of Japan, according to the International Energy Agency[10]. In Europe alone, the electricity consumption by data centers is expected to double by 2030[11]. Much of this increased electricity demand is expected to be driven by AI data centers, which are particularly computing-intensive[10]. In the medium term, this surge in energy demand risks undermining governments' decarbonization targets by increasing greenhouse gas (GHG) emissions[12], particularly as companies consider fossil fuels, nuclear energy, or delaying coal phase-outs to meet their surging energy demand. Data centers also can strain local water supplies and yield only limited local economic benefits in terms of jobs and tax revenues. In the United States, by 2025, news reports linked local opposition from 142 activist groups working across 24 states to the blocking and delay of $64 billion worth of data center developments[13]. Similar backlash to data center construction has emerged and impacted data center development across Africa, Asia, Europe, and Latin America[14].

The political dilemma for democratic governments is how to develop their digital economies and promote their digital sovereignty agendas while maintaining public support as data centers' environmental and economic footprint becomes more salient. Yet, despite the growing political salience of data centers, we lack a systematic understanding of how the public thinks about the environmental, economic, and geopolitical tradeoffs that data centers entail. Studies have highlighted the importance of public opinion to studying the energy transition[15,16] and digital sovereignty[8] separately, but not in tandem.

One possibility is that the public shares some of the government's concerns over digital sovereignty and is more likely to support those data center developments that advance digital sovereignty goals. Research shows that citizens in many countries prefer domestic over foreign investments in strategic industries[17–20]. Polling from several European countries also demonstrates strong support for rules that mandate storing certain data and technology inside the European Union[21], as well as broad skepticism toward US-based technology companies that collect and process large shares of Europeans' data[22].

At the same time, data centers' impact on the environment and electricity prices are likely to elicit public backlash. Studies show widespread public demand for action against climate change in Europe, including Germany[23]. Thus, people may be skeptical towards data centers that rely on fossil fuels. Moreover, local environmental damage is often a main reason why communities oppose developments, including those that directly benefit the green transition, such as wind turbines[24,25] and lithium mines[26]. And voters' concerns over household electricity prices directly feed into support for populist parties[27,28].

Understanding how people weigh the tradeoffs over digital sovereignty, climate change, and the local impact of data centers not only helps governments and businesses anticipate which types of data centers are more likely to face resistance but potentially reveals new political cleavages in the 'twin transition'—the joint promotion of decarbonization and the digital transformation. While scholars concur that societal factors are essential for energy transition modeling, they do not always know which factors matter most[29].

We contribute to this understanding by studying public preferences toward data centers through two experiments embedded in an online survey in Germany, with a sample broadly representative of the general German public ($n = 2523$). The German government explicitly strives to make Germany the "beacon of Europe" for data centers under the banner of achieving digital sovereignty[30]. Yet, like in other countries, the construction of new data centers has created public opposition on environmental and economic grounds[31,32]. We first use a priming experiment to examine whether explicitly raising the salience of digital sovereignty concerns—centered on either data protection for users or the competitiveness of the national digital economy—increases overall support for data center construction. We subsequently use a conjoint experiment to evaluate how Germans make the trade-off between three components along which data centers vary: national origins of data center operators, climate change impact, and local environmental and economic impact.

Our findings reveal that while priming people with digital sovereignty concerns only marginally increases support for constructing more data centers in general, nationality features prominently in how respondents evaluate specific data center projects, alongside concerns about data centers' impact on the environment and local electricity prices. Data centers run by US firms are about 20 percentage points less likely to be favored than data centers operated by German companies. The nationality effect is comparable to the effect of a data center that would increase local electricity prices by twenty percent. Chinese data centers are even less popular, particularly among people who believe that technologies like AI carry more societal risks than rewards. Thus, foreign-owned data centers would have to be much more careful about local economic and environmental impact than German data centers in order to attract public support. This presumes that European alternatives are available; an issue we return to in the Discussion section.

Local jobs and tax revenues are not strong drivers of support. We also find no strong evidence that the primary purpose of data centers matters much, with the exception that Germans strongly dislike data centers for crypto-mining. Together, these results imply that support for and opposition to data centers is not driven by abstract views about the digital revolution but by assessments of the implications of data centers on matters that people feel strongly about: geopolitics, climate change, pocketbook economic concerns, and local environmental impact. For example, we find that people who support the far-right Alternative for Germany (AfD), which has campaigned against green transition policies[28], do not prefer data centers that run on renewable energy over data centers powered by coal. This finding suggests that data center politics feed into pre-existing political cleavages and concerns.

Results

Digital sovereignty primes and general support for data centers

We first use a priming experiment to examine whether making digital sovereignty concerns explicit increases overall support for building more data centers in Germany. We randomly sort respondents into four groups. Respondents in the control group receive information about the basic economic and environmental tradeoffs of building more data centers in Germany. The vignette emphasizes data centers' potential positive impact on innovation, investment, and jobs. At the same time, respondents are told that data centers may drive up local electricity prices and generate more greenhouse emissions through their high electricity consumption and strain local water supplies. We also include a blank control group that did not get any information at all.

In addition to the same information about the basic tradeoffs of data centers, respondents in the two treatment groups received additional information emphasizing either data centers' role in facilitating local data storage and strengthening data protection (data protection treatment) or data centers' importance to develop digital technologies in Germany and reduce dependence on foreign providers (competitiveness treatment). Concerns over data protection in the context of cross-border data transfers have frequently led to international tensions, most notably between the EU and the United States[33–35], and shaped the proliferation of data localization policies globally[6,7]. Meanwhile, governments' concerns over their dependence on foreign—particularly US-based—digital technology companies have shaped repeated calls to develop domestic data infrastructures, particularly in the EU[36]. Additional information on the survey design is provided in the Methods section and Table 1.

Table 1 | Treatment vignettes (blank control omitted from table)

Control	Data protection treatment	Competitiveness treatment
Proponents of building more data centers in Germany point out that data centers are essential for the digital economy and that data centers provide important economic benefits by promoting innovation, attracting investment, and creating new jobs.	Proponents of building more data centers in Germany	Proponents of building more data centers ....
	Building more data centers also makes it possible to store and process German users' data within Germany, which strengthens data protection.	*Building more data centers also enables the development of competitive digital technologies in Germany, thereby reducing dependence on foreign providers.*
Opponents highlight that data centers consume large amounts of electricity, which can drive up electricity costs for consumers and undermine Germany's goal of reducing greenhouse gas emissions. Data centers also need a lot of cooling water, which can strain local water supplies.	Opponents highlight ...	Opponents highlight...

Overall, public support slightly outweighs opposition, but most Germans neither support nor oppose more data center construction (Supplementary Fig. 1). Attitudes toward data center construction are also largely consistent across states and do not correlate with the number of existing data centers in a state (Supplementary Table 2). In line with our pre-registration, we present the digital sovereignty effect sizes in reference to the basic tradeoff control group. This approach allows us to isolate the causal effect of just the digital sovereignty primes. Supplementary Table 3 shows that introducing the basic economic and environmental tradeoffs reduces support for data centers slightly compared to the blank control, although the effect is not significant.

The digital sovereignty primes do not shift respondents' overall support for building more data centers in Germany in substantively or statistically significant ways (Fig. 1). The coefficient signs for the data protection and competitiveness primes are positive, in line with our pre-registered expectations, but not significant at the pre-registered 95% confidence level ($p = 0.1025$ for the data protection treatment; $p = 0.0716$ for the competitiveness treatment). The competitiveness treatment is significant at the lower, not pre-registered 90% confidence level. The effect is substantively small: a 0.12 point shift in support for data center construction, which is measured on a seven-point scale. We also include a pooled digital sovereignty treatment, which we did not pre-register. This pooled treatment is significant at the 95% confidence level ($p = 0.047$), but the effect remains substantively small.

We pre-registered heterogeneous effects by self-placement on a political left-right scale. We expected that left-leaning respondents would be more affected by the data protection treatment, whereas right-leaning respondents would be driven more by national competitiveness. The data protection treatment leads to a statistically significant increase of support among left-wing respondents by 0.32 points on the seven-point scale ($p = 0.020$), but it does not move support among right-leaning respondents. We find no evidence of heterogeneous responses to the competitiveness treatment by political ideology.

Based on exploratory analysis (not pre-registered), we find that the treatments significantly increase support for data center construction among those who are more concerned about climate change, but not among those not concerned about climate change (Supplementary Fig. 14). This finding suggests that concerns about digital sovereignty may mitigate at least some of the climate change-related opposition to data center projects.

Trade-offs in support for data center projects

Even as Germans do not have strong overall preferences for more or less data center construction in the country in general, they may well have strong views about what types of data center projects they prefer in their local communities. Understanding this is especially important as opposition has been local and selective: some data center construction has moved ahead with little or no opposition, whereas other projects have attracted fierce opposition.

We examine how the public makes tradeoffs using a conjoint experiment. Conjoint experiments are particularly useful to evaluate how citizens assess tradeoffs in multidimensional policy spaces[37] and have likewise been used to assess public support for large energy infrastructure investments[38]. We informed respondents about plans to build new data centers in their communities and presented them with side-by-side profiles of potential data center developments that randomly varied relevant attributes. Respondents then chose their preferred project and rated each project on a five-star scale. Each respondent completed five tasks. Table 2 shows the attributes, levels, and our pre-registered expectations.

The attributes varied across four theoretically and policy-relevant dimensions: the nationality of the company operating the data center, decarbonization, local economic and environmental impact, and what the data center would be used for. First, respondents are told whether the data center is operated either by a German, EU-based, US, or Chinese company. Foreign companies' involvement in operating digital infrastructure, including data centers, in Europe has been particularly central in European debates over digital sovereignty[36,39]; and US and—to a lesser extent—Chinese companies are the dominant foreign providers of cloud and AI services in Europe[40,41].

Second, we examined the tensions with the energy transition by varying whether the data center relies on renewable energy, natural gas, or coal. If decarbonization goals matter, then we would expect Germans to be most favorable towards renewable energy and least favorable towards coal-powered data centers. Although public support for gas has been decreasing[42], we still expect publics to prefer gas over coal.

Third, we examined four aspects of the local economic and environmental impact of data centers: jobs, tax revenues, energy prices, and implications for the local water supply. Although data centers may generate substantial employment benefits at the national level by promoting the digital economy[43], these employments do not necessarily accrue locally. The number of permanent operational jobs (after completion of construction) data centers create is generally limited (around 30-50) compared to many other industries[44]. These numbers informed our design, but we also created a scenario with more substantial employment gains (250 jobs). In the United States, data centers are estimated to raise household electricity by an average of 8% by 2023, with much higher (more than 25%) increases in regions like Northern Virginia where many data centers are located[45]. Similarly, in Germany data centers' electricity demand is expected to increase

https://doi.org/10.1038/s41467-026-76500-9

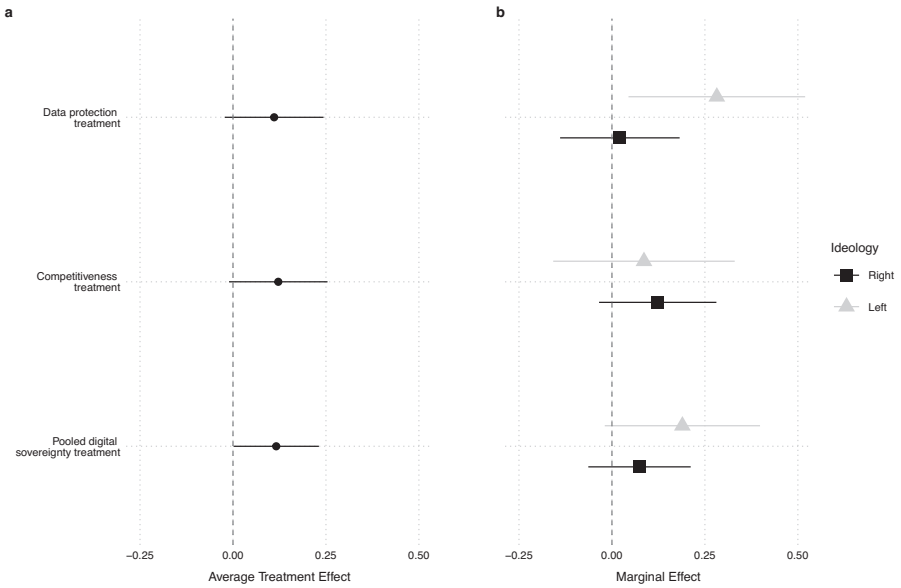


Fig. 1 | Effect of digital sovereignty informational treatments on public support for building data centers in Germany, among all respondents and disaggregated by political ideology. a Point estimates show the average treatment effect of each of the two individual informational treatments—the data protection treatment ($n = 624$) and the competitiveness treatment ($n = 631$)—as well as a pooled digital sovereignty treatment ($n = 1255$) on public support for building more data centers in Germany, relative to the text control ($n = 638$). **b** Point estimates show the average marginal effects of the same treatments by political ideology. Respondents are classified as left-leaning ($n = 785$) if they self-place below 5 on a 10-point left–right scale and as right-leaning ($n = 1725$) otherwise. Public support is measured on a 7-point Likert scale ranging from "Don't support at all" (1) to "Strongly support" (7). Error bars represent 95% confidence intervals. Results for the blank control group are not included in this graph but are reported in Supplementary Table 3.

Table 2 | Attributes, levels, and pre-registered expectations for support of data centers

Attribute	Level	Expectations
Headquarter of data center operator	• USA • China • Germany • EU (not Germany)	Support for data center operators from Germany > EU (not Germany) > USA > China.
Local jobs created	• 10 • 50 • 250	As the number of local jobs increases, support for data centers increases.
The primary purpose of a data center	• Artificial Intelligence (AI) • Crypto mining • Social Media • E-commerce	Support for data centers will be lower when the data center is used for crypto mining as opposed to other technologies.
Local tax revenues	• Minimal • Medium • High	Support for data centers increases with higher local tax revenues.
Increase in electricity prices for local consumers	• 0% • 5% • 10% • 20%	As local electricity prices increase, support for data centers decreases.
Energy source	• Renewable energy • Coal • Gas	Support for data centers using renewable energy will be higher than for those using coal or gas.
Strain on the local water supply	• Minimal • Medium • High	As the strain on the local water supply increases, support for data centers decreases.

electricity prices by around 15% over the next decade, even with the expansion of renewables[46]. German agencies have warned that data centers could trigger surges in local demand for electricity that affect local electricity prices[47,48]. We included four treatment levels from no impact to a maximum 20% increase in prices. For taxes and water supply, we used more qualitative indications of the effects (minimal, medium, and high).

Finally, while data centers often process and store data from a variety of businesses across different sectors, some data centers are specifically built for the development of artificial intelligence and for mining cryptocurrencies. We also add two other use cases, social media and e-commerce, which are data-intensive and consumer-facing digital business models that respondents are likely familiar with.

The conjoint analysis reveals that respondents differentiate strongly based on the characteristics of proposed data centers. The left panel (A) of Fig. 2 shows the average marginal component effects (AMCEs), which reflect how each attribute level (relative to a baseline category) causally affects the probability that a respondent selects a given data center project. The right panel (B) of the figure shows the marginal means for each attribute level, which can be interpreted as the absolute level of support for a data center with a given feature, averaging over all other attributes.

Concerns about rising energy prices and the impact on the local water supply have a strong effect on public support. As expected, respondents become less likely to support data centers as these facilities increase local electricity prices. For example, data centers that would increase electricity prices by 20 percent were on average nearly 20 percentage points less likely to be supported, holding everything else constant. Projects that put a high strain on the local water supply received 13 percentage points less support than those that put minimal strain on water supplies.

By contrast, potential positive local economic benefits of data centers on jobs and taxes had relatively little influence on preferences. As expected, data centers that create more local jobs were viewed more favorably, but even data centers that would create 250 additional jobs only increased support for a project by about 10 percentage points. Given that most data centers create fewer than 50 long-term jobs and generate little local tax revenue, our findings suggest that public environmental and affordability concerns are unlikely to be mitigated by highlighting data centers' economic benefits.

The purposes of data centers have little effect on public support. The only exception is crypto-mining facilities, which, as expected, are less supported than other types of data centers. This opposition to crypto data centers could be driven by crypto-mining's known negative environmental footprint[49], respondents' perceptions that cryptocurrencies provide limited societal benefits, or a combination of both. Yet, Germans do care about how a data center is powered. Respondents were much less likely to support coal- (15 percentage points) and, to a lesser extent, gas-powered data centers, compared to those that use renewables.

Sovereign control has the strongest effect on preferences over data center projects. Respondents favored a German operated data center by 18 percentage points over a US-owned data center and by 26 percentage points over a data center operated by a Chinese firm. The nationality penalty for US-owned versus a German-owned data center is comparable to that of a 20 percent increase in local electricity prices or that of a coal-powered versus a renewable powered data center. This finding is particularly striking in a country like Germany, which had the highest average household electricity prices across all EU member states in 2024[50], and where the public has widespread concerns about climate change and strongly supports the phaseout of coal power[51,52].

The forced choice outcome only allows us to examine what type of data center the public prefers. We also asked respondents to rate

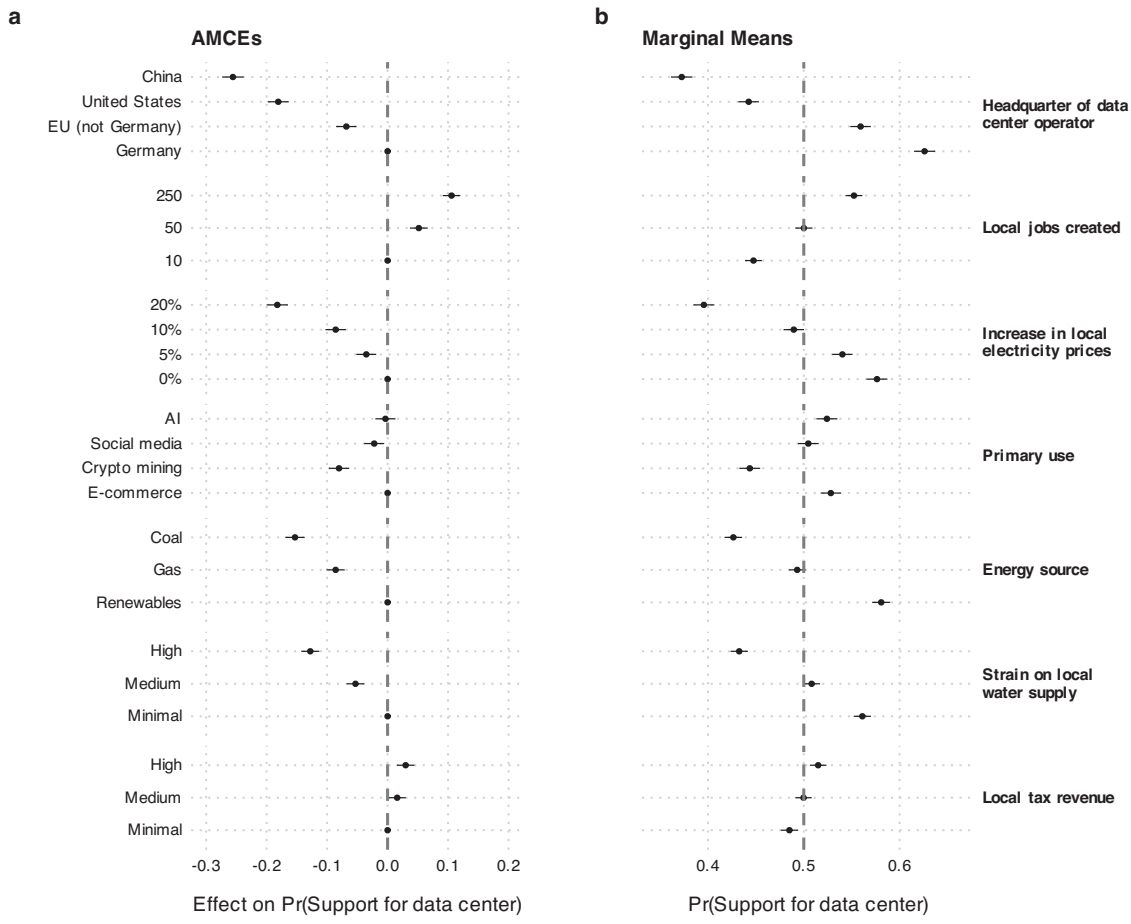


Fig. 2 | Effect of data center attribute levels on public support for the data center project, and average support by attribute level. a Point estimates show the estimated average effect of each attribute level on the probability of choosing a data center project (average marginal component effects, AMCEs), relative to the attribute's baseline category. **b** Estimated average probability of choosing a data center project with that attribute level (marginal means). In both panels, public support is measured as the probability of choosing one data center project over another in a side-by-side comparison, and error bars represent 95% confidence intervals. Estimates are based on 2559 respondents and 25,390 rated profiles.

https://doi.org/10.1038/s41467-026-76500-9

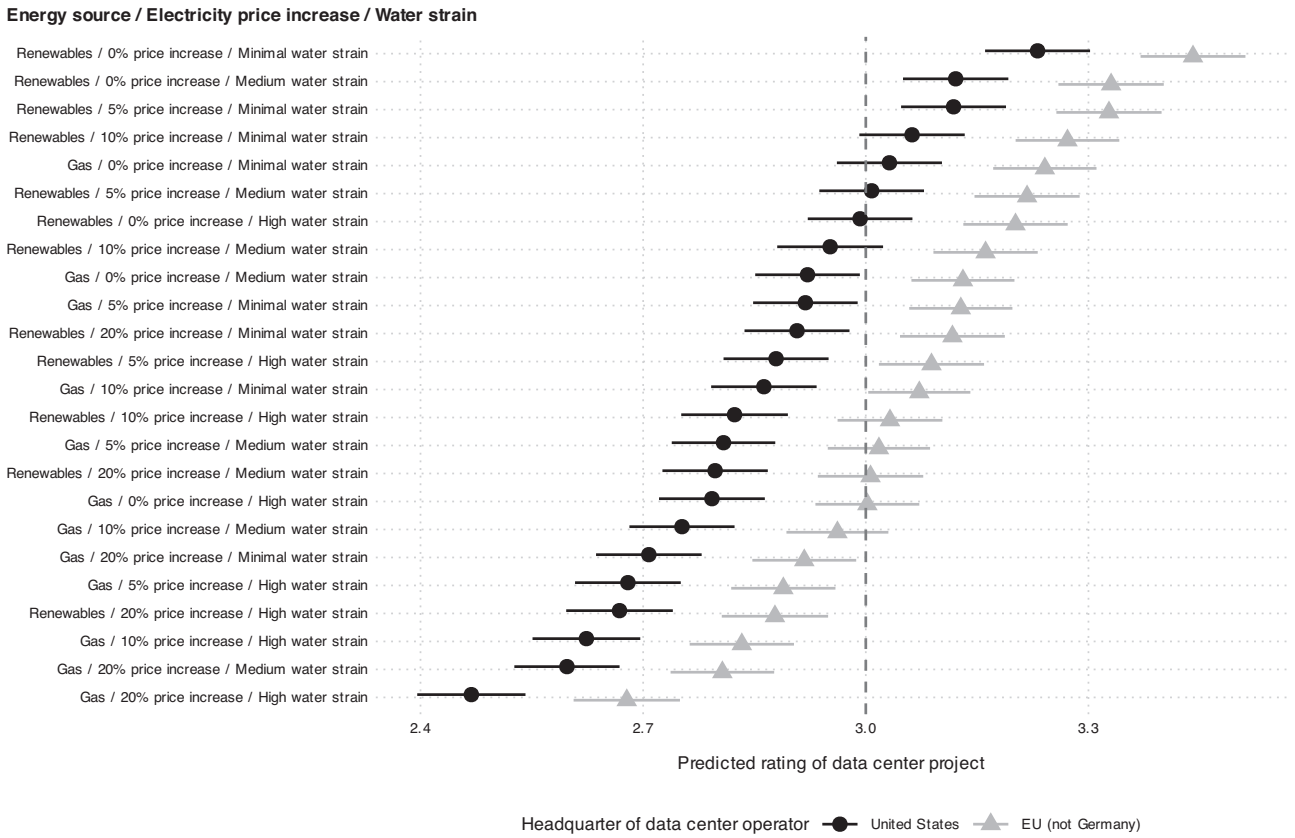


Fig. 3 | Predicted ratings for data center projects across different combinations of energy source, electricity price increase, and water strain, by operator nationality. Point estimates show the predicted average rating on a 5-star scale, comparing operators headquartered in the United States and the EU (not Germany). Each row represents a unique combination of energy source, electricity price increase, and strain on local water supply, with the remaining data center attributes held constant (Primary use = AI, Local jobs = 50, Local tax revenue = Medium). Coal is excluded from the energy source levels. Predictions are derived from a linear model fit to 25,284 rated profiles from 2559 respondents (ratings of 0, indicating non-response, excluded), with standard errors clustered by respondent. The dotted vertical line shows the mid-point of the 5-star scale. Points show predicted mean ratings with 95% confidence intervals.

each proposed project on a scale from one star ("very bad") to five stars ("very good"). We use the three-star mid-point of the scale as a threshold for broad public support. Figure 3 plots the predicted public support for a set of "most likely" types of data centers, comparing data centers operated by US providers—which dominate the cloud and AI compute market in Europe—to those operated by EU-based companies. We vary the energy source, effect on local electricity prices, and water strain, which our previous analysis showed to be the most salient features, while holding fixed the use of the data center (AI), the local tax revenue (medium), and the number of local jobs created (50). We exclude coal as an energy source from the graph, given that the German government has committed to phase out coal power by 2038[52].

This exploratory analysis allows us to examine what types of data centers likely receive broad public support in Germany. Of the 24 different data center projects presented in Fig. 3, only three are viewed favorably when the data center is operated by a US company. When the data center operator is an EU-based firm, more than half of the projects clear the three-star threshold. Whereas the German public is somewhat favorable toward a European operated data center project, even when it increases local electricity prices by 20%, as long as the data center is powered by renewables and only minimally strains local water supplies, the same project is opposed when it is operated by a US firm.

In other words, the German public appears to be willing to tolerate a broader set of negative environmental and economic impacts of data centers when they are operated by European rather than US-based providers. The contrast is even starker when we compare predicted ratings for Chinese and German data centers (Supplementary Fig. 5): none of the hypothetical projects clear the three-star threshold when they are operated by Chinese providers. The substantive interpretation is highly similar when we generate a binary support measure based on the ratings scale that treats three-star ratings as an indicator that respondents neither support nor oppose a specific project and exclude these responses from the analysis[53] (Supplementary Fig. 19).

Contrary to our pre-registered expectations, we did not find that the digital sovereignty primes from the vignette experiment affected respondents' stated preferences in the conjoint experiment. We expected that those primed with digital sovereignty conditions would increase their preference for German and European data center operators while decreasing the relative importance of local economic and environmental factors. However, we did not find evidence for significant interaction effects between the priming treatments and the marginal means in the conjoint. These null results are presented in Supplementary Fig. 6.

Political polarization

We pre-registered expectations that preferences over decarbonization would vary along party lines. To assess subgroup preferences, we use marginal means rather than AMCEs[54]. As shown in Fig. 4, respondents on the environmental left—respondents who voted either for the Greens or Die Linke in the 2025 federal elections—are more supportive of renewable-powered data centers and less favorable toward coal-powered ones compared to other voters. Meanwhile, AfD voters do not differentiate at all between data centers powered by renewables, gas, and even coal. This finding aligns with recent studies that show

https://doi.org/10.1038/s41467-026-76500-9

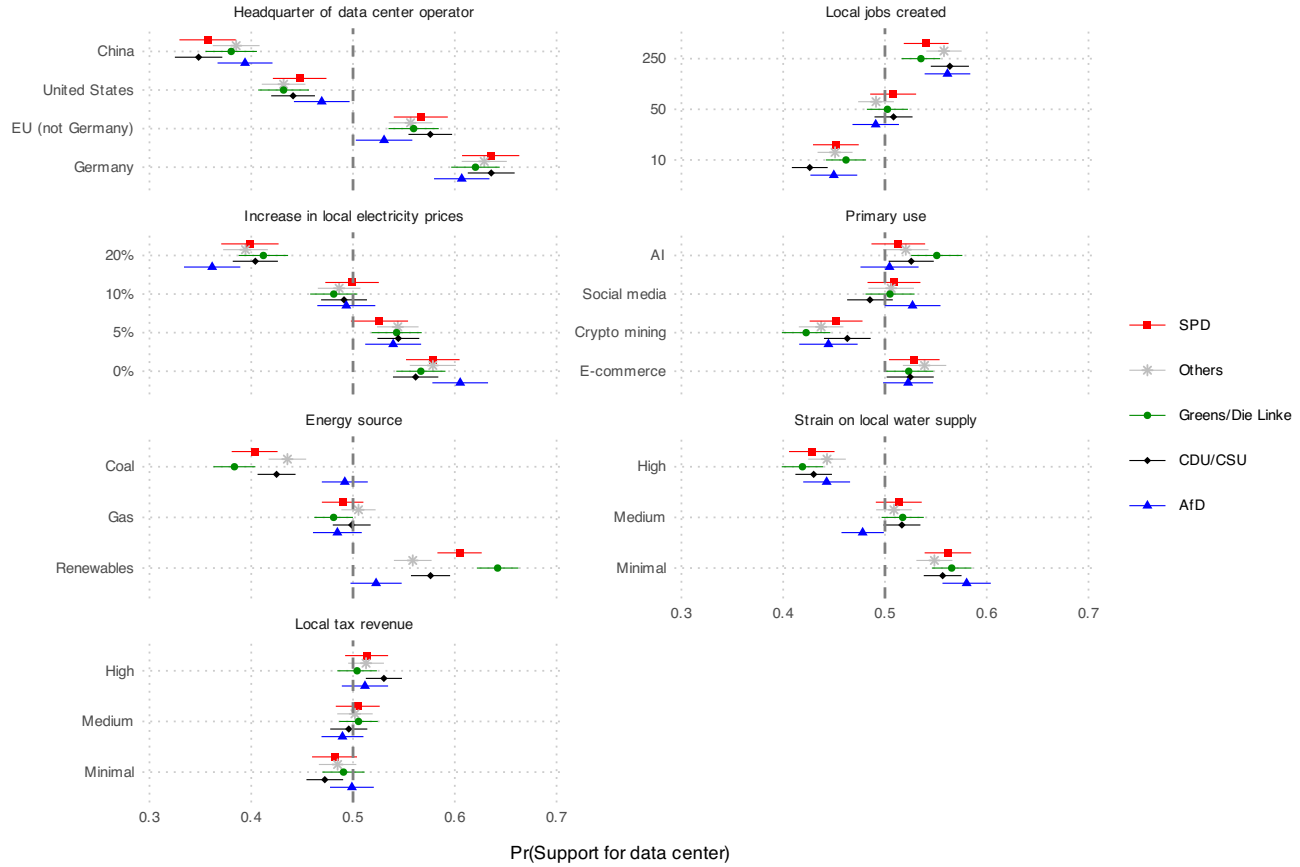


Fig. 4 | Average support for data center projects across attribute levels, disaggregated by political party. Point estimates show the probability of choosing a data center project for each attribute level (marginal means), estimated separately by the political party respondents reported having voted for in the 2025 German federal election. Public support is measured as the probability of choosing one data center project over another in a side-by-side comparison. Error bars represent 95% confidence intervals. Number of respondents (clusters) by party: SPD = 416; Others = 646; Greens/Die Linke = 514; CDU/CSU = 580; AfD = 403.

that the AfD's opposition to green transition policies has become an integral part of its campaign strategy[55]. Thus, existing cleavages over the politics of the green transition also map on to the politics of data center construction.

We find almost no polarization along party lines for other data center attributes. AfD voters have a slightly smaller relative preference for European over American data centers. Similarly, AfD voters are slightly more sensitive to high increases in local electricity prices and place a greater premium on data centers that do not increase electricity bills. Yet, those partisan differences are negligible compared to the polarization we see with regard to data centers' energy source.

Contrary to our expectations, we do not find that voters who align with parties on the "economic left" (SPD & Die Linke) are more sensitive to data centers' impact on electricity prices (Supplementary Fig. 7). We also do not find that respondents who reported having recently engaged in energy-saving measures for financial reasons are more concerned about changes in household electricity prices. These null results are presented in Supplementary Fig. 8.

Technology optimism

Finally, we examine whether general attitudes toward digital technologies affect preferences toward various attributes of data centers. Figure 5 shows the estimated marginal means for technology optimists and technology pessimists. Prior to the treatment, we asked respondents about four technologies: AI, social media, e-commerce, and crypto-mining. We asked them whether each technology would provide more societal benefits than risks. We then constructed a technology optimism measure. In constructing this measure, we slightly deviate from our pre-registration to exclude respondents who are ambivalent about the benefits and risks of digital technologies, rather than including these respondents with the pessimists. Details on how we calculated this measure are provided in the Methods section, and results based on the pre-registered technology optimism measure are also reported in Supplementary Fig. 10.

We find that respondents who are particularly optimistic about the benefits of digital technologies are slightly less concerned about the nationality of the data center operator compared to those who view digital technologies as bearing more risks than benefits. Tech pessimists are especially worried about Chinese ownership and more strongly favor German ownership. One potential implication is that tech pessimists may believe that German ownership will minimize some of the risks associated with data centers.

Optimists are also somewhat less concerned about data centers that have a strong impact on water supplies. Regarding the use case of data centers, those more pessimistic toward digital technologies tend to be more supportive of data centers used for social media and e-commerce and less supportive of AI data centers, compared to the optimists. Other differences are not statistically significant.

Discussion

Why do the publics support some data centers while they oppose others? Answering this question becomes more important as both data center construction and public backlashes intensify. Data centers are the backbone of the digital economy, and governments have not only strong economic but also geopolitical incentives to want to locate them within their national boundaries, as concerns over digital

https://doi.org/10.1038/s41467-026-76500-9

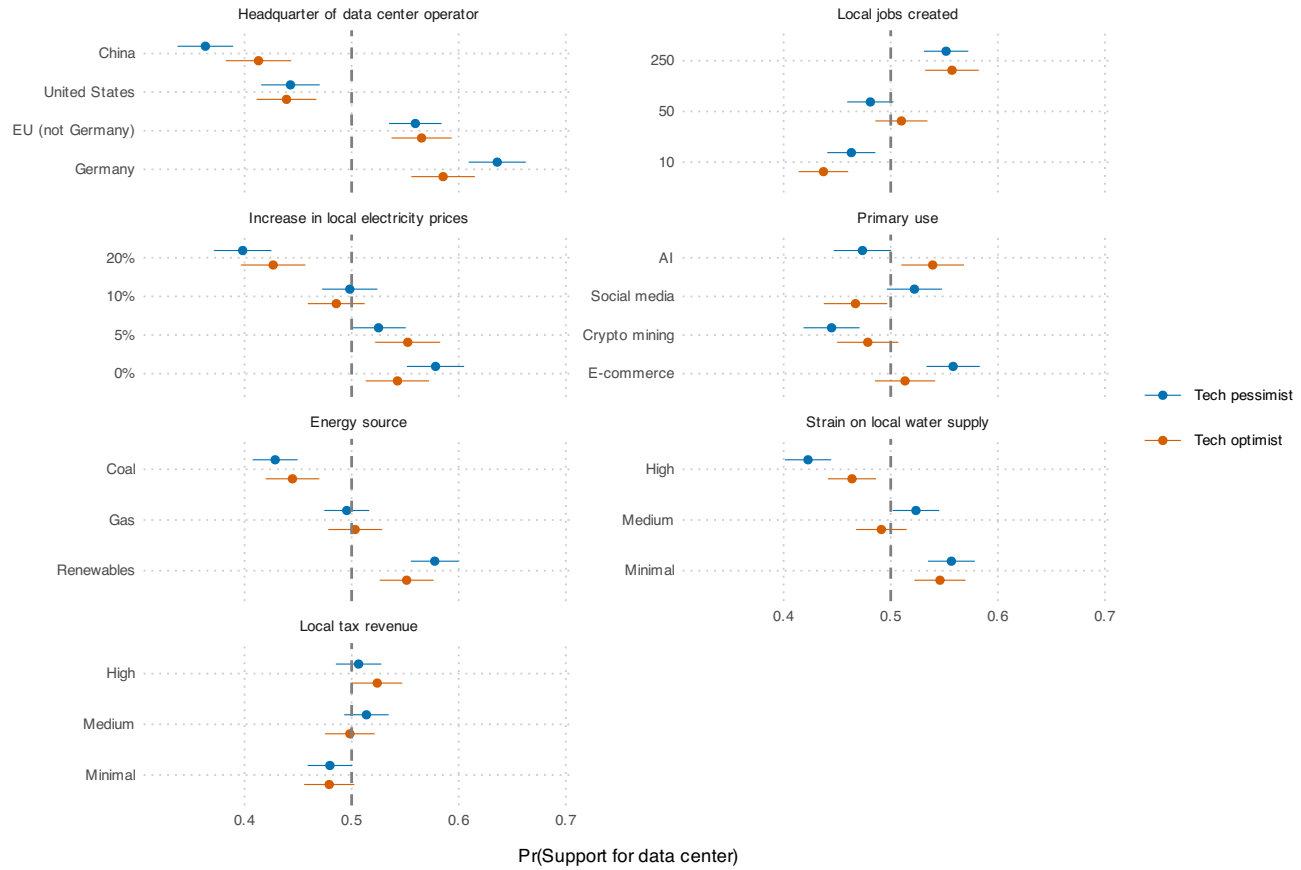


Fig. 5 | Average support for data center projects across attribute levels, by respondents' general optimism about digital technologies. Point estimates show the probability of choosing a data center project for each attribute level (marginal means), estimated separately for technology optimists and technology pessimists. Technology optimism is measured using pre-treatment assessments of four digital technologies (artificial intelligence, blockchain/cryptocurrency, social media, and e-commerce) on a five-point benefits-versus-risks scale. Respondents whose average score is at least one standard deviation below the sample mean are classified as optimists ($n = 363$); those at least one standard deviation above the mean are classified as pessimists ($n = 452$); ambivalent respondents are excluded. Public support is measured as the probability of choosing one data center project over another in a side-by-side comparison. Differences in marginal means are presented in Supplementary Fig. 11; results using the pre-registered threshold for tech optimism are presented in Supplementary Fig. 10.

sovereignty abound. Yet, data centers also require tremendous amounts of energy, which creates tensions with climate goals and can raise the price of energy for local consumers. How do the public navigate these tradeoffs?

We offer a systematic analysis of this question using an original survey conducted in Germany. We find that public support for data centers is strongly conditional on three critical features: that the data center operator is German (or European) rather than American (or Chinese), that it does not increase electricity prices much, and that it consumes renewable energy. The nationality effect is particularly large, suggesting that foreign companies could face particular hurdles in building data centers. A data center operated by a non-European firm but using renewables is about as unpopular as a European data center powered by coal (Supplementary Fig. 13).

By contrast, when we primed respondents with digital sovereignty concerns about data privacy and competitiveness, without mentioning the nationality of operators, we did not find statistically significant or substantively important effects on public support for data centers. This suggests that public concerns about digital sovereignty are tied to perceptions of providers from specific countries (e.g., US and Chinese technology companies). Future research should examine this with different experimental designs. Digital sovereignty is a multi-faceted concept. It includes concerns about rights, competitiveness, nationalism, security, and other issues tied to control over data and technology. Much remains unknown over how the publics make trade-offs between these aspects and how the various components of digital sovereignty concerns interact in shaping public perceptions. There are also broader trade-offs between digital sovereignty and the overall development of the digital economy that should be explored. In some settings, the alternative to US operated data center is not a data center run by a domestic firm, but no data center at all. The lack of data center development may stifle technology adoption and innovation. We should thus examine how citizens make trade-offs between innovation, led by foreign firms, and digital sovereignty concerns.

Our findings highlight that Germans have a strong bias against Chinese and American owned data centers. Anecdotal evidence from news reports suggests that numerous data center projects in Europe planned by large US firms, like AWS (Amazon), Google, Microsoft, and Meta, were canceled or delayed while also facing strong public opposition (Supplementary Table 5). This suggests that European companies may have a significant competitive advantage over US-based companies in terms of overcoming public opposition against data center construction. Future research should further examine this issue.

Future studies should examine these questions in other settings. The German public may be especially motivated by energy transition concerns. Moreover, our survey was conducted amidst heightened tensions between the US and Germany and widespread concerns over the power of US Big Tech companies in Europe, although these concerns are unlikely to go away. The contrast between the substantial nationality effect in the conjoint experiment and the limited effect of

the digital sovereignty primes may reflect a ceiling effect amid already heightened digital sovereignty concerns. Future studies should also examine whether there is something particular about data centers that triggers such strong nationalist sentiments. For example, we may compare support for a data center to support for a manufacturing plant or a mine with similar economic and environmental implications. If firm nationality indeed uniquely shapes public opinion on data centers through digital sovereignty concerns, then we may expect that people care more about who operates a data center than who operates a factory or other production site.

More broadly, our findings underscore the urgency of studying the tradeoffs between the development of the AI-driven digital transformation and the energy transition. While AI development may overall benefit the energy transition in the long run[56,57], with proper regulatory guardrails in place[58], AI infrastructure development generates immediate, localized environmental costs and distributional conflict. Understanding how publics weigh these tradeoffs then becomes critical for governments as they seek to balance their digitalization and decarbonization objectives.

Methods

Survey sample

The survey was fielded through Bilendi in July 2025. We used quotas based on gender, age, and region to recruit a sample broadly representative of the German public. Quotas were calculated based on 2024 census estimates by the German federal statistics office[59]. Our final sample for the vignette experiment included 2523 respondents, as we excluded respondents who did not finish the survey. For the conjoint analysis, we used all available data, including from respondents who did not finish the survey but completed at least one of the conjoint tasks, yielding a sample of 2559 respondents and 25,390 profiles.

Prior to the first experiment, we administered an attention check. In line with our pre-registration, we include respondents who fail this pre-treatment attention check in our analysis, although results are unaffected when we exclude them (Supplementary Fig. 15). After the priming experiment and prior to the conjoint experiment, we administered a manipulation check. For the main results from the conjoint experiment, we find that AMCEs tend to be even larger for respondents who pass the manipulation check. Results are reported in Supplementary Fig. 16.

The study was exempt from review by Georgetown University's Institutional Review Board (STUDY00009361). At the end of the survey, respondents were debriefed and told that the information about data centers potentially being built in their community was fictional and used only for this study.

Data was collected trough Qualtrics and all data analysis was conducted with R (version 4.5.1).

Priming experiment

After answering pre-treatment demographic questions and questions used to estimate heterogeneous effects, respondents are randomly split into four groups, two treatment and two control groups. The relevant outcome measure for the priming experiment is a question asking whether respondents support building more data centers in Germany. Support is measured on a 7-point Likert scale.

Respondents in our baseline control group, who received information about the basic environmental and economic tradeoffs of data centers, were slightly less supportive of building more data centers than those who did not receive any additional information, although this difference is not statistically significant (Supplementary Table 3).

Conjoint

In line with our pre-registration, we estimate average marginal component effects (AMCEs) to assess how different attributes of data centers affect support for a data center project. We present AMCEs for the binary choice outcome in the main text of the study, but also report results for an outcome where respondents rated each data center project on a 5-star scale (Supplementary Fig. 4). The overall interpretation of our findings remains the same when using this alternative outcome measure.

To assess subgroup and heterogeneous effects, we estimate marginal means instead of AMCEs[54]. To predict public support for different types of data center projects presented in Fig. 3 and Supplementary Fig. 5, we fit a linear regression of respondents' ratings on all seven attributes, with standard errors clustered by respondent. We then construct a focal grid in which operator nationality, energy source (excluding coal), electricity price increase, and water supply strain vary across all combinations of their levels, while the remaining attributes are held constant at realistic baseline values (50 local jobs, AI as the primary use, and medium local tax revenue). For each profile, we generate predicted ratings from the fitted model. For the results presented in Supplementary Fig. 19, we generate a binary support measure that treats 1-2-star ratings as opposition and 4-5-star ratings as support; we exclude three-star ratings as abstentions[53]. We then fit a binary logistic regression and estimate predicted probabilities of support following the same approach as discussed above. In both cases, we exclude profiles that respondents did not rate (0.4% of all profiles).

Another issue is measurement error in conjoint tasks arising from inconsistency in respondents' choices across tasks. Since our conjoint design did not include a repeated task, we estimate intra-respondent reliability ($\tau = 0.706$) by extrapolation, using the projoint R package, following recommendations by Clayton et al.[60]. Corrected AMCEs are presented in Supplementary Fig. 17. The corrected AMCEs are consistently larger than the uncorrected ones, suggesting that the results presented in Fig. 2 are conservative estimates. In some cases, the corrected AMCEs are substantially larger: the penalties of having a data center operated by a Chinese or US firm, a 20% electricity price increase, high water strain, and for a coal-powered data center are even stronger once we account for measurement error. However, since we did not pre-register this analysis, we use the corrected AMCEs as a robustness check only.

Second priming experiment

We included a third experiment at the end of the survey to assess whether priming individuals with digital sovereignty concerns shaped public support for using nuclear energy to power data centers. This experiment was motivated by the specific political context in Germany, where nuclear power plants have been phased out and the public simultaneously strongly opposes nuclear energy while supporting the transition away from fossil fuels[61]. We wanted to examine whether these preferences would shift once respondents considered the digital sovereignty-linked imperative to expand energy-intensive data centers domestically.

After completing the conjoint scenarios, respondents were split into three groups. Respondents who were either in the blank control or the control group that received the basic tradeoffs in the first priming experiment received no additional information. Respondents who were in the competitiveness condition in the first priming experiment were reminded of the competitiveness benefits of data centers, while respondents who were in the data protection condition were reminded of the data protection benefits of building more local data centers. We then asked respondents whether they support reactivating decommissioned nuclear power plants to supply electricity for data centers. Support was measured on a 7-point Likert scale.

We do not find that the treatments move public support for reactivating nuclear power plants to supply electricity to data centers. We do not present this result in the main text but do report it in Supplementary Table 4. By placing this experiment at the end of the survey, we avoid any potential priming effects that raising the issue of

nuclear energy in the German context might have on the conjoint experiment. At the same time, we cannot rule out that completing the conjoint tasks affects how individuals subsequently respond to the repeated sovereignty primes. As such, findings from this experiment should be interpreted with caution.

Measurement of pre-treatment co-variates used to estimate heterogeneous effects

Energy poverty: Prior to the treatment, respondents are asked whether they have engaged in any of the following behaviors in the past six months to save money on energy costs: kept their house/apartment colder/warmer than preferred, took a shorter shower than preferred, and changed their energy provider. We use both a dichotomous measure, based on whether respondents took any of those actions (Supplementary Fig. 8), and a scale (Supplementary Fig. 9) to assess whether energy poverty status drives heterogeneous responses to data centers' impact on household electricity prices.

Tech optimism: We use pre-treatment measures of general attitudes toward various digital technologies (AI, blockchain/crypto, social media, e-commerce) to generate a measure of technology optimism. For each technology, respondents are asked whether they believe the technology provides more societal benefits than risks, measured on a 5-point Likert scale, from 1 (much more benefits than risks) to 5 (much more risks than benefits). We then average responses for all four technologies at the respondent level. In our pre-registration, we said that we would categorize respondents who are below a 3 as optimists and the rest as technology pessimists. To better capture true optimists and pessimists, we take a modified approach in the study: respondents who are less than or equal to one standard deviation below the sample average on the technology preference scale are categorized as optimists and those who are equal to or greater than one standard deviation above the mean are categorized as pessimists. As such, we exclude respondents who view the societal impacts of digital technologies as ambiguous. However, we also report results based on the pre-registered threshold in Supplementary Figs. 10 and 12.

Preregistration

The study was preregistered with OSF. The preregistration and survey instrument can be accessed at the Open Science Framework (OSF) under https://osf.io/yx6hu. To improve the readability of the paper, we report some of the pre-registered analysis in the appendix. This includes some analysis based on the 5-star rating outcome and some of the heterogeneous effects for the conjoint experiment, the interaction between the priming and conjoint experiments, and a second priming experiment that was administered at the end of the survey to examine how priming digital sovereignty concerns affects support for using nuclear energy to power data centers in Germany. However, we mention the findings from these other pre-registered analyses in the main text of the study.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data used in the analysis presented in this paper are available at the Open Science Framework (OSF) with the identifier https://doi.org/10.17605/OSF.IO/NQEGR.

Code availability

The code to replicate all analysis presented in the main text and supplementary material is available at the Open Science Framework (OSF) with the identifier https://doi.org/10.17605/OSF.IO/NQEGR.

References

1. European Commission. Eu launches *InvestAI* initiative to mobilise €200 billion of investment in artificial intelligence. https://ec.europa.eu/commission/presscorner/detail/en/ip_25_467 (2025).
2. The White House. Accelerating federal permitting of data center infrastructure. https://www.whitehouse.gov/presidential-actions/2025/07/accelerating-federal-permitting-of-data-center-infrastructure/ (2025).
3. Pohle, J. & Thiel, T. Digital sovereignty. *Internet Policy Rev.* **9**, https://doi.org/10.14763/2020.4.1532 (2020).
4. Chander, A. & Sun, H. Sovereignty 2.0. *Vand. J. Transnat. Law* **55**, 283–324 (2023).
5. Weymouth, S. Digital disintegration: Techno-blocs and strategic sovereignty in the ai era. *Int. Org.* **79**, S57–S70 (2025).
6. Weymouth, S. *Digital Globalization: Politics, Policy, and a Governance Paradox* (Cambridge University Press, 2023).
7. Han, S. Data and statecraft: Why and how states localize data. *Bus. Polit.* **26**, 263–288 (2024).
8. Girard, T. & Wilhelm, A. Local data policies, global data politics: How citizens evaluate data localization policies and political responses. *Foreign Policy Anal.* **21**, oraf007 (2025).
9. Lee, A. What is sovereign ai? https://blogs.nvidia.com/blog/what-is-sovereign-ai/ (2024).
10. International Energy Agency. *Electricity 2024* (International Energy Agency, https://iea.blob.core.windows.net/assets/18f3ed24-4b26-4c83-a3d2-8a1be51c8cc8/Electricity2024-Analysisandforecastto2026.pdf (2024).
11. Naschert, C. & Dlin, S. European data center power demand to double by 2030, straining grids.https://www.spglobal.com/commodity-insights/en/news-research/latest-news/electric-power/073025-european-data-center-power-demand-to-double-by-2030-straining-grids (2025).
12. Bianchini, S., Damioli, G. & Ghisetti, C. The environmental effects of the "twin" green and digital transition in european regions. *Environ. Resour. Econ.* **84**, 877–918 (2023).
13. Taft, M. A political battle is brewing over data centers.https://www.wired.com/story/a-political-battle-is-brewing-over-data-centers/ (2025).
14. Mozur, P., Satariano, A. & Mega, E. R. From mexico to ireland, fury mounts over a global a.i. frenzy. https://www.nytimes.com/2025/10/20/technology/ai-data-center-backlash-mexico-ireland.html?smid=nytcore-ios-share&referringSource=articleShare (2025).
15. Gazmararian, A. F., Mildenberger, M. & Tingley, D. Public opinion foundations of the clean energy transition. *Environ. Politics* **35**, 846–868 (2025).
16. Bernauer, T. & McGrath, L. F. Simple reframing unlikely to boost public support for climate policy. *Nat. Clim. Change* **6**, 680–683 (2016).
17. Chan, Z. T. & Meunier, S. Behind the screen: Understanding national support for a foreign investment screening mechanism in the european union. *Rev. Int. Organ.* **17**, 513–541 (2022).
18. Robertson, G. B. & Teitelbaum, E. Foreign direct investment, regime type, and labor protest in developing countries. *Am. J. Political Sci.* **55**, 665–677 (2011).
19. Tingley, D., Xu, C., Chilton, A. & Milner, H. V. The political economy of inward fdi: Opposition to chinese mergers and acquisitions. *Chin. J. Int. Politics* **8**, 27–57 (2015).
20. Alkon, M. & Hadden, J. Home field advantage: How developer identity shapes public opinion about energy projects in major emerging economies. *Int. Stud. Q.* **69**, sqaf078 (2025).
21. Putois, C. Les citoyens veulent-ils vraiment de la souveraineté numérique ? 10 points sur une enquête mondiale. https://legrandcontinent.eu/fr/2025/09/25/souverainete-technologique-10-points/ (2025).

22. People vs. Big Tech. A large majority of the French, German and Spanish public backs a tough EU stance on big tech, despite the risk to Trump's relations. https://peoplevsbig.tech/large-majority-of-french-german-and-spanish-public-back-tough-eu-stance-on-big-tech-despite-risk-to-trump-relations/ (2025).
23. Andre, P., Boneva, T., Chopra, F. & Falk, A. Globally representative evidence on the actual and perceived support for climate action. *Nat. Clim. Change* **14**, 253–259 (2024).
24. Otteni, C. & Weisskircher, M. Global warming and polarization. wind turbines and the electoral success of the greens and the populist radical right. *Eur. J. Political Res.* **61**, 1102–1122 (2022).
25. Sine, W. D. & Lee, B. H. Tilting at windmills? the environmental movement and the emergence of the us wind energy sector. *Adm. Sci. Q.* **54**, 123–155 (2009).
26. Brooks, S. M., Lacroix Eussler, S. & Voeten, E. Environmental, economic, and geopolitical trade-offs in critical mineral mining projects: Evidence from a conjoint experiment in Argentina. *Extr. Ind. Soc.* **27**, 101925 (2026).
27. Bosetti, V., Colantone, I., De Vries, C. E. & Musto, G. Green backlash and right-wing populism. *Nat. Clim. Change* **15**, 822–828 (2025).
28. Voeten, E. The energy transition and support for the radical right: Evidence from the netherlands. *Comp. Political Stud.* **58**, 394–428 (2025).
29. Fisch-Romito, V., Jaxa-Rozen, M., Wen, X. & Trutnevyte, E. Multi-country evidence on societal factors to include in energy transition modelling. *Nat. Energy* **10**, 460–469 (2025).
30. CDU, CSU und SPD. *Koalitionsvertrag 2025–2029: Verantwortung für Deutschland* (SPD, https://www.spd.de/fileadmin/Dokumente/Koalitionsvertrag2025bf.pdf 2025).
31. Pesch, S. Bund-petition gegen microsoft-rechenzentrum im rheinischen revier. https://www1.wdr.de/nachrichten/rheinland/BUND-fordert-aenderung-bei-microsoft-rechenzentrum-106.html (2025).
32. Diener, A. Rechenzentren in hattersheim: Totschweigen ist der falsche Weg. https://www.faz.net/aktuell/rhein-main/wirtschaft/buergerinitiative-gegen-neue-rechenzentren-in-hattersheim-19708626.html (2024).
33. Farrell, H. Constructing the international foundations of e-commerce–the eu-us safe harbor arrangement. *Int. Organ.* **57**, 277–306 (2003).
34. Farrell, H. & Newman, A. L. *Of Privacy and Power: The Transatlantic Struggle over Freedom and Security* (Princeton University Press, Princeton, NJ, 2019).
35. Beaumier, G., Heering, J. & Newman, A. Running out the digital clock: transatlantic privacy politics and veto points in time. *J. Eur. Integr.* **46**, 993–1013 (2024).
36. Draghi, M. *The Future of European Competitiveness: A Competitiveness Strategy for Europe* (European Commission, https://commission.europa.eu/document/download/97e481fd-2dc3-412d-be4c-f152a8232961_en (2024).
37. Hainmueller, J., Hopkins, D. J. & Yamamoto, T. Causal inference in conjoint analysis: Understanding multidimensional choices via stated preference experiments. *Political Anal.* **22**, 1–30 (2014).
38. Caggiano, H., Constantino, S. M., Greig, C. & Weber, E. U. Public and local policymaker preferences for large-scale energy project characteristics. *Nat. Energy* **9**, 1230–1240 (2024).
39. Adler-Nissen, R. & Eggeling, K. The discursive struggle for digital sovereignty: Security, economy, rights and the cloud project gaia-x. *JCMS J. Common Mark. Stud.* **62**, 993–1011 (2024).
40. Lehdonvirta, V., Wú, B. & Hawkins, Z. Weaponised interdependence in a bipolar world: How economic forces and security interests shape the global reach of US and Chinese cloud data centres. *Rev. Int. Political Econ.* **32**, 1442–1467 (2025).
41. Hawkins, Z. J., Lehdonvirta, V. & Wu, B. AI compute sovereignty: Infrastructure control across territories, cloud providers, and accelerators. Preprint at https://ssrn.com/abstract=5312977 (2026).
42. Evensen, D. et al. Growing importance of climate change beliefs for attitudes towards gas. *Nat. Clim. Change* **13**, 240–243 (2023).
43. German Economic Institute (IW). *Spillover Effects of Data Centers: The Backbone of the AI Revolution in Germany* (2025).
44. Joint Legislative Audit & Review Commission. *Data Centers in Virginia*. (2024).
45. Wade, C. et al. *Electricity Grid Impacts of Rising Demand from Data Centers and Cryptocurrency Mining Operations* (Open Energy Outlook Initiative, Carnegie Mellon University Wilton E. Scott Institute for Energy Innovation and North Carolina State University, 2024).
46. Liebensteiner, M., Ocker, F. & Abuzayed, A. High electricity price despite expansion in renewables: How market trends shape germany's power market in the coming years. *Energy Policy* **198**, 114448 (2025).
47. Zebner, H., Kögl, S. & Maatsch, H.-W.*Grünstromversorgung von Rechenzentren* (dena – Deutsche Energie-Agentur, https://www.dena.de/infocenter/gruenstromversorgung-von-rechenzentren/ (2023).
48. Bundesnetzagentur. Versorgungssicherheit Strom - Bericht 2025: Stand und Entwicklung der Versorgungssicherheit im Bereich der Versorgung mit Elektrizität. Tech. Rep., Bundesministerium für Wirtschaft und Energie. (2025).
49. Chamanara, S., Ghaffarizadeh, S. A. & Madani, K. The environmental footprint of bitcoin mining across the globe: Call for urgent action. *Earth's. Future* **11**, e2023EF003871 (2023).
50. Eurostat. Electricity price statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics (2025).
51. Brehm, J. & Gruhl, H. Increase in concerns about climate change following climate strikes and civil disobedience in germany. *Nat. Commun.* **15**, 2916 (2024).
52. Rinscheid, A. & Wüstenhagen, R. Germany's decision to phase out coal by 2038 lags behind citizens' timing preferences. *Nat. Energy* **4**, 856–863 (2019).
53. Smith, E. K. & Kolcava, D. Measuring absolute and relative levels of policy support using conjoint choice experiments. Preprint at https://osf.io/preprints/osf/837ws (2024).
54. Leeper, T. J., Hobolt, S. B. & Tilley, J. Measuring subgroup preferences in conjoint experiments. *Political Anal.* **28**, 207–221 (2020).
55. Heddesheimer, V., Hilbig, H. & Voeten, E. The green transition and political polarization along occupational lines. *Am. Political Sci. Rev.* **120**, 853–875 (2026).
56. Wang, Q., Li, Y. & Li, R. Ecological footprints, carbon emissions, and energy transitions: the impact of artificial intelligence (ai). *Humanit. Soc. Sci. Commun.* **11**, 1043 (2024).
57. Wang, B., Wang, J., Dong, K. & Nepal, R. How does artificial intelligence affect high-quality energy development? evidence from china's provinces. *Energy Policy* **186**, 114010 (2024).
58. Dong, Z., Tan, C., Ma, B. & Ning, Z. The impact of artificial intelligence on the energy transition: The role of regulatory quality as a guardrail, not a wall. *Energy Econ.* **140**, 107988 (2024).
59. Destatis. Statistischer Bericht – Bevölkerungsfortschreibung auf Basis des Zensus 2022 – Berichtsjahr 2022. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Bevoelkerung/Bevoelkerungsstand/Publikationen/Downloads-Bevoelkerungsstand/statistischer-bericht-bevoelkerungsfortschreibung-zensus-2022-jaehrlich-5124108247005.html (2025).
60. Clayton, K., Horiuchi, Y., Kaufman, A. R., King, G. & Komisarchik, M. Correcting measurement error bias in conjoint survey experiments. *Am. J. Political Sci.* https://doi.org/10.1111/ajps.70076 (2026).
61. Renn, O. & Marshall, J. P. Coal, nuclear and renewable energy policies in Germany: From the 1950s to the "Energiewende". *Energy Policy* **99**, 224–232 (2016).

Acknowledgements
The authors thank participants at the 2025 American Political Science Association Annual Meeting, "The Politics of AI" workshop at the Institut Barcelona d'Estudis Internacionals, and the DIGITAL-EU Research Network × s University of Lincoln SSPS seminar for helpful comments and feedback on earlier versions of this paper.

Author contributions
J.H. and E.V. contributed equally to designing the study, analyzing the results, and drafting the manuscript.

Funding
J.H. discloses support for the research of this work from the Institute for Humane Studies [Grant no. IHS01913]. E.V. discloses support for the research of this work from Georgetown University's Earth Commons Impact Award. J.H. and E.V. disclose support for the publication of this work from the Tech & Public Policy Center at the McCourt School of Public Policy at Georgetown University.

Competing interests
J.H. and E.V. declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-026-76500-9.

Correspondence and requests for materials should be addressed to Jonas Heering.

Peer review information *Nature Communications* thanks the anonymous reviewers for their contribution to the peer review of this work. A peer review file is available.

Reprints and permissions information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

© The Author(s) 2026