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Natural gas savings in Germany during the 2022 energy crisis

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Russia curbed its natural gas supply to Europe in 2021 and 2022, creating a grave energy crisis. This Article empirically estimates the crisis response of natural gas consumers in Germany—for decades, the largest export market for Russian gas. Using a multiple regression model, we estimate the response of small consumers, industry and power stations separately, controlling for the nonlinear temperature-heating relationship, seasonality and trends. We find significant and substantial gas savings for all consumer groups, but with differences in timing and size. For instance, industry started reducing consumption as early as September 2021, while small consumers saved substantially only since March 2022. Across all sectors, gas consumption during the second half of 2022 was 23% below the temperature-adjusted baseline. We discuss the drivers behind these savings and draw conclusions on their role in coping with the crisis.

Europe is amid the most severe energy crisis since the oil price shock of 1973. Since mid-2021, spot prices of natural gas have been on a steep rise, reaching levels of €100–200 MWh^{-1} in 2022. This is about ten times the long-term pre-COVID-19 pandemic price levels of €15–20 MWh^{-1}. Specific events, such as Russia's invasion of Ukraine on 24 February 2022 and Russia's announcement of closing the Nord Stream 1 pipeline on 19 August 2022 (ref. 1), led prices to spike up to €227 and €339 MWh^{-1}, respectively. Meanwhile, the average gas price paid by German industry has increased sixfold when it peaked in September 2022, somewhat lagged and dampened by long-term contracts. Average German residential retail prices increased more than twofold between January and November 2022, before a political intervention substantially reduced households' energy bills in December 2022 (Fig. 1).

While the post-pandemic recovery has driven up energy prices around the world, the most important driver of European natural gas prices has been Russia's reduced supply. Even before Russia invaded Ukraine, Russia's Gazprom avoided filling its European gas storages during 2021 and stopped supplying the spot market in the fall of the same year. Starting in the winter, long-term contracts with individual countries and firms were no longer supplied either. By September 2022, imports from Russia to Germany via the Nord Stream 1 pipeline had ceased completely. With domestic European gas supply being limited, Europe turned to liquefied natural gas as a substitute, but global liquefied natural gas markets are tight, and European import terminal capacity is limited[2]. As a result, reducing gas consumption has become key to European security of energy supply.

Previous non-academic surveys among German and European households find that every second to third respondent reported saving energy in response to the 2022 crisis[3–5] (Supplementary Table 1 provides a summary). These surveys support the hypothesis of energy savings by households and provide insight into the motivation behind it. Notably, some respondents mentioned independence from Russian gas as the main driver of energy savings, in addition to increasing energy prices. However, in the context of studying environmentally motivated energy savings, the validity of self-reported measurements has often been questioned (ref. 6 provides a review). Also, the surveys cannot be used to estimate the magnitude of energy savings resulting from the indicated behavioural changes. Similarly, energy-intensive industries have been self-reporting production cuts since autumn 2021, but these insights cannot be translated into how much natural gas has been saved in the industry as a whole (collection of press releases in ref. 7).

Moreover, many existing analyses of the current energy crisis have reported reduced natural gas consumption based on comparing current with last year's consumption[8–11]. Most importantly, these calculations do not control for temperature and hence cannot distinguish between savings in response to the crisis and the effect of stochastic weather variations. While more elaborate models have been used to

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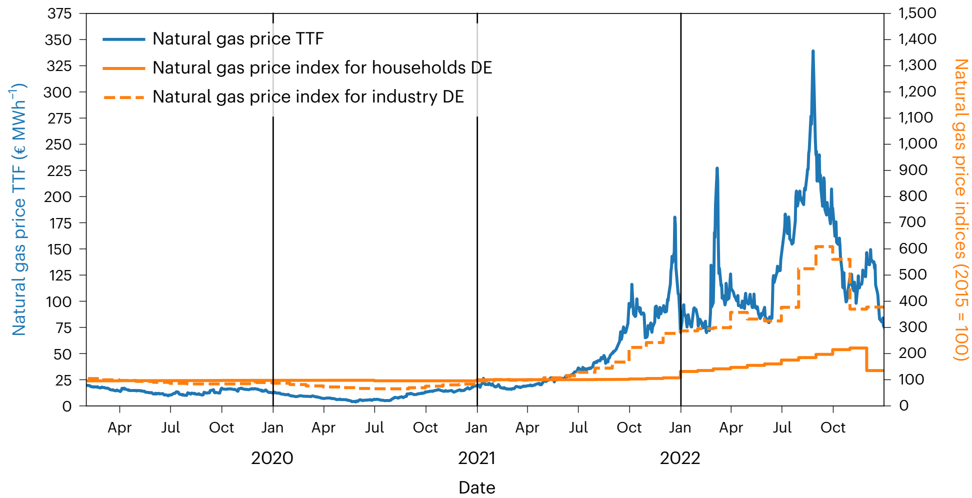

Fig. 1 | Prices of natural gas at the European wholesale and at the German retail market. Wholesale prices from the Title Transfer Facility (TTF) spot market; retail prices are indexed average prices for natural gas paid by German (DE) households and industrial consumers according to the Federal Statistical Office (DESTATIS). The indexes are normalized to 100 in 2015. Month names are abbreviated.

analyse energy demand before (for example, refs. 12–15), previous analyses of the current crisis methodically lag behind these earlier studies. Meanwhile, findings of earlier studies may be complemented with more sophisticated analysis on the current crisis, given the extraordinary size of the observed supply shock.

The aim of the present Article is to provide timely evidence on reductions in gas consumption of households and firms in the current energy crisis. We use multiple near-time datasets and an econometric model that allows us to control for confounders and to identify the change in natural gas consumption *as a response to the crisis*. Such response could be driven by rising prices, expected future price rises, media attention for energy topics, awareness of energy issues and saving options or, in the case of households, by ethical considerations since the Russian invasion of Ukraine on 24 February 2022. We apply our model to Germany, which is an interesting case study as it is the largest export market for Russian natural gas. Gas savings in Germany can therefore make a substantial contribution to solving the crisis at a European level. Furthermore, natural gas plays an essential role in Germany's industrial production and space heating. If Germany purchased its annual natural gas consumption of close to 1,000 TWh at wholesale prices of €200 MWh^{-1}, the increase in the gas bill corresponded to about 5% of the gross domestic product (€3.57 trillion in 2021).

We find a significant and substantial crisis response across consumer groups. German industry started to reduce consumption by 4% as early as in September 2021 and steadily increased its savings up to 27% in October 2022. Small consumers, including households, started to respond substantially only in March 2022. The temporal pattern of their savings follows the seasonality of heating demand, with relative savings peaking in September 2022 at 28%. Savings in the power sector are somewhat more volatile and not only driven by reduced Russian gas supply. Across all sectors and on average over the second half of 2022, gas consumption was reduced by 23%. Although we estimate the effect of the crisis event and cannot disentangle the causal effect of prices from other potential drivers such as public attention, we show that the identified changes in natural gas consumption correlate with increasing prices for natural gas. This suggests that prices are at least one of several effective means of incentivizing gas savings. For public policy, this implies that energy subsidies, many of which have been introduced to mitigate the crisis, will drive up natural gas consumption, which will then further inflate prices.

The estimated reduction in natural gas consumption

We estimate the reduction in the aggregated German natural gas consumption of small, industrial and power-sector consumers, respectively. Sectoral gas-consumption data were gathered from the German market operator Trading Hub Europe (THE) and the German statistical office, and we estimate three separate regression models with monthly dummy variables from September 2021 to December 2022 to identify a potential crisis response. Distinguishing these three groups of consumers is informative, as it turns out that their response to the energy crises has been very different.

The main challenge for identifying a natural gas savings of small and industrial consumers is related to the fundamental importance of temperature-dependent space heating. To account for this, we carefully model the nonlinear relationship between spatially resolved temperature data and the national space heating demand on the basis of simulated heating-demand profiles. The simulation is based on 'standard load profiles' from the German gas industry and accounts for the characteristics of the national building stock (such as insulation) and pre-crisis consumer behaviour. We also control for annual seasonality and time trends (Methods). We deliberately do not include prices in our model to avoid problems with endogeneity[16] and measurement error (Supplementary Note 1). However, we provide descriptive evidence on the relationship between gas savings and prices and discuss other potential drivers of the crisis response further below.

Figure 2 displays the estimated monthly crisis responses of small, industrial and power-sector consumers (Supplementary Table 2 provides the numerical results and Supplementary Note 2 provides a comparison with the pre-crisis residuals). The estimates can be interpreted as a change in natural gas consumption of these consumer groups compared to the counterfactual baseline consumption, that is, what would have been expected without a crisis response. We find that small consumers significantly reduced consumption from March 2022 onwards. Meanwhile, a significant response of industrial consumption started as early as September 2021 and increased over time, except for November 2021. Gas consumption in the power sector was also reduced in most months since September 2021 but without an obvious pattern. Across all sectors, we estimate a maximum absolute reduction of 25 TWh per month in November 2022. We will discuss the three sectors in turn.

Households and small businesses show a salient reduction from March 2022 onwards. This late response compared with other

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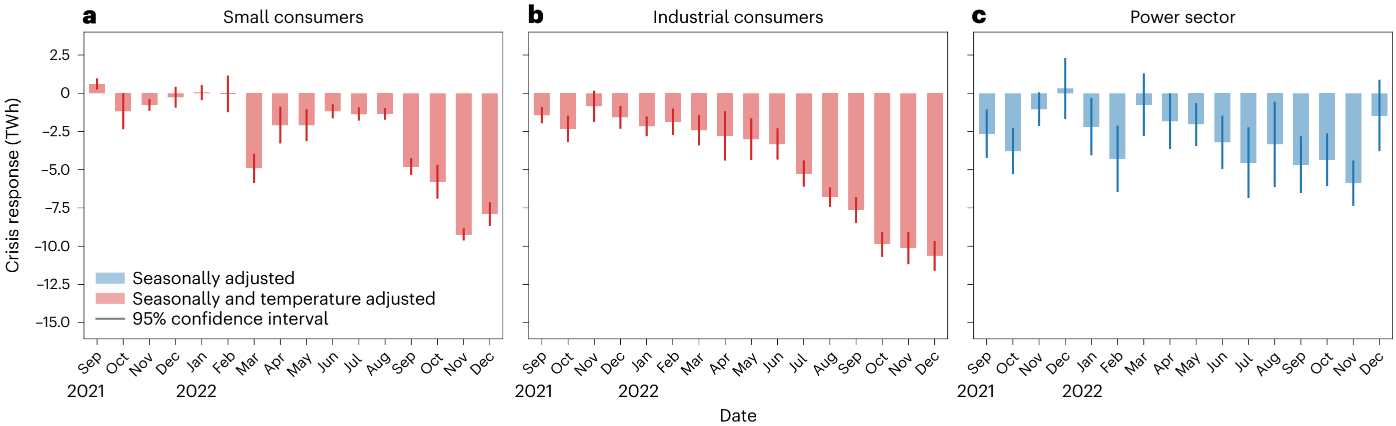

Fig. 2 | Estimated monthly crisis response of natural gas consumption. **a**–**c**, We distinguish between small consumers (**a**), industrial consumers (**b**) and the power sector (**c**). For the power sector, we control only for time trend and seasonality (blue). For small and industrial consumers, we additionally control for temperature (red). The bars indicate the monthly point estimates and the vertical lines the corresponding 5–95% confidence intervals. Month names are abbreviated.

consumer groups is in line with expectation because small consumers typically have retail contracts with fixed prices over longer time spans such as a year. In other words, most consumers in this segment were not exposed to rising wholesale prices they could respond to (Fig. 1). The abrupt reduction in residential consumption in March 2022, however, cannot well be explained by steadily increasing household prices. By contrast, the stark reduction after Russia's invasion of Ukraine on 24 February may be driven by increased attention (Supplementary Note 3) and ethical concerns in line with refs. 3–5.

Industrial consumers show a first significant response in September 2021 and then a more substantial response in October 2021. This coincides well with the timing of when wholesale prices of natural gas and industrial retail prices started to surge, substantially before the beginning of the war in Ukraine (Fig. 1). Furthermore, the industrial crisis response increases over time, which may be driven by two factors. First, wholesale prices and industrial retail prices have increased further since September 2021. Second, the response of some industrial consumers may be subject to inertia, being constrained by long-term contracts on their output products, which can only gradually be adjusted.

One illustrative example of the response of industrial consumers is ammonia production, which is one of the largest single gas-consuming processes in Germany, accounting for roughly 6% of industrial gas consumption. In an earlier study[7], we identified the peak reduction in domestic ammonia production in September and October 2021, when gas spot prices first surged. This saved about 0.6 TWh per month of natural gas. Thus, ammonia alone explains about a third of the estimated aggregated reduction during these months. In November 2021, ammonia production recovered as ammonia prices increased faster than natural gas prices, allowing German producers to pass on higher gas costs. This also matches with the insignificant savings coefficient in November 2021. The further reduction in the aggregate consumption during the first quarter of 2022 cannot be explained by ammonia production, which remained relatively stable. These savings must therefore stem from other industries.

The temporal pattern of power-sector gas consumption does not exhibit a close correlation to gas prices. This is not surprising. As early as May 2021, natural gas prices were high enough to make gas-fired power plants the most expensive generators, that is, inducing fuel switching towards coal plants. Beyond this point, gas prices do not have a major impact on the dispatch of gas-fired power stations, but power-sector developments dominate. Those include the availability of renewable energy generation (August, October and February were above average)[17], the administrative phase out of coal and nuclear plants in Germany[18] and extraordinarily low availability of French nuclear power[19] and a lack of hydroelectric energy following a severe drought in Southern Europe[20], triggering large exports from Germany. Gas-fired power generation may also be reduced through a decrease in electricity consumption as a response to increasing electricity prices. However, disentangling these various drivers of gas consumption in the electricity sector would require a structural model of the power sector, which is beyond the scope of this study.

Comparing observed consumption to the estimated baseline

Figure 3 puts these savings into perspective with the estimated baseline consumption, which is strongly heterogeneous across sectors and seasons. For small consumers, the first substantial reduction of 4.9 TWh in March 2022 translates into relative savings of 10% compared with the estimated baseline consumption (Methods). Meanwhile, a similar absolute reduction in September 2022 of 4.8 TWh leads to the largest relative savings of 28%. For industrial consumers, the first substantial reduction of 1.4 TWh in September 2021 corresponds to savings of 4%, which steadily increase up to 27% in October 2022. For the power sector, relative changes vary from 2% above baseline in December 2021 to 44% below baseline in July 2022. The highest relative reduction in total German gas consumption has been achieved in September 2022 with 28% of the estimated monthly baseline. In the second half of 2022, total gas consumption was reduced by 23% on average.

Note that the relative changes in monthly natural gas consumption are heavily affected by the seasonality of heat demand. During summer, outside the heating season, we see hardly any response, although prices have already been high, probably because consumption was already so low that it could not be reduced much further. During the heating season, the absolute reduction is higher, which can be explained by the large effect of behavioural changes such as reducing indoor temperatures[21]. However, in the colder winter months, the same absolute reduction yields a smaller relative response, because of the larger baseline consumption. Put differently, the same behavioural change, for example, reducing indoor temperatures by 1 °C, can lead to larger relative savings during autumn and spring, compared with winter (Fig. 4).

Drivers of the crisis response

Our analysis focuses on the monthly effect that the event of the energy crisis had on natural gas consumption, and we deliberately did not include prices in our model. Nevertheless, comparing our estimated

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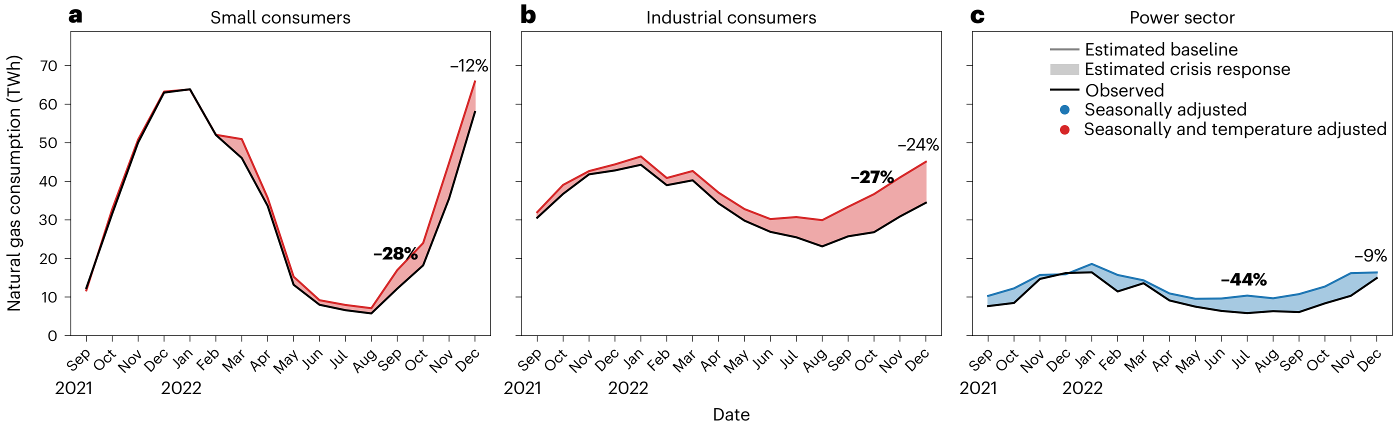

Fig. 3 | Observed versus estimated baseline consumption of natural gas. **a**–**c**, We distinguish between small consumers (**a**), industrial consumers (**b**) and the power sector (**c**). For the power sector, we control only for time trend and seasonality (blue). For small and industrial consumers, we additionally control for temperature (red). The difference between observed and estimated baseline gas consumption indicates the estimated crisis effect. The maximum relative reduction is annotated in bold letters. Month names are abbreviated.

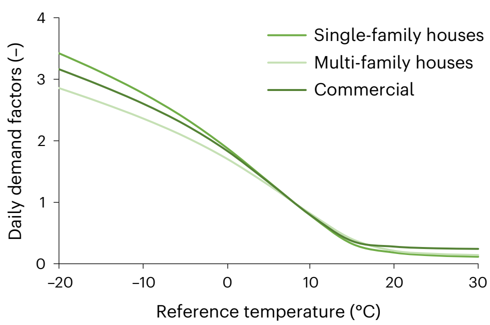

Fig. 4 | Daily demand factors for small consumers in Germany. The daily demand factors capture the nonlinear relationship between heating consumption of different subgroups of small consumers and the reference temperature, which is a rolling average of the ambient temperature.

crisis response to the observed increase in retail prices can yield preliminary insights into the price elasticity of demand (Fig. 5).

For small consumers, prices have increased by 130% between 2019–2021 and their peak in November 2022. Meanwhile, in November 2022, we estimate a consumption reduction of 21%. If consumers were primarily responding to current prices, this would imply a short-term price elasticity of −0.16, which is in line with the estimates in the literature[15,22,23]. This rough estimate should be interpreted with caution for four reasons. First, the observed consumption reductions may actually comprise both a short-term response and a long-term response to previously observed prices[15,22–24]. Second, as discussed above, relative savings may heavily be driven by the seasonality of heat demand. For instance, approximating a price elasticity based on September data would yield a substantially higher value of −0.27. Third, the available household price data are probably subject to measurement error (Supplementary Note 1). Finally, after Russia's invasion of Ukraine, public attention to the topics of natural gas and energy crisis soared, and the German government launched an information campaign on energy savings in June 2022 (Supplementary Note 3). Meanwhile, in addition to prices, surveys reported ethical motives of households to reduce energy consumption[2–4]. If this increase in public attention and ethical considerations had driven part of the reduction, estimates of small consumers' price elasticity would be inflated.

For industrial consumers, the same simple comparison of price and consumption changes suggests that they have been less responsive to price changes. As of September 2022, average gas prices for industrial consumers peaked at 580% of pre-crisis levels (January 2019 to September 2021). Together with the estimated 23% consumption reduction in September 2022, this would imply a small own-price elasticity of −0.04. This figure is in line with previous findings and can be explained by the fact that industry may be able to pass on higher energy costs to end consumers[25]. Two aspects should be considered when interpreting this number. First, like households, industrial purchase prices are prone to measurement error. During our period of observation, few industrial consumers have received government support, implying a reduced exposure to industrial purchase prices, while others may be able to resell their contracted gas volumes at the spot market, implying the exposure to higher spot prices (Supplementary Note 1). Second, industrial natural gas consumption may not be affected only by price changes but by other external factors such as economic activity. Indeed, economic activity was relatively high in many crisis months (Supplementary Note 4). This suggests that the actual price response was even larger.

Discussion and conclusions

We show that German consumers of natural gas have responded significantly and substantially to the current energy crisis. The timing, size and mechanism seem to be different for small, industrial and power-sector consumers. Industry started responding as early as in September 2021 with a 4% reduction in gas consumption that increased up to 27% a year later. This response was most likely triggered by surging wholesale gas prices but partly mitigated by rising output prices like that of ammonia. Small consumers started to reduce consumption later than industry. This pattern can be explained by the lagged pass through of wholesale prices to retail tariffs but also by non-financial motives to reduce gas consumption after Russia's invasion of Ukraine. After significantly reducing consumption by 10% in March 2022, they reached a maximum reduction of 28% in September 2022. However, large relative reductions during the summer translate to small absolute values, because small consumers use little gas during the summer, in contrast to industry, where seasonality is much less pronounced. Power-sector gas consumption was driven by various developments in electricity markets, in particular the poor availability of hydroelectric and nuclear power plants.

Aggregated across these three consumer groups, we estimate a maximum relative reduction of natural gas consumption by 28% in September 2022. While the estimated relative savings were slightly lower during the colder months, November and December, they remained significant. Over the second half of 2022, aggregate savings amounted

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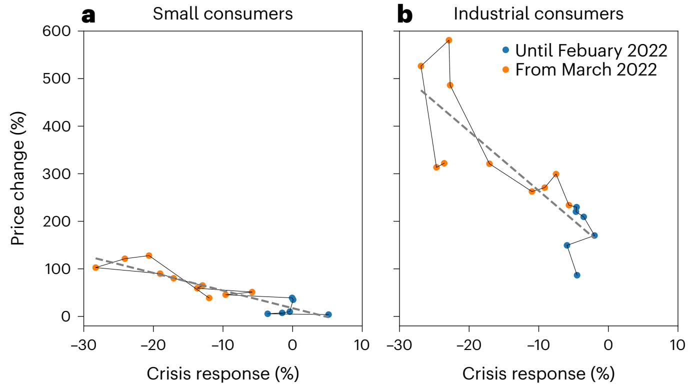

Fig. 5 | Crisis response and price changes. a,b, We distinguish between small consumers (**a**) and industrial consumers (**b**). We plot estimated monthly consumption reductions (% change compared to baseline; Methods) against monthly changes of residential and industrial prices. Price changes are calculated as the respective price level of a given crisis month divided by 2019–2021 pre-crisis average price level. A linear trend has been added across all points.

Table 1 | Data sources

Parameter	Source
Gas consumption of small and large consumers	Trading Hub Europe[28]
Gas-fired electricity generation, hourly unit-level data	ENTSO-E[30]
Gas-fired electricity generation, monthly national data	Destatis[29]
Simulated residential and commercial heating profiles	When2Heat dataset[31]
Weather data	Climate Data Store[32]

to 23% of baseline consumption. This is a substantial contribution to achieving the EU and German targets of reducing gas consumption from August 2022 to March 2023 by 15% and 20%, respectively[26,27].

Our findings have important implications for policy. Market prices appear to be an effective means of coordinating and incentivizing savings—especially in times of extreme events such as the current energy crisis. Our findings suggest that exposing consumers to prices and avoiding price dilution through subsidies is important to reduce gas consumption. Support policies and relief packages are needed to cushion hardship but should be designed in a way that they keep gas savings incentives intact.

Methods

Econometric model

We use an econometric model to identify the response of small (equation (1)), industrial (equation (2)) and power-sector (equation (3)) consumers to the 2021/2022 energy crisis. The effect of the crisis on monthly consumption levels is captured with 14 dummy variables for the crisis period from September 2021 until October 2022. The challenge is to distinguish between normal consumption variations, for example, due to space heating's temperature dependency, and exceptional variations, which can be attributed to the current crisis. We address this challenge by controlling for various factors driving natural gas consumption. We control for a linear time trend and for annual seasonality using dummies for the month of the year. Most importantly, we control for the simulated weather dependency of heating using simulated heating profiles. In several sensitivity runs, we omit the simulated heating profiles; omit the time trend; additionally control for economic activity, real wages, ambient temperature and solar radiation (Supplementary Note 4); and exclude the first year of the COVID-19 pandemic from our sample.

The econometric models are based on the following equations:

$$\mathrm{gas}^{\mathrm{s}}_t = a_0 + \boldsymbol{a}_1\mathbf{crisis}_t + \boldsymbol{a}_2\mathbf{time}_t + a_3\mathrm{heat}_t + e_t \tag{1}$$

$$\mathrm{gas}^{\mathrm{i}}_t = a_0 + \boldsymbol{a}_1\mathbf{crisis}_t + \boldsymbol{a}_2\mathbf{time}_t + a_3\mathrm{heat}_t + e_t \tag{2}$$

$$\mathrm{gas}^{\mathrm{p}}_t = a_0 + \boldsymbol{a}_1\mathbf{crisis}_t + \boldsymbol{a}_2\mathbf{time}_t + e_t \tag{3}$$

where $\mathrm{gas}^{\mathrm{s}}_t$, $\mathrm{gas}^{\mathrm{i}}_t$, $\mathrm{gas}^{\mathrm{p}}_t$ is gas consumption of small, industrial and power-sector consumers, respectively, $\mathbf{crisis}_t$ is the vector of monthly crisis dummies, $\mathbf{time}_t$ is the vector of monthly time dummies and a linear time trend, heat_t is a simulated heating profile, $\boldsymbol{a}_0...\boldsymbol{a}_3$ are model parameters (often vectors) and e_t is an error term.

Vectors are denoted in bold. The subscript *t* indicates the monthly temporal resolution of the model. In the main sections, we report the results for $\boldsymbol{a}_1$, which estimates the monthly consumption response to the crisis. Model parameters are estimated with an ordinary least squares estimator using heteroscedasticity and autocorrelation robust standard errors.

Note the same estimated consumption response could be obtained by training a model on pre-crisis data and comparing forecasted consumption from this model to observations during the crisis. The advantage of our approach is that it allows for assessing the uncertainty and hence statistical significance of the estimated consumption changes.

Our model is applied to data starting in 2017 for industry and power stations and in 2018 for small consumers, yielding a total of 70 and 58 monthly observations, respectively. The data sources are summarized in Table 1 and explained in the following. The stationarity of dependent and independent variables is discussed in Supplementary Note 5.

Gas consumption of large and small consumers

We use separate data on the aggregated natural gas consumption of large and small consumers. Large consumers (German: 'Kunden mit registrierender Leistungsmessung, RLM') are metered daily with an annual consumption above 1.5 GWh. They include the industrial, power and district heating sectors and account for 60% of the overall gas consumption. Small consumers (German: 'Kunden mit Standardlastprofil, SLP') are metered only on an annual basis, including mainly the residential and service sectors and accounting for the 40% of the overall gas consumption.

Both datasets for small and large consumers were retrieved from the German gas-market area manager THE in daily resolution and aggregated to months[28]. In addition to the monthly aggregated data, we run our model with daily data without finding notable changes (Supplementary Note 4). THE publishes preliminary data near real time and provides corrected and final data about one and two months later. When this study was conducted, December 2022 was the last month with final data. We refrained from including more recent preliminary data, which are subject to substantial revisions. For instance, the average consumption of small consumers in October 2022 was 7% higher according to corrected instead of preliminary data.

In the absence of direct sub-annual metering, we use data for small consumers that is inferred from measurements of the overall consumption minus large consumers' metered consumption (this is referred to as the residual load of small consumers or 'SLP-Restlast' in German). Note that THE also publishes allocation data on small consumers (which we used in an earlier version of this study), but this is only partly inferred from measurements (if 'analytical standard load profiles' are applied) and mostly estimated (if 'synthetical standard load profiles' are applied).

Gas consumption in the power sector

We further disentangle the natural gas consumption of large consumers into that of the power sector and that of other industrial consumers. To this end, we used monthly data on gas consumption by public power plants from the German Federal Statistical Office (Destatis)[29]. For our sensitivity analysis with a daily resolution, we combine monthly data from Destatis with high-resolution data on gas-fired electricity generation from the European Network of Transmission System Operators for Electricity (ENTSO-E)[30]. The resulting time series of monthly gas consumption in the power sector is deducted from the aggregated gas consumption of large consumers obtained from THE before using the residual time series as $\mathrm{gas}_t^{\mathrm{i}}$ in equation (2).

Simulated heating profiles

To control for the weather dependency of natural gas consumption, we simulated heating profiles based on the method of standard load profiles. This method was developed by the German Association of Energy and Water Industries, the German Association of Local Utilities and European Association of Local Energy Distributors, and is the industry standard for simulating synthetic gas-consumption profiles. The parameters of the standard load profiles are empirically determined, and we are using parameters from ref. 31, which was published in 2015. Hence, these parameters capture the temperature dependency of heating demand before the energy crisis.

The standard load profiles model a nonlinear relationship between ambient temperature and space heating using a sigmoid function (Fig. 4). This nonlinear relationship emerges from the heterogeneity of the building stock characteristics and occupants' behaviour. For instance, the curvature around 15 °C reflects the varying individual heating thresholds, that is, the temperatures below which individual consumers start heating. Furthermore, the diminishing slope at lower ambient temperatures accounts for a less temperature-dependent heating behaviour at these temperatures. Finally, standard load profiles are based on a rolling average of the ambient temperature, capturing thermal inertia of buildings.

These nonlinear effects cannot be accounted for by simply controlling for ambient temperature or the difference between ambient temperature and the heating threshold. Our main model based on standard load profiles yields an adjusted R^2 of 0.999, whereas substituting the standard load profiles with the difference between ambient temperature and an assumed heating threshold of 16 °C (based on ref. 32) results in a smaller adjusted R^2 of 0.994. While this change in the adjusted R^2 may seem minor, it can have substantial implications for our monthly crisis-response estimates. For example, the estimated crisis response of small consumers in October 2022 increases from 5.8 to 6.8 TWh when using the difference between ambient temperature and the heating threshold instead of standard load profiles. Note that it is important to also control for a time trend and seasonality. Excluding these additional control variables, the adjusted R^2 decreases to 0.991 when using standard load profiles.

We applied standard load profiles to spatial data of the ambient temperature and constructed a national population-weighted average as described in refs. 31,33–35. More precisely, we constructed one time series that aggregates the expected heating demand in residential and commercial sectors. This matches the scope of the gas-consumption data on small consumers that we are using for estimating the crisis response.

As a sensitivity, we additionally control for the population-weighted ambient temperature and population-weighted solar radiation, as solar radiation can negatively impact heating demand (Supplementary Note 4). None of these variables notably improves model accuracy when applied in addition to the simulated heating profiles, which is why we omitted them in our main model specification. All weather data were downloaded from Climate Data Store[36].

While decentralized heating is mostly included in the group of small consumers, the consumption of industrial consumers also exhibits significant temperature dependency. This is because our time series of industrial consumption, after deducting power-sector gas consumption, still includes gas consumption of district heating plants. Because high-resolution data on district heating gas consumption are not available, deducting their consumption from the aggregate series, as done with the power sector, is not possible. Moreover, some industrial processes may also be dependent on outside temperature, but we cannot disentangle this from the temperature dependency of district heating. Therefore, we also control for the above-mentioned simulated national space heating-demand time series in the model for industrial consumers.

Estimated baseline consumption

The baseline consumption $\mathrm{gas}_t^{\mathrm{base}}$ is estimated as follows:

$$\mathrm{gas}_t^{\mathrm{base}} = \mathrm{gas}_t - \hat{\boldsymbol{a}}_1 \boldsymbol{\mathrm{crisis}_t} \quad (4)$$

where gas_t is the gas consumption of small or industrial consumers ($\mathrm{gas}_t^{\mathrm{s}}$ or $\mathrm{gas}_t^{\mathrm{i}}$), $\hat{\boldsymbol{a}}_1$ is the estimated vector of the absolute crisis response and $\boldsymbol{\mathrm{crisis}_t}$ is the vector of monthly crisis dummies.

To derive the crisis response in relative terms, we compare our absolute model estimates with the baseline consumption according to the following equation:

$$\hat{\boldsymbol{a}}_1^{\mathbf{rel}} = \hat{\boldsymbol{a}}_1 \sum_t \left(\boldsymbol{\mathrm{crisis}_t} \mathrm{gas}_t^{\mathrm{base}}\right)^{-1} \quad (5)$$

Data availability

The original data used in this study are publicly available. The compiled dataset is published on Zenodo at https://doi.org/10.5281/zenodo.7782052.

Code availability

The code is published under an open license on GitHub at https://github.com/oruhnau/gas_savings.

References

1. Elliott, S., Bowles, A. & Montgomery, B. European gas prices surge on renewed Russian gas supply uncertainty. *S&P Global* (22 August 2022); https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/082222-european-gas-prices-surge-on-renewed-russian-gas-supply-uncertainty
2. Ravikumar, A. P., Bazilian, M. & Webber, M. E. The US role in securing the European Union's near-term natural gas supply. *Nat. Energy* **7**, 465–467 (2022).

3. *Ukraine-Krieg: Die Hälfte der Deutschen spart fossile Energie ein* (Bitkom, 2022); https://www.bitkom.org/Presse/Presseinformation/Ukraine-Krieg-Haelfte-spart-fossile-Energie
4. *Energy Prices Consumers' Fears for the Future and Opinions in 10 European Countries Regarding the Evolving Energy Prices* (YouGov, 2022); https://commercial.yougov.com/rs/464-VHH-988/images/YouGov%20Report_Energy%20Prices_Europe_Nordic.pdf
5. *55% der Deutschen haben seit Beginn des Ukraine-Krieges ihren Energieverbrauch gesenkt* (Tado, 2022); https://www.tado.com/at-de/pressemitteilungen/energy-consumption-poll
6. Lange, F. & Dewitte, S. Measuring pro-environmental behavior: review and recommendations. *J. Environ. Psychol.* **63**, 92–100 (2019).
7. Stiewe, C., Ruhnau, O. & Hirth, L. *European Industry Responds to High Energy Prices: The Case of German Ammonia Production* (ZBW - Leibniz Information Centre for Economics, 2022).
8. Zachmann, G. & McWilliams, B. The European Union demand response to high natural gas prices. *Bruegel* https://www.bruegel.org/blog-post/european-union-demand-response-high-natural-gas-prices (2022).
9. Löffelholz, J. *Zahl der Woche/Sinkender Gasverbrauch: Ein Drittel weniger Gas....* (BDEW, 2022); https://www.bdew.de/presse/presseinformationen/zahl-der-woche-sinkender-gasverbrauch-ein-drittel-weniger-gas/
10. *Indicators of Natural Gas Use by Industry* (Statistics Netherlands & Gas Network Operator, 2022); https://www.cbs.nl/nl-nl/visualisaties/indicatoren-aardgasgebruik-van-de-industrie
11. Honoré, A. *Demand Response to High Gas Prices in Europe in 2021 and Early 2022* (Oxford Institute for Energy Studies, 2022).
12. Ito, K. Do consumers respond to marginal or average price? Evidence from nonlinear electricity pricing. *Am. Econ. Rev.* **104**, 537–563 (2014).
13. Hirth, L., Khanna, T. & Ruhnau, O. *The (Very) Short-Term Price Elasticity of German Electricity Demand* (ZBW - Leibniz Information Centre for Economics, 2022).
14. Labandeira, X., Labeaga, J. M. & López-Otero, X. A meta-analysis on the price elasticity of energy demand. *Energy Policy* **102**, 549–568 (2017).
15. Auffhammer, M. & Rubin, E. *Natural Gas Price Elasticities and Optimal Cost Recovery Under Consumer Heterogeneity: Evidence from 300 Million Natural Gas Bills* (National Bureau Of Economic Research, 2018); https://doi.org/10.3386/w24295
16. Wooldridge, J. M. *Introductory Econometrics: A Modern Approach* (Cengage Learning, 2016).
17. *Monthly Renewable Share of Public Electricity Generation in Germany* (Energy Charts, 2022); https://www.energy-charts.info/charts/renewable_share/chart.htm?l=de&c=DE&interval=month
18. Joly, J. Germany begins nuclear phase-out, shuts down three of six nuclear power plants. *Euronews* https://www.euronews.com/2021/12/31/germany-begins-nuclear-phase-out-shuts-down-three-of-six-nuclear-power-plants (2021).
19. Hirth, L. & Schlecht, I. Die zweite krise: Frankreichs kernenergie. *Tagespiegel Background* https://background.tagesspiegel.de/energie-klima/die-zweite-krise-frankreichs-kernenergie (2022).
20. Joint Research Centre *Drought in Europe: July 2022: GDO Analytical Report* (European Commission Publications Office, 2022).
21. Sperber, E., Frey, U. & Bertsch, V. Turn down your thermostats—a contribution to overcoming the European gas crisis? The example of Germany. Preprint a *SSRN* https://doi.org/10.2139/ssrn.4288068 (2022).
22. Lavín, F. V., Dale, L., Hanemann, M. & Moezzi, M. The impact of price on residential demand for electricity and natural gas. *Climatic Change* **109**, 171–189 (2011).
23. Bastos, P., Castro, L., Cristia, J. & Scartascini, C. *Does Energy Consumption Respond to Price Shocks? Evidence from a Regression-Discontinuity Design* (ZBW - Leibniz Information Centre for Economics, 2011).
24. Thomas, A., Massol, O. & Sévi, B. How are day-ahead prices informative for predicting the next day's consumption of natural gas? Evidence from France. *Energy J.* **43**, 67–91 (2022).
25. Li, R., Woo, C.-K., Tishler, A. & Zarnikau, J. How price responsive is industrial demand for natural gas in the United States? *Util. Policy* **74**, 101318 (2022).
26. *Council Adopts Regulation on Reducing Gas Demand by 15% This Winter* (European Council, 2022); https://www.consilium.europa.eu/en/press/press-releases/2022/08/05/council-adopts-regulation-on-reducing-gas-demand-by-15-this-winter/
27. *Energieeinspar-Verordnungen zur Senkung des Gas- und Stromverbrauch* (German Federal Ministry for Economic Affairs and Climate Action, 2022); https://www.bmwk.de/Redaktion/DE/Downloads/Energie/energiesparverordnung.pd
28. *Publication of the Aggregate Consumption Data* (Trading Hub Europe, 2022); https://www.tradinghub.eu/en-gb/Publications/Transparency/Aggregated-consumption-data
29. *Destatis* (German Federal Statistical Office, 2022); https://www.destatis.de
30. *Transparency Platform* (European Network of Transmission System Operators for Electricity, 2022); https://transparency.entsoe.eu
31. *Abwicklung von Standardlastprofilen Gas* (German Federation of the Gas- and Water Industry, 2015); https://www.bdew.de/media/documents/Leitfaden_20160630_Abwicklung-Standardlastprofile-Gas.pdf
32. Kozarcanin, S., Andresen, G. B. & Staffell, I. Estimating country-specific space heating threshold temperatures from national gas and electricity consumption data. *Energy Build.* **199**, 368–380 (2019).
33. Ruhnau, O., Hirth, L. & Praktiknjo, A. Time series of heat demand and heat pump efficiency for energy system modeling. *Sci. Data* https://doi.org/10.1038/s41597-019-0199-y (2019).
34. Ruhnau, O. & Muessel, J. Update and extension of the When2Heat Dataset. Preprint at *EconStor* https://ideas.repec.org/p/zbw/esprep/249997.html (2022).
35. *Anwendung von Standardlastprofilen zur Belieferung nicht-leistungsgemessener Kunden* (German Federation of the Gas- and Water Industry, 2006); http://www.gwb-netz.de/wa_files/05_bgw_leitfaden_lastprofile_56550.pdf
36. Hersbach, H. et al. ERA5 hourly data on pressure levels from 1959 to present. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)* https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview (2018).

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O.R.: conceptualization, formal analysis, writing–original draft, visualization, data curation, project administration. C.S.: conceptualization, formal analysis, writing–original draft, visualization, data curation. J.M.: conceptualization, formal analysis, writing–original draft, visualization, data curation. L.H.: conceptualization, writing–original draft, supervision.

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