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Working Paper

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Gas demand in times of crisis: energy savings by consumer group in Germany

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Russia curbed its natural gas supply to Europe in 2021 and 2022, creating a grave energy crisis. This paper 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 non-linear temperature-heating relationship, seasonality, and trends. For industrial consumers, we find a strong and sustained response, with reductions steadily increasing from 4% in September 2021 to 29% in October 2022. For small consumers, including households and small enterprises, we find reductions between 10% and 42% from March to October 2022. Gas savings in the power sector are more volatile and not only driven by reduced Russian gas supply. We discuss the drivers behind these consumption reductions 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 in 2022. This is about ten times the long-term pre-Covid price levels of 15–20 €/MWh. Specific events, like Russia's invasion of Ukraine on 24 February 2022 and Russia's announcement of closing the North Stream 1 pipeline on 19 August 2022[1], led prices to spike up to 227 and 339 €/MWh, respectively. Meanwhile, the average gas price paid by German industry has increased six-fold, somewhat lagged and dampened by long-term contracts. Average German residential retail prices increased substantially since January 2022, having more than doubled by October 2022 (Figure 1).

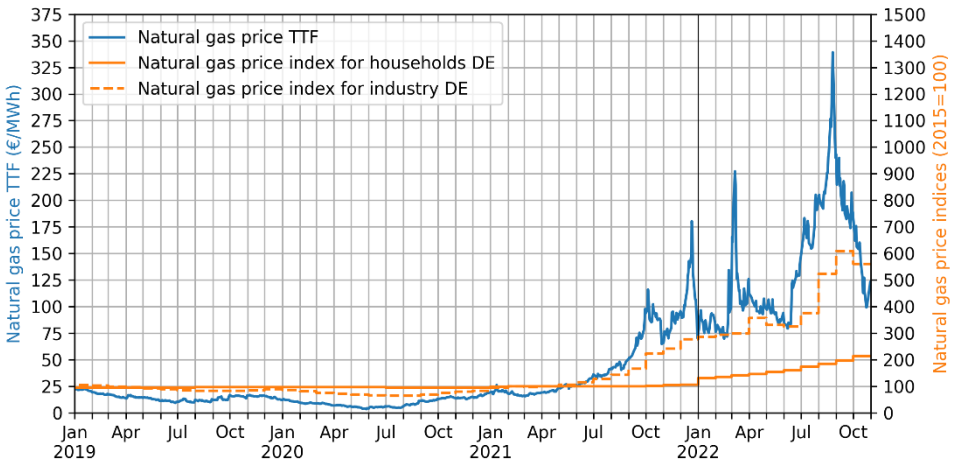

Figure 1: Prices of natural gas at the European wholesale market and at the German retail market. *Wholesale prices from the Title Transfer Facility (TTF) spot market (ranging from trades in two business days ahead to the end of the month); retail prices are indexed average prices for natural gas paid by German household and industrial consumers according to the Federal Statistical Office (DESTATIS)*

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 North Stream 1 pipeline have ceased completely. With domestic European gas supply being limited, Europe turned to liquified natural gas (LNG) as a substitute, but global LNG 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.

We are interested in understanding if and to what extent firms and households have responded to the energy crisis by reducing their consumption of natural gas. 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 household, by ethical considerations, in particular since the Russian invasion of Ukraine on 24 February 2022.

Previous non-academic surveys among German and European households find that every second to third respondent reported saving energy in response to the current crisis (refs.[3–5], see Supplementary Information S1 for a summary). These surveys support the hypothesis of energy savings by households and provide insight into the motivation behind it. Noteworthily, 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 (see ref.[6] for a review). Also, the surveys cannot be used to estimate the magnitude of energy savings resulting from the indicated behavioral changes. Similarly, energy-intensive industries have been self-reporting production cuts since fall of 2021, but these insights cannot be translated into how much natural gas has been saved in the industry as a whole (see our collection of press releases in ref.[7]).

Moreover, many existing analyses of the current energy crisis 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 analyze energy demand in the more distant past (e.g., refs.[12–15]), previous analyses of the current crisis methodically lack behind these earlier studies. Meanwhile, findings of earlier studies may not be applicable to the current crisis, because of the unprecedented size of the observed supply shock.

The aim of the present article is to provide timely evidence on reductions in gas consumption in the current energy crisis based on an innovative combination of sound statistical methods and multiple near-time datasets. More precisely, we use 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*. Although we show that the identified changes in natural gas correlate with increasing prices for natural gas, we estimate the effect of the crisis event rather than the causal relationship between prices and demand.

Our methodical contribution is related to the huge importance of space heating for European gas consumption. To account for this, we carefully model the non-linear relationship between spatially resolved temperature data and the national space heating demand. This approach accounts for the characteristics of the national building stock (like insulation) and pre-crisis consumer behavior. We also control for annual seasonality and time trends. To identify potential reductions in consumption during the crisis, we include monthly crisis response variables from September 2021 onwards. We deliberately do not include prices in our model to avoid problems with endogeneity[16] and measurement error (see

S2). However, we provide descriptive evidence on the relationship between gas savings and prices and discuss other potential drivers of the crisis response.

We apply our model to the aggregated German natural gas consumption of small and large consumers, respectively. We use further datasets to disentangle the natural gas consumption of large consumers into that of the power sector and that of other industries. Distinguishing these three groups of consumers is informative, as it turns out that their response to the energy crises has been very different. Germany is an interesting case study as it is the largest export market for Russian natural gas. Reductions 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 as well as space heating. If Germany purchased its annual natural gas consumption of close to 1,000 TWh at wholesale prices of 200€/MWh, the increase in the gas bill corresponded to about 5% of GDP (3.57 trillion € in 2021).

We find a significant and substantial crisis response across consumer groups. German industry started to reduce demand by 4% as early as in September 2021 and steadily increased its response to 29% in October 2022. This finding aligns well with increasing wholesale and industrial retail prices. Small consumers, including households, started to respond substantially only in March 2022. During the summer of 2022, when the expected baseline consumption of small consumers was low at higher ambient temperatures, estimated savings are still significant, albeit much smaller in absolute terms. Larger absolute savings by small consumers become evident again in September and October 2022, when low ambient temperatures led to a higher baseline consumption level. The lagged response of residential compared to industrial consumers can partly be explained by a delayed price exposure.

These findings matter for public policy because they suggest that prices are an effective means of incentivizing demand reductions. In turn, 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

Three separate models have been estimated for small, industrial, and power sector consumers of natural gas. We included monthly dummy variables from September 2021 to October 2022 to identify a potential crisis response. To control for the temperature dependency of residential and industrial gas consumption, we include simulated temperature-dependent heating demand profiles as covariates in the first two models. Sectoral gas consumption data was gathered from the German market operator Trading Hub Europe (THE), and the German statistical office (see Methods for details).

Figure 2 displays the estimated monthly crisis responses of small, industrial, and power sector consumers (see S3 for the numerical results and S4 for 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, i.e., 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. Each of the three consumer groups reached a maximum reduction of about 7–14 TWh/month in October 2022. We will discuss the three sectors in turn.

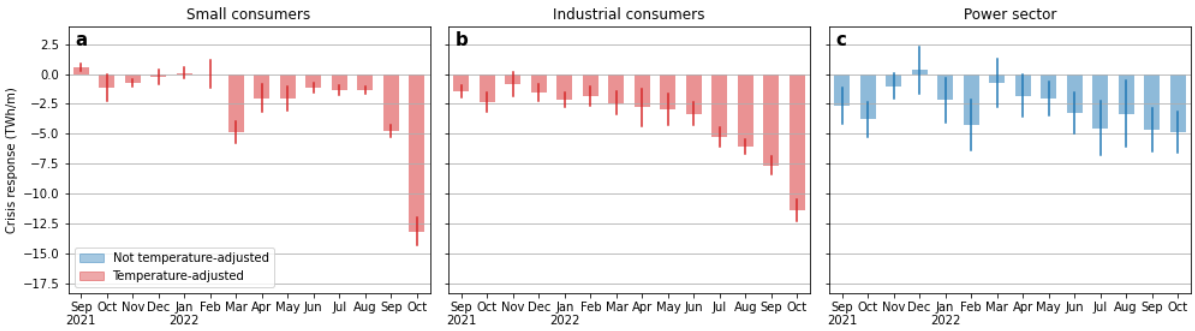

Figure 2: Estimated monthly crisis response of natural gas consumption
For the power sector, we only control for time trend and seasonality (blue). For small and industrial consumers, we additionally control for temperature (red). The bars indicate the monthly point estimates and the vertical lines the corresponding 5-95% confidence intervals.

Households and small businesses show a salient reduction from March 2022 onwards. This late response compared to other consumer groups makes sense since 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 (see Figure 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 February 24 may be driven by increased attention (see S6) 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 wholesale prices of natural gas as well as industrial retail prices starting to surge (see Figure 1). Furthermore, the industrial crisis response tends to increase over time, which may be driven by two factors. First, the response may increase because wholesale prices and industrial retail prices have increased somewhat 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/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 well with the insignificant savings coefficient in November 2021. The further reduction in the aggregate demand 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 demand does not witness a close correlation to gas prices. This is not surprising. As early as by May 2021, natural gas prices were high enough to make gas-fired power plants the most expensive generators, i.e., inducing fuel switching toward 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] as well as a lack of hydroelectric energy following a severe drought in South Europe[20], triggering large exports from

Germany. Gas-fired power generation may also be reduced through a decrease in electricity demand, as a response to increasing electricity prices. However, disentangling these various drivers of gas demand 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 absolute reduction of 4.9 TWh in absolute terms in March 2022 translates into a relative reduction of 10% compared to the estimated baseline consumption (see Methods for details). In October 2022, the absolute reduction of 13.2 TWh implies a relative reduction of as much as 42%. For industrial consumers, the absolute reductions of 1.4 TWh in September 2021 and 11.4 TWh in October 2022 correspond to relative reductions of 4% and 29%, respectively. For the power sector, relative reductions vary from 0% to about 40% in September and October 2022. Across consumer groups, the absolute 29 TWh/month reduction in October 2022 is 35% of the estimated baseline consumption of 83 TWh/month.

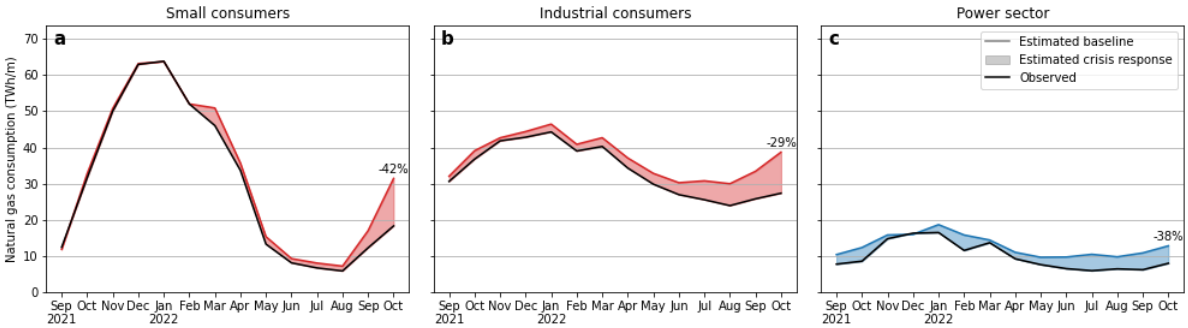

Figure 3: Observed versus estimated baseline consumption of natural gas demand
For the power sector, we only control for time trend and seasonality (blue). For small and industrial consumers, we additionally control for temperature (red). The difference between observed and estimated baseline gas consumption indicates the estimated crisis effect.

Note that the relative changes in the monthly natural gas consumption are heavily affected by the seasonality of heat demand. During summer, outside the heating season, we hardly see 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, we expect that the absolute reduction potential is higher, e.g., through reducing indoor temperatures. However, the same absolute reduction would yield a larger relative response during spring and autumn, compared to winter, because of the smaller baseline consumption. Put differently, the same behavioral change, e.g., reducing indoor temperatures by 1°C, can lead to a large relative reduction in consumption during autumn and spring, compared to winter (see Figure 5).

Drivers of the estimated 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, it seems interesting to compare our estimated crisis response to the observed increase in retail prices for some preliminary insights into the price elasticity of demand (Figure 4).

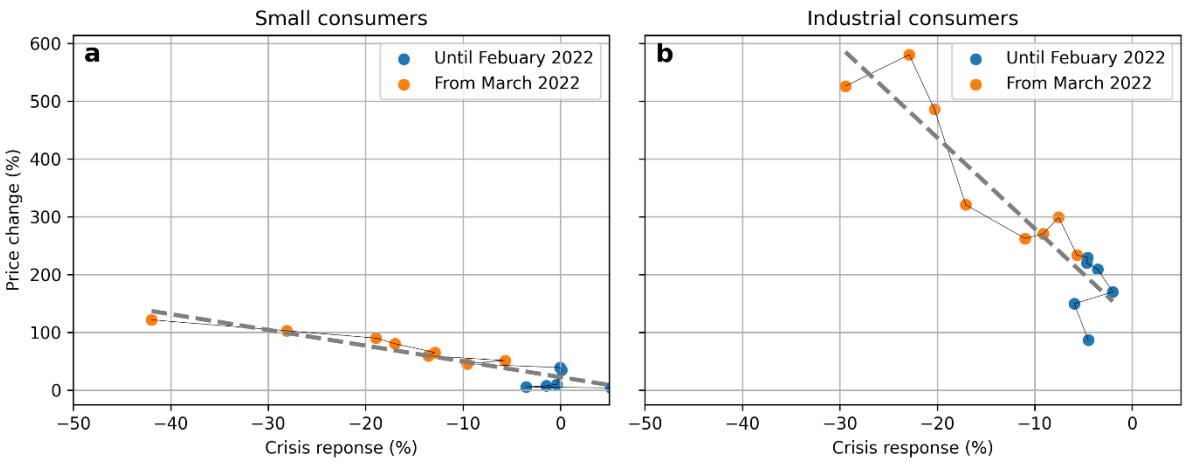

Figure 4: Crisis response and price changes

We plot estimated monthly demand reductions (% change compared to baseline, see 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.

For small consumers, prices have increased by 120% between 2019-2021 and October 2022. Meanwhile, in October 2022, we estimate a consumption reduction of 42%. If consumers were primarily responding to current prices, this would imply a short-term price elasticity of -0.35, which is at the upper end of estimates in the literature[21–23]. 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[21–24]. Second, as discussed above, the relative demand reduction may heavily be driven by the seasonality of heat demand. During a fall month like October, the relative reduction potential may be smaller than during winter (when it matters most), which could lead to a monthly price elasticity above the annual average. Third, the available household price data are likely subject to measurement error (see S2). 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 (see S6). 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 October 2022, average gas prices for industrial consumers increased by 530% compared to pre-crisis levels (January 2019 to September 2021). Together with the estimated 29% reduction in October 2022, this would imply a small own-price elasticity of -0.06. 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 (see S2). Second, industrial natural gas consumption may not only be affected by price changes but by other external factors such as economic activity. Indeed, economic activity was relatively high in many crisis months (see S5). This suggests that the actual price response was even larger.

Conclusions

Our findings suggest 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 to 29% 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 42% in October 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 that natural gas consumption in October 2022 was reduced by as much as 29 TWh/month, or 35% of baseline consumption. This is a significant contribution to achieving the EU and German targets of reducing gas consumption by 15% and 20% from August 2022 to March 2023, respectively[26,27].

Given these findings, we believe continued substantial gas savings to be possible. With a further pass-through of elevated wholesale gas prices to industrial and household consumers, the savings incentives will remain high or even increase. As a result, we would expect further significant reductions in industrial gas consumption. The consumption of small consumers during the winter is more uncertain since, for most of them, this will be the first crisis winter. Sustained savings in the power sector will depend on further developments in European electricity markets.

Our findings have important implications for policy. Market prices appear to be an effective means of coordinating and incentivizing demand reductions—especially in times of extreme events like 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 (Eq. 1), industrial (Eq. 2), and power sector (Eq. 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, e.g., 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, and additionally control for temperature as well as solar radiation (see S5).

The econometric models are based on the following equations:

$$gas_t^s = a_0 + \boldsymbol{a_1 crisis_t} + \boldsymbol{a_2 time_t} + a_3 heat_t + e_t \quad (1)$$

$$gas_t^i = a_0 + \boldsymbol{a_1 crisis_t} + \boldsymbol{a_2 time_t} + a_3 heat_t + e_t \quad (2)$$

$$gas_t^p = a_0 + \boldsymbol{a_1 crisis_t} + \boldsymbol{a_2 time_t} + e_t \quad (3)$$

where

$gas_t^s, gas_t^i, gas_t^p$	gas consumption of small, industrial, and power sector consumers
$\boldsymbol{crisis_t}$	vector of monthly crisis dummies
$\boldsymbol{time_t}$	vector of monthly time dummies as well as a linear time trend
$heat_t$	simulated heating profile
$a_0 \dots a_3$	model parameters (often vectors)
e_t	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 a_1, which estimates the monthly consumption response to the crisis. Model parameters are estimated with an ordinary least squares (OLS) 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 S7.

Table 1: Data sources

Parameter	Source
Gas consumption of small and large consumers	Trading Hub Europe
Gas-fired electricity generation, hourly unit-level data	European Network of Transmission System Operators of Electricity (ENTSO-E)
Gas-fired electricity generation, monthly national data	Eurostat NRG_IND_342M
Simulated residential and commercial heating profiles	When2Heat dataset
Weather data	Climate Data Store

Gas consumption of large and small consumers

We use separate data on the aggregated natural gas consumption of large and small consumers. Large consumers ("RLM-Kunden") 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 ("SLP-Kunden") 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 an daily resolution and aggregated to months[28]. In addition to the monthly aggregated data, we run our model with daily data, without finding significant changes (see S5). THE publishes preliminary data near real time and provides corrected and final data about one and two months later. When this study was conducted, September 2022 was the last month with final data, and October 2022 was included based on corrected 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*). 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 DESTATIS[29]. However, these data are published with a time lag and, at the time when this analysis was conducted, they were available only until September 2022. To fill the gap for October 2022, we estimate the power sector's gas consumption based on real-time data on the gas-fired electricity generation from ETNSO-E[30]. To do so, we calculate the ratio between the power sector's gas consumption and gas-fired electricity generation in September 2022 and assume the same ratio for October 2022. This neglects a potential change in the gas-to-electricity conversion efficiency with increasing (decreasing) gas-fired electricity generation, as power plants using the same fuel are generally dispatched in decreasing order of conversion efficiency. Also, more plants may run at reduced electric efficiency in October 2022 as more thermal energy is extracted to meet district heating demand at the beginning of the heating season. 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 gas_t^i in Eq. (2). The extrapolation for October 2022 implies that power sector gas consumption is potentially underestimated, meaning that industrial consumption (large minus power sector consumption) may be somewhat inflated. The estimate of industrial consumption reduction in October is thus on the conservative end, while the opposite applies to estimated power sector reductions.

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 (BDEW), the German Association of Local Utilities (VKU) & European Association of Local Energy Distributors (GEODE) and is the industry standard for simulating synthetic gas demand 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 non-linear relationship between ambient temperature and space heating using a sigmoid function (Figure 5). This non-linear relationship emerges from the heterogeneity of the building stock characteristics and occupants' behavior. For instance, the curvature around 15°C reflects the varying individual heating thresholds, i.e., the temperatures below which individual consumers start heating. Furthermore, the diminishing slope at lower ambient

temperatures accounts for a less temperature-dependent heating behavior at these temperatures. Finally, standard load profiles are based on a rolling average of the ambient temperature, capturing thermal inertia of buildings.

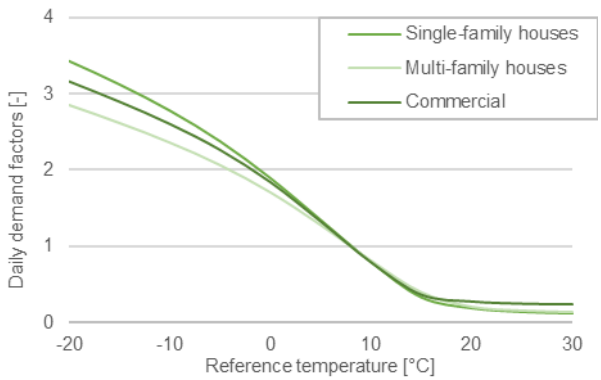

Figure 5: Daily demand factors as a function of the reference ambient temperature for different consumer groups in Germany

These non-linear 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 decreases from 13.2 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 as well as population-weighted solar radiation, as solar radiation can negatively impact heating demand (see S5). None of these variables significantly 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 was 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. Since high-resolution data on district heating gas consumption is 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 gas_t^{base} is estimated as follows:

$$gas_t^{base} = gas_t - \hat{\boldsymbol{a}}_{\boldsymbol{1}}\, \boldsymbol{crisis_t} \tag{4}$$

where

gas_t	gas consumption of small or industrial consumers (gas_t^s or gas_t^i)
$\hat{\boldsymbol{a}}_{\boldsymbol{1}}$	estimated vector of the absolute crisis response
$\boldsymbol{crisis_t}$	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:

$$\hat{\boldsymbol{a}}_{\boldsymbol{1}}^{\boldsymbol{rel}} = \hat{\boldsymbol{a}}_{\boldsymbol{1}} \sum_t \left(\boldsymbol{crisis_t} \cdot gas_t^{base}\right)^{-1} \tag{5}$$

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Competing interests

The authors declare no competing interests.