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**Working Paper**

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*Suggested Citation:* Ruhnau, Oliver; Stiewe, Clemens; Muessel, Jarusch; Hirth, Lion (2022) : Gas demand in times of crisis: energy savings by consumer group in Germany, ZBW – Leibniz Information Centre for Economics, Kiel, Hamburg

This Version is available at:

<https://hdl.handle.net/10419/265522>

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

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**Updated version from October 2022**  
([link](#) to earlier version from July 2022)

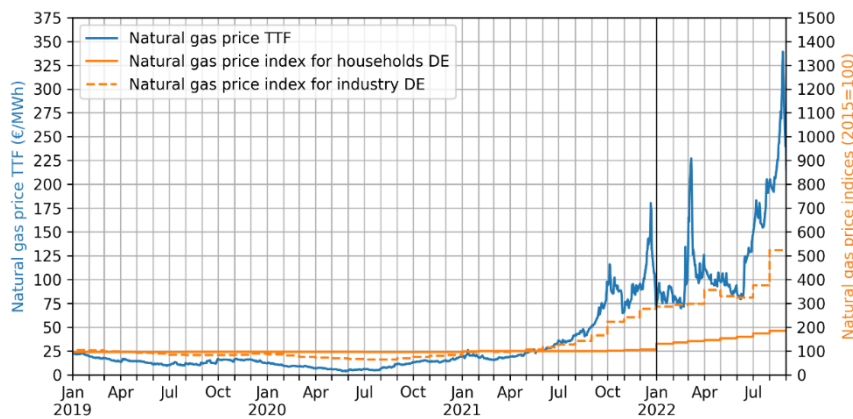
**When Russia curbed natural gas supply to Europe in 2021 and 2022, it created a grave energy crisis. This paper empirically estimates the crisis response of natural gas consumers in Germany—for decades the largest export market for Russian gas. Using a multiple regression model, we estimate the response of small consumers, industry, and power stations separately, controlling for the non-linear temperature-heating relationship, seasonality, trends, and economic activity. For industrial consumers, we find a strong and sustained response, with reductions steadily increasing from 4% in September 2021 to 19% in September 2022, roughly following wholesale price levels. For small consumers, including households and small enterprises, we find a response between 10% and 36% from March to September 2022. However, large relative reductions during the summer translate to small absolute values, because small consumers use little gas during this season anyway. The amount of gas burned in power stations is primarily driven by electricity sector events that are not directly linked to reduced Russian gas supply. These findings suggest that voluntary reductions in gas consumption have played a significant role in coping with the crisis.**

Europe is amid the most severe energy crisis since the oil price shock of 1973. Since mid-2021, natural gas prices have been on a steep rise, with average wholesale prices at the TTF spot market well above 100 €/MWh between October 2021 and mid-2022 and prices of around 240 €/MWh in August. This is about ten times higher than the long-term pre-Covid price levels of 15–20 €/MWh. While other commodities, including steam coal, crude oil and oil products, carbon allowances, and electricity also have witnessed strong price increases, the increase in gas prices stands out. The surge in European spot prices has resulted in higher natural gas prices paid by German industry, which was somewhat lagged and dampened by fixed-price long-term contracts. By August 2022, the average price that industry paid for natural gas has quintupled compared to pre-crisis levels. Average German residential retail prices have also increased, but with an even larger time lag (Figure 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, usually justified with dubious reasons. By September 2022, imports from Russia to Germany via the North Stream 1 pipeline have ceased completely. Specific events, like the Russian invasion of Ukraine on 24 February 2022, led prices to spike up to 227 €/MWh before returning to a less extreme yet upward-trending pathway.

With domestic European gas supply being limited, Europe turned to liquefied natural gas (LNG) as a substitute, but tight global LNG markets and limited European import terminal capacity led to a surge in European natural gas prices<sup>1</sup>. As Russia might reduce deliveries further or stop flows completely any time, 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 so far. Such response could be driven by rising prices, expected future price rises, media attention for energy topics and related awareness of energy issues and saving options, or (in the case of households) by ethical considerations, in particular since the Russian invasion of Ukraine on 24 February 2022.



**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 household and industrial consumers according to the Federal Statistical Office of Germany (DESTATIS)

In several (non-academic) surveys among German and European households, every second to third respondent reported saving energy in response to the current crisis (ref.<sup>2-4</sup>, see Supplementary Information S1 for a summary). In the context of studying environmentally motivated energy savings, the validity of self-reported measurements has often been questioned (see ref.<sup>5</sup> for a review). Also, the surveys cannot be used to estimate the magnitude of energy savings resulting from the indicated behavioral changes. Nevertheless, the surveys support the hypothesis of energy savings by households and provide insight into the motivation behind it. It is noteworthy that some respondents mentioned independence from Russian gas as the main driver of energy savings, in addition to increasing energy prices.

With gas prices reaching all-time highs in the fall of 2021, news emerged that energy-intensive industries were reducing their production (see our collection of press releases in ref.<sup>6</sup>). Ammonia and aluminum industries were the first to do so in September-November 2021 when natural gas prices reached 50 €/MWh. In March 2022, when natural gas prices temporarily spiked above 200 €/MWh, production cuts were reported by further industries, including paper, brick, and steel. However, this self-reported, eclectic, and often qualitative evidence cannot be translated into the quantification of how much natural gas has been saved in the industry as a whole.

Existing analyses of the current energy crisis reported reduced natural gas consumption, often comparing current with last year's consumption<sup>7-10</sup>. These calculations should be taken with caution for five reasons: first, some are based on preliminary data, which we found to be quite unreliable. Second, the first half of 2021 saw an above-trend industrial gas demand during the post-Covid recovery, which inflates the year-on-year reduction found for 2022. Third, figures are often not disaggregated in sectors, while the prices that households face are fundamentally different from those paid by industry. Fourth, such comparisons do not allow us to judge the statistical significance of changes. Maybe they are just picking up random fluctuations. Finally, and most fundamentally, these year-on-year comparisons often do not control for temperature, business cycles, or electricity sector events.

While more elaborate models had been used to analyze energy demand in the more distant past (e.g., ref.<sup>11-14</sup>), the current analyses of the energy crisis methodically lack behind these earlier studies and may hence not be sensibly interpreted as a response to the crisis. On the other hand, findings of earlier studies may not be applicable to the current crisis, because of the unprecedented size of the observed price increases.

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 the identified changes in natural gas match 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 gas consumption. To account for this, we carefully simulate the non-linear relationship between spatially resolved temperature data and the national space heating demand. This non-linear relationship accounts for the characteristics of the national building stock (like insulation) and behavior of the entirety of consumers as it was before the crisis. We also control for pre-crisis annual seasonality and time trends. To identify potential reductions in consumption during the crisis, we include monthly crisis response variables from September 2021 onwards and assess their size and statistical significance.

We deliberately do not include prices in our model to avoid problems with reverse causality, meaning that the effect of prices on consumption cannot easily be isolated from the reverse effect that consumption has on prices. Another reason for excluding prices from our model is that available price data are prone to measurement error. On the one hand, small gas consumers in multi-family houses are often informed about price changes only with a substantial lag. On the other hand, it is unclear to which extent industrial consumers can resell their contracted gas volumes at the spot market, which would imply that they were exposed to spot prices instead of industrial purchase prices. Both reverse causality and measurement errors could induce a downwards bias on price elasticities based on average residential and industrial gas prices, respectively.

In terms of data, we apply our model to the nationally aggregated natural gas consumption of small and large consumers in Germany. 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 very 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 current wholesale prices, the increase in the gas bill corresponded to about 4.5% of GDP.

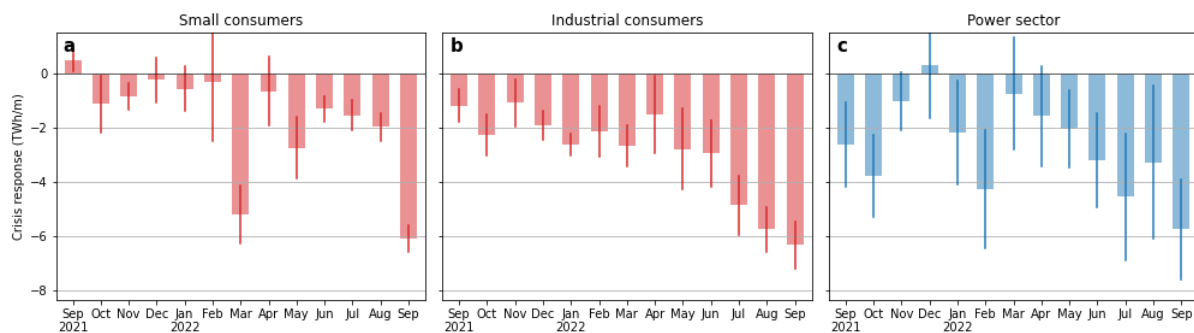
We find a significant and substantial crisis response across consumer groups. Industry started to reduce demand by 4% as early as in September 2021 and steadily increased its response to 19% in September 2022. This finding aligns well with increasing wholesale and industrial retail prices. Small consumers, including households, started to respond substantially only in March 2022. During the summer of 2022, when consumption of small consumers is generally 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 2022, when lower temperatures would have predicted a higher baseline consumption level. The lagged response of residential compared to industrial consumers can be explained by limited 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 August 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 regulator BNetzA, the German market operator 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 Supplementary Information S2 for the numerical results). 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 reduced consumption from March 2022 onwards, except for April 2022. Meanwhile, a significant response of industrial consumption started as early as September 2021 and increased over time. 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 6 TWh/month in September 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 during March 2022 and a sustained reduction in consumption from May 2022 onwards. This late response compared to other consumers groups makes sense since small consumers are typically signed up to retail contracts with fixed prices over 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 with steadily increasing household prices. By contrast, the stark reduction may be an ethical response to Russia’s invasion of Ukraine on February 24 in line with ref <sup>2-4</sup>.

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

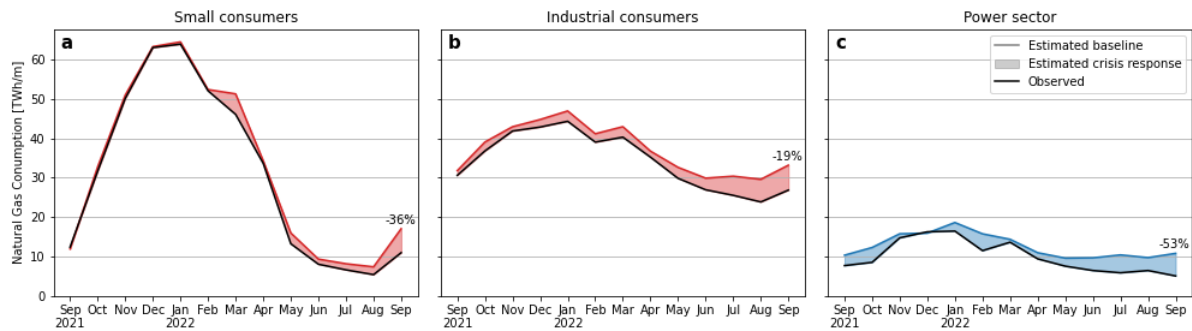
retail prices starting to surge (see Figure 1). Furthermore, the industrial demand response tends to increase over time, which may be driven by two factors. First, the response may increase because wholesale prices and industrial retail prices have increased somewhat further since September 2021. Second, 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 for 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 the industrial gas consumption. In an earlier study<sup>6</sup>, 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 somewhat smaller estimates of the aggregated demand reduction at the end of 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)<sup>15</sup>, the administrative phase-out of coal and nuclear plants in Germany<sup>16</sup>, and extraordinarily low availability of French nuclear power<sup>17</sup> as well as a lack of hydroelectric energy following a severe draught in South Europe<sup>18</sup>, 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 5 TWh in absolute terms in March 2022 translates into a relative reduction of 10% compared to the estimated baseline consumption (see Methods for details). Meanwhile, the similar absolute reduction of 6 TWh in September 2022 implies a relative reduction of as much as 36%. For industrial consumers, the absolute reductions of 1 TWh in September 2021 and 6 TWh in September 2022 correspond to relative reductions of 4% and 19%, respectively. For the power sector, relative reductions vary from 0% to more than 50% in September 2022. Across consumer groups, the absolute 18 TWh/month reduction in September 2022 is 30% of the estimated baseline consumption of 60 TWh/month.



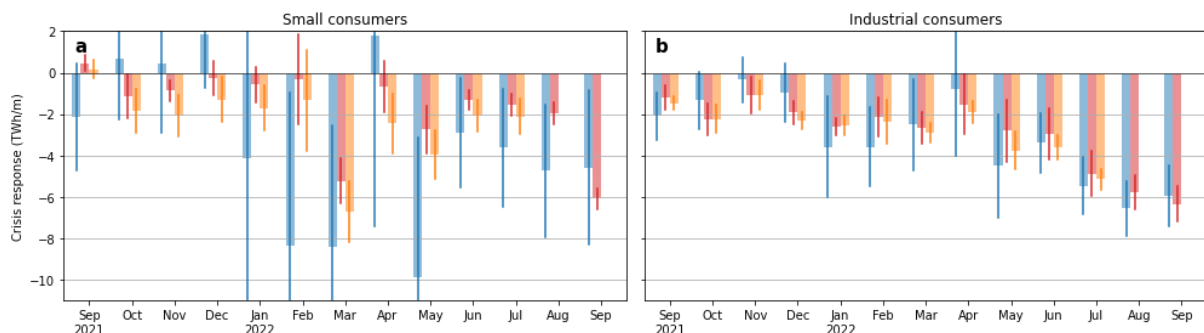
**Figure 3: Observed versus estimated baseline consumption of natural gas demand**

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.

Not 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

To analyze the drivers of our estimated crisis response, we conducted additional model runs for small and industrial consumers without controlling for temperature-dependent standard load profiles and with additional control variables for economic activity. More precisely, we are using sales indices for the retail and hospitality sectors as covariates for small consumers and a production index for the manufacturing sector as a covariate for the industrial sector (see Methods for details). Figure 4 summarizes our model estimates.



**Figure 4: Drivers of the estimated crisis response**

We incrementally control for temperature and economic activity in the case of small and industrial consumers. The leftmost bars (blue) indicate the point estimates with no control variables except for a time trend and seasonal dummies. The center bars (red) indicate results when additionally controlling for temperature, which is our main model specification (also presented in Figure 2). The rightmost bars (yellow) additionally control for economic activity, for which data is available only until July 2022. The vertical lines on these bars indicate the estimates' 5-95% confidence intervals.

Without controlling for temperature, the estimated crisis response for small consumers varies substantially and is subject to high uncertainty, as indicated by the large error bars (blue bars in Figure 2a). As a result, estimates are often insignificant. Only when accounting for temperature can we identify a more consistent and more significant crisis response. For the crisis response of industrial gas consumers, model estimates change less when controlling for temperature. However, the model can better explain the monthly variations in gas demand, and the confidence intervals of the estimated demand responses narrow.

When also controlling for economic activity, we find that the effect of these economic indicators is insignificant for small consumers but significant and positive, yet small for industrial consumers. In many months, controlling for economic activity slightly increases the estimated crisis response of industrial consumers. This implies that economic activity was higher than usual, and gas consumption has been lower than usual, nevertheless. Hence, as a response to the crisis, gas consumption was disproportionately reduced compared to economic activity in manufacturing. Put differently, industrial consumption reduction was not caused by a general economic downturn in the manufacturing sector but rather by a specific crisis response, such as switching fuels or substituting domestic production of energy-intensive products with imports. One illustrative example for this is, again, the case of German ammonia production. As we have shown in an earlier analysis, the decline in German ammonia production was largely compensated by an increase in imports, allowing downstream fertilizer production in Germany to remain fairly stable.<sup>6</sup>

## Preliminary insights into price elasticities

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.

For small consumers, prices have increased by about 90% between 2019-2021 and August 2022 (the latest month for which consumer prices are available). Meanwhile, in August 2022, we estimate a consumption reduction of 27%. If consumers were primarily responding to prices, this would imply a price elasticity of -0.30, which is at the upper end of estimates in the literature<sup>19,20</sup>. This rough estimate should be interpreted with caution for three reasons. First, as discussed above, the relative demand reduction may heavily be driven by the seasonality of heat demand. During a summer month like August, the reduction potential may be small, which could lead to a monthly price elasticity below the annual average. Second, the available price data are likely subject to measurement error as small gas consumers in multi-family houses are often informed about price changes only with a substantial lag. Furthermore, surveys reported ethical motives to reduce energy consumption after Russia's invasion of Ukraine<sup>2-4</sup>. If such 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 August 2022, average gas prices for industrial consumers increased by 490% compared to pre-crisis levels from January 2019 to August 2021. Together with the estimated 19% reduction in August, 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 consumers<sup>21</sup>.



## 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, however, 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 19% 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 36% 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 that natural gas consumption in September 2022 was reduced by as much as 18 TWh/month, or 30% 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<sup>22,23</sup>.

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 are an effective means of coordinating and incentivizing demand reductions. This implies that energy subsidies, many of which have been hastily introduced to mitigate the crisis, drive up natural gas consumption, which in turn will further inflate prices. 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 should be carefully designed to cushion hardship but 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 13 dummy variables for the crisis period from September 2021 until September 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 (with dummies for the month of the year). Most importantly, we control for the simulated weather-dependency of heating using simulated heating profiles. As a sensitivity analysis, we additionally include economic activity as a control variable.

The econometric models are based on the following equations:

$$gas_t^s = a_0 + \mathbf{a_1 crisis}_t + \mathbf{a_2 time}_t + \mathbf{a_3 heat}_t + \mathbf{a_4 econ}_t^s + e_t \quad (1)$$

$$gas_t^i = a_0 + \mathbf{a_1 crisis}_t + \mathbf{a_2 time}_t + \mathbf{a_3 heat}_t + \mathbf{a_4 econ}_t^i + e_t \quad (2)$$

$$gas_t^p = a_0 + \mathbf{a_1 crisis}_t + \mathbf{a_2 time}_t + e_t \quad (3)$$

where

$gas_t^s, gas_t^i, gas_t^p$	gas consumption of small, industrial, and power sector consumers
$\mathbf{crisis}_t$	vector of monthly crisis dummies
$\mathbf{time}_t$	vector of monthly time dummies as well as a linear time trend
$\mathbf{heat}_t$	vector of the simulated heating profile as well as an interaction term of the simulated heating profile and time
$econ_t^s$	vector of economic activity of retail and hospitality sectors (sales indices)
$econ_t^i$	economic activity of manufacturing sector (production index)
$a_0 \dots a_4$	model parameters (often vectors)
$e_t$	error term

Vectors are denoted in bold. The subscript  $t$  indicates the monthly 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 heteroskedasticity and autocorrelation robust standard errors.

For our main results, the models are applied to data from January 2017 (for small consumers: from January 2018) to September 2022. Results for shorter datasets, omitting some of the oldest data, turn out to be robust. The data sources are summarized in Table 1 and discussed in the following.

**Table 1: Data sources**

Parameter	Source
Measured gas consumption of large consumers	<a href="#">Trading Hub Europe</a>
Inferred gas consumption of small consumers	<a href="#">BNetzA</a>
Gas-fired electricity generation, hourly unit-level data	<a href="#">European Network of Transmission System Operators of Electricity (ENTSO-E)</a>
Gas-fired electricity generation, monthly national data	<a href="#">Eurostat NRG_IND_342M</a>
Simulated residential and commercial heating profiles	<a href="#">When2Heat dataset</a>
Weather data	<a href="#">Climate Data Store</a>
Economic activity	<a href="#">German Statistical Office (DESTATIS)</a>

### 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.

The data for large consumers were retrieved from the German gas market area manager Trading Hub Europe (THE) in an hourly resolution and aggregated to months<sup>24</sup>. Data is published as “preliminary”, “corrected”, and “final”. When this study was conducted, August 2022 was the last month with “final” data, and September 2022 was included based on “corrected” data. The data for small consumers (“SLP-Kunden”) were retrieved from the German regulator BNetzA in a monthly resolution<sup>25</sup>. In the absence of direct sub-annual metering, this data is inferred from measurements of the overall consumption minus large consumers’ metered consumption. Note that THE also publishes data on small consumers (which we used in an earlier version of this study), but we learned that 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

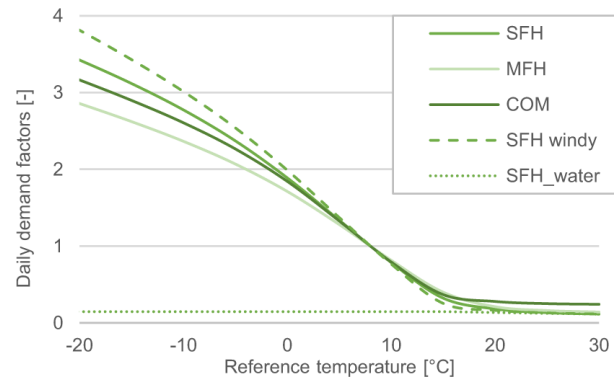
We further disentangle the natural gas consumption of large consumers into that of the power sector and that of other industrial consumers. To this end, we used monthly data on gas consumption by public power plants from DESTATIS<sup>26</sup>. However, these data are published with a time lag and, at the time when this analysis was conducted, they were available only until July 2022. To fill the gap for August and September 2022, we estimate the power sector’s gas consumption based on real-time data on the gas-fired electricity generation from ETNSO-E<sup>27</sup>. To do so, we calculate the ratio between the power sector’s gas consumption and gas-fired electricity generation in July 2022 and assume the same ratio for August and September 2022. This neglects a potential decrease in the gas-to-electricity conversion efficiency with increasing gas-fired electricity generation in August 2022, 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 September 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 August and September 2022 implies that power sector gas consumption is potentially underestimated, meaning that industrial consumption (large minus power sector consumption) may be somewhat inflated. Estimates of industrial consumption reductions in August and September are 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. <sup>28</sup>, 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: Sigmoid-shaped daily demand factors for Single Family Households (SFH) and Multi-Family Households (MFH)**

These non-linear effects cannot be accounted for by simply controlling for temperature or heating degrees, i.e., the difference between ambient temperature and the heating threshold. Our main model based on standard load profiles yields an adjusted  $R^2$  of 0.998, whereas substituting the standard load profiles with heating degrees results in a smaller adjusted  $R^2$  of 0.992. 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 September 2022 decreases from 6.09 to 3.99 TWh when using heating degrees 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 0.988 when using standard load profiles and to 0.956 when using heating degrees.

We applied standard load profiles to spatial data of the ambient temperature and constructed a national population-weighted average as described in refs.<sup>28–31</sup>. 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.

In addition, we include an interaction term between the linear time trend and the simulated national heat demand in the model. With this interaction term, we control for a potential trend in how the simulated heating profile affects the observed consumption, e.g., due to building efficiency improvements. We found evidence for such a time trend in the models' residuals, which show different time trends at warm or cold ambient temperatures when not accounting for this interaction term.

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. None of these variables significantly improves model accuracy when applied as a substitute or 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<sup>32</sup>.

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.

#### Economic activity

Indexed time series of economic activity in different sectors are retrieved from the German Statistical Office DESTATIS<sup>26</sup>. Small consumers include private households as well as small commercial businesses such as bakeries, supermarkets, or hotels. We hence control for economic activity in the retail and hospitality sectors using these sectors' inflation-adjusted sales index. For industrial consumers, we control for economic activity in the manufacturing sector using the inflation-adjusted production index.

#### Estimated baseline consumption

The baseline consumption  $gas_t^{base}$  is estimated as follows:

$$gas_t^{base} = gas_t - \hat{a}_1 crisis_t \quad (4)$$

where

$gas_t$  gas consumption of small or industrial consumers ( $gas_t^s$  or  $gas_t^i$ )

$\hat{a}_1$  estimated vector of the absolute crisis response

$crisis_t$  vector of monthly crisis dummies

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

$$\hat{a}_1^{rel} = \hat{a}_1 \sum_t (crisis_t \cdot gas_t^{base})^{-1} \quad (5)$$

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## Acknowledgments

The authors gratefully acknowledge research assistance by Nieves Casas. This work was supported by the German Federal Ministry of Education and Research via the ARIADNE Project [FKZ 03SFK5K0].

## Author contributions

**Oliver Ruhnau:** Conceptualization, Formal analysis, Writing – Original Draft, Visualization, Data curation, Project administration; **Clemens Stiewe:** Conceptualization, Formal analysis, Writing – Original Draft, Visualization, Data Curation; **Jarusch Müßel:** Conceptualization, Formal analysis, Writing – Original Draft, Visualization, Data Curation; **Lion Hirth:** Conceptualization, Writing – Original Draft, Supervision

## Competing interests

The authors declare no competing interests.