Turn down your thermostats – a contribution to overcoming the European gas crisis? The example of Germany

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Abstract

The current gas crisis in Europe calls for immediate political action to reduce natural gas consumption and alleviate costs for consumers. This paper provides an in-depth analysis of thermostat adjustments for the example of single-family houses buildings in Germany. Following a novel bottom-up approach to estimate gas consumptions at building archetype level, we find that about 14 to 30 TWh/a of gas – equivalent to 3 to 6 % of Russian gas imports to Germany as of 2020 – could be saved if temperature setpoints are reduced by 2 to 4 °C. The biggest absolute savings are possible for old and large buildings. Furthermore, we show that thermostat adjustments can cut households’ CO$_2$ emissions by 3 to 6 %. Thus, they are a promising measure, independently of the current crisis. Taking a consumer’s perspective, we find that lowering temperature from 21 to 20 °C can reduce the gas bill by 4 to 9 % depending on the building type. However, the financial burden due to increased gas prices outweighs these savings. Old buildings are significantly more burdened than newer ones. Policymakers should therefore a) implement residential thermostat adjustments and b) consider the building type when planning financial relief mechanisms for consumers.

Keywords: Gas crisis, temperature setpoint, gas savings, consumer bill, reduced-order building model, building characteristics
1 Introduction

Russia’s war of aggression on Ukraine has triggered an international energy crisis. The already tight energy markets have experienced a shock the likes of which have not been felt since the last oil crisis at the end of the 1970s. This external shock hit Europe and Germany in particular, which are heavily dependent on cheap gas from Russia – both as an energy carrier and as a resource, e.g., for the chemical industry. Before the war, about 40 % of natural gas imports to the European Union originated from Russia (including transits from Ukraine and Belarus) (Eurostat, 2022). Significantly less gas has been flowing since mid-May 2022 through Nord Stream 1, the most important pipeline for Russian gas to the European Union, and finally stopped by the end of August (Destatis - Federal Statistical Office of Germany, 2022a). This puts energy security at high risk. For Germany, Russian gas imports were as high as 55 % in 2020 (Statista, 2021). Currently, supply from Russia has been disrupted.

Markets have anticipated this shortfall and prices of natural gas have increased significantly. Meanwhile, at Europe’s most important trading point “Title Transfer Facility” (TTF), futures for winter 2022/2023 temporarily are at over 300 €/MWh – a twenty-fold increase from 2020 levels (THEICE, 2022). Furthermore, this gas price shock has translated into rising electricity wholesale prices in many European markets (Uribe et al., 2022). Retail prices are also increasing, although with delay. In Germany, the consumer price index for natural gas in October 2022 was about 3 to 4 times the previous year’s level (Verivox, 2022).

Thus, pressure mounted rapidly for politicians to act. In its “Save gas for a safe winter” plan, the council of the European Union proposed a voluntary gas demand reduction target of 15 % from 1 August 2022 to 31 March 2023 (European Commission, 2022). Several measures have been discussed to comply with this target (Agora Energiewende, 2022; BDEW - German Association of Energy and Water Industries, 2022b; European Commission, 2022; Forschungszentrum Jülich, 2022). These proposed measures apply to all sectors of the energy system. On the one hand, this includes short-term measures like fuel switching in the industry and power generation as well as savings in households and the commercial sector. On the
other hand, more long-term, structural measures are the decarbonization of the building sector as well as the massive expansion of renewable energies and hydrogen production. Apart from that, it is suggested that natural gas imports should be diversified, e.g. by increasing the LNG import capacity.

Figure 1 summarizes the European Commission’s assessment of different measures. In total, these measures should almost close the gas supply gap induced by shortages from Russia. Although this already provides indications of promising measures, a more in-depth analysis of individual measures is required to both robustly determine their effectiveness and assess potential societal implications. Ultimately, this is critical to designing effective and equitable policy instruments.

This paper therefore analyses (voluntary) energy savings, in particular thermostat adjustments in residential buildings (Figure 1, yellow marking). With gas import diversification and price-induced demand reduction, this is one of the most promising measures. The high relevance of the building heating sector from the energy system perspective and the individual consumer’s point of view add to its importance.
In Europe, residential heating accounts for about a third of final energy consumption (European Commission et al., 2022). In turn, space heating is highly dependent on natural gas – the fuel covers about half of the European Union’s primary energy demand for space heating (European Commission et al., 2022). As a consequence, household consumption expenditures are also highly dependent on gas prices. German households, for instance, used to spend about 7% of their income for energy in 2020. As soon as March 2022, however, this share increased to 9.4% and could well be much higher in future due to rising gas prices (Praktiknjo and Priesmann, 2022).

Thus, reducing temperature in buildings could save gas and money for consumers, which underlines the measure's political feasibility and possible benefits for both sides. Even better, it could be implemented relatively easily and quickly and comes at no cost, in comparison to measures like ramping up of LNG imports or massive heat pump expansion.

First assessments of adjusting thermostats indicate a promising effect in terms of gas savings at the energy system level (Agora Energiewende, 2022; European Commission, 2022; Forschungszentrum Jülich, 2022) (see also Figure 1). However, these assessments are quite undifferentiated and only state a snapshot saving potential at the system level. In particular, these estimations do not take into consideration the different drivers of gas consumption and corresponding saving potentials in buildings.

For instance, gas consumption is highly dependent on building characteristics such as size, age and residence type (Brounen et al., 2012; Namazkhan et al., 2020; Wyatt, 2013). In addition, Sperber et al. (2020) showed that buildings’ thermal response to reducing temperature setpoints is strongly influenced by building age and refurbishment status. Finally, weather can be a decisive factor for residential gas demand (Elkhafif, 1996; Harold et al., 2015). It follows that the gas savings potential is also dependent on building characteristics, temperature setpoints as well as weather.

This paper aims to go beyond such undifferentiated snapshots at the system level. Hence, we calculated gas consumption as well as corresponding gas and CO₂ saving potentials for
different building types, temperature setpoints and weather years. To this end, we applied a set of validated reduced-order models of the thermal behaviour of building archetypes that we developed in a previous study (Sperber et al., 2020). Furthermore, we contrasted the estimated gas saving potential with the gas costs and monetary savings of individual consumers, considering different price scenarios for natural gas.

Our approach tries to answer three pressing questions of high political relevance. First, at a national level, how much natural gas can be saved annually by lowering heating temperature setpoints in buildings, considering building characteristics and weather dependencies? With these more nuanced calculations, initial estimations are substantiated by considering different drivers of saving potentials, and the “low hanging fruits” for saving natural gas in the short term are revealed. Once it is understood how different building types "react" to temperature reduction in terms of gas consumption, targeted policy measures can be derived.

Second, how are CO₂ emissions affected by lowering temperature setpoints? This allows to assess whether thermostat adjustments – beyond their short-term contribution to the gas crisis – are also an important measure in the medium term by contributing to climate protection.

Third, on an individual consumer level, how large is the influence of adjusting thermostats with regard to the consumer’s energy bill? Can “freezing” offset high prices of natural gas use that may persist even after the end of the war due to CO₂ pricing instruments?

Exploring the consumer’s perspective is important for assessing how likely the saving potential will be realized, since adjusting thermostats in residential buildings is a voluntary measure that cannot be enforced politically. Furthermore, it is crucial to measure the monetary impacts on consumers, both to gauge the acceptability of the saving measure and to determine the need for consumer relief due to surging prices.

Our calculations focus on Germany. It is the largest consumer of natural gas in the European Union with an annual consumption of around 870 TWh in 2020 (BMWK - Federal Ministry for Economic Affairs and Climate Action, 2022b). More than half of the 40 million apartments in
Germany are heated with natural gas (BDEW - German Association of Energy and Water Industries, 2022a). Thus, many households are affected by the gas crisis and the corresponding surge in prices. Nevertheless, the trends of our results as well as their implications are transferable to other countries, especially those located in similar climatic zones and comparable building structures.

The remainder of this paper is structured as follows. Chapter 2 describes the methods we used to determine gas consumption and associated savings potentials, CO₂ emissions and cost. Chapter 3 presents and discusses the results on gas consumption at the building level (section 3.1) and system level (section 3.2); section 3.3 shows the induced CO₂ savings and section 3.4 the costs for consumers. This is followed by a discussion of limitations in section 3.5. Finally, conclusions and policy implications are drawn in chapter 4.

2 Methods

This chapter first describes the computation of heating demands of typical buildings depending on temperature setpoints (section 2.1). Section 2.2 then explains how these heating demands are translated into gas consumption for individual buildings as well as into potential savings at the national level. The computation of induced CO₂ savings is described in section 2.3, and finally, the calculation of consumer cost is addressed in section 2.4.

2.1 Heat demand calculation for typical buildings

To adequately determine saving potentials as a function of building characteristics, temperature setpoints and weather, we used a set of validated reduced-order bottom-up models of building thermodynamics (Sperber et al., 2020). These models compute the space heating demand of buildings for given weather data and temperature setpoints in a high temporal resolution (e.g. 15 minutes). Building thermodynamics are described by lumped resistance-capacitance thermal networks, accounting for transmission and ventilation losses, solar and internal heat gains as well as thermal inertia. Models are available for twelve typical German single-family houses (SFH) in three insulation states that differ in building age, size,
construction materials and heating distribution systems. Thus, they represent the stock of German SFH. Compared to thermal simulation software like, e.g., TRNSYS (Klein et al., 2011), the reduced-order model are computationally highly efficient and allow multiple parameter variations. The development and validation as well as the parameters of the models is described in detail in (Sperber et al., 2020).

The buildings considered are taken from the German residential building typology (Loga et al., 2015). The focus is on detached SFH, because these are the most prevalent building category with approx. 10 million detached SFH out of 19 million buildings in total (Loga et al., 2015). In addition to that, detached houses generally have higher specific gas consumption levels than other types of dwellings (Namazkhan et al., 2020). Table 1 provides an overview of the building types as well as their stock in Germany. In the remainder of our study, the labelling of the building types is after their construction period. For each of these basic types, three variants are specified, which differ according to their energy refurbishment level: 1) the status quo condition, i.e. not or only marginally refurbished, 2) the condition after moderate energy refurbishment in accordance with legal minimum standards, and 3) the condition after ambitious energy refurbishment that corresponds to the usual insulation standards for passive houses.
Table 1: Stock of SFH according to the German residential building typology (Loga et al., 2015)

<table>
<thead>
<tr>
<th>Code of building type acc. to original study</th>
<th>Building type label in our study</th>
<th>Construction period</th>
<th>Heated living area in m²</th>
<th>Building stock in thousands</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFH A &lt;1859</td>
<td>&lt; 1859</td>
<td>199</td>
<td>330</td>
<td></td>
</tr>
<tr>
<td>SFH B &lt;1919</td>
<td>1860 - 1918</td>
<td>129</td>
<td>966</td>
<td></td>
</tr>
<tr>
<td>SFH C &lt;1949</td>
<td>1919 - 1948</td>
<td>275</td>
<td>1,131</td>
<td></td>
</tr>
<tr>
<td>SFH D &lt;1958</td>
<td>1949 - 1957</td>
<td>101</td>
<td>859</td>
<td></td>
</tr>
<tr>
<td>SFH E &lt;1969</td>
<td>1958 - 1968</td>
<td>110</td>
<td>1,509</td>
<td></td>
</tr>
<tr>
<td>SFH F &lt;1979</td>
<td>1969 - 1978</td>
<td>158</td>
<td>1,507</td>
<td></td>
</tr>
<tr>
<td>SFH G &lt;1984</td>
<td>1979 - 1983</td>
<td>196</td>
<td>704</td>
<td></td>
</tr>
<tr>
<td>SFH H &lt;1995</td>
<td>1984 - 1994</td>
<td>137</td>
<td>1,160</td>
<td></td>
</tr>
<tr>
<td>SFH I &lt;2002</td>
<td>1995 - 2001</td>
<td>111</td>
<td>1,035</td>
<td></td>
</tr>
<tr>
<td>SFH J &lt;2010</td>
<td>2002 - 2009</td>
<td>133</td>
<td>907&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>SFH K &lt;2016</td>
<td>2010 - 2015</td>
<td>160</td>
<td>494&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>SFH L &lt;2022</td>
<td>&gt; 2016</td>
<td>160</td>
<td>507&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> numbers derived from Federal Statistical Office (Destatis - Federal Statistical Office of Germany)

<sup>b</sup> stock end of 2021

To investigate the effect of temperature reductions, we varied the indoor air temperature setpoints for the heating period between 17 °C and 23 °C in 1 °C steps. This setpoint is assumed to be applicable at daytime between 6 a.m. and 10 p.m. For the remaining time, we assumed a night setback temperature that is 0.85 times the day temperature setpoint (Loga et al., 2015). For the sake of simplification, we considered an average temperature for the whole building, i.e. we did not account for different thermal zones.

The reduced-order model requires ambient temperature and total solar radiation on the southern vertical surface as input data. We retrieved ambient temperature, surface solar radiation downwards as well as total sky direct solar radiation at surface from ERA5 reanalysis data (Hersbach et al., 2018) for the city of Frankfurt am Main, Germany. Solar radiation data was then processed with TRNSYS to the required orientation. We employed two different weather data sets – 2010 and 2018 – to determine the range of energy demand between particularly cold and particularly warm years. The year 2010 is a typical representative of a
cold year in the recent past and 2018 is a warm one according to the heating degree days for the selected climate\(^1\) (IWU - Institute for Housing and Environment, 2022).

### 2.2 Calculation of gas consumption

The calculated annual building-level heat demands were transformed to natural gas demands by dividing by building type specific gas heater efficiencies. They differ according to the building construction period and refurbishment levels, since these are decisive factors for the heating system temperatures (Sperber et al., 2020) and hence for efficiencies. The parameters used in the calculations are given in Table 2.

Table 2: Gas boiler parameters (Loga et al., 2015; Steinbach, 2015)

<table>
<thead>
<tr>
<th>Building types</th>
<th>Refurbishment level (^a)</th>
<th>Heater technology</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1859 – &lt;2002</td>
<td>SQ</td>
<td>Low-temperature boiler</td>
<td>83 %</td>
</tr>
<tr>
<td>&lt;1859 – &lt;2002</td>
<td>MR, AR</td>
<td>Condensing boiler</td>
<td>91 %</td>
</tr>
<tr>
<td>&lt;2016 – &lt;2022</td>
<td>SQ, MR, AR</td>
<td>Condensing boiler</td>
<td>93 %</td>
</tr>
</tbody>
</table>

\(^a\) Abbreviations: SQ = status quo, MR = moderately refurbished, AR = ambitiously refurbished

These gas demands were then multiplied with a building-specific correction factor to adjust them to typical gas consumption values, in accordance with the procedure that also underlies the German residential building typology (Loga et al., 2015). This correction factor varies between 1.1 and 0.6 depending on the area-specific gas demand and is lower for buildings with high demands. It addresses the fact that the measured energy consumption is on average accordingly lower than the calculated demand, especially for poor energy standards (Loga et al., 2015) – possibly due to different user behaviour depending on the energetic building condition (Greller et al., 2010).

\(^1\) 2,371 heating degree days in 2010 and 1,768 heating degree days in 2018 IWU - Institute for Housing and Environment (2022).
Finally, building-level gas consumptions were extrapolated to the nation-wide stock of SFH with statistical data on the number of buildings (Table 1) as well as the corresponding gas heater market penetration (Table 3).

Table 3: Gas heater market penetration by building age (Destatis - Federal Statistical Office of Germany, 2020)

<table>
<thead>
<tr>
<th>Building types</th>
<th>Gas heater market penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1859 – &lt;1949</td>
<td>63 %</td>
</tr>
<tr>
<td>&lt;1958 – &lt;1979</td>
<td>47 %</td>
</tr>
<tr>
<td>&lt;1984 – &lt;1995</td>
<td>49 %</td>
</tr>
<tr>
<td>&lt;2002 – &lt;2010</td>
<td>65 %</td>
</tr>
<tr>
<td>&lt;2016 – &lt;2022</td>
<td>46 %</td>
</tr>
</tbody>
</table>

2.3 Estimation of induced CO$_2$ savings

CO$_2$ emissions as well as savings due to thermostat adjustments at system level were calculated by multiplying the aggregated gas consumption and related savings per temperature setpoint with the CO$_2$ emission factor for natural gas from Russia. The latter is derived from Juhrich (2016) and amounts to 198.6 tCO$_2$/GWh$_{\text{Natural gas}}$.

2.4 Computation of consumer cost

Gas cost on building level were computed for different gas price scenario assumptions (Table 4). While the scenario “LOW” reflects the average price for natural gas for German households at pre-crisis level in the second half of 2021 (Destatis - Federal Statistical Office of Germany, 2022b) and which is still valid for many longer-term contracts, the medium scenario “MED” corresponds to the average price level for households in October 2022 (Verivox, 2022). As an upper level, the scenario “HIGH” represents average prices for new customers during a high-price period in August 2022 (NDR, 2022). Fixed price components that apply irrespective of gas consumption level or price tariffs that are dependent on the consumption level were not considered in this analysis.
Table 4: Natural gas retail prices for different scenarios considered (Destatis - Federal Statistical Office of Germany, 2022b; NDR, 2022; Verivox, 2022)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Price level</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW</td>
<td>6.9 €ct/kWh</td>
</tr>
<tr>
<td>MED</td>
<td>20.5 €ct/kWh</td>
</tr>
<tr>
<td>HIGH</td>
<td>40.0 €ct/kWh</td>
</tr>
</tbody>
</table>

3 Results and Discussion

3.1 Gas consumption at building level

In order to highlight the dependence of gas consumption for space heating on building characteristics such as their construction period and insulation levels, we present the annual gas consumption for space heating for different building types for a fixed setpoint of 20 °C (Figure 2). Consumption is shown for the warmer year 2018, while error bars indicate consumption levels for the cold year 2010. Consistent with a number of studies on residential gas consumption (Brounen et al., 2012; Harold et al., 2015; Namazkhan et al., 2020; Wyatt, 2013), our results show that consumption is higher in old buildings (left in the diagram). Gas consumption decreases with the insulation level, i.e. status quo buildings (blue bars) consume most, followed by moderately refurbished buildings (orange) and ambitiously refurbished buildings (grey). The annual gas consumption varies between 12 and 187 kWh/(m²,a) for 2018.

In line with literature (Elkhafi, 1996; Harold et al., 2015), our results indicate that weather has a large influence on gas consumption. Across all building types, consumption in the cold year 2010 is about 32 % higher on average.
For the analysis of the possible gas savings by adjusting thermostats, we now focus on the status quo energetic condition ("SQ") for the buildings, since this is decisive for short-term changes in gas consumption.

Figure 3 shows gas consumption for space heating of different building types as a function of the temperature setpoint.
Figure 3: Gas consumption for space heating by building type and temperature setpoint (base weather year = 2018, error bars = 2010)

Compared to heating at 17 °C, the gas consumption for heating at 23 °C is around one third higher for old buildings constructed earlier than 1969 and almost twice as high for newer buildings built after 2002. For the high-consuming building type “<1949_SQ”, for instance, this corresponds to a difference of 15 MWh/a (weather year 2018). In principle, the absolute savings potentials (in MWh/a) by turning down thermostats are significantly greater for older buildings, while relative savings (in percent) tend to be higher in the newer building types. The latter is possibly due to the fact that newer, well insulated buildings profit more from free heating sources like internal or solar gains, which cover the remaining heating demand at reduced setpoints disproportionately high.

Note that the lower the initial temperature setpoint is before reduction, the higher the relative saving potential. This can be explained by thermal losses through the building envelope that are reduced with lower indoor temperatures. Figure 4 illustrates this relationship by indicating relative savings from lowering the heating temperature setpoint by 1 °C compared to different
initial temperatures. The relative saving potential ranges from 3 % annually for older buildings
with high initial temperatures to more than 11 % annually for newer buildings with low initial
temperatures. By lowering the room temperature from 21 to 20 °C, 6.3 % of gas can be saved
per year on average across all building types.

<table>
<thead>
<tr>
<th>Building type</th>
<th>18 → 17 °C</th>
<th>19 → 18 °C</th>
<th>20 → 19 °C</th>
<th>21 → 20 °C</th>
<th>22 → 21 °C</th>
<th>23 → 22 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1859_SQ</td>
<td>6.4%</td>
<td>5.8%</td>
<td>5.1%</td>
<td>4.5%</td>
<td>4.0%</td>
<td>3.5%</td>
</tr>
<tr>
<td>&lt;1919_SQ</td>
<td>6.2%</td>
<td>5.6%</td>
<td>5.0%</td>
<td>4.4%</td>
<td>3.9%</td>
<td>3.4%</td>
</tr>
<tr>
<td>&lt;1949_SQ</td>
<td>7.2%</td>
<td>6.6%</td>
<td>6.0%</td>
<td>5.4%</td>
<td>4.8%</td>
<td>4.2%</td>
</tr>
<tr>
<td>&lt;1958_SQ</td>
<td>6.1%</td>
<td>5.5%</td>
<td>4.9%</td>
<td>4.3%</td>
<td>3.8%</td>
<td>3.2%</td>
</tr>
<tr>
<td>&lt;1969_SQ</td>
<td>6.1%</td>
<td>5.5%</td>
<td>4.9%</td>
<td>4.3%</td>
<td>3.7%</td>
<td>3.2%</td>
</tr>
<tr>
<td>&lt;1979_SQ</td>
<td>7.4%</td>
<td>6.7%</td>
<td>6.1%</td>
<td>5.5%</td>
<td>4.9%</td>
<td>4.4%</td>
</tr>
<tr>
<td>&lt;1984_SQ</td>
<td>8.5%</td>
<td>7.8%</td>
<td>7.1%</td>
<td>6.5%</td>
<td>6.0%</td>
<td>5.4%</td>
</tr>
<tr>
<td>&lt;1995_SQ</td>
<td>8.6%</td>
<td>7.8%</td>
<td>7.2%</td>
<td>6.6%</td>
<td>6.1%</td>
<td>5.5%</td>
</tr>
<tr>
<td>&lt;2002_SQ</td>
<td>9.3%</td>
<td>8.5%</td>
<td>7.9%</td>
<td>7.3%</td>
<td>6.7%</td>
<td>6.2%</td>
</tr>
<tr>
<td>&lt;2010_SQ</td>
<td>11.3%</td>
<td>10.4%</td>
<td>9.7%</td>
<td>9.1%</td>
<td>8.6%</td>
<td>8.1%</td>
</tr>
<tr>
<td>&lt;2016_SQ</td>
<td>11.1%</td>
<td>10.1%</td>
<td>9.5%</td>
<td>8.8%</td>
<td>8.4%</td>
<td>7.8%</td>
</tr>
<tr>
<td>&lt;2022_SQ</td>
<td>10.9%</td>
<td>10.0%</td>
<td>9.3%</td>
<td>8.7%</td>
<td>8.3%</td>
<td>7.7%</td>
</tr>
</tbody>
</table>

Figure 4: Annual gas savings per °C temperature setpoint reduction (weather year 2018)

Savings effects due to higher temperature reduction levels are shown in Figure 5. The range
of savings across all building types is shown, provided that the temperature is reduced from
21 °C to lower temperatures. On average, they account for 12 % for 2 °C reduction to 26 % for
4 °C reduction. Some buildings (particularly newer ones) can save 18 % of gas by lowering
temperatures by 2 °C. Other (older) buildings only achieve this level of savings with a reduction
of 4 °C. The savings increase largely linearly with the amount of temperature reduction.
3.2 Aggregated gas consumption and savings potential

Of particular relevance to energy policy are the extrapolated gas consumption and savings potentials for the entire stock of SFH, because these determine the overall effectiveness of the measure. Therefore, Figure 6 shows the aggregated gas consumption for space heating for different temperature setpoints and weather years. For a setpoint of 21 °C, the total gas consumption for space heating amounts to between 129 TWh/a (weather year 2018) and 152 TWh/a (weather year 2010).
While using validated models for the calculation of gas demands, a validation of this result was not possible due to the lack of statistical data concerning gas consumption in different building types. However, a plausibility check can be made with the assumption that SFH have twice as high a space heating demand as apartment buildings (Fleiter et al., 2017). Based on our results for the year 2018 (Figure 6) and assuming an average room temperature of 21 °C, the total gas consumption for domestic space heating (SFH plus apartment buildings) would amount to 194 TWh/a. According to the energy statistics (BMWK - Federal Ministry for Economic Affairs and Climate Action, 2022b), consumption was 202 TWh/a in 2018 – an acceptable deviation of only 4%.

The potential savings of natural gas when turning down thermostats from 21 °C to lower temperatures are shown in Figure 7: for the entire stock of German SFH, about 14 TWh/a

\(^2\) Note that data on the temperature settings in residential buildings is not available either.
(equivalent to around 10%) of natural gas can be saved with a temperature reduction to 19 °C. With a massive reduction to 17 °C, the savings could even amount to approximately 30 TWh/a (around 20%).

<table>
<thead>
<tr>
<th>Weather year</th>
<th>21 → 20 °C</th>
<th>21 → 19 °C</th>
<th>21 → 18 °C</th>
<th>21 → 17 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>6.5</td>
<td>13.4</td>
<td>20.8</td>
<td>28.6</td>
</tr>
<tr>
<td>2018</td>
<td>7.2</td>
<td>14.7</td>
<td>22.4</td>
<td>30.3</td>
</tr>
</tbody>
</table>

Figure 7: Total gas savings for variable temperature reduction levels

Based on the Russian natural gas import volume of 495 TWh/a before the crisis (Forschungszentrum Jülich, 2022), up to 6% could be saved by a large reduction of temperature setpoints in SFH from 21 to 17 °C. A more moderate setpoint reduction to 19 °C could bridge the import gap to nearly 3%.

Somewhat counterintuitively, absolute gas savings by reducing temperatures are slightly higher for warmer weather. This can be explained by lower losses through the building envelope at higher ambient temperatures; the remaining heating demand can then be covered to a larger extent by heat gains inside the buildings. Generally, the absolute savings are quite independent of the weather year.

Our estimations regarding the gas saving potential are generally lower than findings of other studies for comparable temperature reduction levels (Table 5). This is possibly due to the fact that we consider space heating in SFH only, while the other studies estimate saving potentials for the total or at least a larger fraction of the building stock. To get a comparable basis, consider that SFH account for about half of the total energy demand for space heating in Germany (Ruhnau and Muessel, 2022). As an approximation – data on gas heater penetration is not available for German commercial buildings – the gas saving potential for the entire building stock in Germany can thus be estimated to be twice as high as for SFH only, i.e. approximately 14 to 28 TWh/a for a setpoint reduction of 1 to 2 °C. With these considerations in mind, our results on the saving potential at system level are in line with the studies mentioned.
in Table 5. However, our study goes far beyond the mentioned studies by demonstrating important dependencies of gas savings on e.g. building types and weather, and by contrasting the individual consumer’s perspective.

Table 5: Results of various studies on gas savings effects through temperature reduction in buildings

<table>
<thead>
<tr>
<th>Study</th>
<th>Quantification method for gas savings</th>
<th>Buildings considered</th>
<th>Temperature reduction level</th>
<th>Gas saving potential in TWh/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Agora Energiewende, 2022)</td>
<td>Top down by lumped saving factor</td>
<td>All buildings</td>
<td>0.5 – 1.0 °C 1.0 – 1.5 °C</td>
<td>14 22</td>
</tr>
<tr>
<td>(Forschungszentrum Jülich, 2022)</td>
<td>Top down by ratio of temperature setpoints</td>
<td>Residential buildings</td>
<td>1.0 – 2.0 °C</td>
<td>40 a</td>
</tr>
<tr>
<td>Our study</td>
<td>Bottom up considering building characteristics</td>
<td>Single-family houses</td>
<td>1.0 °C 2.0 °C</td>
<td>7 14</td>
</tr>
</tbody>
</table>

*Includes effect by substituting gas boilers for domestic hot water generation by electrically powered instantaneous water heaters*

3.3 Induced CO₂ savings

The temperature setpoint for space heating not only affects gas consumption, but also CO₂ emissions. Figure 8 shows the aggregated CO₂ emissions for the stock of German SFH for different setpoints and weather years. They are proportional to the gas consumption at system level and sum up to 26 Mt/a (weather year 2018) or 30 Mt/a (weather year 2010) for a setpoint of 21 °C.
Figure 8: Annual CO\textsubscript{2} emissions for stock of German SFH by temperature setpoint and weather year

Figure 9 reveals the total CO\textsubscript{2} saving potential at system level for increasing temperature reduction levels for an initial temperature of 21 °C. Based on the annual CO\textsubscript{2} emission level of German households of 90 Mt/a (BMWK - Federal Ministry for Economic Affairs and Climate Action, 2022b), 3 % and up to 6 % could be saved by a setpoint reduction of 2 °C to 4 °C. This means that thermostat adjustments are an important flanking measure for climate protection beyond the current gas crisis.

<table>
<thead>
<tr>
<th>Weather year</th>
<th>21 → 20 °C</th>
<th>21 → 19 °C</th>
<th>21 → 18 °C</th>
<th>21 → 17 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 Mt/a</td>
<td>1.3</td>
<td>2.7</td>
<td>4.1</td>
<td>5.7</td>
</tr>
<tr>
<td>2018 Mt/a</td>
<td>1.4</td>
<td>2.9</td>
<td>4.4</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Figure 9: Total CO\textsubscript{2} savings for variable temperature reduction levels

3.4 Impact on consumer bills

From an individual consumer’s perspective, gas cost and corresponding saving potentials are directly proportional to consumption (see Figure 10). Assuming a medium gas price of
20.5 €ct/kWh, the annual bill amounts to 7,200 € to 10,240 € depending on the temperature setpoint for old and large buildings (building type “<1949_SQ”, weather year 2018). For smaller and well insulated buildings, only 850 to 1,560 €/a apply. For a reduction of temperature setpoints from 21 to 20 °C, the annual bill can be reduced by 4 to 9 % depending on the building type. This translates to 500 €/a of annual savings for building type “<1949_SQ” and for 100 to 200 €/a for newer buildings.

Figure 10: Gas bill for space heating by building type and temperature setpoint for the medium gas price (20.5 €ct/kWh; base weather year = 2018, error bars = 2010)

However, as Figure 11 demonstrates, consumer costs are highly sensitive to gas prices. Annual bills can reach up to 20,000 €/a for old and large buildings in cold winters if gas prices surge to 40 €ct/kWh. Even residents of energetically better buildings in such cases have to spend more than 3,000 €/a on space heating. If the average consumption expenditure of German households is taken as a basis (Destatis - Federal Statistical Office of Germany, 2022c), annual spending for space heating could rise from 2 % (before the gas crisis) to 10 % for new buildings and from 12 % to even 67 % for large and old buildings in this scenario.
Compared to pre-crisis levels (scenario “LOW”), annual bills would then be almost six times higher.

![Figure 11: Gas bill for space heating by building type and gas price at a fixed temperature of 20 °C (base weather year = 2018, error bars = 2010)](image)

These price spikes are also relevant for total consumer bills. As shown in Figure 12, the additional cost for consumers due to an increase of prices from pre-crisis levels (“LOW”) to high prices (“HIGH”) outweigh potential savings by turning down thermostats from 20 °C to 18 °C by far. Inhabitants of newer buildings are better off: while price-induced cost increases amount to 480 % for all building types, cost savings by reducing temperature by 2 °C at high prices amount up to 20 % in newer buildings but only to 10 % in older ones.
Figure 12: Additional gas cost due to price increases from LOW to HIGH for a fixed temperature of 20 °C versus savings by turning down thermostats from 20 to 18 °C (weather year = 2018)

Note that these results consider only gas consumption for space heating. Of course, the total consumer bill could be even higher, if natural gas is also consumed for domestic hot water generation.

3.5 Limitations

The results and their implications should be interpreted in the light of the limitations of this study.

First, we demonstrated a novel bottom-up method for the calculation of gas savings, taking the example of German detached SFH only. While we consider the national focus very relevant given Germany's high importance in terms of overall gas consumption and import dependency on Russia (compare chapter 1), the focus on the building category was because of its
relevance in energetic terms (compare chapter 2.1). Nevertheless, we believe that our main findings are transferable to other countries and building categories.

This is especially true for our general finding that gas consumption as well as induced gas savings, CO$_2$ emissions and cost are strongly dependent on the building type, and hence, that political measures should be planned accordingly. We consider these findings particularly transferable for countries located in similar climate zones and that are dependent on natural gas for space heating, such as the Netherlands, United Kingdom, Slovakia or Italy (European Commission et al., 2022). Finally, as our method is easily adaptable to other climates, further studies could analyse gas savings by thermostat adjustments in different countries with similar building conditions.

Second, when computing the total gas savings potential, we considered only buildings in the status quo energetic condition according to the German residential building typology. Thus, buildings that had been refurbished were not considered. This is due to the fact that data on the refurbishment status of buildings are hardly available for German residential buildings. However, due to the described demand-consumption adjustment, the potentially overestimated standard consumption of old, uninsulated buildings should be relativized.

Finally, our study was limited to the evaluation of the effects of temperature reduction in buildings regarding gas consumption, CO$_2$ emissions and cost. This means that possible side effects of adjusting thermostats were not considered, in particular health effects (Xiong et al., 2015), thermal comfort violation (Peeters et al., 2009) and mould growth (Nielsen et al., 2004).

While we believe these limitations have not biased the primary outcome of our work, future studies could seek to include better data on the buildings’ status quo, e.g. the level of refurbishment or current temperature setpoints. Avenues for future research include the integration of behavioural science in terms of thermal comfort and the acceptability of thermostat adjustments, or considering the related price-elasticity. Regarding the impact on consumer bills, it could be interesting to include socio-economic drivers of residential gas
consumption such as income in order to address the distributive justice of possible relief measures.

4 Conclusion and Policy Implications

Facing an international energy crisis, various policy measures are currently discussed in order to reduce imports of natural gas and to provide financial relief for private households due to higher gas prices. This paper provides an in-depth analysis of thermostat adjustments in residential buildings, which might be one of the most effective measures for saving gas in the short term. In order to shed light on this measure from different perspectives, we used a novel bottom-up approach to calculate gas consumption as well as induced gas, CO$_2$ and cost savings subject to varying temperature setpoints and weather conditions at building archetype level. We demonstrated this approach using the example of German single-family houses.

Our study confirms a promising potential for natural gas savings by thermostat adjustment in German single-family houses. According to our calculations, about 14 to 30 TWh/a of natural gas could be saved if temperature setpoints are reduced by 2 or 4 °C. This corresponds to 3 to 6 % of Russian gas imports to Germany as of 2020.

Our results indicate significant differences in gas savings depending on building characteristics such as age and size. Relative savings vary between 4 and 9 % if thermostats are turned down from 21 °C to 20 °C, and are higher for newer buildings. However, the biggest absolute savings are possible for old and large buildings. Furthermore, savings are found to be highly dependent on temperature settings, i.e. they are greater for lower initial temperatures prior to setpoint reduction.

From an emission perspective, about 3 to 6 Mt/a of CO$_2$ savings are induced by turning down thermostats by 2 to 4 °C. This is equivalent to 3 to 6 % of German household’s annual CO$_2$ emissions. As such, setpoint reduction can be an import measure also beyond the upcoming winter(s).
Taking an individual consumer’s perspective, we calculated that 100 to 500 €/a can be saved with a thermostat reduction by 1 °C at a gas price of 20.5 €ct/kWh. The older and larger the building, the higher the absolute savings. The increased gas prices are a considerable burden on private households. However, the results of our investigations show that households are affected differently depending on the type of building: space heating could account for 10 % for new buildings and even for 67 % for large and old buildings of average consumer spending in Germany in a worst case scenario (high natural gas price, cold winter). Generally, monetary savings due to thermostat adjustments do not outweigh surge prices in the course of the crisis.

Our results have two major implications for policymakers. First, we conclude that thermostat adjustments are an important no-regret measure for reducing the gas dependency at the system level. Our findings support initial estimations on the effectiveness of adjusting thermostats in terms of gas savings. On top of that, we could show that while gas consumption is highly weather dependent, the absolute saving potentials at system level do not vary significantly for different weather conditions and are thus quite robust.

Compared to other measures like building refurbishment or renewable energy expansion, thermostat adjustments come at no investment cost and can be realized immediately without any time lags due to, e.g. delivery bottlenecks or shortage of skilled workers, which might apply for other gas saving measures. Thus, thermostat adjustment could also help to bridge possible gas shortages in the following winters at short notice, while more structural measures such as heat pump installations will only be available to a limited extent. In addition, thermostat adjustments have important side-benefits with regard to their CO₂ saving potential. Finally, as gas prices are also expected to increase in many countries due to CO₂ pricing mechanisms, thermostat adjustments will remain an important financial saving measure for many households.

For the planning and assessment of corresponding political instruments, our building-specific results should be considered. On the one hand, we could show that the lion’s share of possible absolute gas savings is with old and large buildings, especially those constructed between
1919 and 1948 (which are, in addition to that, very prevalent in Germany). At the same time, these building types suffer the most economically by rising gas prices. Thus, there is probably a high incentive for voluntary demand reduction. On the other hand, monetary benefits of gas savings are limited for newer and energetically better buildings, thus also threatening the acceptability of the measure for these customers. As a consequence, the realizable gas saving potential could have to be corrected downwards by the (small) contribution of these newer buildings.

Furthermore, policymakers should take into consideration that gas savings due to temperature reduction in residential buildings cannot be subject to obligation, since each homeowner controls his or her own heating. Therefore, policymakers should raise awareness among households on the saving effects of thermostat adjustments – not only to ensure energy security, but also to save money and to contribute to climate protection.

Finally, many consumers are not yet exposed to scarcity prices due to long-term contracts with their suppliers. Thus, we think it is important that policymakers and energy suppliers provide early information about possible price increases, as a high gas price can be considered as an important signal to reduce consumption (Labandeira et al., 2017).

Our second major policy implication addresses the financial burden of rising gas prices for consumers, which is significantly higher for older buildings than for younger ones. We therefore conclude that households should be relieved financially according to building type. Our results provide suggestions for the design, possible impacts as well as governmental expenditures of such consumer relief measures.

A relief model that is currently discussed for many European countries is the introduction of a discounted basic energy consumption for households. For instance, Germany plans to provide customers a state-guaranteed price for 80 % of the previous year's gas consumption. For the remaining 20 % of gas consumption, the (probably high) market price must be paid (BMWK - Federal Ministry for Economic Affairs and Climate Action, 2022a). Austria, in contrast, has implemented an electricity cost subsidy based on a fixed basic consumption, i.e. only
consumption above a fixed threshold must be paid for at market prices (Republic of Austria - Parliament, 2022). Similar models for space heating with natural gas could follow.

If such models are implemented, our findings imply that, depending on the building type, there could be a high level of inequality for the residual consumption that is exposed to high market prices. Taking the German proposal as an example, newer buildings could realistically avoid the market price by reducing their temperature by slightly more than 2°C, as this corresponds to a 20% saving. However, for older buildings, which are substantially more affected by the crisis, a 20% saving is very ambitious. It translates into a 4°C reduction, which may have side effects such as negative health effects. Models that rely on a fixed basic consumption, like the Austrian measure for electricity consumption, are to be regarded as particularly vulnerable in terms of distributive justice in view of our findings. Energetically poor buildings, for example, could hardly benefit from a subsidised basic consumption (at least if this is oriented at average consumption levels), while newer buildings could be overcompensated and make high windfall profits.

While the focus of our calculations is on German buildings, the overall implications of our results are valid for other countries. This is especially true for countries located in similar climate zones and that have a high share of natural gas for space heating, such as the Netherlands, United Kingdom, Slovakia or Italy. In concrete terms, this means that thermostat adjustments could be an important measure to reduce gas consumption for many countries in Europe. However, considering the overall gas supply gap, thermostat adjustments alone cannot be the only way out of the gas crisis. Therefore, further measures are needed to reduce import dependency, like the energetic refurbishment of buildings or the expansion of renewable energies. The question remains whether these can be realized quickly enough to close the gap.
CRediT authorship contribution statement

**Evelyn Sperber**: Conceptualization, Methodology, Software, Writing – original draft, Visualization. **Ulrich Frey**: Conceptualization, Writing – original draft, Supervision. **Valentin Bertsch**: Conceptualization, Writing – original draft, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We gratefully acknowledge internal funding by the German Aerospace Center within the project “SoGuR – Selbstoptimierende Gebäude und urbane Räume”.
References


https://www.dashboard-deutschland.de/energie/energie.


https://doi.org10.1016/0140-9883(96)00010-2.


https://www.verivox.de/gas/verbraucherpreisindex/.

https://doi.org/10.1016/j.enpol.2013.05.037.

https://doi.org/10.1016/j.buildenv.2015.07.032.