Climate impact comparison of electric and gas-powered end-user appliances

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Key Points:

- Oktoberfest could save 87% of total carbon emissions from energy consumption if all gas-powered end-use appliances were replaced with electric appliances
- Globally, electricity is the more climate-friendly energy source compared with natural gas in only seven of the 25 countries studied
- The development of carbon emissions over time shows for several countries electricity will soon be the more climate-friendly energy source

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Abstract

Natural gas is considered a bridging technology in the energy transition because it produces fewer carbon emissions than coal, for example. However, when leaks exist, methane is released into the atmosphere, leading to a dramatic increase in the carbon footprint of natural gas, as methane is a much stronger greenhouse gas than carbon dioxide. Therefore, we conducted a detailed study of methane emissions from gas-powered end-use appliances and then compared their climate impacts with those of electricity-powered appliances. We used the Munich Oktoberfest as a case study and then extended the study to 25 major natural gas consuming countries. This showed that electricity has been the more climate-friendly energy source at Oktoberfest since 2005, due to the extensive use of renewable electricity at the festival and the presence of methane emissions, particularly caused by incomplete combustion of natural gas appliances. Further, our global study shows that using electric appliances for cooking and heating would be more climate-friendly not only at Oktoberfest but also in several countries around the world, depending on the energy mix used and the leakage rate of natural gas. With this study, we demonstrate one way in which countries with a high renewable share in power generation, in particular, can reduce a significant amount of carbon emissions in the future.

Plain Language Summary

Although natural gas is considered a relatively climate-friendly energy source compared to coal, leakage of methane, the main component of natural gas, can significantly increase the climate impact of natural gas. This is because methane is a very strong greenhouse gas. In this study, we focused on methane leakage from end-use appliances used for cooking and heating. Using the Munich Oktoberfest as a case study, we found that these end-use appliances produce significant methane emissions. Therefore, we investigated at which leakage rates and which electricity mixes it would be better to use electric appliances for cooking and heating instead to reduce overall carbon emissions. We found that despite leakage rates, natural gas is still more climate-friendly than electricity in most countries around the world. However, as the share of renewable energy in the electricity mix increases in all countries, electricity will be the more climate-friendly energy source in the near future. With this study, we show a relatively simple way for every citizen to reduce their carbon emissions.

1 Introduction

To reach the goal of net-zero greenhouse gas (GHG) emissions, the usage of natural gas is considered to be a bridge technology in many countries, as it is promoted to be more climate-friendly than burning coal (Ladage et al., 2021). However, methane (CH_4), the main component of natural gas, has a much stronger warming potential (GWP_{20} of 86 with the consideration of climate-carbon feedback) than carbon dioxide (CO_2) and is released when natural gas enters the atmosphere incompletely burned (Myhre et al., 2013). Recent studies have shown that anthropogenic fossil CH_4 emissions are generally underestimated (Schwietzke et al., 2016; Hmiel et al., 2020; Alvarez et al., 2018) and that the targets set in the Paris Agreement can only be met if CH_4 emissions are drastically reduced (Nisbet et al., 2019).

To improve the quantification of CH_4 emissions, many studies around the world have focused on determining these CH_4 emissions using various measurement and modeling approaches including mobile street-level measurements with fast in situ analyzers on vehicles (Phillips et al., 2013; Jackson et al., 2014; Gallagher et al., 2015; von Fischer et al., 2017; Weller et al., 2018, 2020; Maazallahi et al., 2020), interpretation of plume measurements utilizing the downwind tracer flux approach (Roscioli et al., 2015; Mitchell et al., 2015; Zimmerle et al., 2015; Omara et al., 2016), larger scale airborne measurements with analyzers on aircraft (Karion et al., 2013; Lyon et al., 2016), local eddy flux measurements (Gioli et al., 2012; Helfter et al., 2016), or FTIR sensor networks (Dietrich et al., 2021; Jones et al., 2021; Hase et al., 2015; Zhao et al., 2019; Makarova et al., 2021; Klappenbach et al., 2021; Chen et al., 2016; Vogel et al., 2019).

To attribute the source and determine the leakage rate, either isotopic signatures of the gas are measured (Menoud et al., 2020; Lu et al., 2021; Menoud et al., 2021; Röckmann et al., 2016; Beck et al., 2012; Fisher et al., 2006; Chamberlain et al., 2016; Zimnoch et al., 2019), the ethane to methane ratio is determined, because ethane is a unique tracer for fossil fuel related methane emissions, or both methods are used simultaneously (Zavala-Araiza et al., 2015; Maazallahi et al., 2020; Allen et al., 2013; Yacovitch et al., 2014, 2015, 2018).

In our study, we focus specifically on total emissions from natural gas compared to electricity in the end-use sector, as these emissions are suspected of contributing considerably to the underestimates in current methane emissions inventories (McKain et al., 2015; Plant et al., 2019). We use the Munich Oktoberfest - a very large festival with more than 6 million visitors per year - as a case study where gas end-use devices are highly concentrated in a limited area. Overall, 40% of the energy demand at Oktoberfest is met by natural gas (mainly for heating and cooking). The event has already been identified as a significant source of CH_4 (Chen et al., 2020), but it remained unclear whether these methane emissions are primarily due to natural gas leakage or biogenic emissions. Despite these CH_4 emissions, Oktoberfest is promoted as a climate-friendly event, as the share of green electricity in the residual energy use has been steadily increased starting in 1999, and since 2012 only renewable electricity has been used (Landeshauptstadt München Redaktion, 2020; Landeshauptstadt München, 2019). Therefore, Oktoberfest is particularly suited for demonstrating the differences in total GHG emissions from natural gas compared to electricity for the case where the share of renewables increases over time.

So far, studies have mainly focused on emissions caused by coal combustion compared to those caused by natural gas (Ladage et al., 2021; Tanaka et al., 2019; Qin et al., 2017; Fulton et al., 2011). However, the contribution of renewable energy has hardly been considered so far. Therefore, our study analyzes the climate impacts of electric and gas-powered appliances for 25 countries to show a potential pathway to reduce global carbon emissions.

2 Materials and Methods

In the present study, we first used isotope and ethane analyses to assign emission sources and then determined the point in time and the break-even share of renewables at which electric appliances are more climate-friendly than gas appliances at Oktoberfest. Afterwards, we extended our study to a global scale and compared the carbon footprint of natural gas and electricity as an energy source for end-user appliances around the world.

2.1 Mobile in situ measurements at Oktoberfest

We carried out mobile in situ measurements at Oktoberfest 2019. For that, we utilized the LI-7810 $CH_4/CO_2/H_2O$ Trace Gas Analyzer from LI-COR, which uses the optical feedback cavity-enhanced absorption technique (OF-CEAS), as a mobile backpack instrument. Simultaneously to the measurements, the current position of each data point was recorded using a GPS application on a smartphone that was time-synchronized to the gas analyzer.

In contrast to our preceding study in 2018(Chen et al., 2020), we were allowed to perform measurements both outside and inside the festival premises as well as inside the tents. To determine the emission strength, only the measurements around the perimeter of Oktoberfest (hereafter referred to as *outer rounds*) were used to allow for an easy comparison to our 2018 results. The measurements on the site (hereafter referred to as *inner rounds*) were mainly used to find emission hotspots.

To cover different days of the week and times of the day, we completed 56 rounds during Oktoberfest and 15 rounds after Oktoberfest ended. The rounds during the festival period were divided into outer and inner rounds. Each inner round was always combined with at least one outer round to obtain background concentrations for CH_4 each time.

For the outer rounds, we chose the shortest possible walking distance around the perimeter of Oktoberfest, which is directly behind the security fences. The walking distance for such a round is about 2.6 km (see Figure S8) and took us on average about 40 min each.

During our measurements inside the festival premises, we followed two routes that were predefined by us. Both of them were chosen to capture the emissions caused by the large tents and booths on the streets best. Therefore, they follow the streets between the tents that are mainly located in the northwest quarter (see Figure S8).

2.2 Modeling the CH_4 emissions

To quantify the CH_4 emissions of Oktoberfest, we combined the measurements around the perimeter of Oktoberfest with the modeling approach developed in Chen et al. (2020). The main differences to these investigations were a different CH_4 analyzer (in 2018, the Picarro G4301 gas scouter that is based on the cavity ring-down principle was used) and wind measurements closer to the festival premises, as the sensitivity study in Chen et al. (2020) indicated a strong influence of the wind measurements to the atmospheric model. Therefore, we established a wind sensor very close to the festival premises on top of a building, which is located approximately 150 m west of Oktoberfest (48.134° N, 11.545° E, 26 m a.g.l.). As a sensor, the Lufft WS200-UMB 2D ultrasonic wind sensor was utilized. The other model parameters such as the number of emitters, prior emission estimate, plume modeling algorithm, averaging approach, etc. were equal.

2.3 Air sampling

In addition to the backpack measurements, we took samples of the environmental air at different locations, such as inside and outside the festival premises, inside the beer tents, next to possible emission hotspots at the festival, and in the subway. For this purpose, Standard FlexFoil air sampling bags from SKC Ltd. with a volume of three liters were used. In total, we filled 30 bags and shipped them afterwards to Utrecht University and TNO in the Netherlands, where they were analyzed in the lab. At Utrecht University, in twelve bags (two of them were background samples) $\delta^{13}C$ and δD were analyzed using Isotope Ratio Mass Spectrometry (IRMS) (Brass & Röckmann, 2010). The device used was the spectrometer model Delta V Plus/Deltaplus XL from Thermo Fisher Scientific Inc. At TNO, the Δethane to Δmethane ratios of the remaining 18 bags (seven of them were background samples) were measured using the Quantum Cascade Laser (QCL) absorption spectrometer model QCL-TILDAS-76 from Aerodyne Research Inc.

2.4 Isotopic analyses of air samples

To determine, whether the measured methane is anthropogenic or biogenic, analyses of the carbon isotopes were made. We used the δ^{13}C method, in which the ratio between ^{13}C and ^{12}C of the sample gas is compared to the ratio of a predefined standard. Similar to δ^{13}C, we also looked at the ratio of deuterium to normal hydrogen using the δD method. The mathematical expressions for these two methods are shown in Section S1.

Since the sampled air also includes the unknown background isotopic signature of the gas, we utilized Keeling plots to determine the isotopic signature of the gas emitted exclusively by Oktoberfest. These plots linearize the relation between the δ^{13}C (or δD) value of the measured air sample and the methane concentration so that the δ^{13}C (or δD) portion added by the unknown source can be determined (Keeling, 1958).

2.5 Ethane to methane ratio of air samples

As a second kind of analysis to determine the origin of the sample gas, we examined the Δethane to Δmethane ratio (Zavala-Araiza et al., 2015; Maazallahi et al., 2020; Allen et al., 2013; McKain et al., 2015; Yacovitch et al., 2014, 2015, 2018). For this purpose, we subtract the background concentrations of methane ($CH_{4,\mathrm{bg}}$) and ethane ($C_2H_{6,\mathrm{bg}}$) from the measured concentrations ($CH_{4,\mathrm{sample}}$ and $C_2H_{6,\mathrm{sample}}$) to obtain the ratio of the gas added by the source:

$$\frac{C_2H_{6,\mathrm{source}}}{CH_{4,\mathrm{source}}} = \frac{\Delta C_2H_6}{\Delta CH_4} = \frac{C_2H_{6,\mathrm{sample}}}{CH_{4,\mathrm{sample}} - CH_{4,\mathrm{bg}}} \tag{1}$$

Thereby, we assumed that the ethane concentration $C_2H_{6,\mathrm{bg}}$ of the background can be set to zero, which is supported by our five background air samples that we took during the time of Oktoberfest 2019. For each sampling point, a Δethane to Δmethane ratio was determined and afterwards compared with the ratio of the Munich gas network. Since the composition of Munich's natural gas is determined only once a month, a weighted average was calculated for the 16 days of Oktoberfest 2019, which took place ten days in September and six days in October 2019. The uncertainties were calculated using the 99% confidence intervals of all gas samples measured in the tent ([2.57%, 2.78%]) combined with the minimum ($r_{\mathrm{ethane,Sept}}$=3.04%) and maximum ($r_{\mathrm{ethane,Oct}}$=3.07%) ethane share in September and October 2019, respectively (SWM Infrastruktur GmbH und Co. KG, 2019a, 2019b).

2.6 Calculation of the climate impact

To find out, whether gas or electric appliances for cooking and heating have a better carbon footprint, the total emission factors in CO_2 equivalents (CO_2eq) are calculated for the case of electric and gas use only. To be able to compare these two different kinds of energy, we assumed that the efficiencies of gas and electrical appliances for heating and cooking are the same, as the energy needs to be transferred completely into heat for both cooking and heating appliances (Landi et al., 2019).

To calculate the emission factor EF_{elect}(t), if only electricity would be used as an energy source, Eq. 2 is utilized:

$$EF_{\mathrm{elect}}(t) = \sum_{n=1}^{8} EF_n \cdot p_{\mathrm{elect,n}}(t) \tag{2}$$

These emissions differ for each country and are time-dependent, as the proportions of fuel types used for electricity production $p_{\mathrm{elect,n}}(t)$ vary over time. In this study, we considered four different types of non-renewable energy sources (coal, oil, gas, and nuclear power) and four different types of renewable energies (hydro, solar, wind, and geothermal/biomass power) with different emission factors EF_n obtained from Amponsah et al. (2014) (see Table S1).

For the case, where we assumed that only natural gas is used for producing the same amount of energy, the emission factor $EF_{\mathrm{NG,total}}$ is calculated by adding the emission factors of combusting natural gas EF_3 (see Table S1) and leaking CH_4, as shown in Eq. 3:

$$EF_{\mathrm{NG,total}} = EF_3 \cdot (1 - r_{\mathrm{leak}}) + \frac{\rho_{\mathrm{CH4}} \cdot GWP_{20,\mathrm{CH4}}}{E_{\mathrm{d,NG}}} \cdot r_{\mathrm{leak}} \quad (3)$$

Where r_{leak} is the leakage rate of natural gas, ρ_{CH4} is the density of CH_4 ($0.668\,\mathrm{kg/m^3}$), $GWP_{20,CH4}$ the 20-year global warming potential of methane considering climate-carbon feedback ($86\,\mathrm{tCO_2eq/t}$) (Myhre et al., 2013) and $E_{\mathrm{d,NG}}$ the energy density of natural gas ($3.6 \cdot 10^{-5}\,\mathrm{TJ/m^3}$)

2.7 Country specific emission data

Eq. 2 and 3 are applied for different countries and years, resulting in a time-dependent country comparison of the carbon footprint of electrical versus gas-driven appliances. We examined the shares and types of non-renewables and renewables in the electricity mix only for countries that account for at least 0.5% of global natural gas consumption (40 countries in total). However, we excluded countries with a renewable energy share of less than 10% in 2019 (which primarily includes Middle Eastern countries), as we want to focus in this study primarily on how an increasing share of renewable energy can make electricity more climate-friendly compared to natural gas. The chosen 25 countries account for 75% of the world's natural gas consumption, with the United States alone accounting for about 21.7%, followed by Russia and China with 12.4% and 5.4%, respectively (WorldData.info, 2020). Similar to the Oktoberfest investigations, in this country comparison, we focused primarily on the climate impact of appliances at the end-user, namely cooking and heating appliances in the household sector.

The data on the electricity mix was taken from the *BP Statistical Review of World Energy, 69th Edition* (bp, 2020). The electricity mix data indicate the type and proportion of energy sources (coal, natural gas, oil, nuclear, and renewables) used to generate electricity from 1965 to 2019 (for some countries only from 2000 to 2019). In this study, we concentrate on the 21st century only. The data on the share of renewable energy was also cross-checked with *Trends in Renewable Energy* provided by the International Renewable Energy Agency (IRENA) (International Renewable Energy Agency, 2020). IRENA provides data from 2000 to 2018.

To obtain a forecast of the emission factors of the individual countries for the next ten years, a simple Generalized Additive Model (GAM) was used. It uses cubic spline smoothing and had a maximum degree of freedom of five. This prediction is purely statistical and does not take into account any planned government decisions to change energy sources for power generation. Therefore, the prediction should be treated with caution. Nevertheless, it provides an initial estimate of when it might be appropriate to switch from gas-fired to electric cooking and heating appliances in each of the countries studied.

2.8 Phase transition plot

To show how the proportions of renewable and non-renewable energy, and the respective sources for these energies, affect the climate friendliness of electricity and natural gas, we used phase transition diagrams. Red shaded areas indicate that natural gas is the more climate-friendly energy, while blue shaded areas indicate that electricity is more climate-friendly.

We used 2019 energy data for both Oktoberfest and each of the 25 countries to create these charts. Since there is little data on the temporal development of the natural gas leakage rate of individual countries, we used a constant value of 1.7% for all countries over the entire period, which corresponds to the global average methane leakage rate (International Energy Agency, 2017). Only for the United States, where several methane leakage studies exist, a different value of 2.3% [2.0%, 2.7%] was used (Alvarez et al., 2018).

To construct the phase transition diagrams, we varied the methane leakage rate from 0 to 15% at 0.1% increments and the renewable share from 0 to 100% in 1% increments to calculate the difference in carbon footprint between CO_2eq emissions from electricity and natural gas. Subsequently, the characteristic value is obtained by intersecting the resulting white line, which represents all points where natural gas and electricity are equally climate-friendly, with the actual methane leakage rate (red vertical dashed line). The y-intercept (indicated by the horizontal orange dashed line) represents the share of renewables needed to make electricity the more climate-friendly energy source compared to natural gas when leakage is taken into account. We then calculated the difference between this share and each country's current (2019) share of renewables and displayed the differences as a bar plot in Figure 5. The error bars were obtained by varying the methane leakage rate by $\pm 1\%$.

3 Results

3.1 CH_4 emission number

Utilizing all 38 outside rounds during Oktoberfest, we determined an emission number of $(8.5\pm0.5)\,\mu g(m^2s)^{-1}$. The value is in the same order of magnitude as the one quantified in 2018: $(6.7\pm0.6)\,\mu g(m^2s)^{-1}$ (Chen et al., 2020). Emissions identified for the period after the end of the festival also have a positive offset in 2019 ($2.5\,\mu g(m^2s)^{-1}$ versus $1.1\,\mu g(m^2s)^{-1}$). Possible reasons for these slightly higher numbers in 2019 include more accurate wind measurements taken closer to the festival premises or real changes in emissions between the two years. Still our 2019 measurements confirm that Oktoberfest is a significant source of CH_4 that can be made more climate friendly if emission sources are accurately located and quantified.

3.2 Source attribution

To find emission sources on the large festival premises, measurements were made in the vicinity of possible sources and a categorization of the sources into biogenic and anthropogenic origin was carried out. For this purpose, we performed mobile in situ measurements inside the festival premises and determined the isotopic signature and the ethane to methane ratios of air samples taken at Oktoberfest.

3.2.1 Inside measurements

During our measurements at the festival premises, we found that gas regulation stations do not show significant CH_4 enhancements, which supports the statement of the Munich public utility company (SWM) that these stations are already carefully monitored and maintained. CH_4 concentrations were significantly elevated especially next to the open doors of the beer tents (see Figure 1). In addition, we were allowed to enter one of the large beer tents with our backpack analyzer to verify our assumption further and localize the sources in more detail. Figure 1 shows that the CH_4 mixing ratios of up to 2900 ppb inside the tents are even higher than in front of the entrance (approximately 2000 to 2600 ppb). Most of the high enhancements were detected when passing the tent kitchen.

On the streets of the festival grounds, we discovered only two additional hotspots during our 18 tours at the site that were not associated with open tent doors and windows or tent chimneys. The first was close to one of the grilled chicken stalls that run on natural gas and the second was next to a place where fish were grilled over charcoal fires.

We conclude that mostly the 17 large beer tents contribute significantly to the CH_4 emissions of Oktoberfest to the atmosphere. This supports the statement of Chen et al.

(2020) that beer tents are the major CH_4 source at Oktoberfest. Therefore, it is a valid approach to model only the large beer tents as sources in order to determine the overall emission strength of Oktoberfest. However, CH_4 is not only emitted by the chimneys but also by open doors and windows of the tents. This should be considered if a spatially higher resolved model is used.

To identify, whether these emissions are of biogenic origin produced by the human bodies or of anthropogenic origin caused by incomplete combustion and leakages of natural gas-driven appliances, air samples were taken and analyzed in the lab afterwards.

3.2.2 Isotopic composition

The results of the isotopic analyses of the samples taken at Oktoberfest are shown in Figure 2 (left and center) as a Keeling plot. The various types of sampling locations, such as in-tent, subway (inside the crowded train between Oktoberfest and Munich Central Station), and background (outside the Oktoberfest premises) samples, are indicated by different colored crosses. To determine the isotopic signature of each of the two source types, a linear regression line is drawn through all sample points of each source type including the background samples for both δ^{13}C and δD. In this Keeling plot analysis, the intercept of the regression line with the y-axis represents the isotopic signature of the gas added by the unknown source. These intercepts are for [δ^{13}C; δD] at [-45.4‰; -192‰] for the in-tent samples and [-66.1‰; -310‰] for the subway sample.

In Figure 2 (right), these isotopic source signatures are compared to typical isotope signatures of different source types, such as natural gas, biomass burning, wetlands, rice, and ruminants. The subway sample (light green cross) shows a clear biogenic signature, which is the expected behavior of a crowd of people. In contrast, the in-tent signature (red cross) is very close to the signature of natural gas, suggesting that the methane emissions of Oktoberfest are primarily caused by fugitive natural gas leakages.

3.2.3 Ethane to methane ratio

The results of the ethane analyses are shown in Figure 3, where the Δethane to Δmethane correlation is shown as a scatter plot using logarithmic axes. In addition to the two source types *in-tent* and *subway* that we also analyzed with respect to the isotopic fingerprint of the samples in Figure 2, another source type, namely air sampled in front of a large charcoal grill, was analyzed. These three source types exhibit significantly different behavior. The nine samples taken inside the tents (red crosses) show an almost constant Δethane to Δmethane ratio of 2.68%. The number is very close to 3.05%, which is the reported averaged ethane to methane ratio of the natural gas used in Munich in September and October 2019 (SWM Infrastruktur GmbH und Co. KG, 2019a, 2019b). Together with the high concentrations measured inside the tents (see Figure 1), this result confirms our hypothesis that the elevated methane levels at Oktoberfest are primarily due to leaking natural gas. In contrast, the subway sample (light green) has a much lower ethane content and the charcoal grill sample (gray) has a higher ethane content, indicating that small amounts of other methane emissions are present in addition to the natural gas leaks.

Dividing the ethane fractions of our Oktoberfest samples ($\mathrm{r}_{\mathrm{ethane,Okt}}$) by that of the Munich natural gas mix ($\mathrm{r}_{\mathrm{ethane,Muc}}$), we calculate the ratio $\mathrm{r}_{\mathrm{fugitive}}$ between the ethane shares of these two gases to be

$$r_{\mathrm{fugitive}} = \frac{r_{\mathrm{ethane,Okt}}}{r_{\mathrm{ethane,Muc}}} = \frac{2.68\%\,[2.57\%, 2.78\%]}{3.05\%\,[3.04\%, 3.07\%]} = 88\%\,[84\%, 91\%]. \tag{4}$$

Based on this calculation, we assume that about 88% of the methane emissions in the tents are attributable to fugitive natural gas. The remaining 12% are likely caused by biogenic processes. The values in squared brackets represent the 99% confidence intervals.

In summary, we conclude that the enhanced methane concentrations measured at Oktoberfest 2018 and 2019 are mainly due to natural gas that is either not fully combusted or leaking from natural gas-fueled equipment, such as heaters, grills, and ovens. According to our investigations, gas regulation stations and pipelines at Oktoberfest do not leak significantly and are, therefore, not the reason for the methane enhancements observed.

3.2.4 Leakage Rate

The leakage rate r_{leak} of CH_4 at Oktoberfest is determined as the ratio between the CH_4 loss measured with our instruments ($M_{CH4,loss}$) and the total CH_4 consumed at Oktoberfest 2019 ($M_{CH4,total}$), the calculation of which is explained more in detail in Section S2:

$$r_{\text{leak}} = \frac{M_{CH_4,\text{loss}}}{M_{CH_4,\text{total}}} = \frac{1.635 \cdot 10^3\text{kg}}{1.186 \cdot 10^5\text{kg}} = 1.4\% \tag{5}$$

The determined leakage rate is very close to the leakage rate determined by Chen et al. (2020) (1.1%) and slightly lower than the leakage rate of the entire global natural gas process (1.7%) (International Energy Agency, 2017). However, only end-use equipment was analyzed for Oktoberfest. All leakage in the upstream and midstream natural gas process is not captured by the measurements in this study. We, therefore, conclude that the leakage rate of end-use appliances at Oktoberfest appears to contribute significantly to the overall leakage rate of the natural gas chain. These results suggest that it is relatively easy to achieve a significant improvement in the carbon footprint of the natural gas chain by simply reducing the leakage rates of end-use appliances. This is likely true not only for Oktoberfest, but for many end-use gas appliances in the world.

3.3 Energy consideration at Oktoberfest

Although the total energy demand of Oktoberfest has risen within the past 20 years, mainly due to an increase in electricity consumption, total carbon emissions have been drastically reduced. This effect is due to the steadily increasing proportion of renewable electricity used at the festival. Since 2011, only green electricity has been used, 100% of which is generated from hydropower, one of the cleanest renewable energy sources (Amponsah et al., 2014). A more detailed analysis of the energy development can be found in Section S3.

We incorporated all energy information determined for Oktoberfest 2019, such as fossil electricity composition, natural gas CO_2eq emissions, renewable energy type, and CH_4 leakage rate, into a phase transition diagram (see Figure 4). This identifies how a changing share of hydropower affects the climate friendliness of electricity compared to natural gas.

From the intersection of the white line with the CH_4 leakage rate (red dashed line), it is possible to determine the fraction of hydropower from which electricity is the more climate-friendly energy source than natural gas with consideration of fugitive CH_4 leakages.

Assuming a methane leakage rate of 1.4% determined in our study, electricity with a renewable share greater than 58% is more climate-friendly than natural gas for Oktoberfest as demonstrated in the phase transition plot in Figure 4 (dashed horizontal orange line). Since the share of renewable energy at Oktoberfest exceeded the threshold

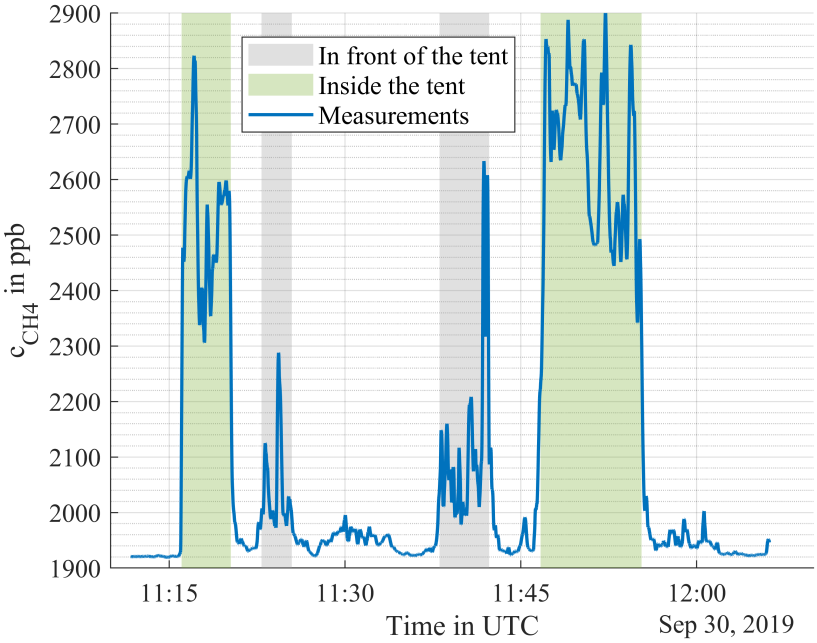

Figure 1. CH_4 mole fractions measured at the Oktoberfest premises. The concentrations are especially enhanced inside (green shaded) and in front of (grey shaded) the beer tents.

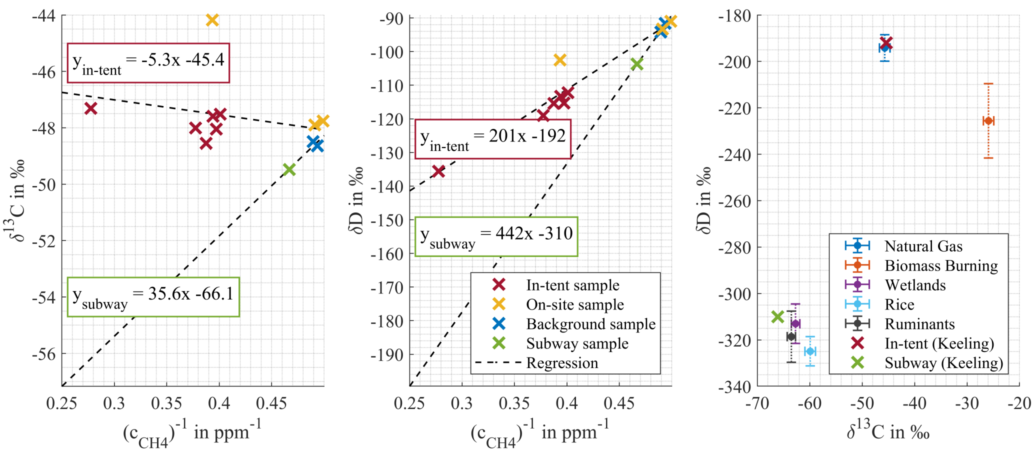

Figure 2. $\delta^{13}C$ (left) and δD (center) Keeling plot of the air samples taken at Oktoberfest. In addition, two regression lines are shown in both figures for the Oktoberfest and subway samples, respectively, to determine the isotopic signatures of the sources. Right: Isotopic fingerprint ($\delta^{13}C$ vs. δD) off different gas sources (dots with whiskers) based on results of Menoud et al. (2021) including source signatures of Oktoberfest, derived from the Keeling plots (crosses). While the signature of the subway measurement (green cross) is close to biogenic sources, the Oktoberfest measurements (red cross) show a comparable signature to natural gas. These results indicate that Oktoberfest emissions are primarily due to natural gas leakage.

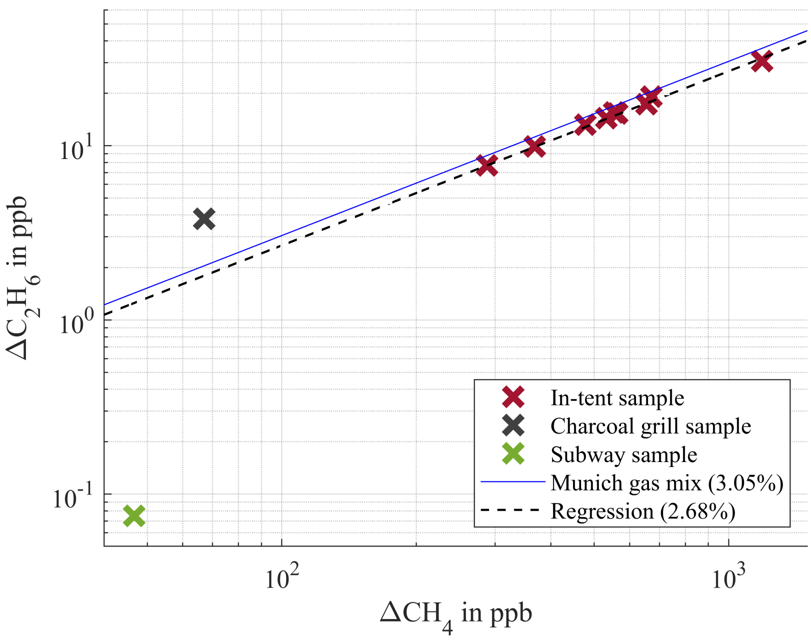

Figure 3. Correlation between Δethane and Δmethane of air sampled at various locations at Oktoberfest in a log-log plot. With the exception of the measurements for the subway (green) and the charcoal grill (gray), which show lower and higher ethane enhancement, respectively, all points lie on a line with slope 1, implying a linear relationship between Δethane and Δmethane. Since the slope of this regression line is very close to that of the Munich natural gas mixture, these results indicate that the high methane enhancement inside the tents is caused by natural gas.

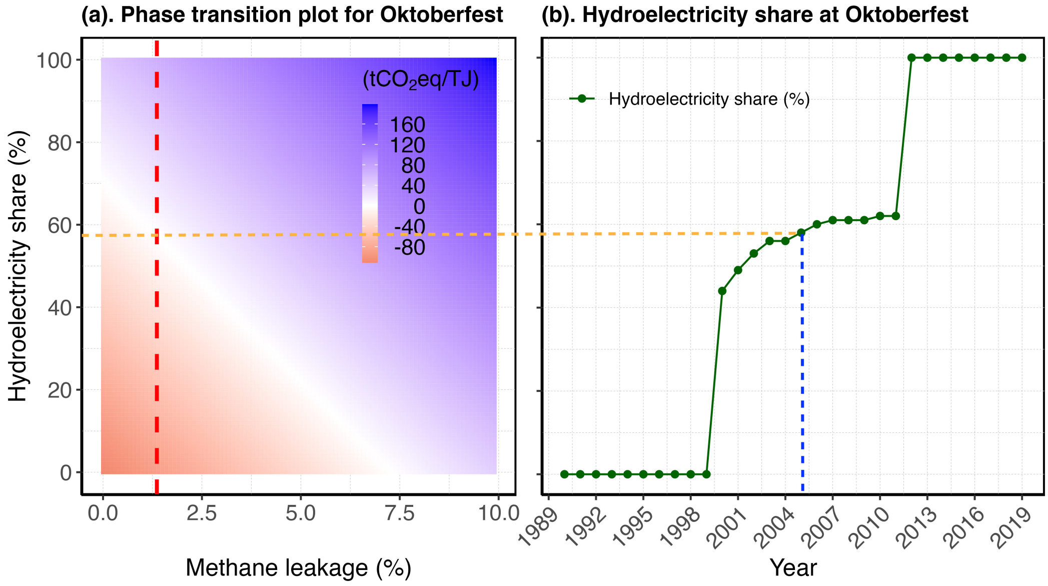

Figure 4. Left: phase transition diagram of hydropower shares in electricity generation versus methane leakage rates. It shows the difference in emissions (in tCO_2eq/TJ) between electricity and natural gas as the energy source for heating and cooking at Oktoberfest. For positive values (blue shaded areas), the use of electricity leads to lower emissions compared to natural gas; for negative values (red shaded areas), the opposite is true. The red vertical dashed line represents the leakage rate of 1.4% measured at Oktoberfest, while the orange horizontal dashed line represents the associated share of renewable energy, where electricity is the more climate-friendly energy source compared to natural gas (58%). Right: share of renewable energies in electricity consumption at Oktoberfest. The dashed orange line shows that the share of renewable energies at the Oktoberfest reached the break-even point from 2005 onwards, which means that electricity has been the more climate-friendly energy source than natural gas at the festival ever since.

of 58% in 2005, it would have been beneficial from a climate change perspective to replace all gas appliances at Oktoberfest with electric appliances starting in this year. In 2019 alone, this could have saved up to 450 tCO_2 emissions.

Such a reduction in emissions for an event that lasts only two weeks and is already quite climate-friendly is remarkable and gives us the opportunity to investigate on a larger scale how the type of energy source could help reduce carbon emissions worldwide.

3.4 Comparison of the climate impact in different countries

The Oktoberfest study showed that whether natural gas or electricity is the more climate-friendly energy source depends very much on the composition of the electricity mix as well as the leakage rate of natural gas. Since each country has its own electricity mix composition, we applied our approach developed for Oktoberfest to 25 major natural gas-consuming countries to understand which of the two energies is more climate-friendly for each of them. For these 25 countries, we studied the climatic impact of electric and natural gas energy sources in two ways. First, by their renewable energy gap in 2019 (shown in Figure 5) and second, by their long-term (2000 to 2019) temporal trends (shown in Figure 6).

3.4.1 Country comparison - renewable energy gap

The results of the phase transition analysis for the 25 countries (see Section S5) are summarized in Figure 5. There, the 25 countries are sorted in ascending order of the percentage growth in renewable energy share required to reach the break-even point. A negative number means that electricity is already (in 2019) the more climate-friendly energy source for household cooking and heating in that country. Still, for most of the countries, the share of renewable energy needs to be improved to make electricity a more climate-friendly energy source compared to natural gas. Only Canada, Brazil, Belgium, France, Venezuela, the United Kingdom, and Spain have already reached this point. In these countries, therefore, electricity is already more climate-friendly than natural gas. For the other countries, the share of renewables in the overall electricity mix needs to rise to make electricity the more climate-friendly alternative to natural gas.

To answer the question, when the break-even point will be reached for the remaining 18 countries, the analysis of the temporal development of the emission factor over the last 30 years helps to make a rough statistical forecast for the next ten years.

3.4.2 Comparison of country emission over time

Figure 6 shows the temporal trend of each countries' emission factor for both natural gas (red solid line) and electricity (green solid line). While the carbon footprint of natural gas has remained nearly constant over the years, the carbon emissions of electricity have fluctuated for most countries. This behavior is due to the widely varying emission factors for the different energy sources used to generate electricity (see Table S1) and is further analyzed in Section S4.

By examining the temporal development of electricity-mix data, these 25 major natural-gas consuming countries can be classified into three groups based on the CO_2 emission factors from electricity (see colored backgrounds in Figure 6). In addition, we provide a rough prediction of how the emission factors of the individual countries will develop in the coming years (black dashed line).

The first group (green) is represented by seven countries where electricity was in 2019 the more climate-friendly source of energy in comparison to natural gas under the assumption of a 1.7% leakage rate in the entire natural gas process (International Energy Agency, 2017). These countries have either a very high share of renewable energies (Brazil, Canada, and Venezuela), or low carbon emissions of non-renewables mainly due to the extensive usage of nuclear power (France and Belgium) or a combination of these two characteristics (Spain and the United Kingdom). These results show that not only the share and type of renewable energy, but also the emission factor of non-renewable sources is decisive in determining whether electricity is the more climate-friendly energy source than natural gas.

The second group (yellow) consists of six countries where absolute carbon emissions from electricity are already close to natural gas levels, while at the same time emissions have been steadily decreasing in recent years, so that the intersection with the natural gas curve may be reached in the next years (until 2030). The reasons for this characteristic are the recent increase of renewables in electricity generation (Germany, Italy, and Japan), the transition from coal (United States) or oil (Argentina) as an energy source to electricity generation by natural gas or a combination of both (the Netherlands) (see Figure S3). For these six countries, a switch to electricity for domestic cooking and heating could save carbon emissions in the near future.

The third group (red) is represented by twelve countries where electricity is currently less climate-friendly than natural gas and where the intersection will not happen in the near future. These twelve countries are characterized either by an electric emission factor close to that of natural gas, but with a moderate expected decreasing rate (Russia, Turkey, Mexico, Egypt, Thailand, and Iran) or by significantly higher absolute emission values of electricity compared to natural gas in 2019 (Malaysia, China, Australia, India, Indonesia, and Poland). For these countries, natural gas consumption could remain more climate-friendly compared to electricity even in the distant future. In fact, for some of these countries with a high proportion of coal as an energy source, such as China, Australia, India, Indonesia, and Poland, large amounts of carbon emissions could be saved if natural gas were used as an energy source for end-use appliances instead, since natural gas is, in general, the more climate-friendly energy source compared to coal even if leakages are taken into account (Ladage et al., 2021).

The countries of the first and third groups are sorted in ascending order according to their absolute carbon emission factors for electricity generation in 2019, while the countries of the second group are sorted according to their predicted year of reaching the break-even point.

3.4.3 Existing obstacles for such carbon reductions

Although, replacing natural gas with electric devices could save significant amounts of global carbon emissions, we recognize that it is not possible to immediately run all cooking and heating appliances on electricity instead of natural gas. First of all, there would not be enough electrical energy available or the electricity would have to be generated from non-renewable energy sources, which in turn would increase the carbon footprint. Furthermore, many appliances cannot be easily replaced due to the lack of electrical infrastructure. In addition, natural gas is in most cases a significantly cheaper energy source than electricity. In Germany, for example, the price per kWh of natural gas is only about half that of electricity (see Figure S7), making it unaffordable for many people to replace gas appliances with electric ones. However, such barriers could be removed by policymakers.

4 Conclusions

In this study, the climate impact of gas appliances used for cooking and heating including the effect of CH_4 leakages was investigated and compared with the carbon footprint of electric appliances. We used the Munich Oktoberfest, the largest beer festival in the world, as a case study and extended our findings to gas appliances around the world. To this end, the source signature of CH_4 enhancements at the festival was investigated utilizing a portable CH_4 gas analyzer combined with isotopic analyses of air samples to determine the δ^{13}C and δD ratios. In addition, the ethane share of the samples was examined.

Both isotopic and ethane analyses of the gas indicated that the CH_4 enhancements were predominately caused by natural gas used for cooking and heating at the festival premises and not by biogenic processes caused by visitors. Incomplete combustion and leakages in the appliances are much more likely the causes than leaks in pipelines. Since most of the cooking and heating takes place inside the beer tents, these tents are the main sources of CH_4 enhancements at Oktoberfest, which is supported by measurements inside the tents. However, food stalls on the street use natural gas driven appliances as well, so that they contribute to the overall CH_4 enhancements of the festival, too. Overall, the leakage rate at Oktoberfest 2019 is found to be 1.4%, which is slightly higher than the rate of 1.1% determined in 2018 (Chen et al., 2020).

Based on the knowledge of an existing leakage rate, we provide a possible solution to mitigate the climate impact of such large festivals by calculating the carbon footprint of natural gas driven appliances considering the leakage rate. Although, natural gas is considered a fairly climate friendly alternative to other fossil fuels, we found that elec-

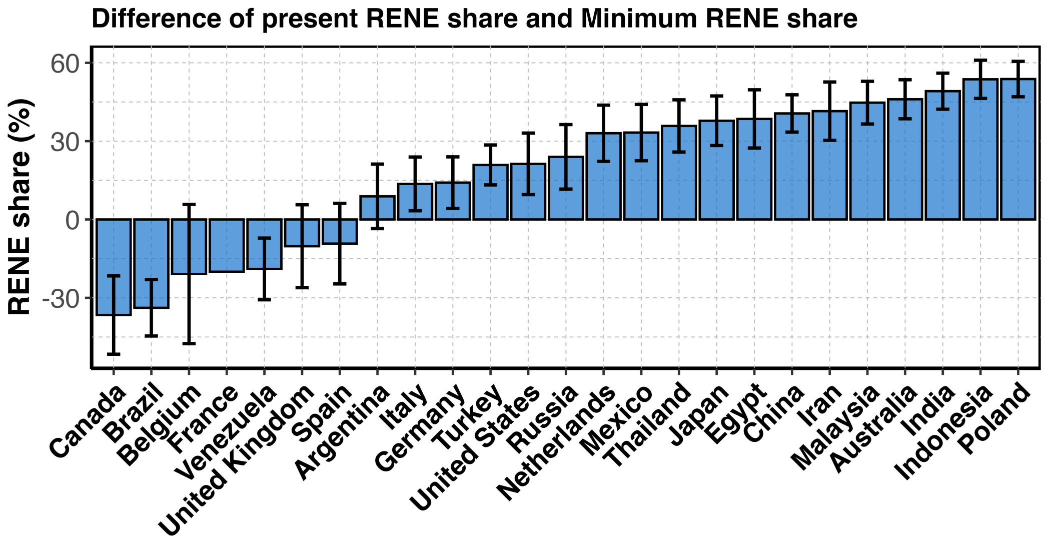

Figure 5. The difference in current renewable energy (RENE) share to reach the break-even point, where natural gas and electricity have the same carbon footprint for 25 countries. Negative values indicate that electricity is already the more climate-friendly energy source compared to natural gas. Values greater than zero represent the increase in RENE share required to make electricity more climate-friendly compared to natural gas. Error bars represent the sensitivity of RENE share to 1% change in leakage rate.

trical appliances at Oktoberfest have a much smaller carbon footprint than natural gas driven ones, since Oktoberfest is supplied by renewable electricity only. Replacing all natural gas driven appliances at Oktoberfest with electrical ones could have saved approximately 450 t of CO_2eq in 2019, which is 87% of the total carbon emissions caused by energy consumption at the festival.

Nevertheless, carbon emissions of Oktoberfest contribute only very little to the global carbon budget, making emission reductions at Oktoberfest not a solution to global climate problems. However, gas appliances are used not only at Oktoberfest but in many households around the world. Therefore, we extended our study to estimate whether replacing gas driven appliances with electric ones in specific countries would save global carbon emissions. To this end, we analyzed the carbon emissions of energy demand in the household sector for 25 major natural gas consuming countries around the world using the approach developed for Oktoberfest. In contrast to Oktoberfest, we used literature values for the leakage rates instead.

Since electricity is generated by different energy sources in each country, the carbon footprint of electricity generation differs significantly between them. To date, only in seven of these countries, electricity is the more climate-friendly energy source than natural gas for cooking and heating in the household sector. However, since the share of renewables is steadily increasing in many countries, electricity could become the more climate friendly energy source than natural gas in the near future.

We conclude that from a climate perspective, in countries with low carbon emissions from electricity generation, it would make sense now or in a few years to replace gas appliances for domestic cooking and heating with electric appliances to save overall carbon emissions. Nevertheless, we recognize the fact that not all gas appliances can

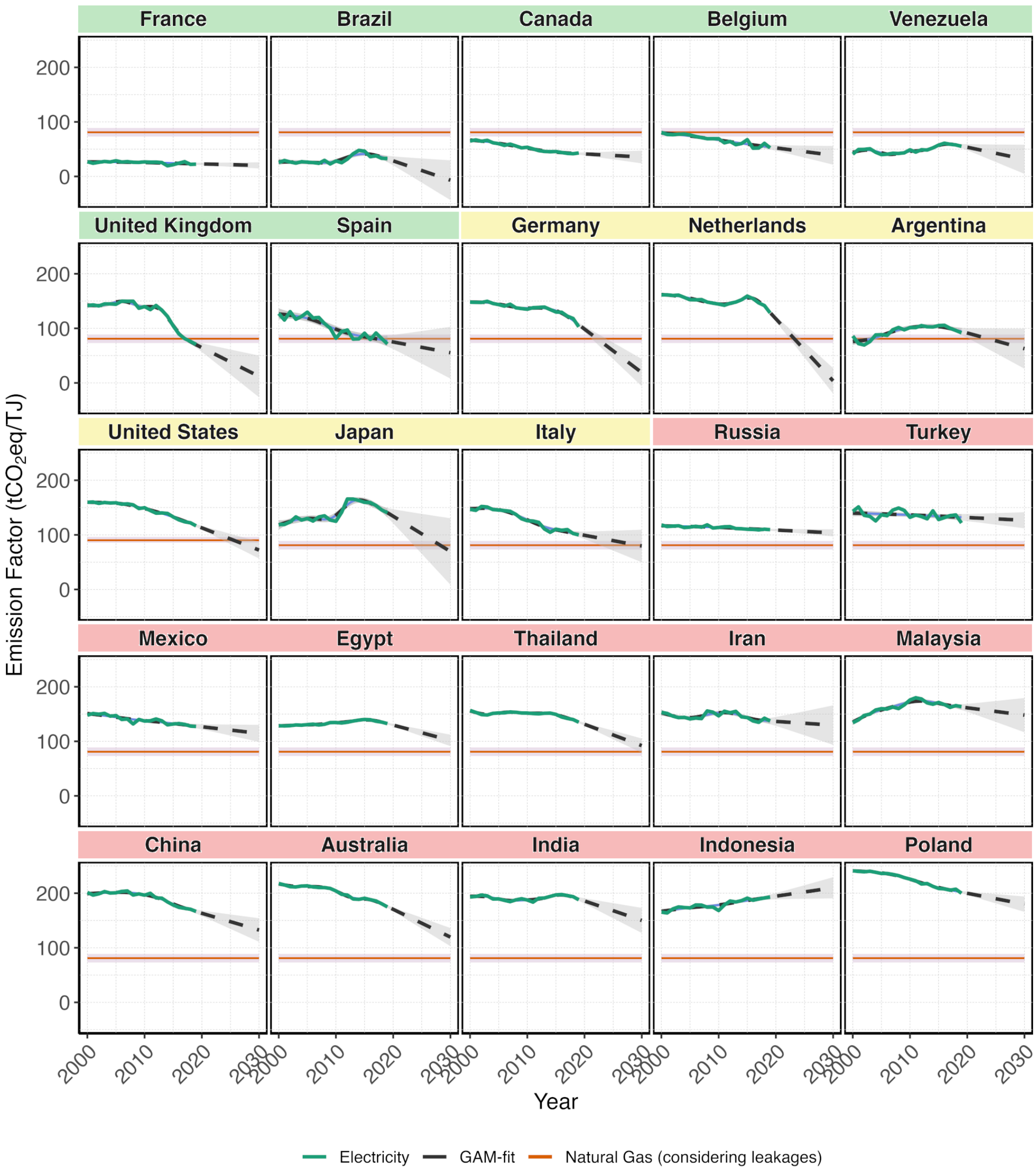

Figure 6. Comparison of CO_2eq emission factors from electricity and natural gas sources over the 20 years from 2000 to 2019 for 25 major natural gas-consuming countries. The methane leakage rate is assumed to be 1.7% with 20% uncertainty (shown as red shaded area). Only for the United States, a leakage rate of 2.3% [2%, 2.7%] is used. The countries are colored based on the time where the break-even point is reached: before 2019 (green), between 2019 and 2030 (yellow), and after 2030 (red).

be replaced by electric appliances globally, e.g. due to the lack of electrical infrastructure. Furthermore, in many countries, natural gas is the cheaper energy source compared to electricity, making it uneconomical for end users to switch from gas to electricity. However, such issues are more political in nature and could be solved by governments. With this study, we therefore show an option in which a significant amount of carbon emissions can be reduced with relatively little effort in the near future.

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Author contributions

FD and JC planned the campaign and designed the concept; SS, KK, JC, FD, GL and AS performed the measurements at Oktoberfest; CvdV and IV analyzed the sample bags; FD, AS, JC, SS and KK analyzed the data; FD, AS and JC prepared the manuscript; HDvdG and TR reviewed and edited the manuscript.

Data availability

All raw data of this study can be provided by the authors upon request.

Supporting Information

The following files are available free of charge.

- SupportingInformation.pdf: additional experimental details, diagrams, and tables to deepen the understanding of the paper

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