

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

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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.

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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 (GWP₂₀ 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

70 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).

75 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).

80 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 CH₄ (Chen et al., 2020), but it remained unclear whether these methane emissions are primarily due to natural gas leakage or biogenic emissions. Despite these CH₄ 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 85 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.

90 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.

100 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 105 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 CH₄/CO₂/H₂O 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.

115 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 perime-

ter 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 CH₄ 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 CH₄ emissions

To quantify the CH₄ 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 CH₄ 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) $\delta^{13}\text{C}$ 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 $\Delta\text{methane}$ 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 $\delta^{13}\text{C}$ 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 $\delta^{13}\text{C}$, 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 $\delta^{13}\text{C}$ (or δD) value of the measured air sample and the methane concentration so that the $\delta^{13}\text{C}$ (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 $\Delta\text{methane}$ 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 ($\text{CH}_{4,\text{bg}}$) and ethane ($\text{C}_2\text{H}_{6,\text{bg}}$) from the measured concentrations ($\text{CH}_{4,\text{sample}}$ and $\text{C}_2\text{H}_{6,\text{sample}}$) to obtain the ratio of the gas added by the source:

$$\frac{\text{C}_2\text{H}_{6,\text{source}}}{\text{CH}_{4,\text{source}}} = \frac{\Delta\text{C}_2\text{H}_6}{\Delta\text{CH}_4} = \frac{\text{C}_2\text{H}_{6,\text{sample}}}{\text{CH}_{4,\text{sample}} - \text{CH}_{4,\text{bg}}} \quad (1)$$

Thereby, we assumed that the ethane concentration $\text{C}_2\text{H}_{6,\text{bg}}$ 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 $\Delta\text{methane}$ 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 ($r_{\text{ethane},\text{Sept}}=3.04\%$) and maximum ($r_{\text{ethane},\text{Oct}}=3.07\%$) 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 ($\text{CO}_{2\text{eq}}$) 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 $EF_{\text{elect}}(t)$, if only electricity would be used as an energy source, Eq. 2 is utilized:

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

These emissions differ for each country and are time-dependent, as the proportions of fuel types used for electricity production $p_{\text{elect},n}(t)$ 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 Ampsonah 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 $EF_{\text{NG},\text{total}}$ 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:

$$EF_{NG,\text{total}} = EF_3 \cdot (1 - r_{\text{leak}}) + \frac{\rho_{\text{CH}_4} \cdot GWP_{20,\text{CH}_4}}{E_{d,\text{NG}}} \cdot r_{\text{leak}} \quad (3)$$

Where r_{leak} is the leakage rate of natural gas, ρ_{CH_4} is the density of CH_4 (0.668 kg/m^3), GWP_{20,CH_4} the 20-year global warming potential of methane considering climate-carbon feedback ($86 \text{ tCO}_2\text{eq/t}$) (Myhre et al., 2013) and $E_{d,\text{NG}}$ the energy density of natural gas ($3.6 \cdot 10^{-5} \text{ TJ/m}^3$)

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 CO₂eq 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 CH₄ emission number

Utilizing all 38 outside rounds during Oktoberfest, we determined an emission number of $(8.5 \pm 0.5) \mu\text{g}(\text{m}^2\text{s})^{-1}$. The value is in the same order of magnitude as the one quantified in 2018: $(6.7 \pm 0.6) \mu\text{g}(\text{m}^2\text{s})^{-1}$ (Chen et al., 2020). Emissions identified for the period after the end of the festival also have a positive offset in 2019 ($2.5 \mu\text{g}(\text{m}^2\text{s})^{-1}$ versus $1.1 \mu\text{g}(\text{m}^2\text{s})^{-1}$). 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 CH₄ 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 CH₄ enhancements, which supports the statement of the Munich public utility company (SWM) that these stations are already carefully monitored and maintained. CH₄ 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 CH₄ 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 CH₄ emissions of Oktoberfest to the atmosphere. This supports the statement of Chen et al.

(2020) that beer tents are the major CH₄ 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, CH₄ 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 δ¹³C 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 [δ¹³C; 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 ($r_{\text{ethane,Okt}}$) by that of the Munich natural gas mix ($r_{\text{ethane,Muc}}$), we calculate the ratio r_{fugitive} between the ethane shares of these two gases to be

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

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.
 345 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 CH₄ at Oktoberfest is determined as the ratio between the CH₄ loss measured with our instruments ($M_{\text{CH}_4,\text{loss}}$) and the total CH₄ consumed at Oktoberfest 2019 ($M_{\text{CH}_4,\text{total}}$), the calculation of which is explained more in detail in Section S2:
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$$r_{\text{leak}} = \frac{M_{\text{CH}_4,\text{loss}}}{M_{\text{CH}_4,\text{total}}} = \frac{1.635 \cdot 10^3 \text{ kg}}{1.186 \cdot 10^5 \text{ kg}} = 1.4\% \quad (5)$$

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.
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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.
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We incorporated all energy information determined for Oktoberfest 2019, such as fossil electricity composition, natural gas CO₂eq emissions, renewable energy type, and CH₄ 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.
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From the intersection of the white line with the CH₄ 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 CH₄ leakages.
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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

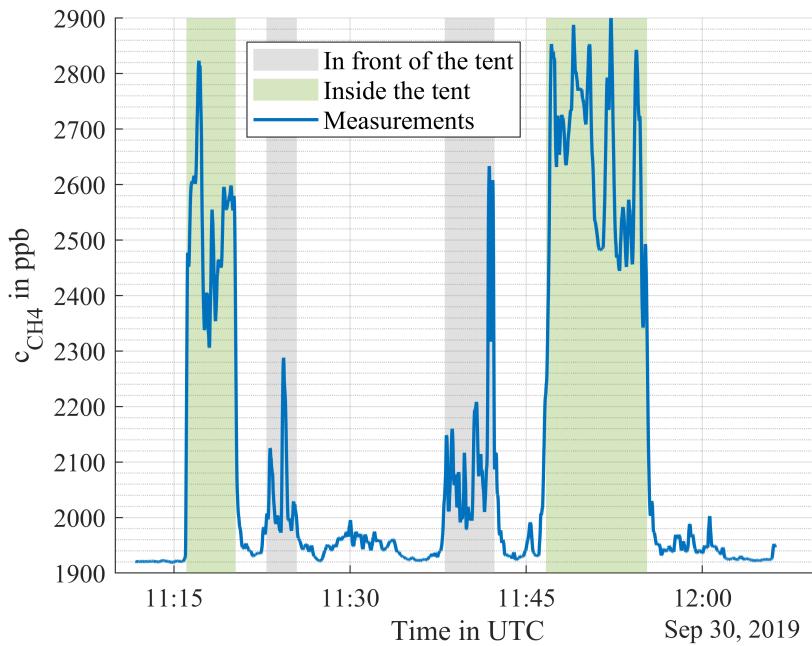


Figure 1. CH₄ mole fractions measured at the Oktoberfest premises. The concentrations are especially enhanced inside (green shaded) and in front of (grey shaded) the beer tents.

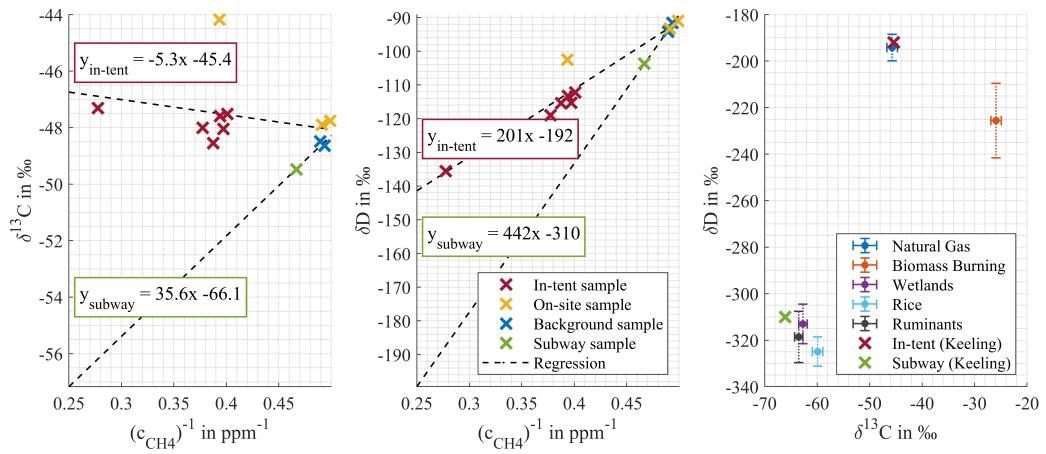


Figure 2. $\delta^{13}\text{C}$ (left) and δD (center) Keeling plot of the air samples taken at Oktoberfest. In addition, two regression lines are shown in both figures for the Oktoberfest and subway samples, respectively, to determine the isotopic signatures of the sources. Right: Isotopic fingerprint ($\delta^{13}\text{C}$ 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.

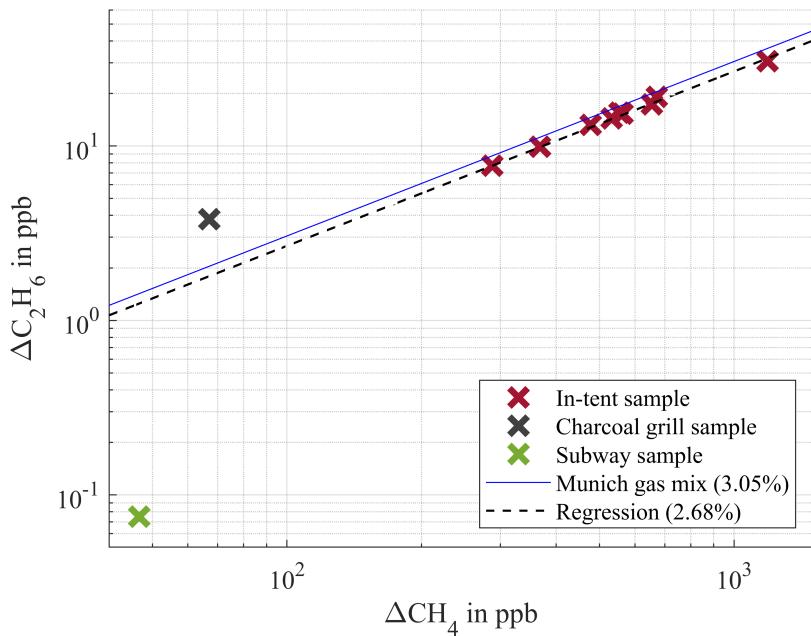


Figure 3. Correlation between Δethane and $\Delta\text{methane}$ of air sampled at various locations at Oktoberfest in a log-log plot. With the exception of the measurements for the subway (green) and the charcoal grill (gray), which show lower and higher ethane enhancement, respectively, all points lie on a line with slope 1, implying a linear relationship between Δethane and $\Delta\text{methane}$. 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.

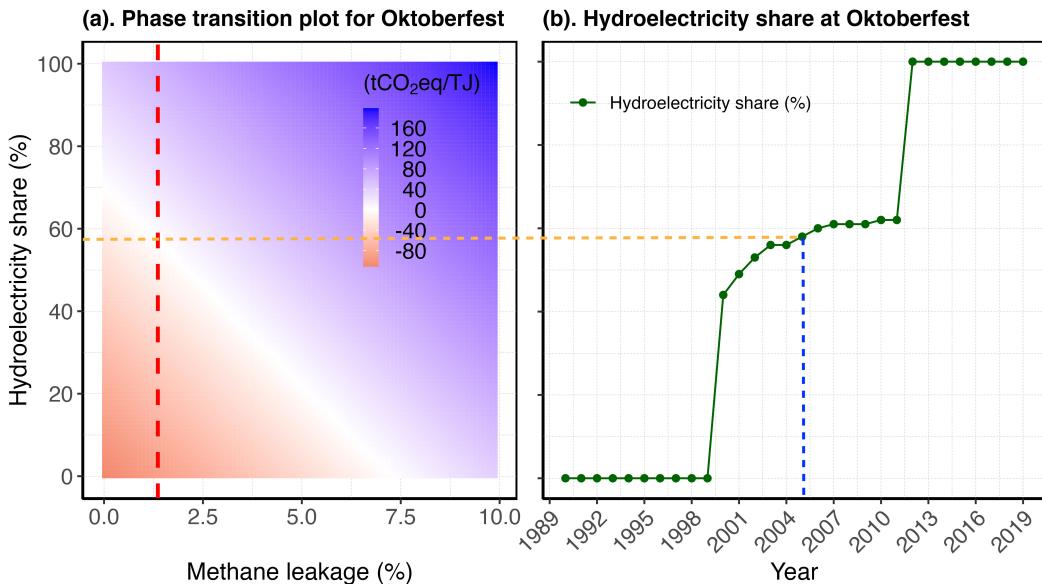


Figure 4. Left: phase transition diagram of hydropower shares in electricity generation versus methane leakage rates. It shows the difference in emissions (in $t\text{CO}_2\text{eq}/\text{TJ}$) between electricity and natural gas as the energy source for heating and cooking at Oktoberfest. For positive 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.

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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 $t\text{CO}_2$ emissions.

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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.

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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
 405 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.
 410

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
 415 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
 420 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)
 425 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 CO₂ emission
 425 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
 430 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
 435 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.
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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 emis-

450 sion 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, 455 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).

460 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

465 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 470 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

480 In this study, the climate impact of gas appliances used for cooking and heating including the effect of CH₄ 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 CH₄ enhancements at the festival was investigated utilizing a portable CH₄ gas analyzer combined with isotopic analyses of air samples to determine the δ¹³C and δD ratios. In addition, the ethane share of the samples was examined.

485 Both isotopic and ethane analyses of the gas indicated that the CH₄ 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 490 sources of CH₄ 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 CH₄ 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).

495 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-

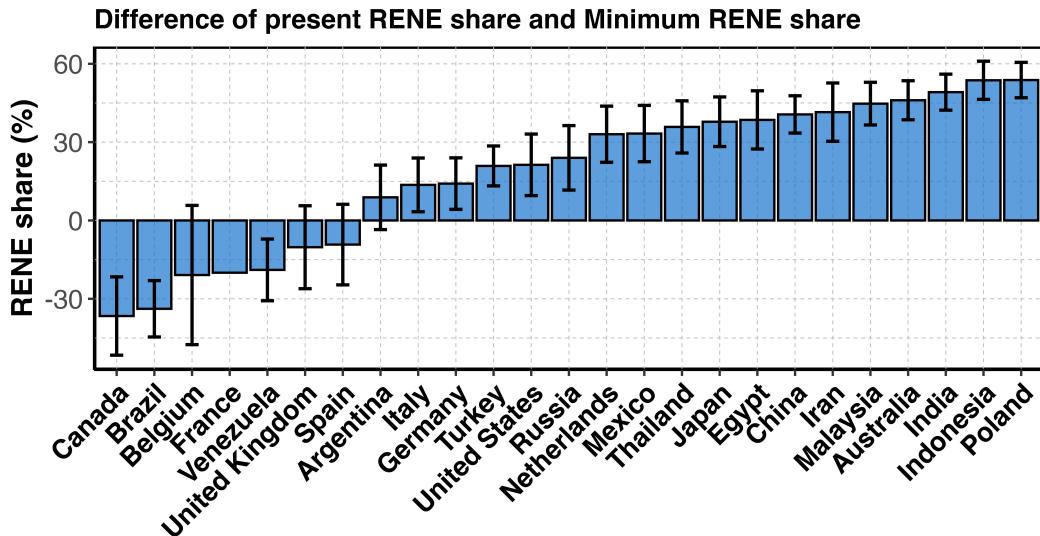


Figure 5. The difference in current renewable energy (RENE) share to reach the break-even point, where natural gas and electricity have the same carbon footprint for 25 countries. Negative values indicate that electricity is already the more climate-friendly energy source compared to natural gas. Values 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 CO₂eq 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

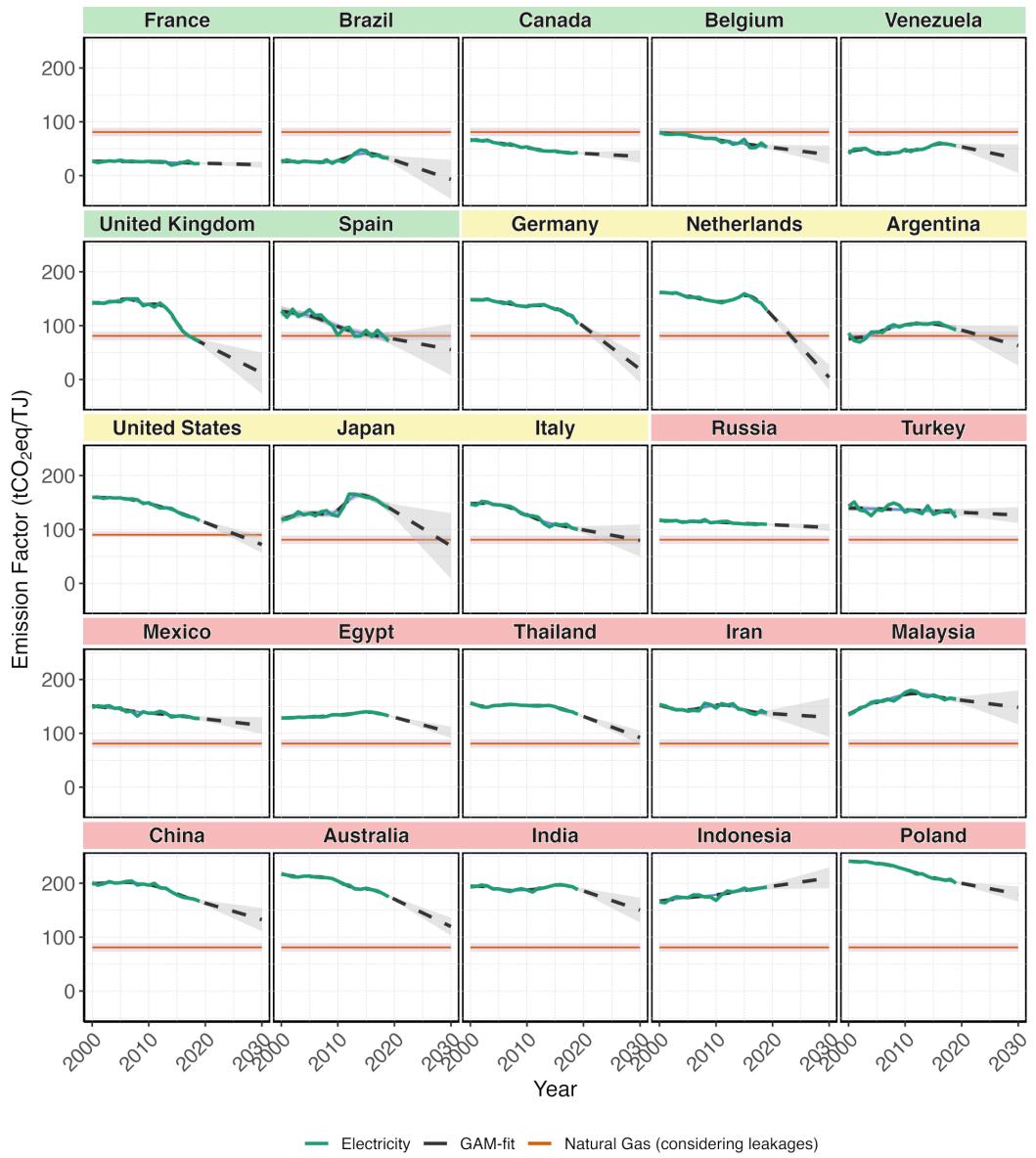


Figure 6. Comparison of CO₂eq emission factors from electricity and natural gas sources over the 20 years from 2000 to 2019 for 25 major natural gas-consuming countries. The methane leakage rate is assumed to be 1.7% with 20% uncertainty (shown as red shaded area). Only for the United States, a leakage 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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Supporting Information for “Climate impact comparison of electric and gas-powered end-user appliances”

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Contents of this file

1. Text S1 to S5
2. Figures S1 to S8
3. Tables S1 to S2

S1. Introduction

This file includes text, figures and tables to deepen the understanding of the publication entitled ‘Climate impact comparison of electric and gas-powered end-user appliances’. All content is referenced in the main manuscript.

S2. Mathematical expressions for $\delta^{13}\text{C}$ and δD method

In this study, we utilized the Vienna Pee Dee Belemnite (VPDB) standard. Eq. 1 shows the mathematical definition of the $\delta^{13}\text{C}$ method:

$$\delta^{13}\text{C}_{sample} = \left(\frac{\left(\frac{^{13}\text{C}}{^{12}\text{C}}\right)_{sample}}{\left(\frac{^{13}\text{C}}{^{12}\text{C}}\right)_{standard}} - 1 \right) \cdot 1000\%_0 \quad (1)$$

Similar to $\delta^{13}\text{C}$, we also looked at the ratio of deuterium to normal hydrogen using the δD method. The equation is analogous to the previous one:

$$\delta D_{sample} = \left(\frac{\left(\frac{CH_3D}{CH_4}\right)_{sample}}{\left(\frac{CH_3D}{CH_4}\right)_{standard}} - 1 \right) \cdot 1000\%_0 \quad (2)$$

As a standard for the δD method, we utilized the Vienna Standard Mean Ocean Water (VSMOW).

S3. Leakage rate calculation for Oktoberfest

To calculate the methane leakage rate (r_{leak}) at Oktoberfest, the total mass of methane consumed at Oktoberfest 2019 ($M_{\text{CH}_4,\text{total}}$) and the mass of methane leaking ($M_{\text{CH}_4,\text{loss}}$) are related.

Knowing the total gas consumption of Oktoberfest 2019 is $m_{\text{gas}} = 185\,000\text{ m}^3$, the density of CH_4 is $\rho_{\text{CH}_4} = 0.668\text{ kg m}^{-3}$ and the CH_4 share of the natural gas in Munich is on average about $r_{\text{CH}_4} = 96\%$ (SWM Infrastruktur GmbH und Co. KG, 2020), the total mass of methane consumed at Oktoberfest can be calculated as:

$$\begin{aligned} M_{\text{CH}_4,\text{total}} &= m_{\text{gas}} \cdot r_{\text{CH}_4} \cdot \rho_{\text{CH}_4} = \\ &= 1.85 \cdot 10^5 \text{ m}^3 \cdot 0.96 \cdot 0.668 \frac{\text{kg}}{\text{m}^3} = \\ &= 1.186 \cdot 10^5 \text{ kg} \end{aligned} \quad (3)$$

To determine the CH₄ losses at Oktoberfest, the emission strength of Oktoberfest ($E_{\text{Okt}} = 8.5 \mu\text{g}(\text{m}^2\text{s})^{-1}$) is multiplied with the fugitives ratio $r_{\text{fugitive}} = 88\%$, the festival area $a_{\text{Okt}} = 3.45 \cdot 10^5 \text{ m}^2$ and the duration t_{Okt} , assuming that the Oktoberfest operates 11 h per day and the emission is continuous throughout the day.

$$\begin{aligned}
 M_{\text{CH}_4, \text{loss}} &= E_{\text{Okt}} \cdot r_{\text{fugitive}} \cdot t_{\text{Okt}} \cdot a_{\text{Okt}} = \\
 &= 8.5 \frac{\mu\text{g}}{\text{m}^2\text{s}} \cdot r_{\text{fugitive}} \cdot (16 \text{ d} \cdot 11 \frac{\text{h}}{\text{d}} \cdot 3600 \frac{\text{s}}{\text{h}}) \cdot 3.45 \cdot 10^5 \text{ m}^2 = \\
 &= 1.635 \cdot 10^3 \text{ kg}
 \end{aligned} \tag{4}$$

S4. Temporal development of energy usage at Oktoberfest

In the 30 years between 1990 and 2019, the average total energy consumption (electricity plus natural gas) of Oktoberfest was 17.4 ± 1.8 (1σ) Tera Joule (TJ) during the 16 to 18 days of the festivity. There was an increasing trend in total energy consumption (Figure S1), which was mainly driven by the increase in electricity usage (Figure S2a), with total electricity consumption increasing from 6.2 TJ in 1990 to about 10.2 TJ in 2019 (64% increase). Natural gas consumption has remained fairly constant over the past 30 years, with the most recent natural gas consumption in 2019 (7.4 TJ) actually being lower than in 1990 (7.7 TJ) (Figure S2a). At the same time, however, the share of renewable energies (in this case pure hydropower) in the electricity supply has increased significantly, from 0% in 1990 to about 44% share in 2000 to full 100% hydropower supply since 2012 (Figure 4, right). This increased share of renewable energy resulted in cleaner electricity and a jump in estimated total CO_{2eq} emissions from electricity consumption in 2000 and in 2012. As a result, the carbon footprint of total natural gas consumption at Oktoberfest was smaller than that of total electricity consumption until 2011, after which

electricity produced the smaller total carbon footprint (Figure S2c). Furthermore, the CO₂eq emission factors were higher for electricity than for natural gas (including leakage) only until 2002, due to the fossil fuel-based electricity supply of Oktoberfest (Figure S2d). After the share of green electricity continued to increase since 2000 until it reached 100% in 2012, CO₂eq emission factors of electrical energy consumed have decreased from 160 t to now 3.6 t CO₂eq/TJ of electricity consumption in 2019. In comparison, the carbon footprint of natural gas has been quite constant over the years, with a value of 71.7 t CO₂eq/TJ in 2019.

S5. Temporal development of global emission factors

Depending on the types and shares of renewable (wind, hydropower, solar and geothermal/biomass) and non-renewable energy (coal, oil, natural-gas and nuclear) used for electricity generation (see Figures S3 and S4), the total emission factors for renewable and non-renewable electricity differ from country to country (see Figure S5). Although the emission factors of renewables also vary over time, these variations do not contribute significantly to the overall emission number, as emissions from non-renewable sources, with the exception of nuclear power, are generally much higher (e.g. 7.22 tCO₂eq/TJ for wind energy vs. 246.67 tCO₂eq/TJ for electricity generated by coal; see Table 1). Only in France the emission factors for non-renewable and renewable electricity are in the same order of magnitude (see Figure S5), since France relies mainly (more than 70% throughout the last 20 years) on nuclear power as a non-renewable source for energy production (see Figure S3).

S6. Country comparison - phase transition plots

The emissions of natural gas versus electricity of these 25 countries for 2019 were examined using phase transition diagrams. Since our Oktoberfest results, as well as many other studies (Alvarez et al., 2012; Wigley, 2011; Pandey et al., 2019; Schneising et al., 2020; Weller et al., 2020), show that there is methane leakage in the upstream, midstream, and downstream natural gas process, we used the emission factor of natural gas, including the climate impact of leaking CH₄.

In these diagrams (see Figure S6), the climate friendliness of the accumulated non-renewable energy sources is indicated by the intersection of the white line with the x-axis. The farther to the left the intersection point is, the less carbon emissions are caused by non-renewable energy resources. One can see that, in addition to France, countries such as Belgium, Canada, Spain and the United Kingdom show comparable small non-renewable energy emissions, all due to a relatively high share of nuclear energy in electricity generation. Such a fact results in less renewable energy needed to reach the break-even point, where electricity and natural gas have the same carbon footprint (see dashed orange lines in Figure S6). In addition, the current shares of renewables for each country are shown as dashed green lines to see, how much effort is still needed to reach the break-even point.

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Table S1. Emission factors EF_n used for electricity generation from different fuels, adopted from (Amponsah et al., 2014).

n	Fuel	Type	Emission factor (EF)
1	Coal	non-renewable	246.67 tCO ₂ eq/TJ
2	Oil	non-renewable	203.61 tCO ₂ eq/TJ
3	Natural gas	non-renewable	138.67 tCO ₂ eq/TJ
4	Solar	renewable	23.61 tCO ₂ eq/TJ
5	Geothermal/Biomass	renewable	11.39 tCO ₂ eq/TJ
6	Nuclear	non-renewable	8.05 tCO ₂ eq/TJ
7	Hydro	renewable	8.05 tCO ₂ eq/TJ
8	Wind	renewable	7.22 tCO ₂ eq/TJ

Table S2. Octoberfest statistics for the years 1990 to 2019. Data are adopted from (oktoberfest.de Redaktion, 2019) (for 2019), (Landeshauptstadt München, 2019) (for 2001 to 2018), (Landeshauptstadt München Redaktion, 2000) (for 2000) and (Landeshauptstadt München Redaktion, 2020) (for 1990 to 1998).

Year	Electricity (in kWh)	Gas (in m ³)	Water (in m ³)	RENE share (in %)	Duration (in days)	Visitors (in mio.)
2019	2,840,000	185,000	105,000	100	16	6.3
2018	2,925,157	200,937	107,090	100	16	6.3
2017	3,247,385	223,156	116,184	100	18	6.2
2016	2,708,001	197,790	111,565	100	17	5.9
2015	2,887,032	233,846	128,855	100	16	5.9
2014	3,007,610	225,902	129,606	100	16	6.3
2013	3,056,207	243,437	122,184	100	16	6.4
2012	2,730,083	220,915	114,612	100	16	6.4
2011	2,972,463	201,516	124,456	62	17	6.9
2010	3,050,370	228,110	123,854	62	17	6.4
2009	2,627,987	183,001	108,643	61	16	5.7
2008	2,630,676	244,295	105,756	61	16	6.0
2007	2,714,537	197,126	104,531	61	16	6.2
2006	2,961,629	198,489	107,641	60	18	6.5
2005	2,866,152	207,191	96,728	58	17	6.1
2004	2,439,799	198,000	88,023	56	16	5.9
2003	2,331,749	184,299	89,587	56	16	6.3
2002	2,721,470	188,489	90,370	53	16	5.9
2001	2,519,276	172,200	84,744	49	16	5.5
2000	2,645,618	203,602	95,221	44	18	6.9
1999	2,452,001	182,841	82,393	0	16	6.5
1998	2,344,720	205,655	80,505	0	16	6.5
1997	2,287,970	195,515	84,000	0	16	6.4
1996	2,174,561	217,026	86,700	0	16	6.9
1995	2,287,968	198,616	86,600	0	16	6.7
1994	2,351,794	198,456	73,594	0	17	6.6
1993	1,922,168	194,170	69,000	0	16	6.5
1992	N/A	N/A	N/A	0	16	5.9
1991	1,955,513	N/A	69,000	0	16	6.4
1990	1,731,190	194,170	65,000	0	16	6.7

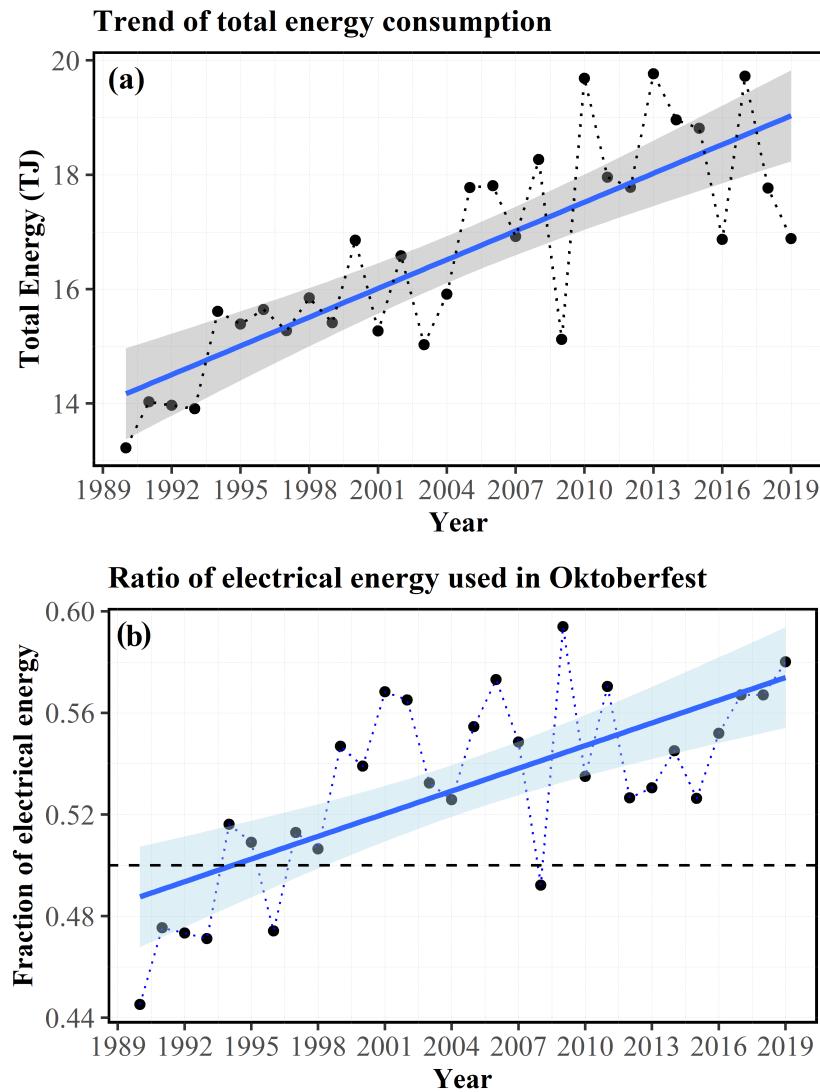


Figure S1. Top: trends in energy consumption at Oktoberfest. Bottom: fraction of electrical energy used at Oktoberfest from 1990 to 2019.

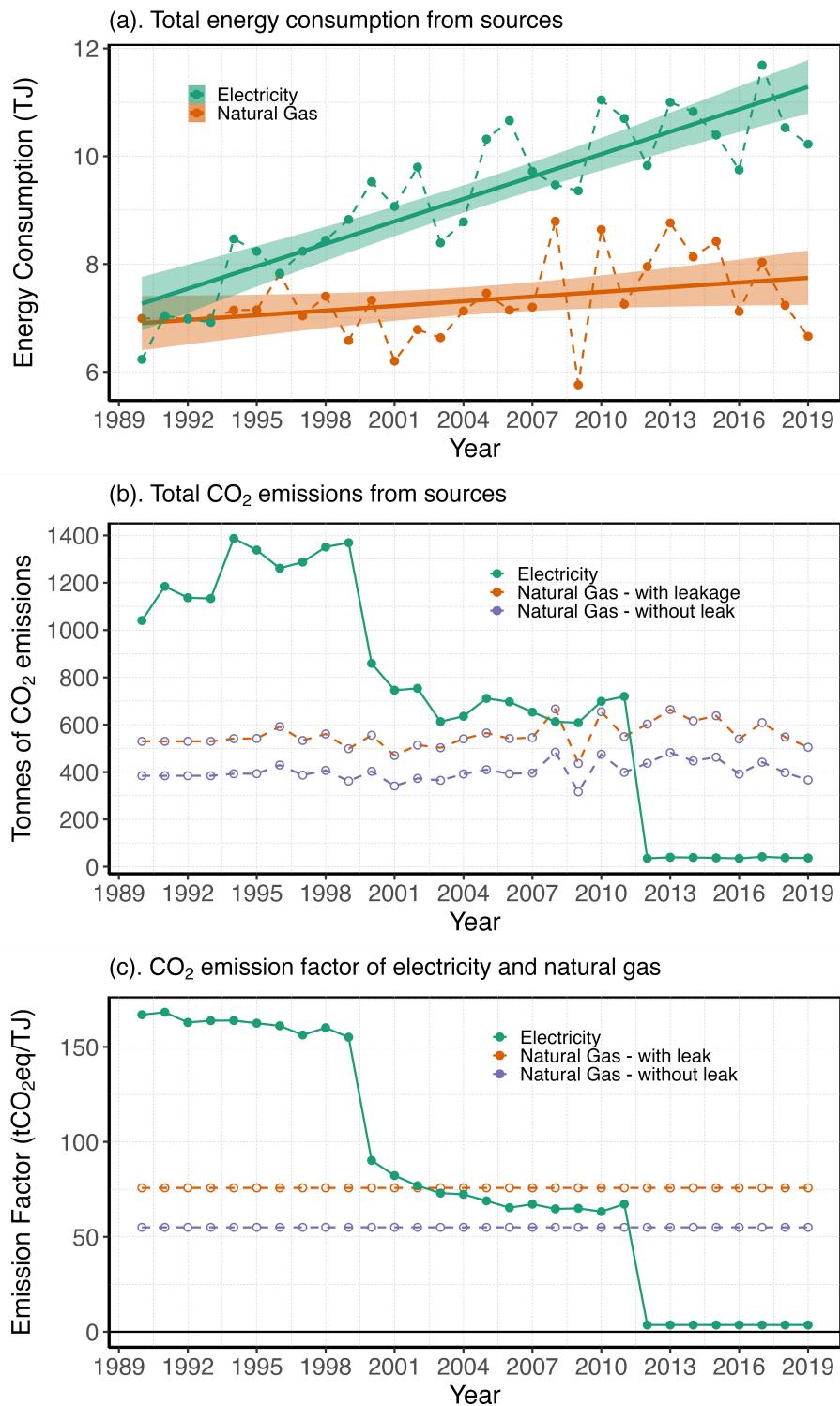


Figure S2. Energy consumption and emission statistics of Oktoberfest by electricity and natural gas sources from 1990 to 2019. (a) total energy consumption; (b) total CO₂ emissions from energy consumed; and (c) CO₂ emission factors for electricity (green), natural gas with 1.4% leakage rate (orange), and no leakage rate (purple).

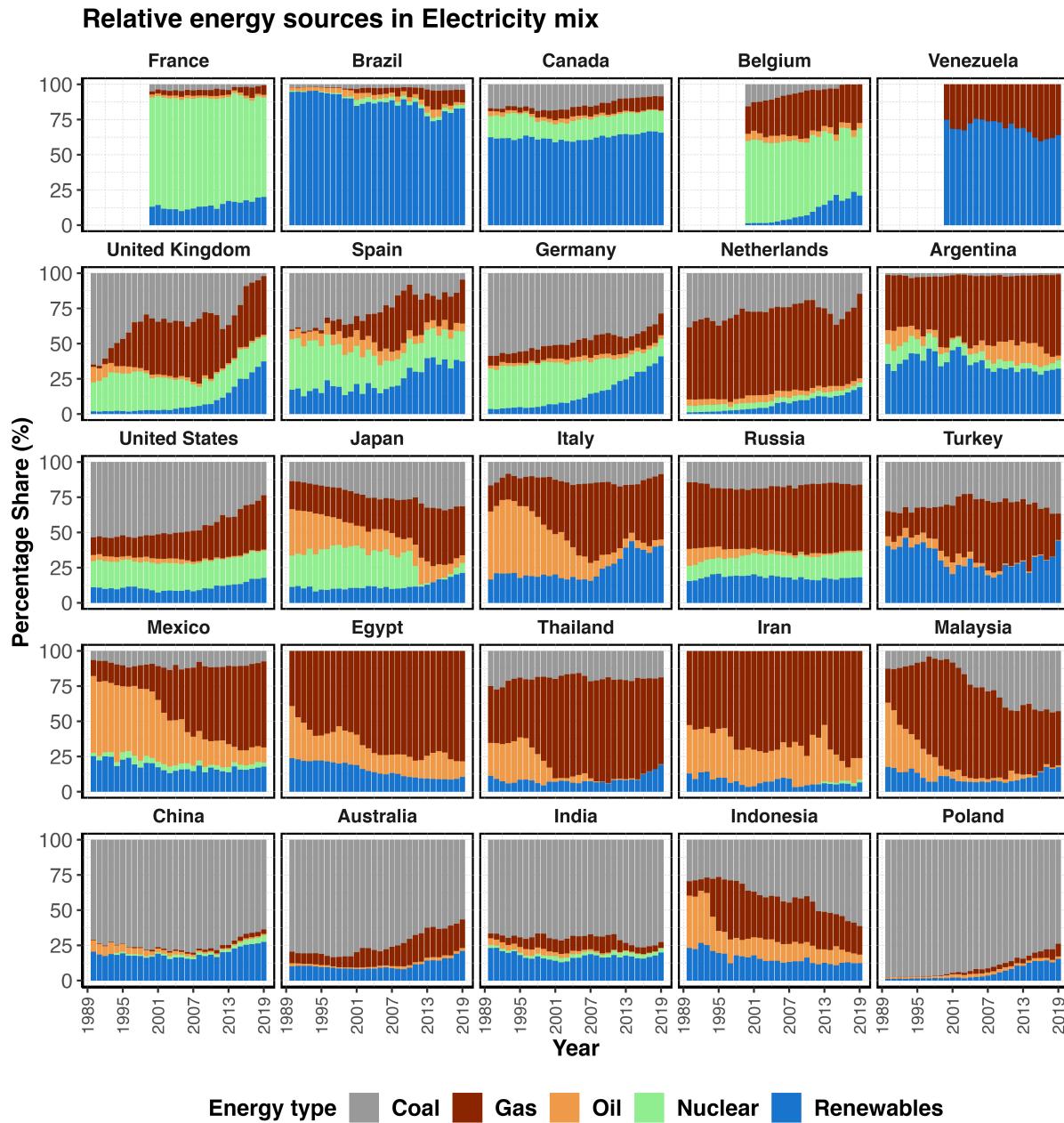


Figure S3. Relative share of the different types of energy sources (fossil fuel and renewable as colored bars) in electricity mix generation over the 30 years from 1990 to 2019 across 25 major natural gas consuming countries (20 years for Belgium, France and Venezuela). Data are adopted from (bp, 2020).

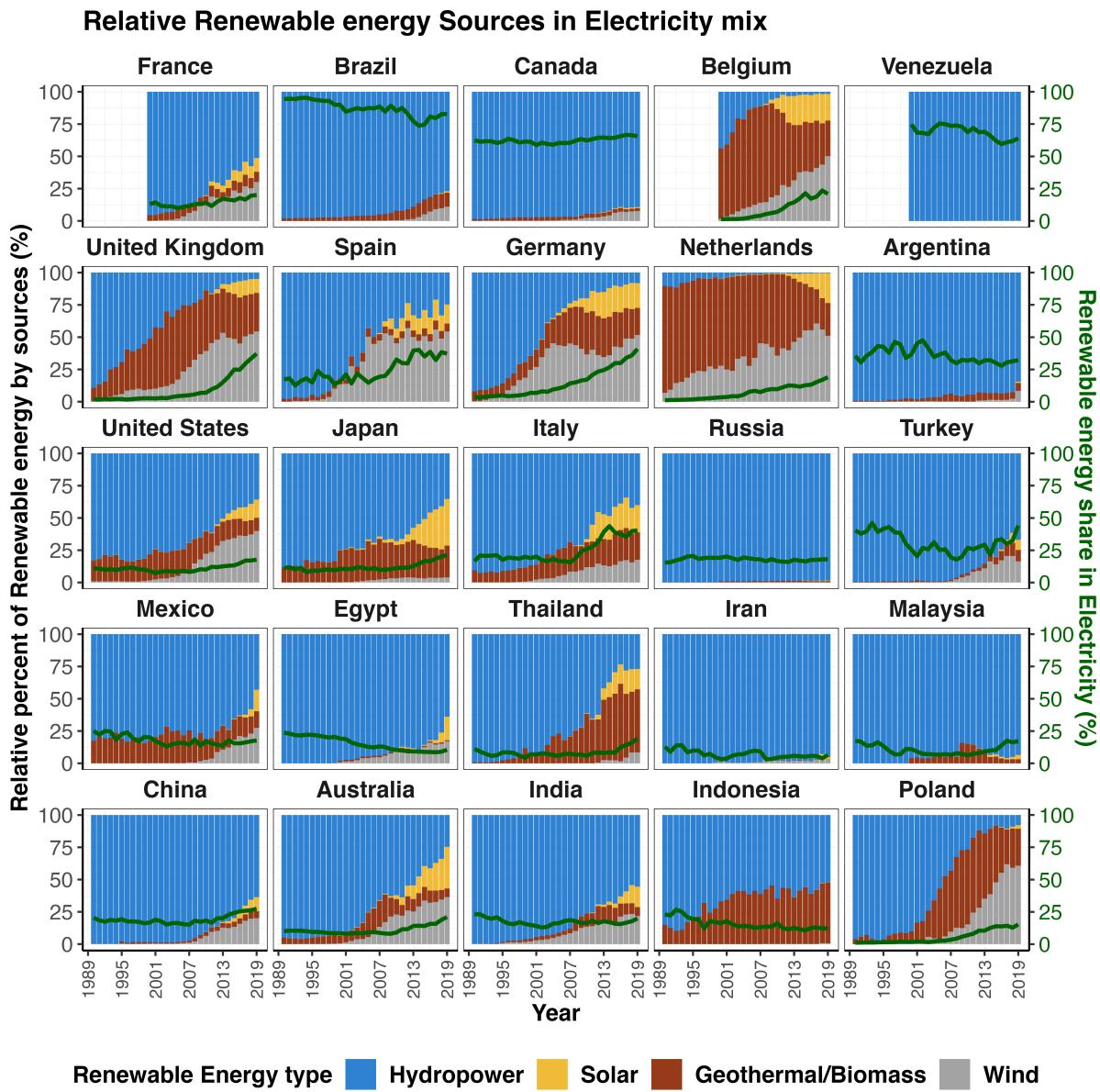


Figure S4. Relative share of the different types of renewable energy sources (colored bars) and share of renewable energy in total electricity consumption (in dark green line) over the 30 years from 1990 to 2019 across 25 major natural gas consuming countries (20 years for Belgium, France and Venezuela). Data are adopted from (bp, 2020).

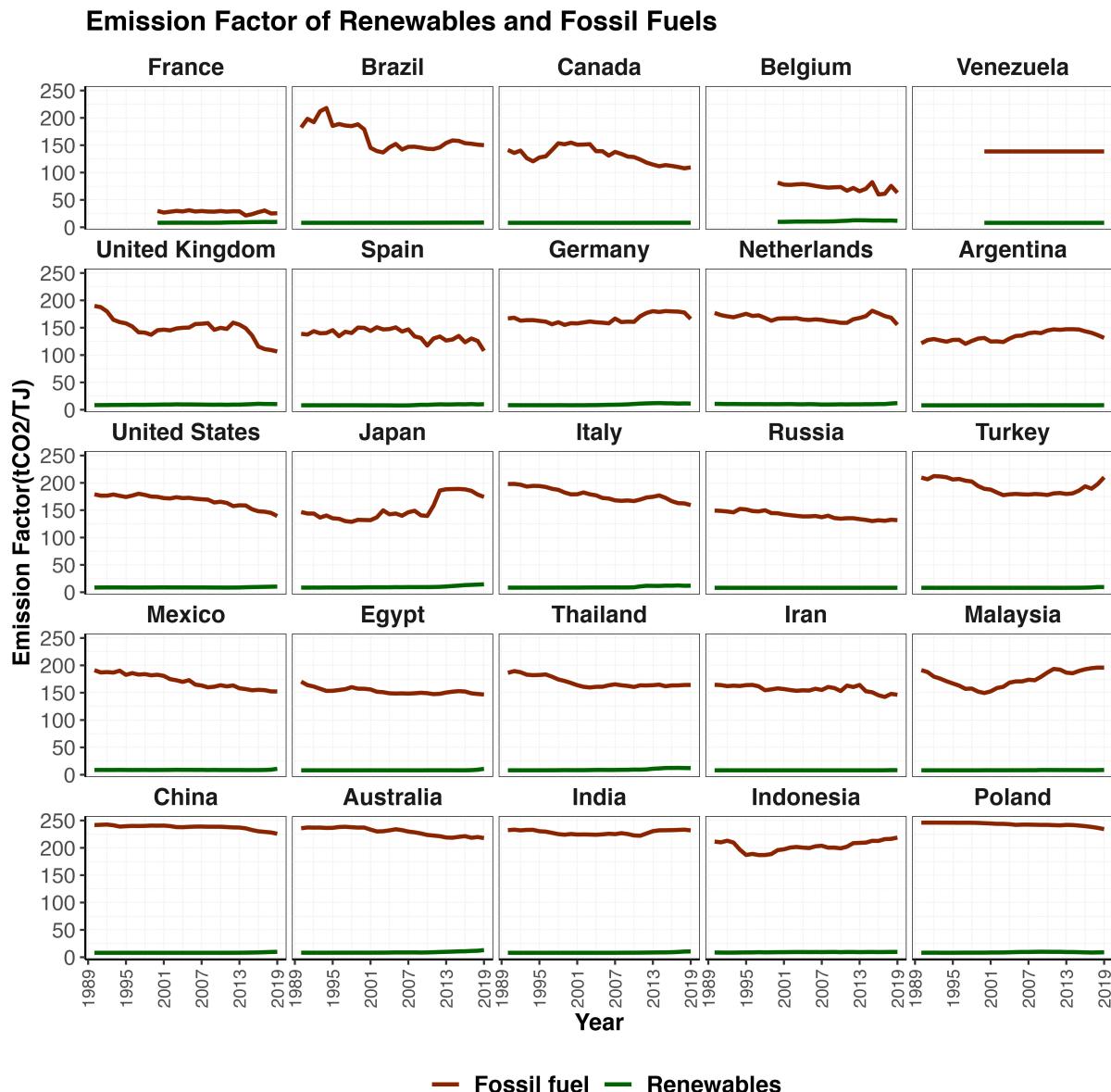


Figure S5. Emission factors of fossil fuel and renewable energy over the 30 years from 1990 to 2019 across 25 major natural gas consuming countries. Data are adopted from (bp, 2020).

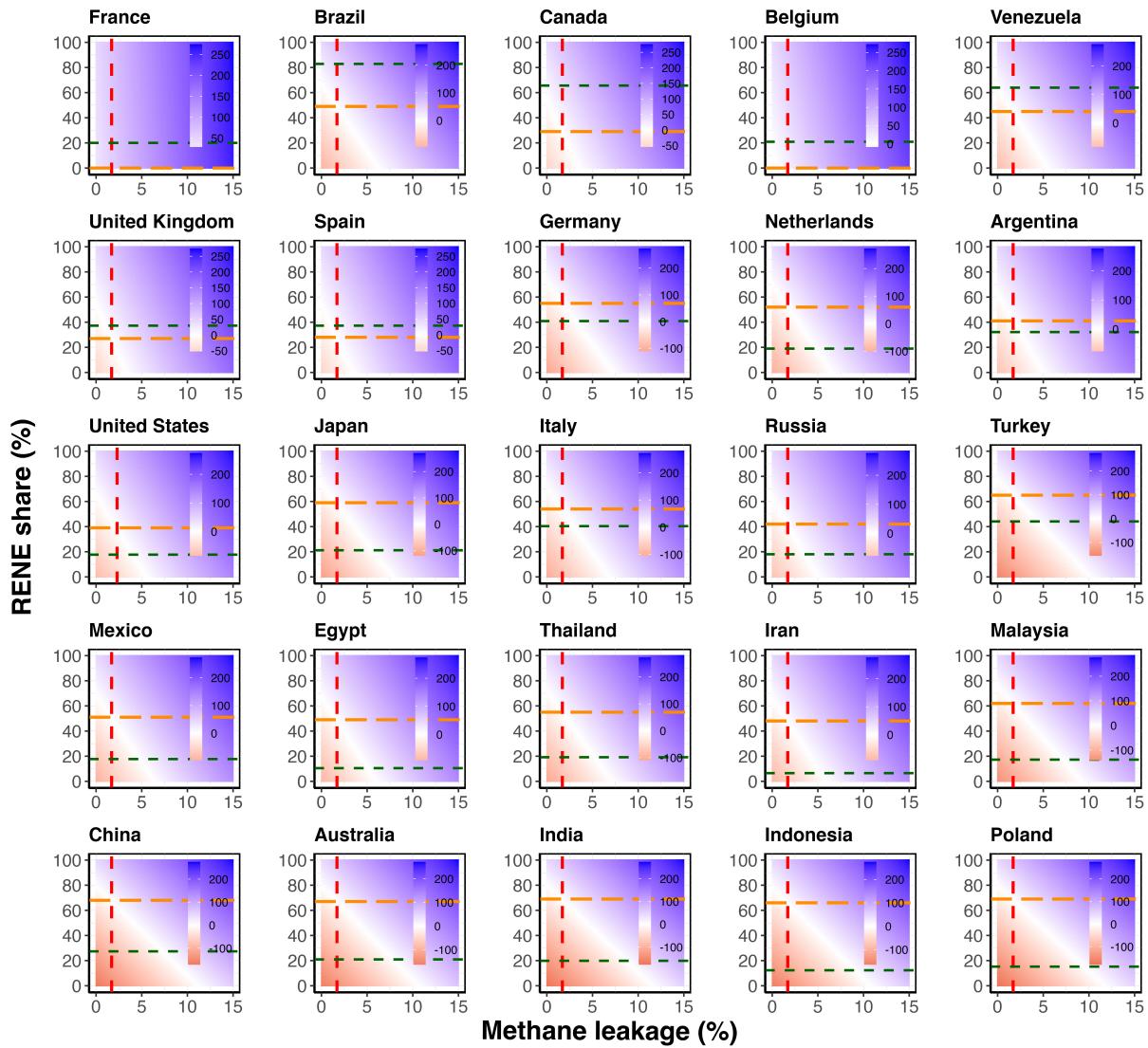


Figure S6. Phase transition plot for 25 countries based on electricity mix of 2019.

The blue/red area represents where electricity/natural-gas is a better energy option. The vertical red line represents the mean methane leakage rate, whereas the horizontal dark green and orange dash line represents the current RENE share and break-even point where natural gas and electricity have the same carbon footprint.

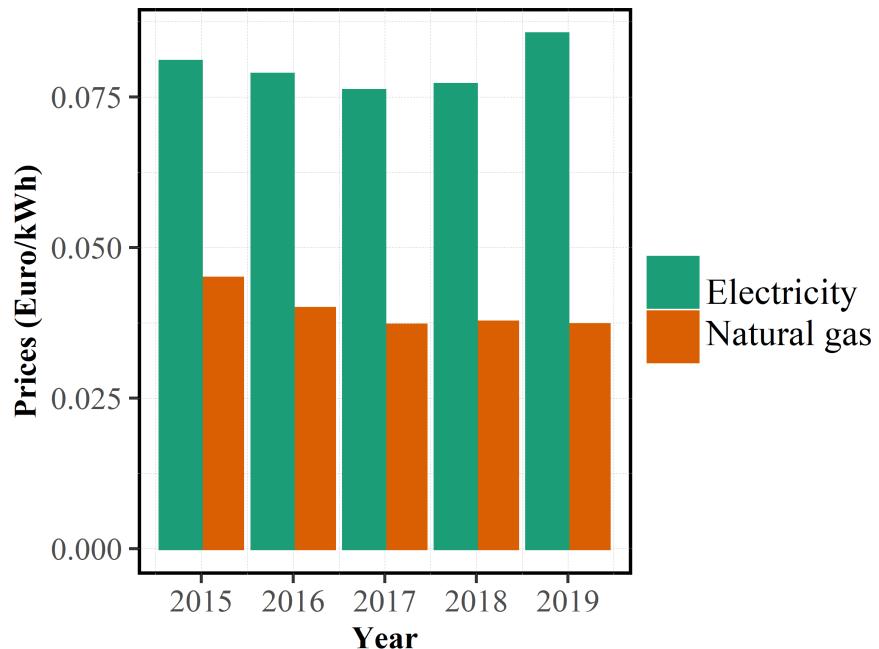


Figure S7. Development of the gas and electricity costs in Germany for 1kWh of energy each. Data are adopted from (Eurostat, 2021a, 2021b).

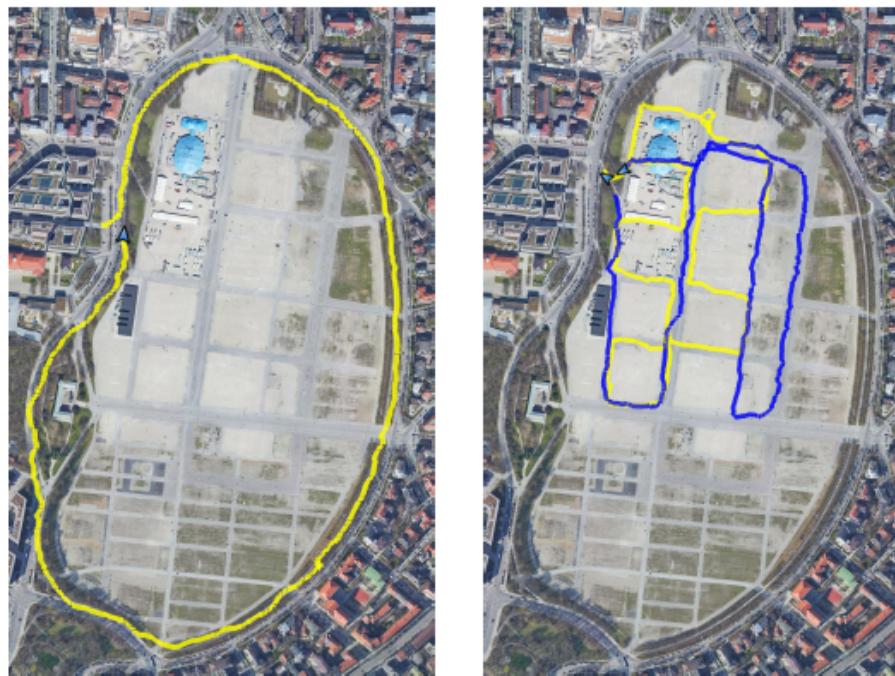


Figure S8. Illustration of the track around the perimeter of Oktoberfest (left; yellow) and the two different tracks on the site (right; yellow and blue). Map data are from ©Google, DigitalGlobe.