# Supporting Information for "Climate impact comparison of electric and gas-powered end-user appliances"

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## 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 $\delta^{13}$C and $\delta$D method

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

$$\delta^{13}C_{sample} = \left( \frac{\left(\frac{^{13}C}{^{12}C}\right)_{sample}}{\left(\frac{^{13}C}{^{12}C}\right)_{standard}} - 1 \right) \cdot 1000‰ \tag{1}$$

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

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

As a standard for the $\delta$D method, we utilized the Vienna Standard Mean Ocean Water (VSMOW).

## S3. Leakage rate calculation for Oktoberfest

To calculate the methane leakage rate ($r_{\mathrm{leak}}$) at Oktoberfest, the total mass of methane consumed at Oktoberfest 2019 ($\mathrm{M}_{\mathrm{CH_4,total}}$) and the mass of methane leaking ($\mathrm{M}_{\mathrm{CH_4,loss}}$) are related.

Knowing the total gas consumption of Oktoberfest 2019 is $m_{\mathrm{gas}}$ =185 000 m$^3$, the density of $CH_4$ is $\rho_{\mathrm{CH4}} = 0.668\,\mathrm{kgm^{-3}}$ and the $CH_4$ share of the natural gas in Munich is on average about $r_{\mathrm{CH4}} = 96\%$ (SWM Infrastruktur GmbH und Co. KG, 2020), the total mass of methane consumed at Oktoberfest can be calculated as:

$$\begin{aligned} M_{\mathrm{CH_4,total}} &= m_{\mathrm{gas}} \cdot r_{\mathrm{CH4}} \cdot \rho_{\mathrm{CH4}} = \\ &= 1.85 \cdot 10^5 \mathrm{m}^3 \cdot 0.96 \cdot 0.668 \frac{\mathrm{kg}}{\mathrm{m}^3} = \\ &= 1.186 \cdot 10^5 \mathrm{kg} \end{aligned} \tag{3}$$

To determine the $CH_4$ losses at Oktoberfest, the emission strength of Oktoberfest ($E_{\mathrm{Okt}} = 8.5\,\mu\mathrm{g}(\mathrm{m}^2\mathrm{s})^{-1}$) is multiplied with the fugitives ratio $\mathrm{r}_{\mathrm{fugitive}} = 88\%$, the festival area $\mathrm{a}_{\mathrm{Okt}} = 3.45 \cdot 10^5\,\mathrm{m}^2$ and the duration $t_{\mathrm{Okt}}$, assuming that the Oktoberfest operates 11 h per day and the emission is continuous throughout the day.

$$
\begin{aligned}
M_{\mathrm{CH_4,loss}} &= E_{\mathrm{Okt}} \cdot r_{\mathrm{fugitive}} \cdot t_{\mathrm{Okt}} \cdot a_{\mathrm{Okt}} = \\
&= 8.5\,\frac{\mu\mathrm{g}}{\mathrm{m}^2\mathrm{s}} \cdot r_{\mathrm{fugitive}} \cdot (16\,\mathrm{d} \cdot 11\,\frac{\mathrm{h}}{\mathrm{d}} \cdot 3600\,\frac{\mathrm{s}}{\mathrm{h}}) \cdot 3.45 \cdot 10^5\,\mathrm{m}^2 = \\
&= 1.635 \cdot 10^3\,\mathrm{kg}
\end{aligned}
\tag{4}
$$

## 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 ($1\sigma$) 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 $CO_2$eq 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 $CO_2$eq 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, $CO_2$eq emission factors of electrical energy consumed have decreased from 160 t to now 3.6 t $CO_2$eq/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 $CO_2$eq/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 $tCO_2$eq/TJ for wind energy vs. 246.67 $tCO_2$eq/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 $CH_4$.

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 $tCO_2eq/TJ$ |
| 2 | Oil | non-renewable | 203.61 $tCO_2eq/TJ$ |
| 3 | Natural gas | non-renewable | 138.67 $tCO_2eq/TJ$ |
| 4 | Solar | renewable | 23.61 $tCO_2eq/TJ$ |
| 5 | Geothermal/Biomass | renewable | 11.39 $tCO_2eq/TJ$ |
| 6 | Nuclear | non-renewable | 8.05 $tCO_2eq/TJ$ |
| 7 | Hydro | renewable | 8.05 $tCO_2eq/TJ$ |
| 8 | Wind | renewable | 7.22 $tCO_2eq/TJ$ |

**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 |

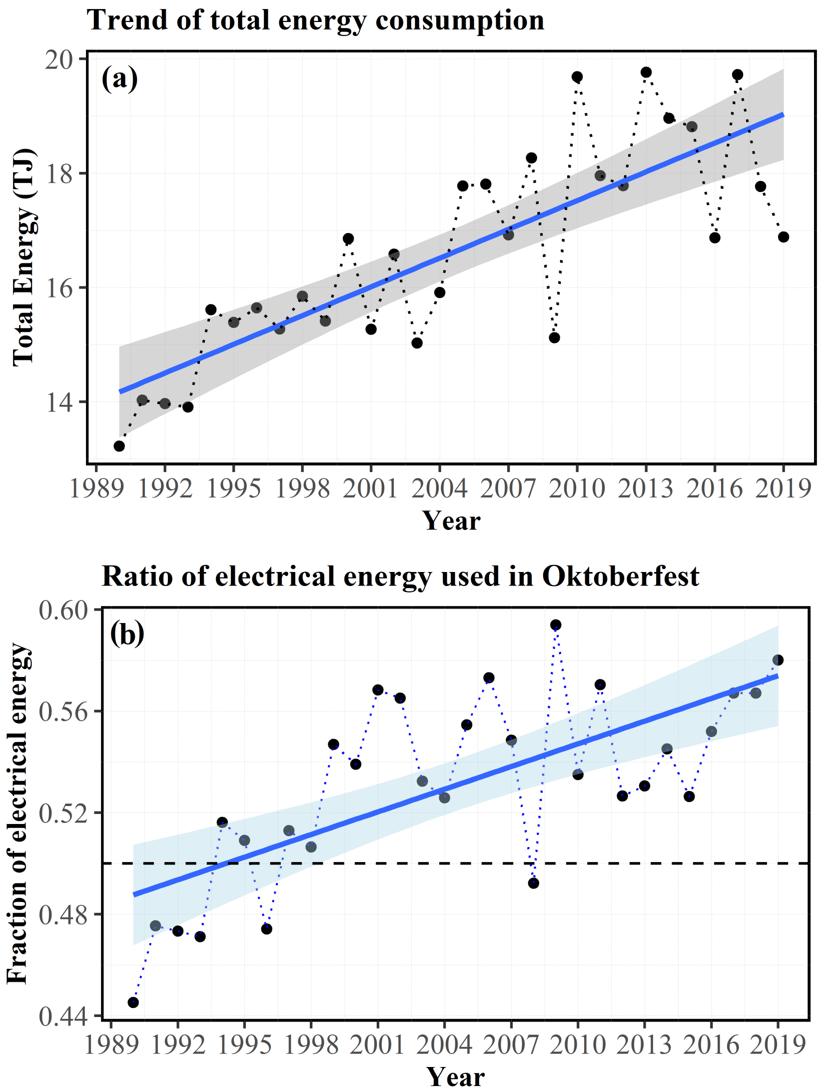


**Figure S1.** Top: trends in energy consumption at Oktoberfest. Bottom: fraction of electrical energy used at Oktoberfest from 1990 to 2019.

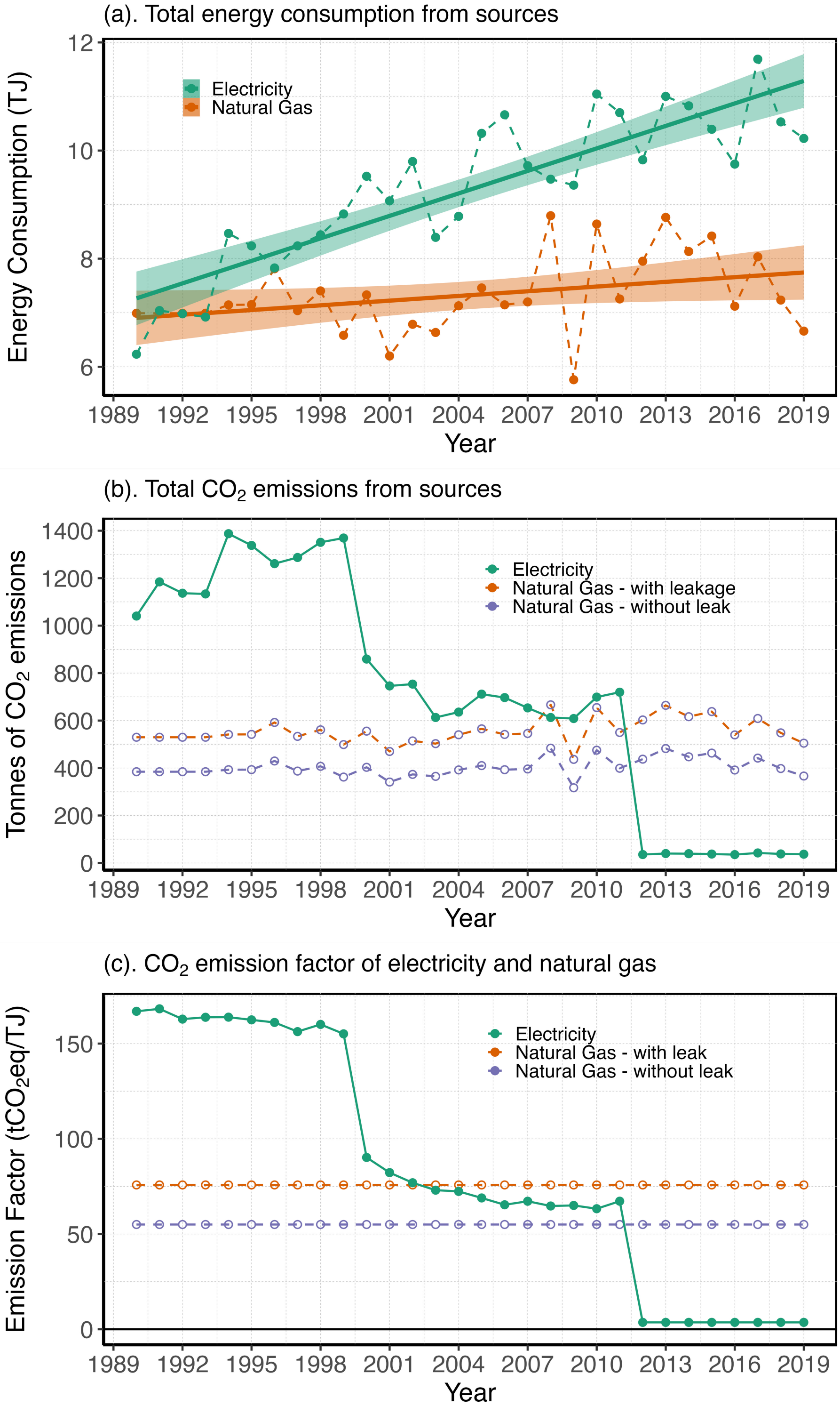


**Figure S2.** Energy consumption and emission statistics of Oktoberfest by electricity and natural gas sources from 1990 to 2019. (a) total energy consumption; (b) total $CO_2$ emissions from energy consumed; and (c) $CO_2$ emission factors for electricity (green), natural gas with 1.4% leakage rate (orange), and no leakage rate (purple).

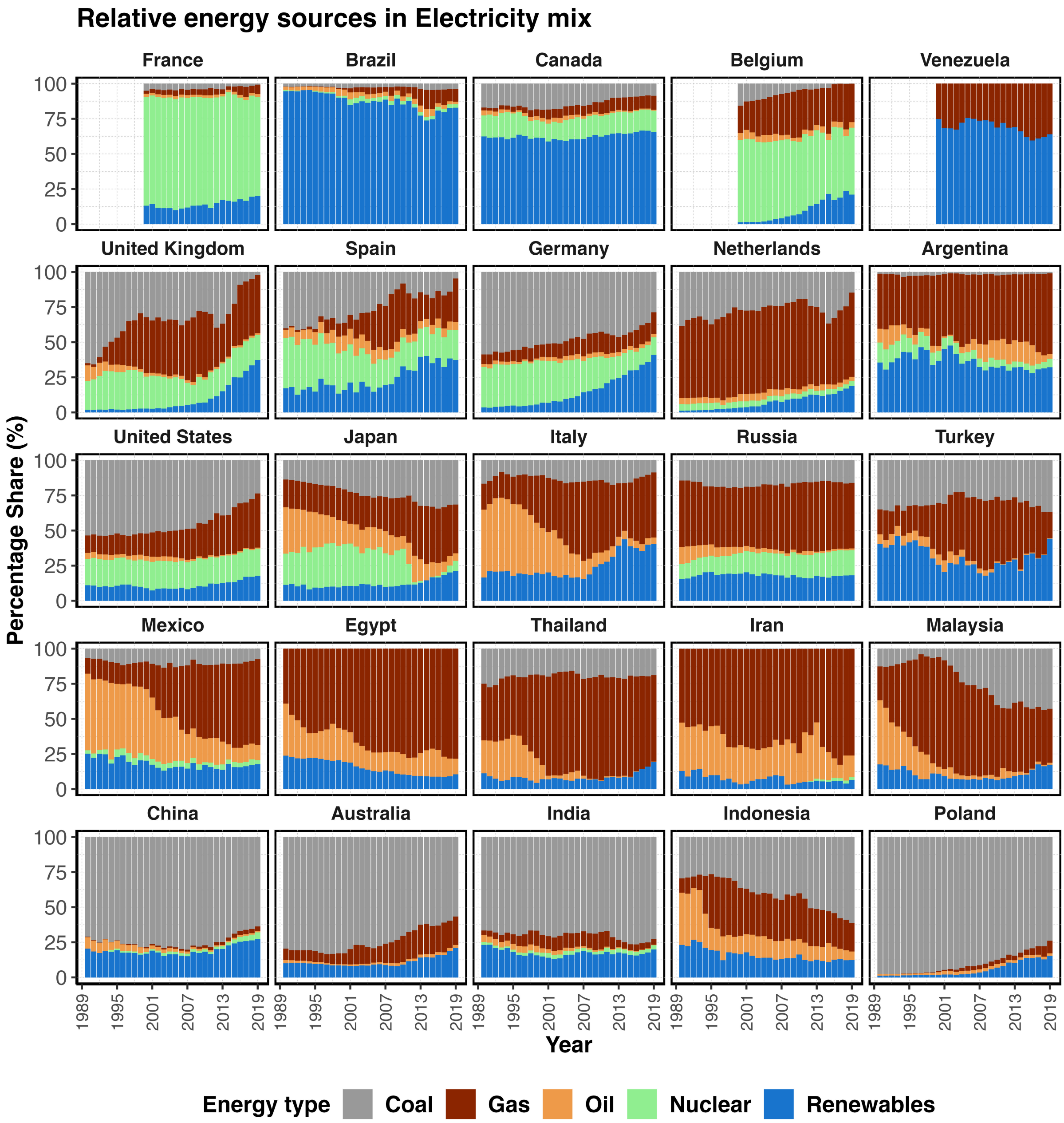


**Figure S3.** Relative share of the different types of energy sources (fossil fuel and renewable as colored bars) in electricity mix generation over the 30 years from 1990 to 2019 across 25 major natural gas consuming countries (20 years for Belgium, France and Venezuela). Data are adopted from (bp,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

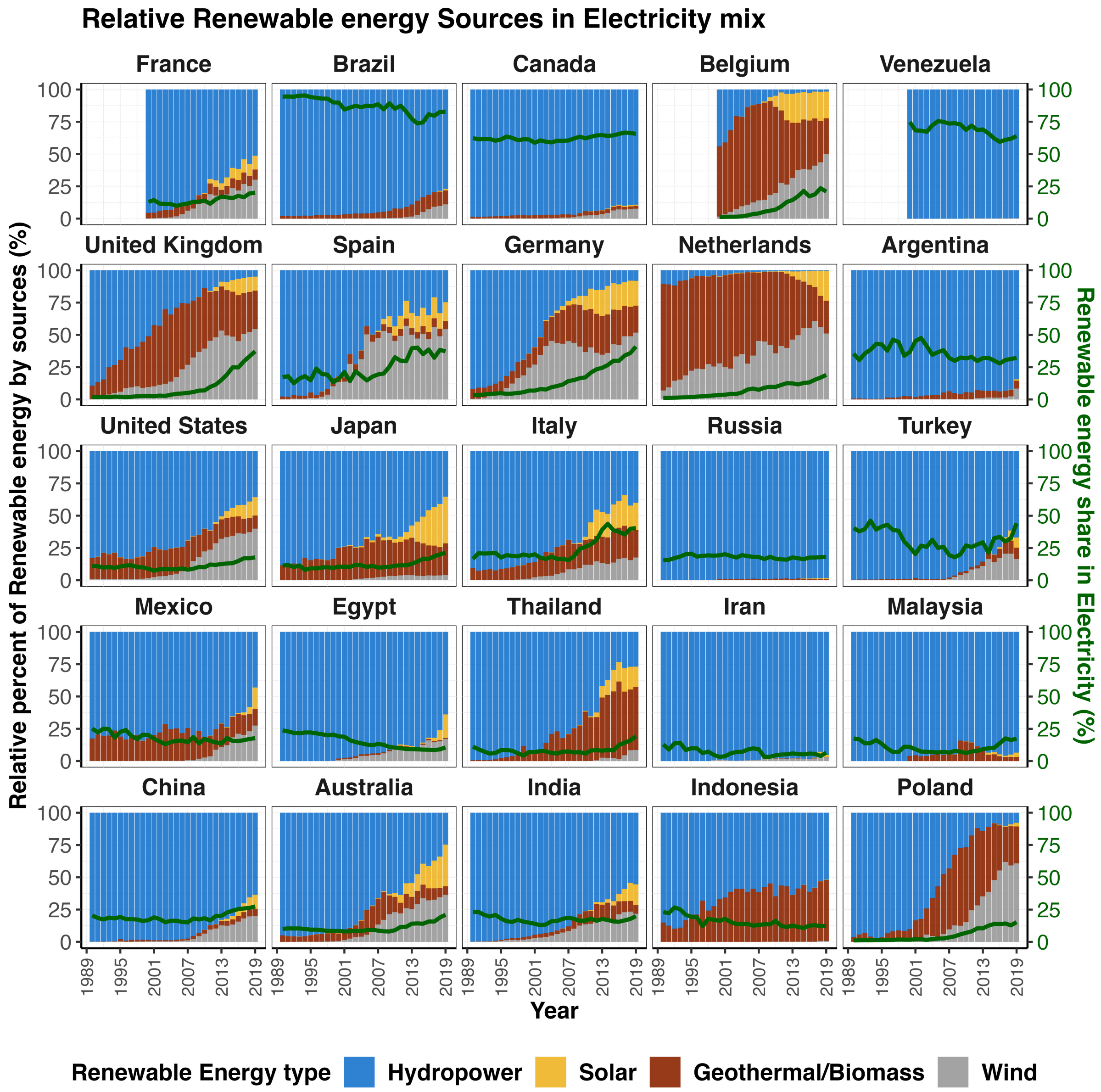


**Figure S4.** Relative share of the different types of renewable energy sources (colored bars) and share of renewable energy in total electricity consumption (in dark green line) over the 30 years from 1990 to 2019 across 25 major natural gas consuming countries (20 years for Belgium, France and Venezuela).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

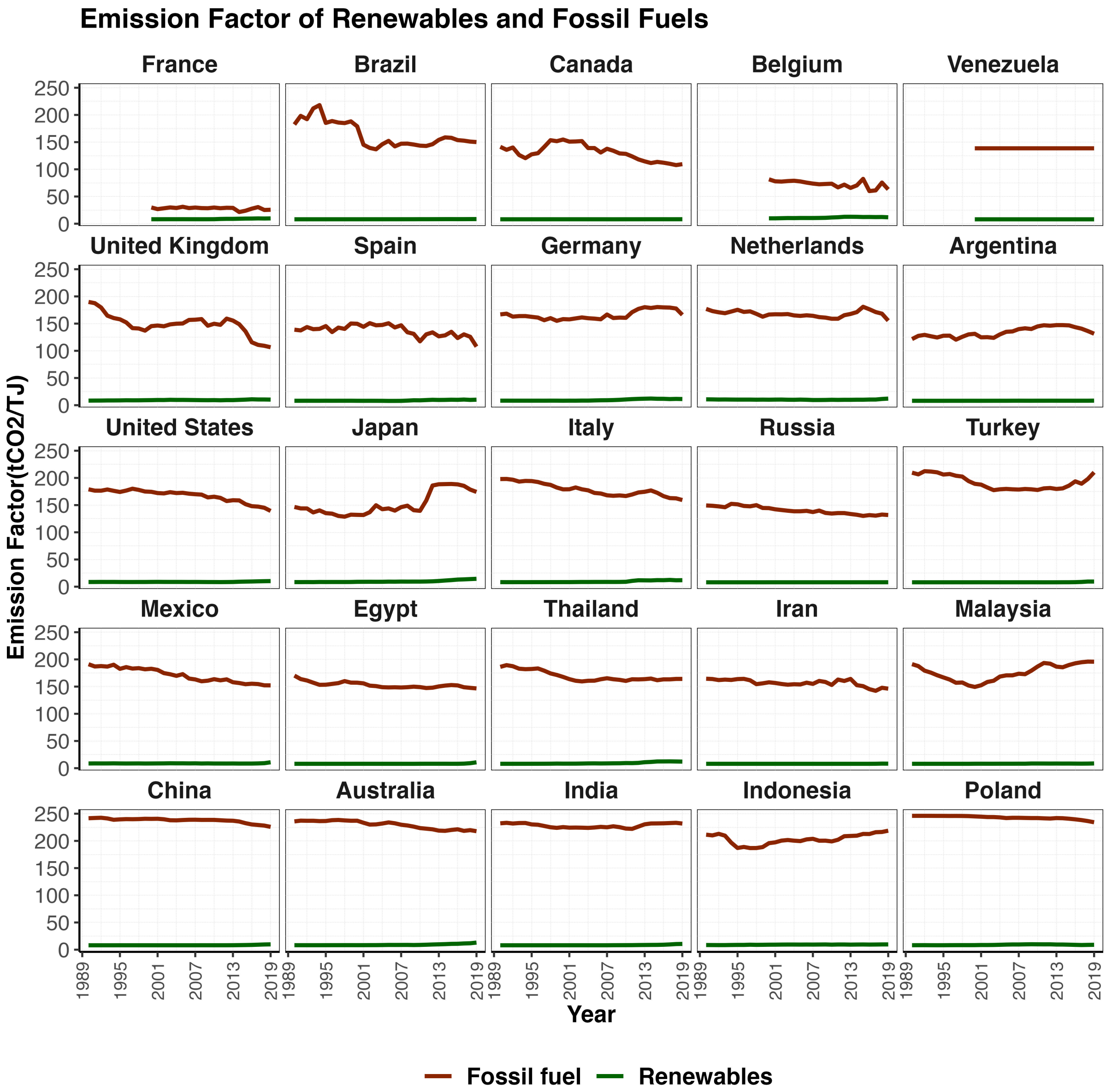


**Figure S5.** Emission factors of fossil fuel and renewable energy over the 30 years from 1990 to 2019 across 25 major natural gas consuming countries. Data are adopted from (bp, 2020).

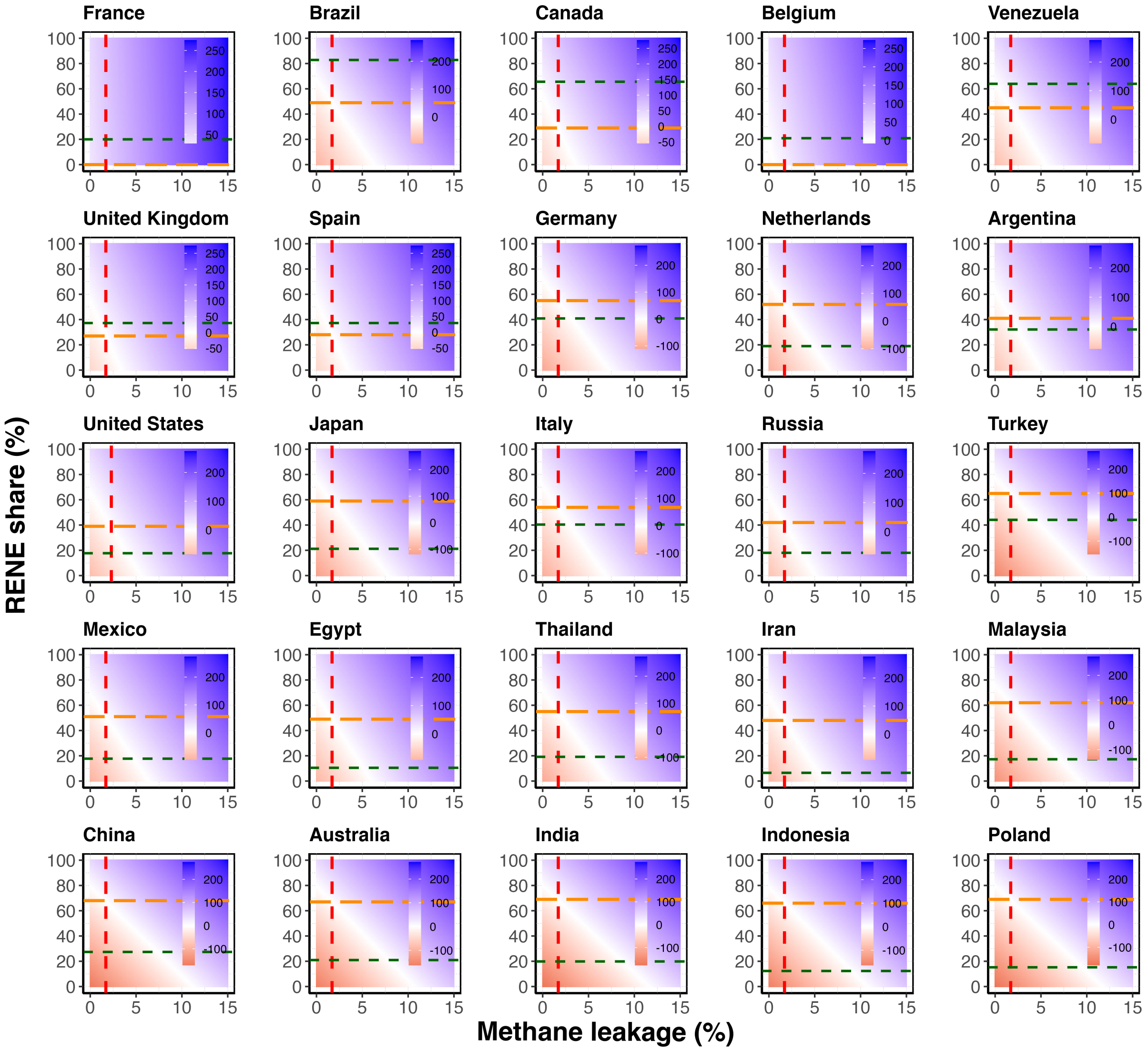


**Figure S6.** Phase transition plot for 25 countries based on electricity mix of 2019. The blue/red area represents where electricity/natural-gas is a better energy option. The vertical red line represents the mean methane leakage rate, whereas the horizontal dark green and orange dash line represents the current RENE share and break-even point where natural gas and electricity have the same carbon footprint.

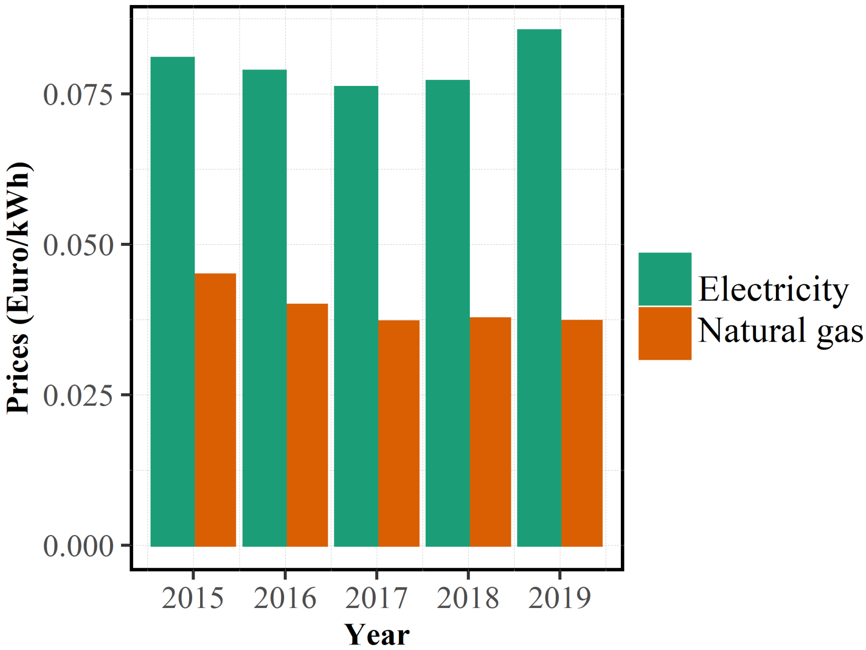


**Figure S7.** Development of the gas and electricity costs in Germany for 1 kWh of energy each. Data are adopted from (Eurostat, 2021a, 2021b).

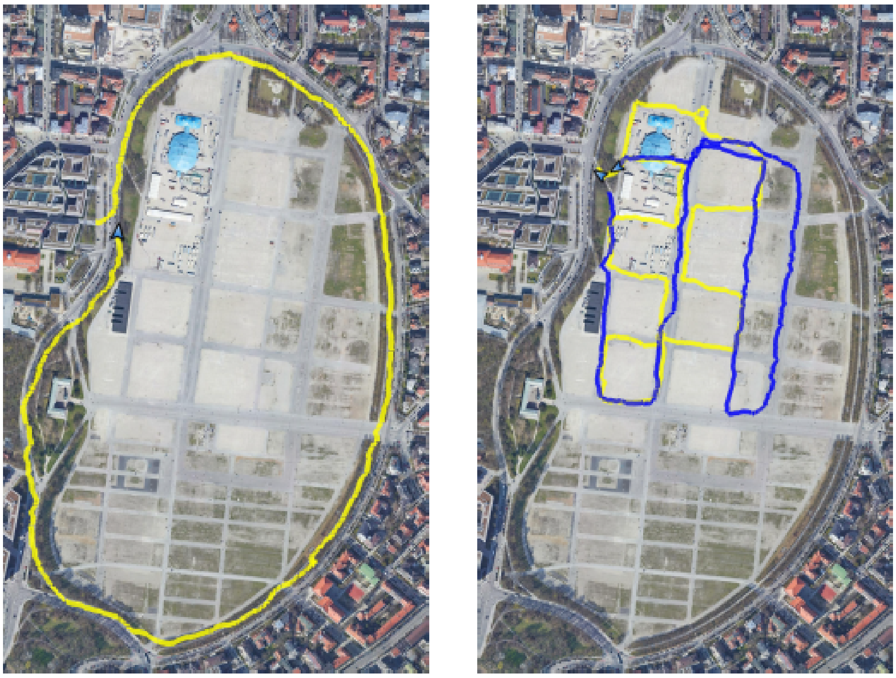

**Figure S8.** Illustration of the track around the perimeter of Oktoberfest (left; yellow) and the two different tracks on the site (right; yellow and blue). Map data are from ©Google, DigitalGlobe.