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Asserting the climate benefits of the coal-to-gas shift across temporal and spatial scales

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24 **Abstract**

25 Reducing CO₂ emissions through a shift from coal to natural gas power plants is a key strategy to support
26 pathways for climate stabilization. However, methane leakage in the natural gas supply chain and emissions of a
27 variety of climate forcers call the net benefits of this transition into question. Here, we integrated a life cycle
28 inventory model with multiple global and regional emission metrics and investigated the impacts of
29 representative coal and gas power plants in China, Germany, India, and the US. We found that the coal-to-gas
30 shift is consistent with climate stabilization objectives for the next 50 to 100 years. Our finding is robust under a
31 range of leakage rates and uncertainties in emission data and metrics. It becomes conditional to the leakage rate
32 in some locations only if we employ a set of metrics that essentially focuses on short-term effects. Our case for
33 the coal-to-gas shift is stronger than previously found, reinforcing the support for coal phase-out.

34

35 **Main text**

36 Under stringent climate goals, the energy system transition to 2050 is projected to involve shifting from coal to
37 natural gas power plants. Natural gas is considered to serve as a bridge fuel until less carbon intensive
38 technologies, such as renewables and carbon capture and storage, become viable for large scale
39 implementation¹. Compared to coal, natural gas releases less than half the amount of CO₂ upon combustion, and
40 gas power plants are generally more efficient than coal power plants. However, natural gas is predominantly
41 composed of CH₄², a potent greenhouse gas (GHG), which can leak at various stages of the supply chain³⁻¹³.
42 Furthermore, combustion of coal and natural gas in power plants releases a different mix of short-lived climate
43 pollutants (SLCPs) to the atmosphere (e.g. black carbon (BC) leading to warming; SO_x and organic carbon (OC)
44 leading to cooling), whose impacts are region-dependent and sensitive to emission locations. These aspects have
45 called into question the climatic advantage of natural gas over coal^{3,9,14-22}.

46 We add a novel perspective to the coal-to-gas debate by applying recent advances in climate impact
47 assessments, which include the multi-*metric* approach²³⁻²⁵ recommended by the United Nations Environmental
48 Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative²⁶. The
49 multi-*metric* approach designates a set of emission metrics to explicitly address short-term (a few decades) and
50 long-term (about a century) climate impacts. Our analysis considers representative power plants in some of the
51 most important countries in terms of global power generation, i.e. China, Germany, India, and the United States

52 (US), for which life cycle emissions of GHGs and SLCPs per unit of electricity production are derived²⁷. We assess
53 the climate impacts of the coal-to-gas shift using a set of global and regional emission metrics²⁸ and investigate
54 the dependency of the results on CH₄ leakage rates, emission and impact locations, and time scales. We show
55 that the coal-to-gas shift reduces short- and long-term climate impacts under a broad range of CH₄ leakage rates
56 and at any emission or impact region. This conclusion is robust with respect to the uncertainties in the emission
57 inventories and metrics assessed through a Monte Carlo analysis. However, the conclusion changes when using a
58 set of metrics emphasizing very short-term outcomes, which is not in line with 50 to 100-year time scales
59 associated with climate stabilization objectives of the Paris Agreement^{29,30}, or when using the multi-basket
60 approach³¹⁻³³, which implicitly neglects the contribution of CO₂ to short-term impacts (particularly important for
61 coal).

62

63 **Coal-to-gas debate**

64 More than three quarters of global total primary energy has been supplied by fossil fuels, including coal and
65 natural gas, for a long period of time³⁴. The late 1980s saw the beginning of the debate as to whether natural gas
66 should be a mid-term bridge fuel to substitute coal temporarily along the long-term pathway for
67 decarbonization^{35,36}. At that time, CH₄ leakage was estimated to be low. However, potentially larger leakage was
68 already a concern³⁷⁻³⁹, leading to several studies that calculated break-even leakage rates above which the
69 climate impacts of natural gas surpass those of coal (or oil)^{37,40,41}. The debate was elevated to a higher level
70 around 2010, when horizontal drilling and hydraulic fracturing (i.e. fracking) to exploit shale formations reached a
71 substantial commercial scale in the US. It was initially claimed that these unconventional sources might have
72 significantly higher CH₄ leakage than conventional sources³ – however, subsequent studies showed otherwise,
73 especially in the US. Nevertheless, the amount of CH₄ leakage from natural gas plants, be it conventional or
74 unconventional, remains uncertain³⁻¹³. Other environmental concerns also fuel the debate, regarding air
75 pollution, drinking water contamination, and induced seismic activities⁴²⁻⁴⁴. Further considerations lie at regional
76 and country levels^{45,46}.

77 Previous studies on the climatic advantage of the coal-to-gas shift yield conclusions ranging from
78 rejections^{3,9,15} to conditional supports^{14,16-22}. A key factor responsible for these diverging outcomes is the
79 abovementioned large uncertainties in CH₄ leakage. Top-down approaches using surface/aircraft/satellite

80 monitoring and atmospheric transport models tend to give higher estimates than those based on bottom-up
81 approaches using measurements at specific facilities or for individual equipments⁴⁷. The gap in estimates is partly
82 due to difficulties in distinguishing emission sources from top-down approaches^{48,49} and to super-emitters⁵⁰ that
83 are under-represented in bottom-up approaches. Additional differences come from system boundaries, plant
84 efficiencies, emission metrics, and climate forcers studied within bottom-up approaches¹⁸.

85

86 **Multi-metric approach**

87 While comprehensive insights require climate models^{15,16,19,21,41,51-53}, climate and environmental analyses such as
88 Life Cycle Assessment often use aggregated CO₂-equivalent (CO₂eq) emissions as a proxy for climate impacts⁵⁴.
89 Non-CO₂ emissions can be aggregated into CO₂eq emissions on the basis of a common metric: typically the
90 Global Warming Potential (GWP)⁵⁵. GWP is defined as the ratio of the *radiative forcing integrated* over a given
91 time horizon (e.g. 100 years) after the emissions of a gas of interest (e.g. CH₄) in a unit amount (e.g. 1kg) relative
92 to that of the reference gas of CO₂. GWP was initially developed for multi-gas climate policies⁵⁶, introduced to
93 the Intergovernmental Panel on Climate Change (IPCC), and then adopted by climate policies and assessments as
94 an accessible tool to capture total climate effects, without requiring a climate model.

95 This metric has, however, received critique because of the underlying scientific assumptions as well as
96 implicit value judgements⁵⁷, resulting in alternative metrics proposed⁵⁸⁻⁶³. A prominent alternative is the Global
97 Temperature change Potential (GTP), in which equivalency is established with respect to the *temperature change*
98 at the *end* of the time horizon⁶⁰. The choice of radiative forcing and temperature change does not strongly affect
99 the emission metric values⁶¹, but the difference between the integrated and end-point perspectives is more
100 fundamental. Furthermore, emission metrics are generally sensitive to the time scale, especially for GHGs and
101 SLCPs whose atmospheric lifetimes are substantially different from that of CO₂. For example, while CO₂ stays in
102 the atmosphere on centennial or even millennium time scales⁶⁴, CH₄ mostly disappears from the atmosphere
103 several decades after emissions⁵⁵. Various stakeholders have debated whether 20- or 100-year time scales should
104 be used⁶⁵.

105 An emerging idea is to combine multiple metrics to address both short- and long-term climate impacts
106 in parallel. However, different combining methods are proposed within the five metrics (i.e. GWP20, GWP100,
107 GTP20, GTP50, and GTP100) available in the IPCC Fifth Assessment Report (AR5)⁵⁵. On one hand, the joint use of

108 GWP100 and GTP100 was recommended through a consensus building process as part of the Life Cycle Initiative
109 under the UNEP-SETAC flagship project²³⁻²⁶. GWP100 and GTP100 were assigned to capture short- and long-term
110 climate impacts, respectively (see the discussion in Climate impact analysis). On the other hand, several previous
111 studies adopted GWP20 and GWP100 complementarily^{3,9,17,22,39,66}, with the intent of supplementing shorter term
112 impacts by using GWP20 in addition to GWP100 (related discussions^{9,14,19,21}). That particular choice of metric
113 combination was further proposed in a more general context^{65,67}. In our analysis, following the UNEP-SETAC
114 recommendations, we assess results on the basis of the complementary insights provided by GWP100 and
115 GTP100, but also use GWP20 and GTP20 to derive additional insights.

116 The multi-metric approach explained above differs from the multi-basket approach³¹⁻³³, which has
117 been proposed for climate policies. While both approaches share concerns involving the single use of GWP100,
118 the multi-basket approach circumvents this problem differently: it separates a suite of climate forcers into
119 multiple baskets according to atmospheric lifetimes and considers multiple impacts from the baskets of climate
120 forcers (i.e. an analogue to the scheme employed for the Montreal Protocol³²). In contrast, the multi-metric
121 approach does not differentiate climate forcers; rather, it applies different emission metrics to the *same* set of
122 climate forcers to derive multiple impacts. For example, the multi-basket approach considers CO₂ only in long-
123 term impacts, while the multi-metric approach accounts for CO₂ in both short- and long-term impacts.

124

125 **Climate impact analysis**

126 By applying GWP100 and GTP100 complementarily, we find that natural gas power plants have smaller short-
127 and long-term impacts than coal power plants (Figure 1) under the CH₄ leakage rates documented in the life
128 cycle inventory models (see Methods). This conclusion is consistent across plant locations. Examining the impacts
129 by stages (stage 1: extraction and transport of the fuel to the power plant; stage 2: fuel combustion at the power
130 plant (see Methods and Supplementary Figure 1)), we find that stage 2 has larger short- and long-term impacts
131 than stage 1 for both coal and gas (Figure 1). In terms of the contributions from individual climate forcers, the
132 influence of CO₂ is dominant in both short- and long-term impacts from coal and gas (Figure 2). If we use GWP20
133 or GTP20, however, the importance of CO₂ is significantly reduced, with non-CO₂ components like SO_x and NO_x
134 gaining more prominence. Of note, short-term cooling impacts from SO_x, which has an atmospheric lifetime of
135 just days/weeks, are most visible with GWP20. In contrast, short-term cooling impacts from NO_x are most

136 evident with GTP20 because of the decadal time scales associated with the CH₄ decrease in response to NO_x
137 emissions⁶⁸.

138 We then assess the influence of larger CH₄ leakage. With leakage rates varied up to 9%, the benefits of
139 the coal-to-gas shift hold with the use of GWP100 and GTP100 (Figure 3): natural gas power plants have smaller
140 short- and long-term impacts than coal power plants. An exception are the results for China at the leakage rate of
141 9%, in which impacts from the gas plant computed with GWP100 become almost equivalent to those from the
142 coal plant. Results from China and India are more sensitive to the changes in CH₄ leakage than those from
143 Germany and the US, but the outcome can be reversed at the high leakage rate only in China mainly because of
144 the higher efficiency of the representative coal plant in China than that in India (see Methods). This exceptional
145 finding comes, however, with limited confidence, given the associated uncertainty ranges quantified by the
146 Monte Carlo analysis (see Uncertainty analysis section in Methods). Note that emission data contribute more
147 uncertainties than emission metrics (Supplementary Figures 2 and 3). We further tested the robustness of the
148 results to additional factors in emission metrics, such as inclusion of climate-carbon feedbacks in metric values⁶⁹,
149 potentially larger SO_x metrics accounting for effects other than the direct effects⁷⁰, and higher CH₄ metrics
150 considering the effects from the shortwave forcing proposed recently⁷¹ (see Emission metrics section in
151 Methods; Supplementary Figure 4). Our conclusions remain valid under this variety of assumptions.

152 However, conclusions change substantially if we look at the results with GWP20. As reported by some
153 previous studies, short-term impacts of natural gas are less than those of coal only under certain conditions (i.e.
154 with leakage rates below 3%, 9%, 5%, and 5% in China, Germany, the US, and India, respectively) (Figure 3). The
155 main reason is that GWP20 emphasizes the impacts from CH₄ relative to those from other climate forcers,
156 increasing the short-term impacts of gas plants at high leakage rates. This explains the more conditional
157 outcomes from previous studies^{14,16-22} using GWP20 to address the climate benefits of the coal-to-gas shift.

158 In general, the commonly used combination of GWP20 and GWP100 is not adequate in addressing
159 long-term climate stabilization as called for by the Paris Agreement⁷². Our argument rests on the premise that it
160 is more appropriate to consider the *end point* time horizon as built in the GTP concept, which is theoretically
161 more suited for cost-effective climate stabilization in the United Nations Framework Convention on Climate
162 Change (UNFCCC)⁷³. Whereas the *integrated* time horizon in the GWP concept does not relate closely to climate
163 stabilization, a correspondence can be made between the time horizons of GWP and GTP. GWP100 numerically

164 falls between GTP20 and GTP40, depending on the climate forcer⁷⁴, which indicates that GWP100 implicitly
165 relates temperature impacts after two to four decades. Thus, this correspondence points to a short-term
166 emphasis inherent to GWP100. The GWP-GTP relationship further reveals that GWP20 implies *very* short-term
167 climate impacts. Thus, the combined use of GWP20 and GWP100 is not consistent with the climate stabilization
168 objectives requiring approximately 50 to 100 years to be achieved, although the choice of GWP20 and GWP100
169 may reflect the practical limitation that only GWP values were provided before the publication of the IPCC AR5.
170 By comparison, we argue that the combined use of GWP100 and GTP100 jointly covers short-term (a few
171 decades) and long-term (about a century) effects from the end-point perspective of climate stabilization. It
172 should be noted that potential high-risk impacts (e.g. tipping points via high levels of very short-term forcing)
173 cannot be captured by this combination of metrics, requiring GWP20 and GTP20 additionally. However, using
174 metrics representing only short-term perspectives implicitly disregards the fundamental long-term nature of
175 climate change mainly driven by CO₂ emissions⁷⁵.

176 An important difference was found in the assessment of short-term impacts between the multi-metric
177 and multi-basket approaches (Supplementary Figure 5). The multi-basket approach shows substantially smaller
178 short-term impacts from coal than the multi-metric approach. This is because the multi-basket approach does
179 not include CO₂ in short-term impacts, reducing the short-term impacts from more CO₂-dominated coal plants.
180 On the other hand, long-term impacts do not significantly differ between the two approaches. Our results
181 highlight a crucial role of CO₂ in determining short-term impacts, which is not captured by the multi-basket
182 approach. Short-term impacts derived from the multi-basket approach cannot be interpreted as *total* short-term
183 impacts if applied to climate impact assessments.

184

185 **Regional dimensions**

186 Emissions of SLCPs, which are not well-mixed in the atmosphere (excluding CH₄), can result in regional impacts
187 that differ from the global average and depend on regions where they are emitted⁷⁶. CH₄ itself is a well-mixed
188 gas, but it leads to formation of O₃, in the presence of precursors, which can generate spatially heterogeneous
189 impacts⁷⁷. The GWP and GTP values used in our preceding analysis (Figures 1 to 3) account for emission regions
190 but consider impacts globally, which we term as “regional-global” metrics. To disentangle regional influences, we
191 conduct sensitivity analyses using i) “global-global” metrics, which are estimated for global emissions and global

192 impacts, and ii) “regional-regional” metrics, which are calculated for specific regions of emissions and impacts.
193 The global-global metrics are conceptually similar to the metrics in the IPCC (e.g. Table 8.A.1 of AR5) in terms of
194 the assumptions for emission and impact locations. Likewise, the regional-regional metrics are similar to the
195 Regional Temperature change Potential (RTP)^{28,78}. Due to data availability, the sensitivity analysis uses only GTP20
196 and its regional variations.

197 By comparing the results from regional-regional metrics with those from regional-global metrics, we
198 illuminated the significance of accounting for impact regions. The differences were largest for the coal plants in
199 China and India (Figure 4). In both cases, short-term impacts are largest in the latitudinal band of 90°S – 28°S and
200 smallest in 60°N – 90°N. The range of short-term impacts can be attributed to the impacts from SO_x and NO_x,
201 which vary across latitudinal bands (Supplementary Figures 6 to 8). Also, we show the significance of accounting
202 for emission regions by comparing the results from global-global metrics with those from regional-global metrics.
203 The difference was largest for the coal plant in India, which is caused by the short-term impacts from NO_x.
204 Overall, we identified influences of emission and impact regions on GTP20-based impacts. However, the benefits
205 of the coal-to-gas shift are not affected by the regional scale of the analysis, neither in terms of the emission
206 region nor the impact area, although further analysis is required to understand regional dimensions more
207 comprehensively.

208

209 **Conclusions**

210 The UNEP-SETAC multi-metric approach jointly using GWP100 and GTP100 shows that the coal-to-gas energy
211 transition is consistent with climate stabilization objectives at various CH₄ leakage rates and at any location
212 considered (summarized in Table 1). This finding is different from previous findings based on GWP20 that are
213 conditional on CH₄ leakage rates. Whereas it is generally assumed that complementing GWP100 with GWP20
214 covers relevant time scales to assess the impacts from a variety of climate forcers, we argue that the
215 complementary use of GWP100 and GTP100 better aligns with century-long time scales in the end-point climate
216 stabilization perspective, while also addressing short time scales. Ways of choosing and applying metrics have a
217 major influence on the interpretation of climate assessment outcomes, underlining the importance for a clear
218 understanding and critical reflection on the meaning of emission metrics used, including the heterogeneities of
219 temporal and spatial responses to different climate forcers at play.

220 Our findings assert the climate benefits of the coal-to-gas shift and reinforce the case for phasing out
221 coal power plants⁷⁹⁻⁸². There are, however, other factors to consider for the coal-to-gas shift; for example, air
222 quality can be evaluated together with climate impacts⁸³, which can probably strengthen the case for the coal-to-
223 gas shift. On the other hand, prioritizing the coal-to-gas shift over other mitigation measures may argue against
224 the shift. Several studies caution about potential side-effects that an expansion of natural gas may delay the
225 deployment of less carbon intensive technologies such as renewables, representing carbon lock-in from fossil
226 fuel infrastructure, and thereby postponing the transition to a decarbonized society^{51-53,84-86}. Furthermore, more
227 detailed datasets could be considered, uncovering spatially-resolved variability associated with different
228 components of the supply chains and trade within and across nations.

229 Finally, metrics are emerging as a key issue in the context of the Paris Agreement^{30,63,87}. Current ways of
230 applying emission metrics vary across communities. Although metrics should in principle be chosen to best meet
231 their application purpose⁵⁷, more consistency in metric usage can be useful in light of the Paris Agreement
232 objectives and implementations. Better alignment of metric usage among scientists and decision makers can be
233 achieved through joint engagement involving broad and interdisciplinary communities.

234

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434

435 **Methods**

436 Overview of emission data

437 Life cycle emissions of GHGs and SLCPs from coal and natural gas power plants are produced using the ecoinvent
438 database version 3.4^{27,88,89} (Supplementary Table 1). We chose representative power plants in China, Germany,
439 the US, and India and mapped direct and indirect emissions along the full supply chain and during power plant
440 operation. A process flow diagram of the value chains for coal and gas plants is provided in Supplementary Figure
441 1, highlighting main stages and emission sources. Life cycle emissions are aggregated in two major stages.

- 442 • Stage 1: direct and indirect emissions to deliver the fuel to the power plant, including mining, extraction,
443 processing, compression, storage, and transport systems
- 444 • Stage 2: fuel combustion at the power plant and minor emissions due to the production and supply of the
445 commodities and chemicals used to run the power plant and disposal of combustion ashes to landfill

446 Power plants are representative of averaged conditions for specific technologies, conversion
447 efficiencies, fuels, and emission factors in the respective countries. The database provides emission inventories
448 for coal and gas plants in 31 sub-regions in China, 13 in India, seven in the US and one in Germany. We compute
449 the average figures considering all sub-regions in each country. Further details in the power plants are found in
450 Coal and natural gas power plants section. Uncertainties in emission factors and variabilities of power plant
451 efficiencies are shown in Supplementary Tables 2 and 3, respectively, and are the basis for the Monte Carlo
452 analysis (see Uncertainty analysis section).

453 A suite of components including SLCPs is considered in our analysis. Emissions of CO₂, CH₄, N₂O, CO,
454 NO_x, VOC, and SO_x are directly derived from the ecoinvent database. CH₄ emissions are varied in our analysis in
455 terms of leakage rates up to 9% (see CH₄ leakage section). For BC and OC emissions, we complemented the
456 database with related estimates gathered from the literature since ecoinvent only reports the emissions of
457 particular matter (PM) (see BC and OC emissions section).

458 In line with the Life Cycle Assessment methodology, our study assumes that all emissions occur
459 instantaneously; we analyze *pulse* emissions without accounting for their temporal distribution given by plant
460 lifetimes or the periods of plant operations. An inclusion of temporally distributed emissions would offer more
461 realistic insights; however, emission metrics we employed are based on fixed time horizons (e.g. 100 years) and
462 are not directly designed to deal with *sustained* emissions occurring at different points in time⁶⁰, although it is
463 possible to apply related interpretations^{90,91}.

464

465 Coal and natural gas power plants

466 Electricity from coal is produced from average hard coal power plants (ecoinvent activity name: “electricity
467 production, hard coal”). Hard coal includes anthracite, coking coal, and other bituminous coal. Average hard coal
468 requirements per unit of electricity produced are 0.493 kg/kWh in China, 0.402 kg/kWh in Germany, 0.458
469 kg/kWh in the US, and 0.733 kg/kWh in India. Hard coal supply considers underground coal mines in the
470 respective countries, except for India, whose coals are imported from the average global market. Hard coal
471 emission inventories include all emissions from mining processes to extract coal from the ground and all the
472 associated upstream emissions from inputs, infrastructure, and energy requirements for mine construction and
473 operation, coal preparation, and gas leakage as well as the country-specific transportation systems. Coal energy
474 content is 22.8 MJ/kg China, 24.0 MJ/kg in Germany, 24.8 MJ/kg in the US, and 19.3 MJ/kg in India⁸⁸
475 (Supplementary Table 3). Additional details on the selected processes and sources for emissions are available in
476 refs.^{27,88,89}.

477 Electricity from natural gas is produced from combined cycle power plants, without associated heat co-
478 generation (ecoinvent activity name: “electricity production, natural gas, combined cycle power plant”). Average
479 natural gas requirements per unit of electricity produced are 0.289 m³/kWh in China, 0.164 m³/kWh in Germany,
480 0.170 m³/kWh in the US, and 0.287 m³/kWh in India. Natural gas market in Germany accounts for internal
481 production on dedicated onshore gas fields (8%), in addition to imports from the Netherlands (21%), Norway
482 (32%), and Russia (38%). Natural gas market in the US accounts for internal production in dedicated onshore gas
483 fields (70%) and on-shore combined oil and gas production (30%). The natural gas availability in China and India
484 considers the supply from the average global market of natural gas, which includes imports (3%) from several
485 countries (e.g. Nigeria, Germany, Algeria, the Netherlands, Norway, and Russia), production in dedicated onshore

486 gas fields (56%), both on- and off-shore combined production of oil and gas (29%), and liquefied natural gas
487 (LNG) (12%). Emission inventories include materials, infrastructure and energy requirements for gas field
488 construction and operation, natural gas processing, sweetening, drying, and all upstream activities as well as gas
489 leakage. Natural gas energy content is 39 MJ/m³ in all four countries⁸⁸ (Supplementary Table 3). In the case of
490 LNG, impacts related to liquefaction, storage, shipping, and regasification are also included in the emission
491 inventories. Energy requirements for compressor stations and gas leakage as well as the construction and
492 operation of pipeline infrastructure for transport of natural gas are specifically considered for different countries.

493 Furthermore, we assess the emissions from liquefaction and regasification associated with LNG.
494 Emission inventories from natural gas and LNG power plants are compared in Supplementary Table 4 (stage 1
495 only). In the ecoinvent database, the LNG supply for the plant in Germany is from Algeria, while the plants in
496 China, the US, and India rely on the LNG supply from Middle East and the rest of the world. Consequently,
497 emissions from the LNG plant in Germany are considerably smaller than those in the other locations. However,
498 the difference in the climate impacts between natural gas and LNG plants (Supplementary Figure 9) is not
499 substantial because emissions from stage 2 are more important in magnitude than those from stage 1,
500 confirming the small contribution of liquefaction and regasification to the total value chain impacts⁶⁶.

501

502 BC and OC emissions

503 Emission factors for BC and OC are calculated using different approaches for stage 1 (and auxiliary processes in
504 stage 2) and the rest of stage 2 (i.e. direct emissions from fuel combustion at the plant). BC and OC emissions
505 from the former are based on the amount of life cycle emissions of PM lower than 10 µm⁹². Emissions from the
506 latter are quantified using plant-specific emission factors. For China and India, BC and OC emissions from the coal
507 plants are 0.077 g/kg_{coal} and 0.254 g/kg_{coal}, respectively, and OC emissions from the gas plants are 0.015 g/kg_{gas}
508 (where no BC emissions occur)⁹³. For Germany and the US, BC and OC emission factors from the coal plants are
509 0.029 g/kg_{coal} and 0.015 g/kg_{coal}, respectively, and those from the gas plants are 0.0084 g/kg_{gas} and 0.092 g/kg_{gas},
510 respectively^{94,95}.

511

512 CH₄ leakage

513 We define CH₄ leakage as the total CH₄ emissions from the natural gas supply chain, including unintended

514 fugitive releases and intended vented releases, although the definition varies across literature¹². It is widely
515 recognized that CH₄ leakage rates are uncertain³⁻¹³. Our analysis uses a range of leakage rates that cover most of
516 reported values. We do not analyze extremely high leakage rates (i.e. super-emitters⁵⁰) since we deal with
517 representative or “average” power plants of four different countries. The 2017 World Energy Outlook from the
518 International Energy Agency reports a global average leakage rate of 1.7%¹². A recent synthesis work gives a
519 leakage estimate of 2.3% for the US (95% confidence interval of 2.0-2.7%)¹³. CH₄ measurements and inventory
520 data are concentrated in the US, leaving the leakage estimates in the other parts of the world more uncertain.
521 Leakage rates outside of the US could be high due to less regulatory oversights on environmental issues among
522 other factors.

523 The CH₄ leakage rates directly obtained from the ecoinvent database are approximately 1% (i.e. 0.62%,
524 0.79%, 1.23%, and 0.62% in China, Germany, the US, and India, respectively). Due to the alternative references
525 used in the ecoinvent database, these figures are lower than average estimates introduced above. In the analysis,
526 we vary the leakage rate up to 9% at each plant location to cover most leakage estimates in the literature⁶⁶.
527 Climate impacts are computed for leakage rates from 2% up to 9%, with 1% progressive increment. Emissions of
528 other gases may also be larger under higher CH₄ leakage (e.g. venting releases) – however, we keep other
529 emissions constant in varying the leakage rate due to the scarcity of data and single out the CH₄ leakage effect.

530

531 Emission metrics

532 Metric values are based on a previous study²⁸ that used radiative forcing calculations from the Task Force on
533 Hemispheric Transport of Air Pollution Source-Receptor global chemical transport models^{96,97}, except for N₂O
534 metric values directly adopted from the IPCC AR5 (Supplementary Tables 5 and 6). Uncertainties in emission
535 metrics considered in this study represent the spreads of model responses to the emissions of SLCPs.
536 Uncertainties associated with the responses to the emissions of long-lived gases (CO₂ and N₂O) are reported^{64,98}
537 but not included in our analysis. The CH₄ metric values are scaled to be consistent with the corresponding AR5
538 values, that is, the long-term ozone contribution is increased to 50% of the CH₄-only part. We further modified
539 the values of all CH₄ metric (including RTP20) to account for the CO₂ production from CH₄ oxidation⁹⁹. The CH₄
540 metrics used here thus correspond to those for “CH₄ of fossil origin” in Table 8.A.1 of the IPCC AR5, although the
541 values are slightly different. The metric values used here are contingent on various assumptions. Below we

542 discuss three main underlying assumptions and their implications to the results.

543 First, metric values used in our analysis do not fully account for climate-carbon feedbacks¹⁰⁰. Like the
544 standard approach in Table 8.A.1 of the IPCC AR5, climate-carbon feedbacks are included only in the
545 denominators of metrics (i.e. the CO₂ emission parts). We provide an alternative set of metric values fully
546 accounting for climate-carbon feedbacks (i.e. both in the denominators and numerators of metrics) in
547 Supplementary Tables 7 and 8, which corresponds to Table 8.SM.15 of AR5. We calculated these metric values by
548 combining the outcomes of previous studies^{28,69}. Note that it was recently reported that AR5 metric values fully
549 accounting for climate-carbon feedbacks need downward correction because of the treatment of the additional
550 CO₂ released from climate-carbon feedbacks in the metric numerators⁶⁹. Our metric calculations are based on
551 the corrected approach. With the use of metric values fully including climate-carbon feedbacks, the short-term
552 climate benefits of the coal-to-gas shift (based on GWP100) become slightly marginalized (Supplementary Figure
553 4b). But such changes are not large enough to affect the overall results summarized in Table 1.

554 Second, our metric calculation approach accounts for only the direct effects of aerosols. Recent studies
555 have attempted to incorporate indirect effects, semi-direct effects, and snow-albedo effects⁷⁰, but values are
556 available only for two emission regions. The SO_x metric values from these studies are approximately twice larger
557 than those used here. Assuming that the values of all SO_x metrics accounting for other effects are twice as large
558 as those used in our analysis, the short-term climate benefits of the coal-to-gas shift could be significantly
559 reduced (Supplementary Figure 4c). The break-even leakage rate of the short-term impacts in China might shift
560 from 9% to 6%, even though this emerges only under a speculative assumption.

561 Third, a revision of GWP100 for CH₄ (i.e. 32), approximately 14% higher than the AR5 estimate of 28,
562 was proposed recently⁷¹. This upward revision is due to the shortwave forcing that were not considered in
563 previous radiative transfer calculations. This upward adjustment can decrease the gain in the short-term climate
564 impacts from the coal-to-gas shift (Supplementary Figure 4d) but does not affect the overall outcome in Table 1.

565

566 Uncertainty analysis

567 The Monte Carlo analysis considers two major strands of uncertainties, those in emission data and those in
568 emission metrics. Emission data have two further sources of uncertainties: emission factors and plant
569 efficiencies. First, uncertainties in emission factors are derived from six semi-quantitative indices describing

570 reliability, completeness, temporal correlation, geographical correlation, technology, and a factor related to the
571 intrinsic measurement uncertainty. Second, uncertainties in plant efficiencies are the variabilities of efficiencies
572 from all power plants with the same technology in different sub-regions of each country (Supplementary Table
573 3). Then, the six uncertainty aspects of emission factors and the variabilities of plant efficiencies are combined to
574 yield the uncertainties in emission data considered in our analysis (Supplementary Table 2). Uncertainties in
575 emission metrics represent the diverse nature of models used to calculate emission metrics (see Emission
576 metrics section; Supplementary Table 6)^{28,96,97}. A triangular distribution is assumed for each uncertain parameter.
577 In the Monte Carlo analysis, we repeated 10,000 model runs by randomly selecting values for a total of 16
578 parameters, which consist of nine parameters for emission data (of nine GHGs and SLCPs) and seven parameters
579 for emission metrics (of seven SLCPs), for each country, fuel type, and emission metric.

580

581 Impact units

582 Our analysis reports short- and long-term climate impacts in gCH₄eq/kWh and gCO₂eq/kWh, respectively¹⁰¹. We
583 deliberately differentiate the units to avoid confusion between different types of impacts, but different units do
584 not affect our conclusions. CH₄eq emissions can be obtained by dividing CO₂eq emissions by associated CH₄eq
585 metric values. In other words, converting CO₂eq-based results to CH₄eq-based results requires only linear scaling.
586 The use of different unit influences the absolute outcomes but does not alter the relative importance of gases
587 and pollutants in climate impacts, thus having no effect on the conclusions of this study.

588

589 Data availability

590 The data that support the findings of this study are available from the corresponding author upon request.

591

592 Code availability

593 The computer codes used to generate results presented in this study are available from the corresponding
594 author upon request.

595

596 **References (Methods)**

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629

630 **Additional information**

631 Supplementary information is available for this paper. Correspondence and requests for materials should be
632 addressed to K.T.

633

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641

642 **Author contributions**

643 K.T. led the study. K.T. and F.C. designed the experiment. O.C. and F.C. derived the emission data. W.J.C. computed
644 the emission metrics. K.T. and O.C. calculated the climate impacts. O.C. performed the Monte Carlo analysis. K.T.
645 generated all the figures and tables. K.T., O.C., W.J.C., and F.C. analyzed the results. K.T. drafted the manuscript,
646 with inputs from O.C., W.J.C., and F.C.

647

648 **Competing interests**

649 The authors declare no competing financial interests.

| | | IMPACT TIME SCALES AND DESIGNATED EMISSION METRICS | | | | | | | |
|-------------------|---------------|--|------|-----------------|------|------------|------|------------|-----|
| OUR APPROACH | | Very short-term | | Very short-term | | Short-term | | Long-term | |
| PREVIOUS APPROACH | | — | | Short-term | | Long-term | | — | |
| EMISSION METRIC | | GTP20 | | GWP20 | | GWP100 | | GTP100 | |
| MULTI-METRIC | | LOWER IMPACT FUEL (OR BREAK-EVEN CH ₄ LEAKAGE RATE) | | | | | | | |
| MULTI-BASKET | | | | | | | | | |
| PLANT LOCATION | China | 5% | 2% | 3% | Coal | 9% | Coal | Gas | Gas |
| | Germany | Gas | 4% | 9% | 4% | Gas | 4% | Gas | Gas |
| | United States | 6% | Coal | 5% | Coal | Gas | Coal | Gas | Gas |
| | India | 6% | Coal | 5% | Coal | Gas | Coal | Gas | Gas |

650

651 **Table 1.** Summary of the impact assessments for representative coal and natural gas power plants in China,
 652 Germany, the United States, and India. The upper part of the table indicates the time scale of impacts and
 653 associated emission metrics used to characterize the impacts in this study and previous studies^{3,9,17,22,39,66}. The
 654 lower part of the table indicates the type of fuel (i.e. coal or gas) estimated to have lower climate impacts, or the
 655 break-even CH₄ leakage rate (considered up to 9%), above which the impacts of gas become larger than those of
 656 coal. Results from the multi-metric approach²³⁻²⁵ employed in this study are shown on the left in each cell; those
 657 from the multi-basket approach³¹⁻³³ are on the right. Bold text indicates the results based on the method
 658 recommended by UNEP-SETAC²⁶ (i.e. the multi-metric approach using GWP100 and GTP100 to capture short- and
 659 long-term climate impacts, respectively).

660 **Figure 1.** Short- (*left*) and long- (*right*) term climate impacts of coal (*top*) and natural gas (*bottom*) power plants
661 in two stages. Emissions from stages 1 and 2 (stage 1: extraction and transport of the fuel to the power plant;
662 stage 2: fuel combustion at the power plant) are on the left and right of the split on each bar, respectively. CN,
663 DE, US, and IN stand for China, Germany, the United States, and India, respectively. GWP20, GWP100, GTP20,
664 and GTP100 are the emission metrics used to quantify the corresponding climate impacts. Impacts based on the
665 metrics recommend by UNEP-SETAC (i.e. GWP100 and GTP100) are shown in filled bars. The multi-metric
666 approach is used. CH₄ leakage rates from natural gas power plants are assumed to be the inventory-based
667 estimates for each country (see Methods). Short- and long-term impacts are shown in gCH₄eq/kWh and
668 gCO₂eq/kWh, respectively (see Methods).

669

670 **Figure 2.** Short- (*left*) and long- (*right*) term climate impacts of coal (*top*) and natural gas (*bottom*) power plants
671 in different GHGs and SLCPs. Black horizontal lines placed from the bars for CO₂ emissions represent net non-CO₂
672 emissions. The outer ends of black horizontal lines thus indicate total net emissions. Emissions from both stages
673 are shown. CH₄ leakage rates from natural gas power plants are assumed to be the inventory-based estimates for
674 each country (see Methods). See caption for Figure 1.

675

676 **Figure 3.** Differences in the climate impacts between coal and natural gas power plants. CH₄ leakage rates from
677 natural gas power plants are varied from the inventory-based rates up to 9%. Results are based on the multi-
678 metric approach and presented by countries. Short- and long-term impacts based on the metrics recommend by
679 UNEP-SETAC (i.e. GWP100 and GTP100, respectively) are shown in solid lines and indicated in bold text in the
680 legend. Emissions from both stages are shown. Positive estimates (grey zone) indicate that natural gas has
681 smaller climate impacts than coal. Error bars are 2σ ranges obtained from the Monte Carlo analysis sampling the
682 uncertainties in emission data and emission metrics.

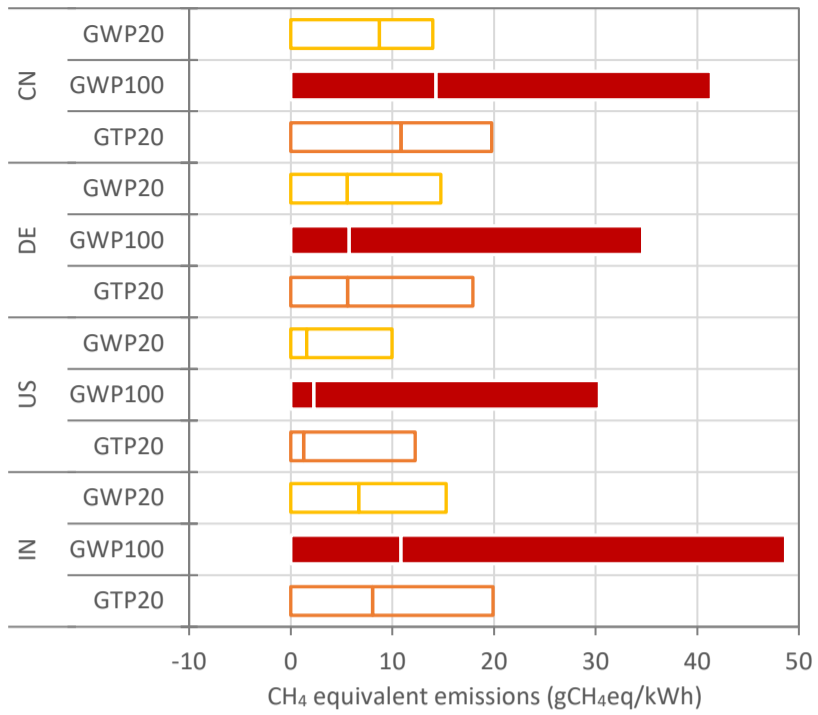
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684 **Figure 4.** Very short-term climate impacts for different emission and impacts locations. Emissions from stages 1
685 and 2 are on the left and right of the split on each bar, respectively. GTP20 for global emissions (i.e. global-global
686 metric), GTP20 for regional emissions (i.e. regional-global metric), and RTP20 (i.e. regional-regional metric) for
687 different latitudinal bands are the emission metrics used to quantify climate impacts, which are expressed as

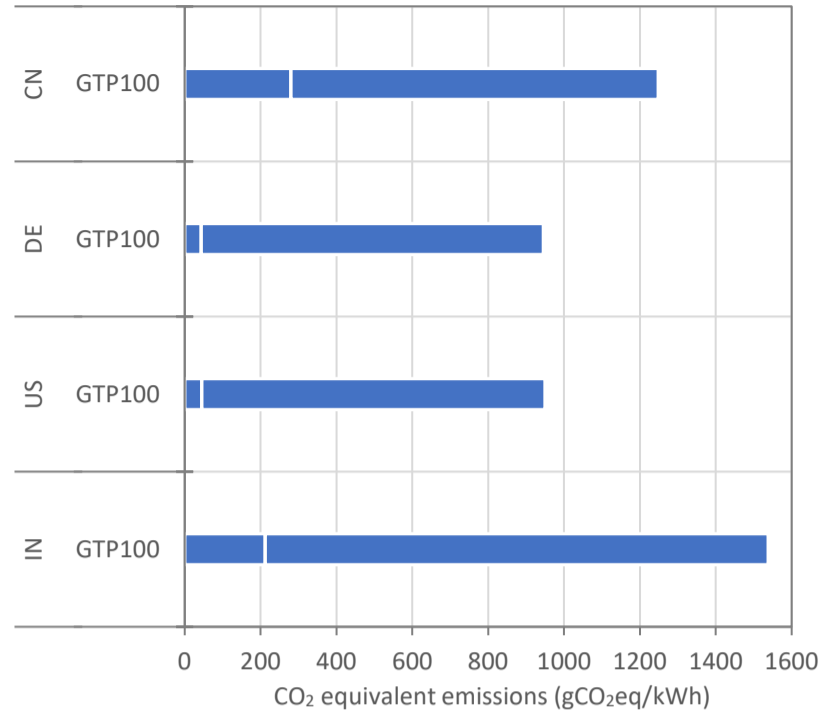
688 bars in grey, black, and other colors, respectively. CN, DE, US, and IN indicate the plant locations. CH₄ leakage

689 rates from natural gas power plants are assumed to be the inventory-based estimates for each country.

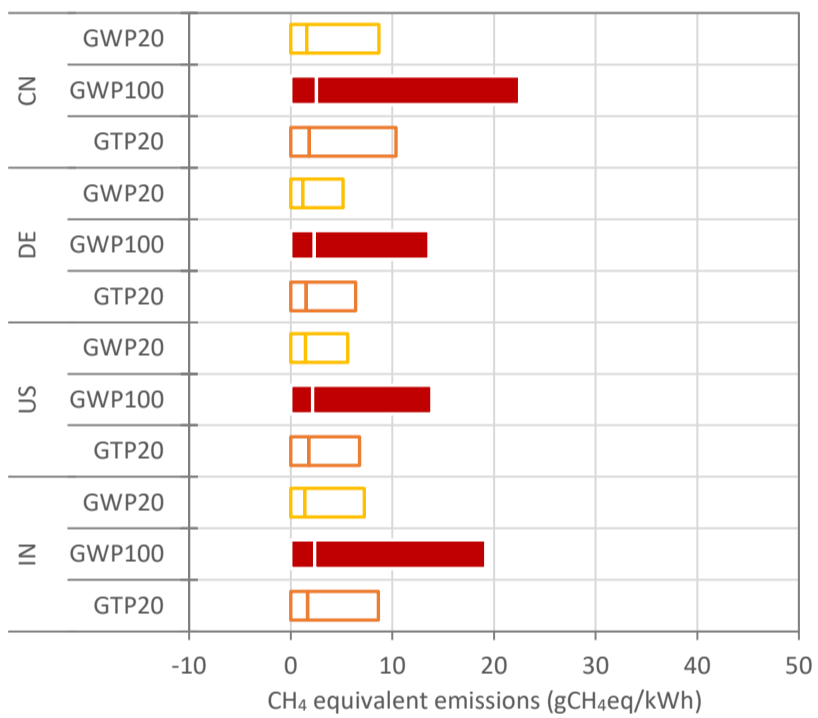
a) Coal, short



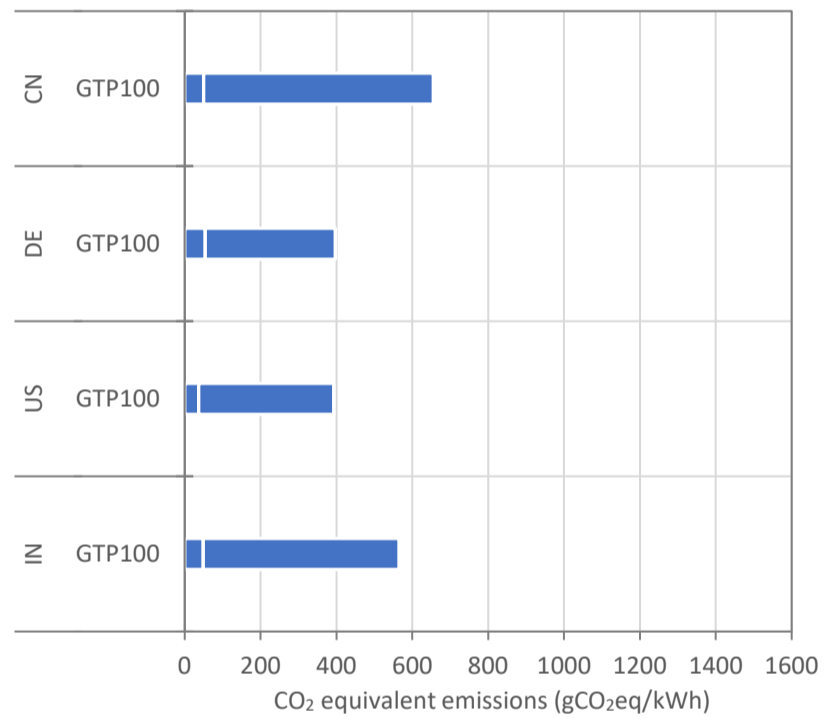
b) Coal, long



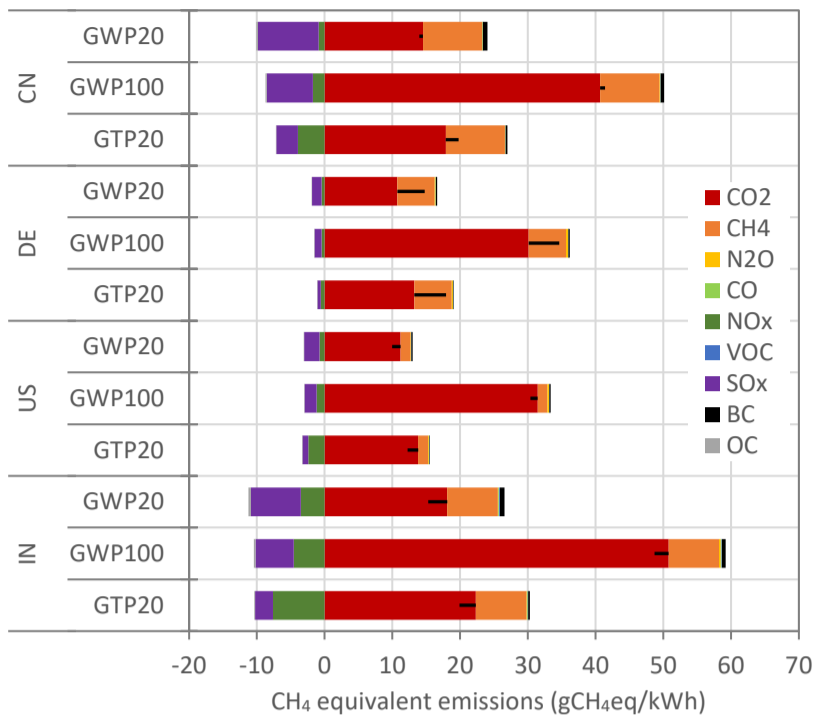
c) Gas, short



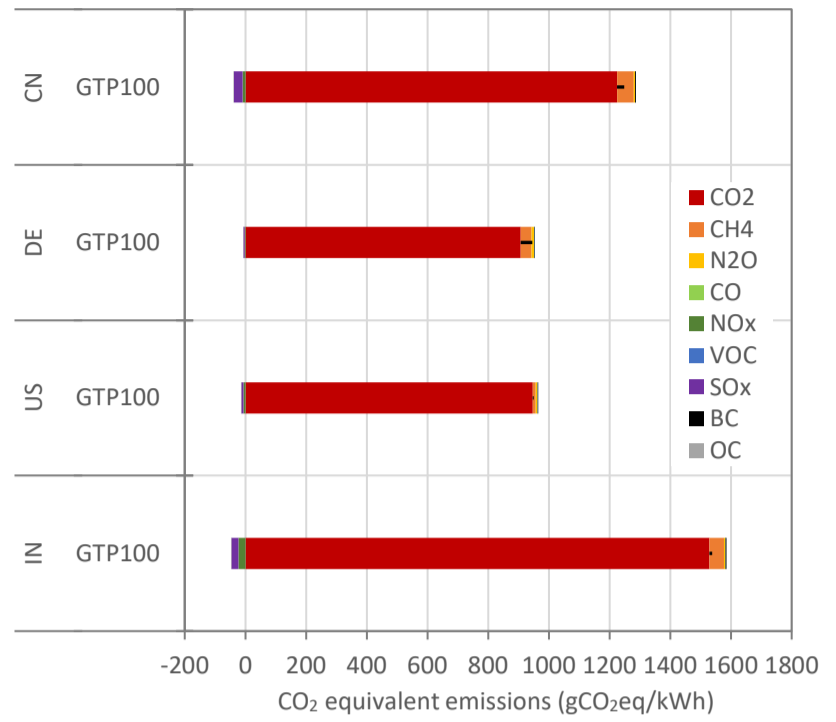
d) Gas, long



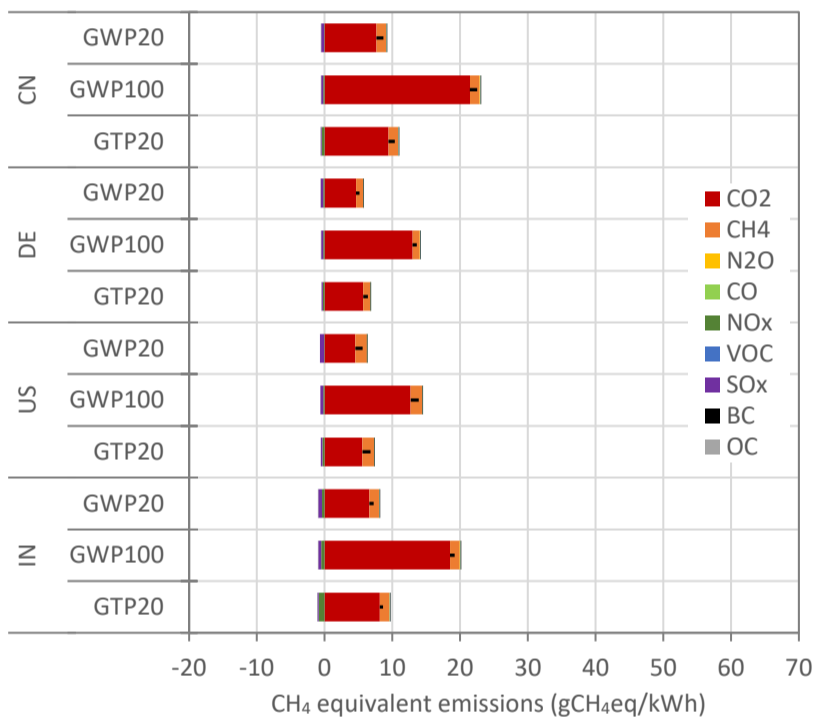
a) Coal, short



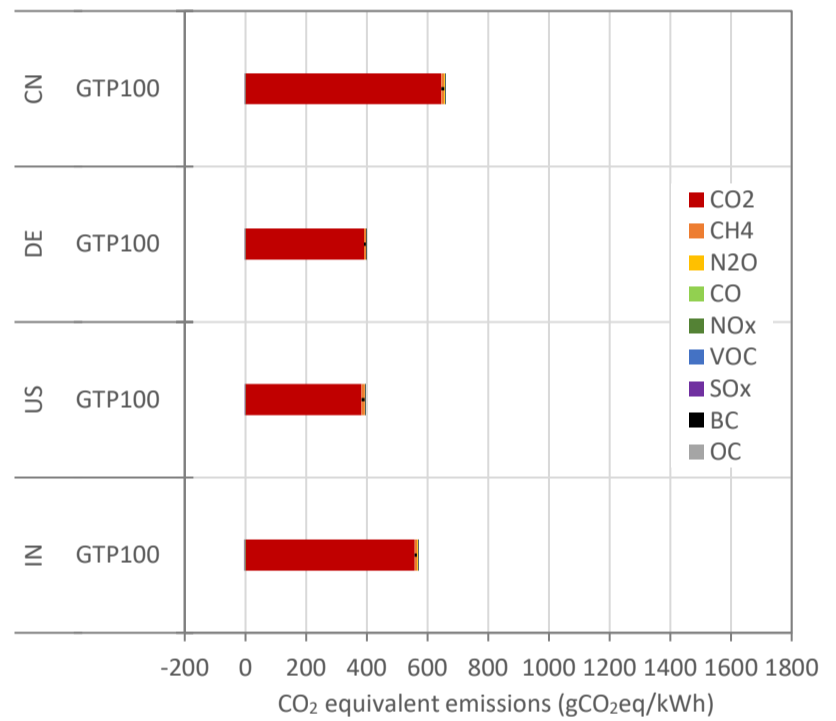
b) Coal, long



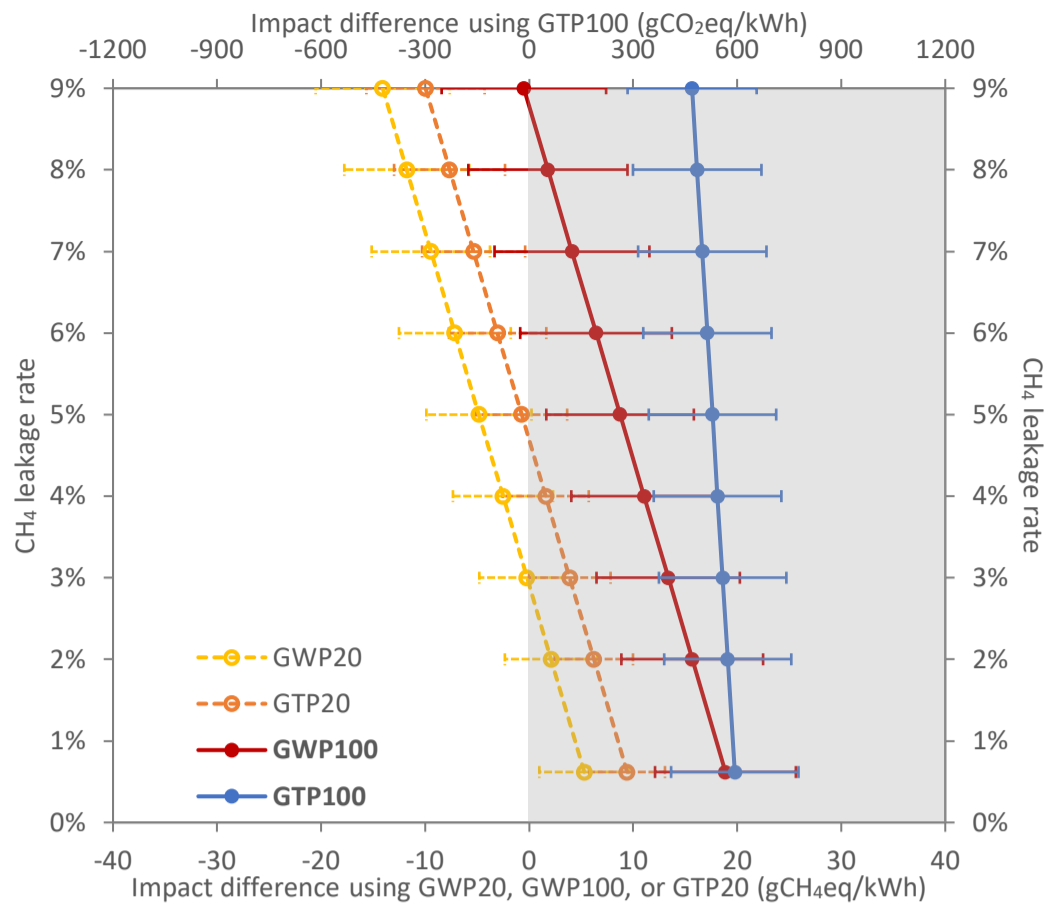
c) Gas, short



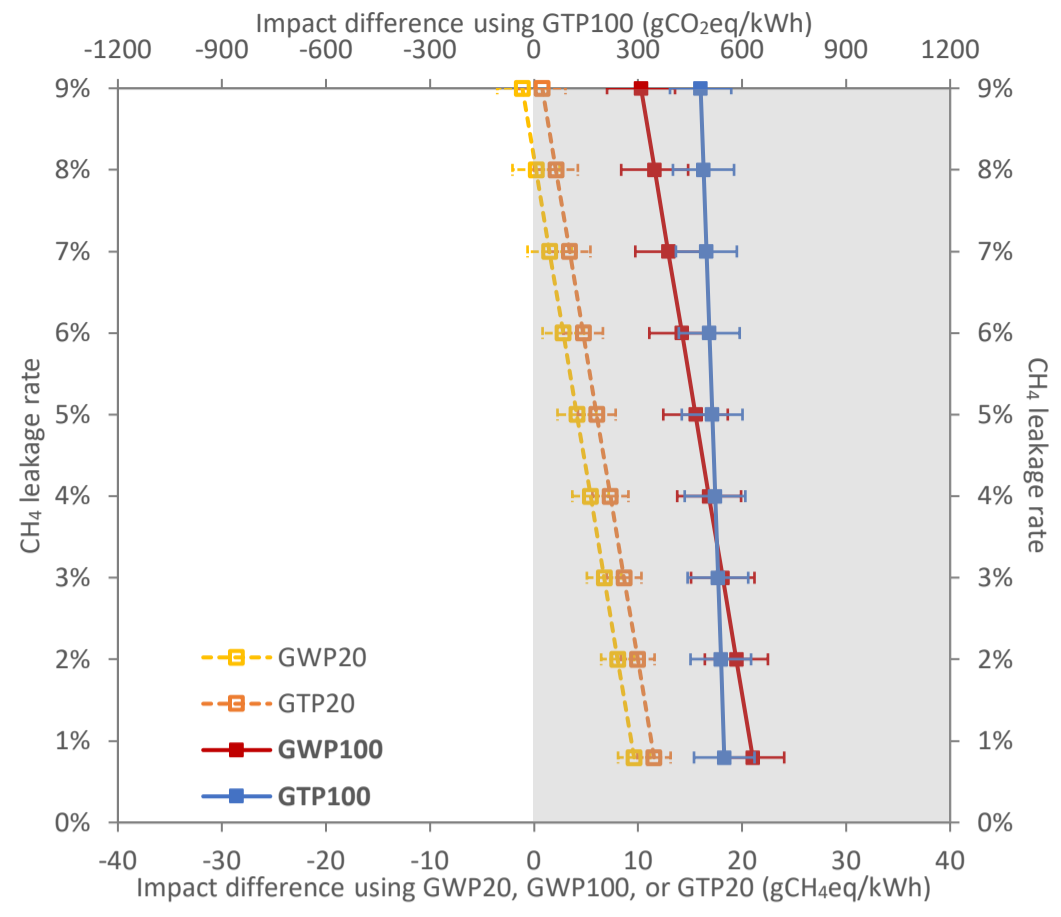
d) Gas, long



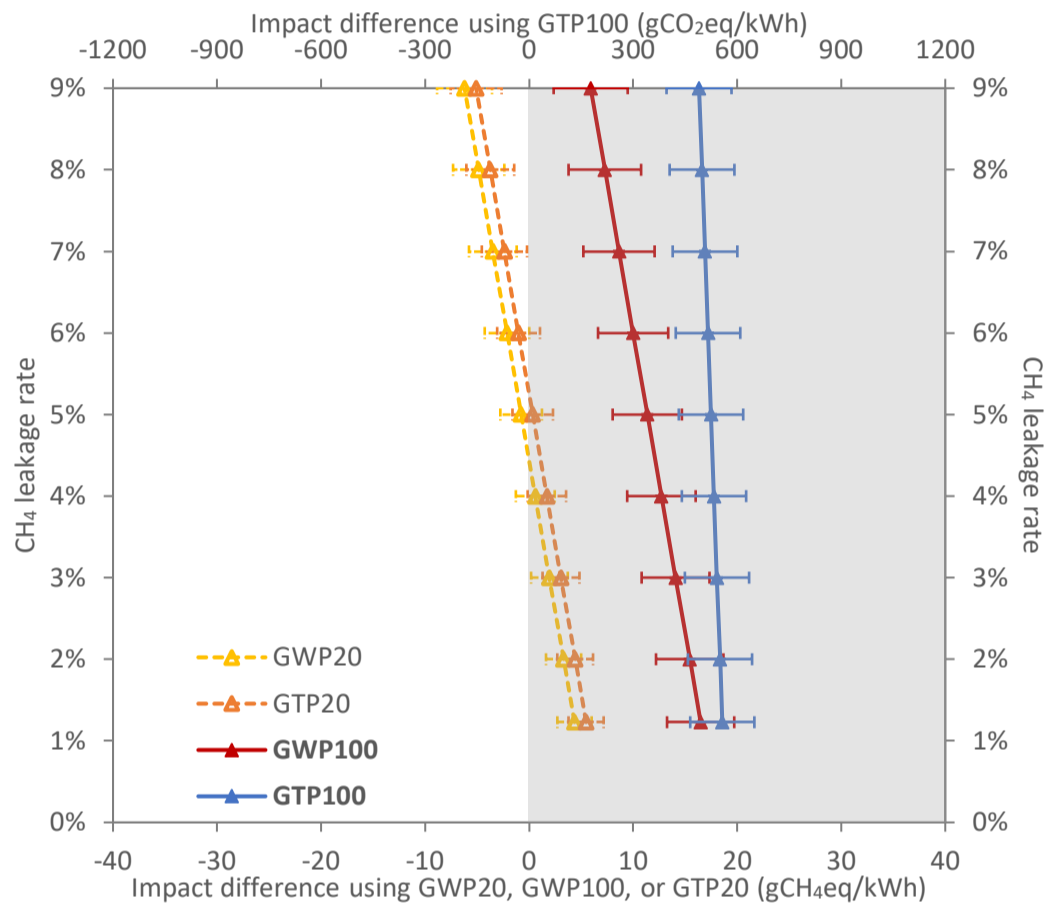
a) China



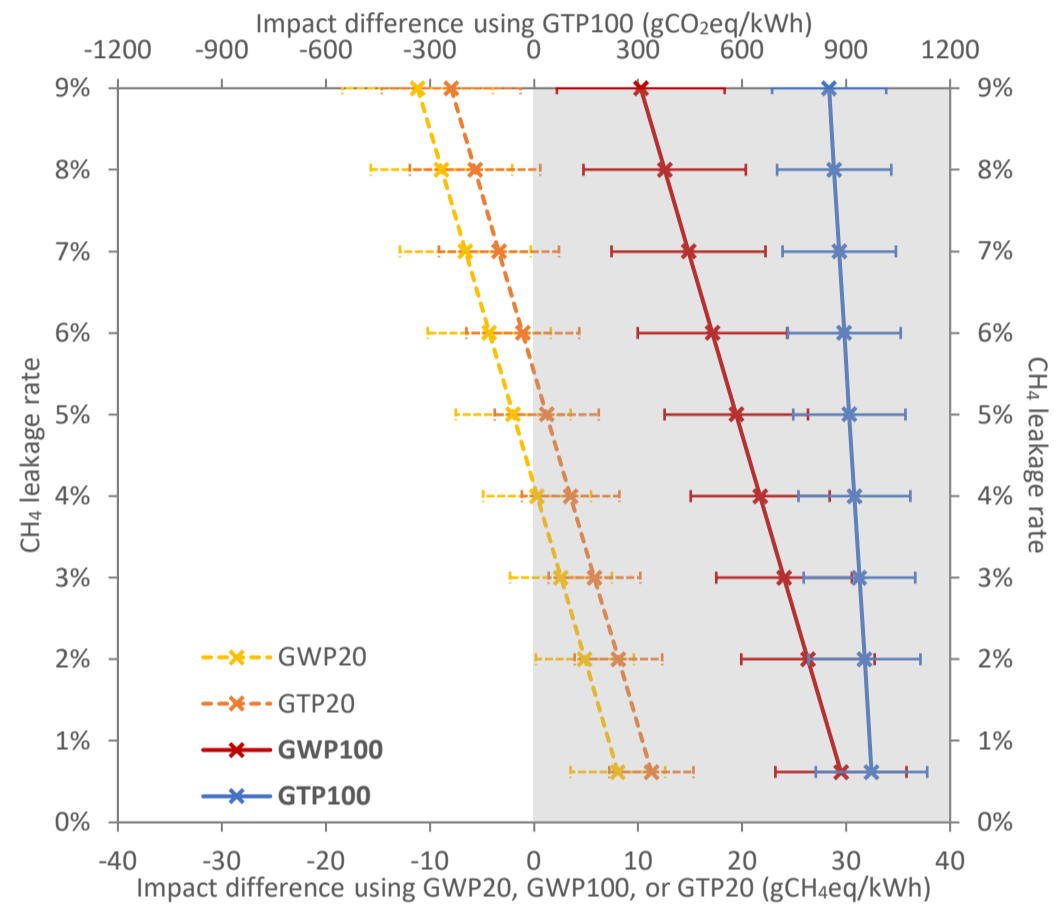
b) Germany



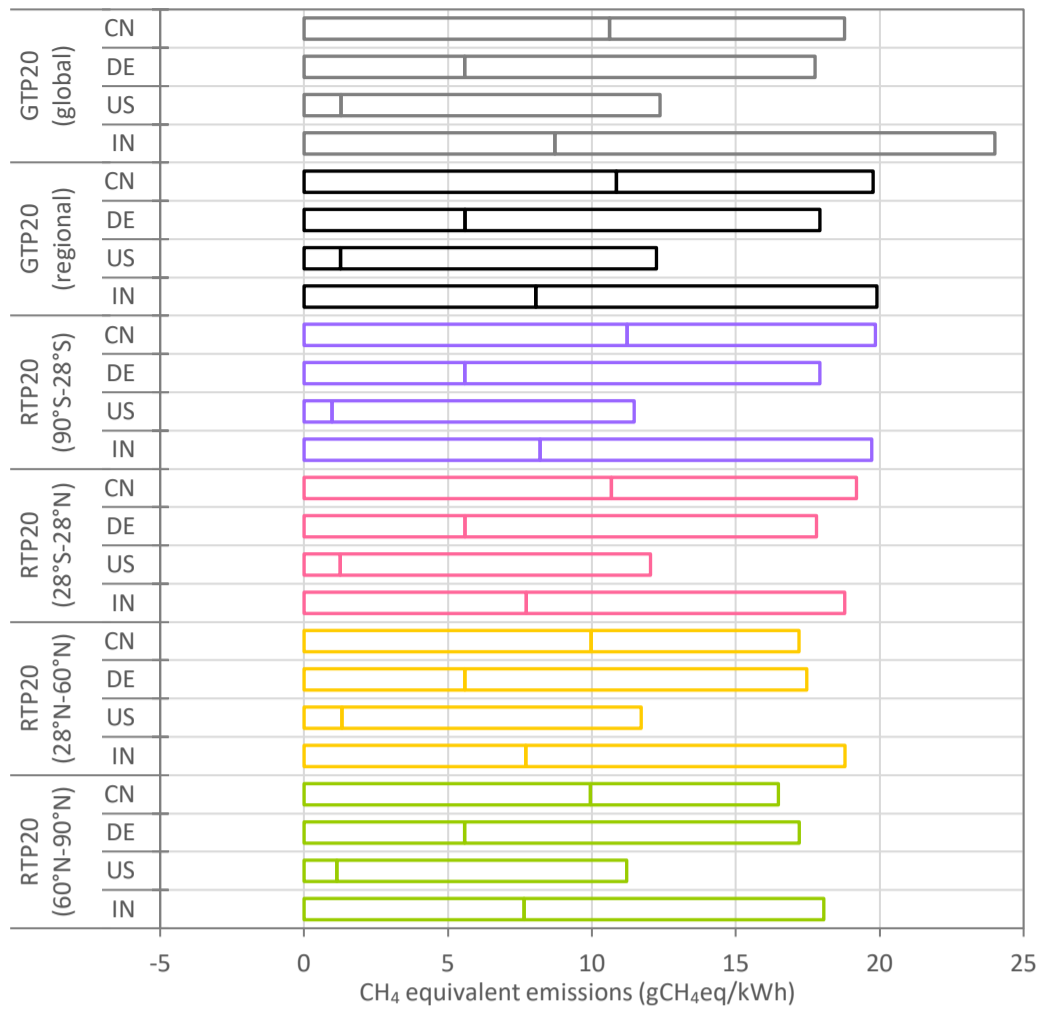
c) United States



d) India



a) Coal



b) Gas

