

# Climate consequences of natural gas as a bridge fuel

Michael Levi

Received: 22 August 2012 / Accepted: 25 November 2012 / Published online: 3 January 2013  
© Springer Science+Business Media Dordrecht 2012

**Abstract** Many have recently speculated that natural gas might become a “bridge fuel”, smoothing a transition of the global energy system from fossil fuels to zero carbon energy by temporarily offsetting the decline in coal use. Others have contended that such a bridge is incompatible with oft-discussed climate objectives and that methane leakage from natural gas system may eliminate any advantage that natural gas has over coal. Yet global climate stabilization scenarios where natural gas provides a substantial bridge are generally absent from the literature, making study of gas as a bridge fuel difficult. Here we construct a family of such scenarios and study some of their properties. In the context of the most ambitious stabilization objectives (450 ppm CO<sub>2</sub>), and absent carbon capture and sequestration, a natural gas bridge is of limited direct emissions-reducing value, since that bridge must be short. Natural gas can, however, play a more important role in the context of more modest but still stringent objectives (550 ppm CO<sub>2</sub>), which are compatible with longer natural gas bridges. Further, contrary to recent claims, methane leakage from natural gas operations is unlikely to strongly undermine the climate benefits of substituting gas for coal in the context of bridge fuel scenarios.

## 1 Introduction

It has become popular to speculate that natural gas might become a “bridge fuel” that could smooth a transition of the global energy system from fossil fuels to zero carbon energy by temporarily offsetting the decline in coal use (Kerr 2010; Nature 2012; Brown et al. 2009; Podesta and Wirth 2009). Those who note this possibility envision natural gas consumption rising well above its expected trajectory to squeeze out coal, before being displaced by zero or near-zero carbon energy sources itself. Yet climate stabilization scenarios in which natural gas provides a significant bridge at a global scale (i.e. in which world consumption of natural

---

**Electronic supplementary material** The online version of this article (doi:10.1007/s10584-012-0658-3) contains supplementary material, which is available to authorized users.

M. Levi (✉)  
Council on Foreign Relations, 58 East 68th, New York, NY 10065, USA  
e-mail: mlevi@cfr.org

gas without carbon capture and sequestration rises substantially relative to the relevant reference case for some time) are almost entirely absent from the modeling literature.

The Energy Modeling Forum led a prominent effort in 2009 that compared “Climate Change Control Scenarios” across ten prominent climate models; none of those generated stabilization scenarios where natural gas consumption was 5 % or more above their respective reference cases at any point in time, and most of the models generated stabilization scenarios in which natural gas consumption was uniformly lower than in their respective reference cases (Clarke et al. 2009). Some stabilization scenarios in the literature see natural gas use for electricity rise above their respective reference cases, squeezing out some coal-fired power, but economy-wide natural gas use in them does not rise; instead, gas use is reduced in other sectors (Clarke et al. 2007). Other stabilization scenarios see natural gas use rise above the reference case in certain countries, but not globally (Massachusetts Institute of Technology 2011). Still other scenarios see natural gas use rise well above business as usual in the near term—the first part of a bridge—but do not include the subsequent transition to zero carbon technologies that is necessary to stabilize CO<sub>2</sub> concentrations and constitute a real bridge (Wigley 2011; International Energy Agency 2011a; Myhrvold and Caldeira 2012). One recent exception (Cathles 2012) constructs three scenarios in which natural gas is indeed a bridge fuel. Yet all of those scenarios envision natural gas use growing for 50 years or more, and remaining above present levels for at least 100 years, significantly limiting the scope of the enquiry. As a result, none stabilize atmospheric CO<sub>2</sub> below 500 ppm, making comparison to many frequently discussed targets (e.g. 450 ppm) impossible.

The prospect of natural gas as a bridge, however, has raised at least two critical questions that cannot be properly addressed without investigating a broad range of scenarios where gas is a genuine bridge fuel. First, if natural gas were to become a bridge from coal to zero-carbon energy, how much of a climate advantage could that offer, relative to a case where a transition away from coal and toward zero-carbon energy was instead delayed? Second, substituting natural gas for either coal or zero-carbon energy can raise emissions of methane, which has recently prompted concern (Howarth et al. 2011; Wigley 2011; Jiang et al. 2011; Cathles et al. 2011). If natural gas were to become a bridge fuel, how much might methane leakage penalize such scenarios relative to ones that instead feature a direct transition from coal to zero carbon sources—and could that extra methane negate the value of gas over coal entirely?

Other work could usefully investigate whether scenarios that feature natural gas as a bridge fuel are economically and politically plausible and compare those features to other scenarios; such assessments are beyond the scope of this paper.

## 2 Scenario construction and properties

To address these questions, we begin by constructing a family of stabilization scenarios that feature gas as a bridge fuel, along with other scenarios for comparison.

Past studies (Wigley 2011; Cathles 2012) have constructed scenarios with high natural gas consumption by adding natural gas to (and subtracting coal from) various business-as-usual reference cases. This has the advantage of simplicity but results in scenarios that stabilize CO<sub>2</sub> concentrations at arbitrary levels (Cathles 2012) or do not stabilize concentrations at all (Wigley 2011). A central goal of this study, however, is to explore the properties of scenarios that feature natural gas as a bridge and that stabilize CO<sub>2</sub> concentrations at or near the oft discussed targets of 450 and 550 ppm. We thus use stabilization

scenarios, rather than business as usual scenarios, as our starting point, and adjust them to obtain scenarios with our desired properties. The approaches used in past studies of high-natural-gas paths also require the modeler to make arbitrary adjustments to coal and gas use in each year in constructing their scenarios. We present a method for constructing scenarios that is admittedly more cumbersome but that reduces room for discretion.

## 2.1 Traditional stabilization scenarios

We begin with the Level 1 and 2 stabilization scenarios developed for the U.S. Climate Change Science Program (Clarke et al. 2007) using each of the MiniCAM (Brenkert et al. 2003), MERGE (Manne et al. 1995), and IGSM (Prinn et al. 1999) energy-economy-climate models, for a total of six scenarios. Levels 1 and 2 correspond roughly to stabilization of CO<sub>2</sub> concentrations at 450 and 550 ppm respectively; these targets are used to identify the scenarios in this paper. These six “Traditional” stabilization scenarios, which extend from the year 2000 to 2100, all see coal, oil, and natural gas use decline relative to their respective reference cases, and energy savings (efficiency and conservation) and zero carbon energy use rise in their place. Each, however, evolves uniquely, due to the different stabilization objectives and assumptions about energy and the economy embedded in the underlying models. Using three families of starting scenarios adds complexity compared to recent studies, but reduces the odds that our ultimate results will be scenario dependent.

Specifically, we describe the traditional stabilization scenarios by the following parameters, all taken from (Clarke et al. 2007).

$Coal_t^i(Y)$	Coal consumption in EJ
$Gas_t^i(Y)$	Gas consumption in EJ
$Oil_t^i(Y)$	Oil consumption in EJ
$Zero_t^i(Y)$	Zero carbon energy consumption in EJ
$CH_4_t^i(Y)$	Methane emissions in TgCH <sub>4</sub>
$N_2O_t^i(Y)$	Nitrous oxide emissions in MtN <sub>2</sub> O
$SF_6_t^i(Y)$	Emissions of long-lived F-gases in ktSF <sub>6</sub>
$HFC134a_t^i(Y)$	Emissions of short-lived F-gases in HFC134a
$CO_2-I_t^i(Y)$	CO <sub>2</sub> emissions from non-energy industrial sources in GtC.

Here,  $i$  ranges over the different CCSP scenarios (Level 1 and Level 2 scenarios created using each of MiniCAM, MERGE, and IGSM), and  $Y$  ranges from 2000 to 2100 at 10 years intervals. Following (Wigley 2011), total CO<sub>2</sub> emissions, excluding land use change, are defined as

$$CO_{2t}^i(Y) = 0.027\text{GtC/EJ}(Coal_t^i(Y) + 0.56Gas_t^i(Y) + 0.75Oil_t^i(Y)) + CO_{2-I}^i(Y) \quad (1)$$

## 2.2 Bridge fuel scenarios

Starting with the six traditional stabilization scenarios, we construct six corresponding “Bridge” scenarios. Later, starting with those, we will construct six “Delayed” scenarios. Table 1 summarizes how those scenario families compare.

There are, in principle, an infinite number of ways to adjust the traditional stabilization scenarios to create bridge scenarios (e.g. natural gas use in any given year can be raised to an arbitrary level, so long as gas is first boosted and then falls). In order to remove the need to make a series of arbitrary assumptions, and to allow comparison of scenarios that differ only in their reliance on

**Table 1** Comparisons of different scenario types. Shaded cells indicate constraints imposed in the scenario constructions. The third column (traditional → delayed) describes the net impact of the two constructions used in the text; the delayed scenario is not actually built from the traditional one. Changes in energy savings and carbon-free energy are incidental to the scenario constructions

	Case Comparison		
	Traditional → Bridge	Bridge → Delayed	Traditional → Delayed
Natural Gas	Increased	Reduced	Unchanged
Coal	Reduced	Increased	Increased
Combined Coal and Natural Gas	Increased	Unchanged	Increased
CO <sub>2</sub> Emissions	Unchanged	Increased	Increased
Energy Savings and Carbon-Free Energy	Reduced	Unchanged	Reduced

natural gas (rather than in their CO<sub>2</sub> emissions too), we proceed roughly as follows: Beginning with each traditional scenario, we increase natural gas consumption, and decrease coal, energy savings, and zero carbon energy, such that annual CO<sub>2</sub> emissions remain unchanged but so that natural gas, rather than zero-carbon energy and energy savings, displaces coal insofar as possible. In this way, we delay the increase in energy efficiency and in zero-carbon energy, without delaying the decline in coal. (This should not be thought of as “correcting” the original scenarios; they are just a useful point for departure.) Comparing Fig. 1a and b (and 1d and 1e) illustrates this.

Specifically, beginning with each traditional stabilization scenario, we start by temporarily restoring coal use to its (higher) level in the relevant reference case. One can think of this as an intermediate scenario in which zero-carbon energy and energy efficiency have failed to drive out coal. Now, in each year, we increase natural gas use and reduce coal use, holding final energy constant, essentially using natural gas to drive out coal instead. (Final energy is calculated assuming that marginal coal and gas are both used in electricity generation.) We continue until either CO<sub>2</sub> emissions are the same as in the original traditional stabilization scenario or coal use reaches zero. If coal use reaches zero, we reduce natural gas use back to such a level that CO<sub>2</sub> emissions are the same as in the traditional case. This forces the gas “bridge” to eventually end.

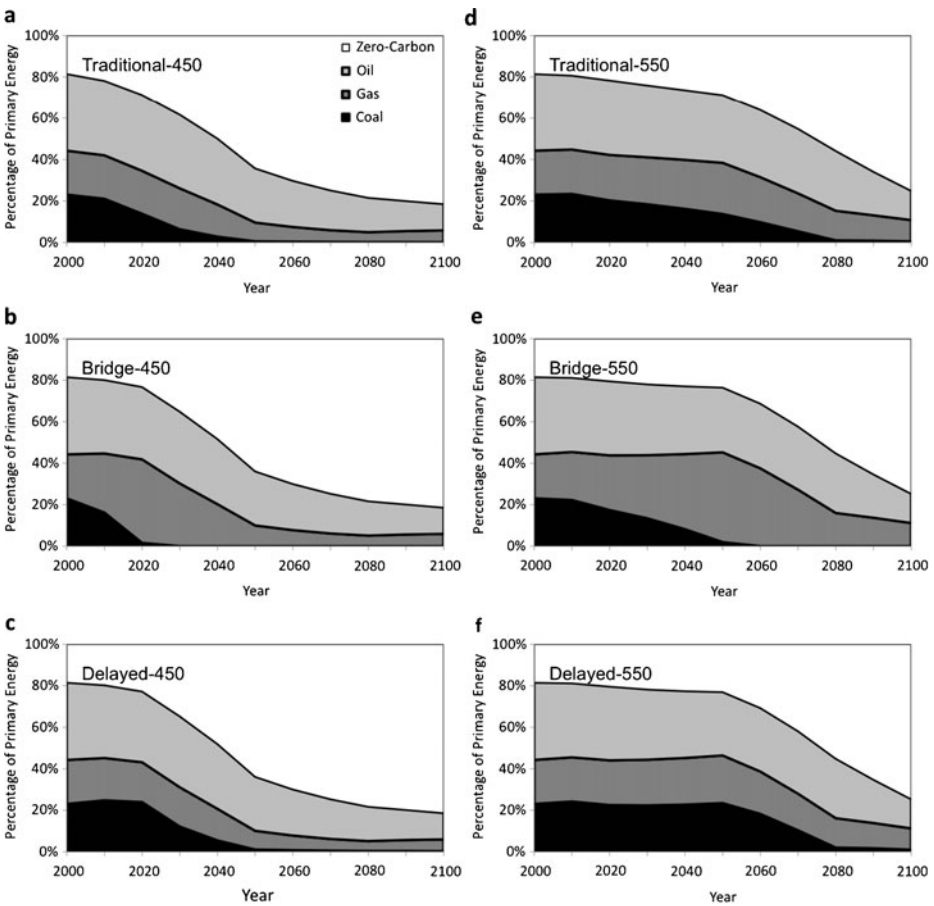
Note that this construction simply maximizes the use of natural gas subject to some basic constraints: new natural gas (beyond what is in the traditional stabilization scenario) can only displace as much coal as there is in the business-as-usual case; and CO<sub>2</sub> emissions must be the same as in the traditional stabilization case. One could in principle construct less extreme bridge fuel scenarios, i.e. ones that do not maximize natural gas use even within these constraints. Focusing on these extreme scenarios allows us to bound the benefits (in avoided coal emissions) and dangers (in methane leakage) of possible bridge fuel scenarios.

One can show that our construction gives

$$Gas_b^i(Y) = Gas_t^i(Y) + \min \left\{ \frac{1}{\sigma} Coal_t^i(Y), \frac{1}{1/\epsilon - \sigma} (Coal_r^i(Y) - Coal_t^i(Y)) \right\} \quad (2)$$

$$Coal_b^i(Y) = \max \left\{ 0, \frac{1}{1 - \epsilon\sigma} (Coal_t^i(Y) - \epsilon\sigma Coal_r^i(Y)) \right\} \quad (3)$$

where  $\epsilon$  is the efficiency of coal combustion relative to gas combustion,  $\sigma$  is the amount of CO<sub>2</sub> produced by using one unit of gas relative to that produced by using one unit of coal,



**Fig. 1** Percentage of primary energy from different sources in scenarios grounded in MiniCAM. (a) shows the traditional stabilization scenario with stabilization near 450 ppm CO<sub>2</sub>; (b) shows the bridge fuel scenario with stabilization near 450 ppm CO<sub>2</sub>; (c) shows the delayed transition scenario with stabilization near 450 ppm CO<sub>2</sub>. (d), (e), and (f) are similar but for stabilization near 550 ppm CO<sub>2</sub>

and the subscript  $r$  indicates relevant values in the CCSP reference cases. We let oil consumption be the same as in the traditional stabilization case and assume that increased natural gas use displaces equal amounts of zero carbon energy and energy savings. (This final assumption has no consequences for our analysis of climate impacts later.) CO<sub>2</sub> emissions are computed as in the traditional case.

The value of  $\epsilon$  is assumed to be 0.9 unless otherwise noted. This figure is estimated from projected changes in coal and gas consumption and electricity generation between 2030 and 2035 in (International Energy Agency 2011b), which reflects detailed modeling of underlying generation technologies. Similar figures are obtained if one uses different years. The relative efficiencies of an arbitrary pair of gas and coal plants, of course, will be different. Some have argued or assumed that  $\epsilon$  is much smaller (e.g. Cathles et al. 2011, Wigley 2011); we test such values below wherever they may be illuminating.

Following Wigley (2011), the value of  $\sigma$  is assumed to be 0.56, which accounts only for differences in direct emissions at the point of use. As in most other recent modeling of

natural gas transitions, we do not distinguish between CO<sub>2</sub> emissions from conventional and unconventional gas, which have similar lifecycle CO<sub>2</sub> profiles (Skone et al. 2011). Using assumptions consistent with other recent work on the subject of natural gas transitions maximizes comparability of the results. None of these omissions alter our (or their) qualitative conclusions.

We compute CH<sub>4</sub> emissions as

$$CH_{4,b}^i(Y) = CH_{4,t}^i(Y) + \alpha L(Gas_b^i(Y) - Gas_t^i(Y)) + \beta(Coal_b^i(Y) - Coal_t^i(Y)) \quad (4)$$

where  $L$  (expressed as a fraction) is the rate of methane leakage from new natural gas operations,  $\alpha=20$  TgCH<sub>4</sub>/EJ, and  $\beta=0.19$  TgCH<sub>4</sub>/EJ represents methane emissions from a mix of surface and deep coal mining (derived from (Wigley 2011)). (One can note immediately from this that if and only if  $L < 0.95$  %, switching from coal to natural gas reduces methane emissions.) The traditional stabilization scenarios already include some methane leakage from expected natural gas and coal use; we thus only add (or subtract) methane emissions from natural gas and coal use in excess (or short) of that use found in the traditional stabilization scenarios.

All other emissions rates are the same as in the traditional scenario. In the six new scenarios that result, coal use declines even more quickly than in the respective “Traditional” stabilization scenarios, but zero carbon energy use and energy savings rise more slowly, with natural gas bridging the gap. The result is a family of six “Bridge” scenarios.

### 2.3 Delayed transition scenarios

Now, starting with the six new “Bridge” scenarios, we construct six “Delayed” transition scenarios. Our goal is to understand how much climate benefit a near term transition to natural gas delivers if the alternative is a delayed transition from coal, with zero-carbon energy and energy savings the same in both cases. Thus, heuristically, we replace the gas bridge with continued coal use for one or more decades. Comparing Fig. 1b and c (and 1e and 1f) illustrates this change. Specifically, starting with the bridge scenarios and holding final energy constant, we increase coal and reduce gas use until the latter falls back to its level in the traditional stabilization scenario. Gas is no longer aggressively pushing out coal. This gives

$$Gas_d^i(Y) = Gas_t^i(Y) \quad (5)$$

$$Coal_d^i(Year) = Coal_b^i(Y) + \frac{1}{\epsilon}(Gas_b^i(Y) - Gas_t^i(Y)) \quad (6)$$

We let oil consumption be the same as in the traditional case, and calculate total CO<sub>2</sub> emissions as in the traditional case. CH<sub>4</sub> emissions are

$$CH_{4,d}^i(Y) = CH_{4,t}^i(Y) + \beta(Coal_d^i(Y) - Coal_t^i(Y)) \quad (7)$$

This formula does not include methane leakage from additional natural gas use beyond the traditional stabilization scenarios. This is because the delayed scenarios feature the same amount of natural gas use as the traditional ones. Emissions rates for all other species are once again the same as in the traditional scenarios. In the six resulting “Delayed” scenarios,

zero carbon energy rises at the same pace as in the “Bridge” scenarios, but coal is phased out more slowly.

## 2.4 Basic scenario properties

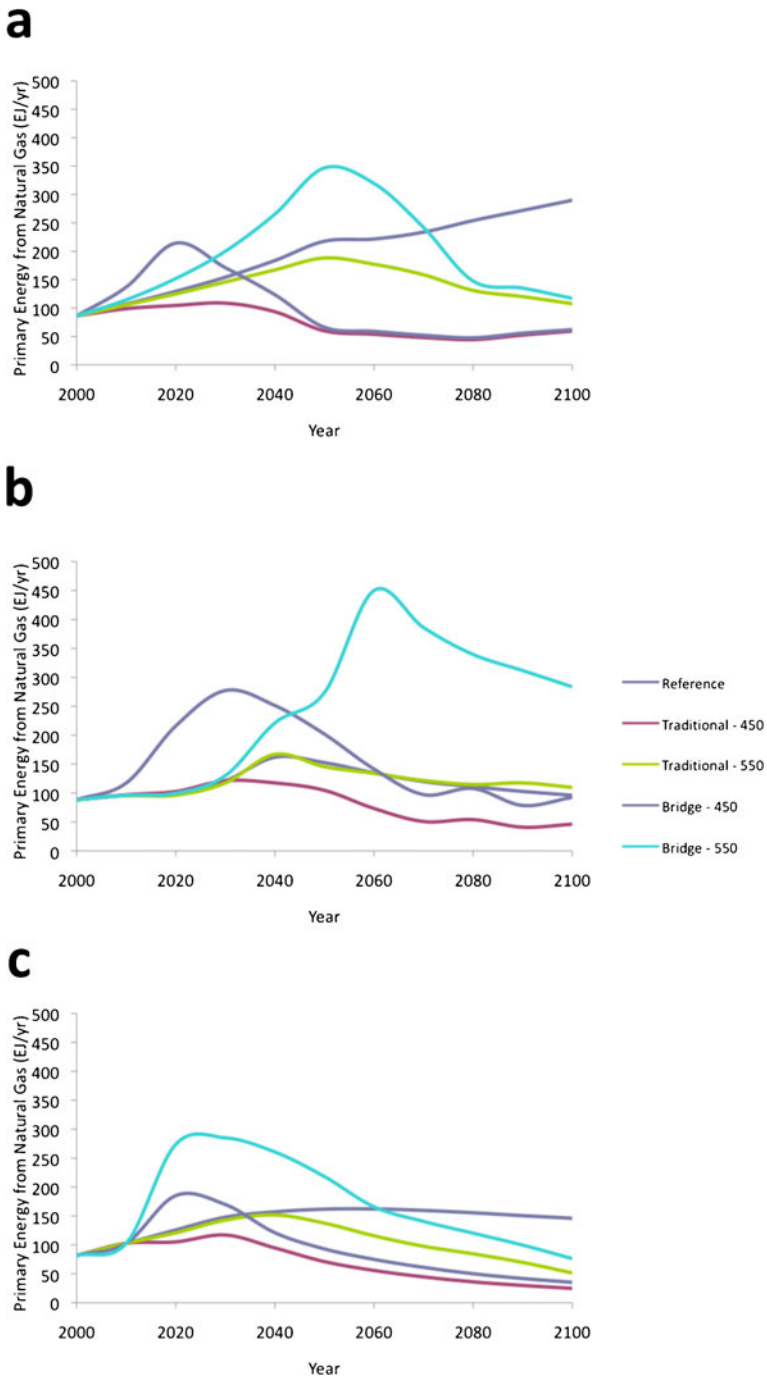
Figure 1a–f show how the shares of coal, gas, and other primary energy evolve in the traditional, bridge, and delayed scenarios grounded in the MiniCAM model. (The patterns are qualitatively similar for scenarios grounded in MERGE and IGSM. We use the phrase “grounded in” throughout this paper simply to identify the scenarios; it should not be interpreted as suggesting that these models could or would actually produce the scenarios that we have manually constructed.) All three scenario types look like what one would expect. In the traditional stabilization scenarios, gas and coal are both displaced by carbon-free energy sources and energy savings, while in the bridge scenarios, coal is first displaced by gas, which is then displaced by other energy sources. The delayed scenario, meanwhile, resembles the traditional one, but with coal and gas displaced by other energy sources more slowly.

Figure 2a–c show the evolution of natural gas consumption in the three reference cases and in all twelve stabilization scenarios. As expected, all bridge scenarios feature much higher gas consumption than in their respective reference and traditional stabilization cases. For all bridge fuel scenarios aimed at stabilizing CO<sub>2</sub> concentrations near 450 ppm, gas consumption peaks around 2020–2030 (though at different levels in the different scenarios), before falling to near the same level as in the traditional scenarios by 2050–2060. In contrast, bridge scenarios aimed at stabilizing CO<sub>2</sub> concentrations near 550 ppm are considerably more varied, reflecting the looser constraint on total emissions. Gas consumption peaks anywhere between 2020 and 2060. In two of the three bridge scenarios, gas consumption falls to near the same level as in the relevant traditional stabilization scenario by 2060–2080, but in one (grounded in the MERGE model), gas consumption remains well above its reference scenario level beyond 2100. Total natural gas consumption in the bridge scenarios ranges from half of the amount in the relevant reference scenario (in the case of the bridge scenario grounded in MiniCAM that stabilizes CO<sub>2</sub> concentrations near 450 ppm) to double it (in the case of the bridge scenario grounded in MERGE that stabilizes concentrations near 550 ppm). The most gas-intensive scenario sees total natural gas consumption of approximately 25,000 EJ during the 21<sup>st</sup> century, a massive amount, but still comparable to or less than that in other scenarios recently discussed in the literature (see examples in (Clarke et al. 2009) and (Wigley 2011)).

The [Electronic Supplementary Material](#) includes an additional discussion of trends in zero-carbon energy deployment and total energy demand in the scenarios.

## 3 Comparing stabilization scenarios

We can now evaluate whether the bridge scenarios yield substantial climate advantages over the ones in which the transition from coal is delayed instead. We focus in particular on the peak temperature rise in each scenario, which has been a central focus in climate modeling and policy. (As in many other studies, our investigation necessarily ends at 2100 due to the scope of the scenarios, even though in some scenarios, temperature rises beyond 2100 will be significant.)



**Fig. 2** Evolution of natural gas consumption in different scenarios. **(a)**, **(b)**, and **(c)** are based on MiniCAM, MERGE, and IGSM scenarios respectively



We model the climate impacts of these scenarios using MAGICC, a simple, widely used coupled gas-cycle/climate model (Wigley 2008), assuming a climate sensitivity of 3 °C to doubling of CO<sub>2</sub> concentrations. To create complete inputs for MAGICC, we define regional SO<sub>2</sub> emissions as follows:

$$SO_2(1)^i(Y) = 0.027k_1(k_{SO_2}(Y)Coal^i(Y) - k_{SO_2}(2000)Coal^i(2000)) - C_1 \quad (8)$$

$$SO_2(2)^i(Y) = 0.027k_2(k_{SO_2}(Y)Coal^i(Y) - k_{SO_2}(2000)Coal^i(2000)) - C_2 \quad (9)$$

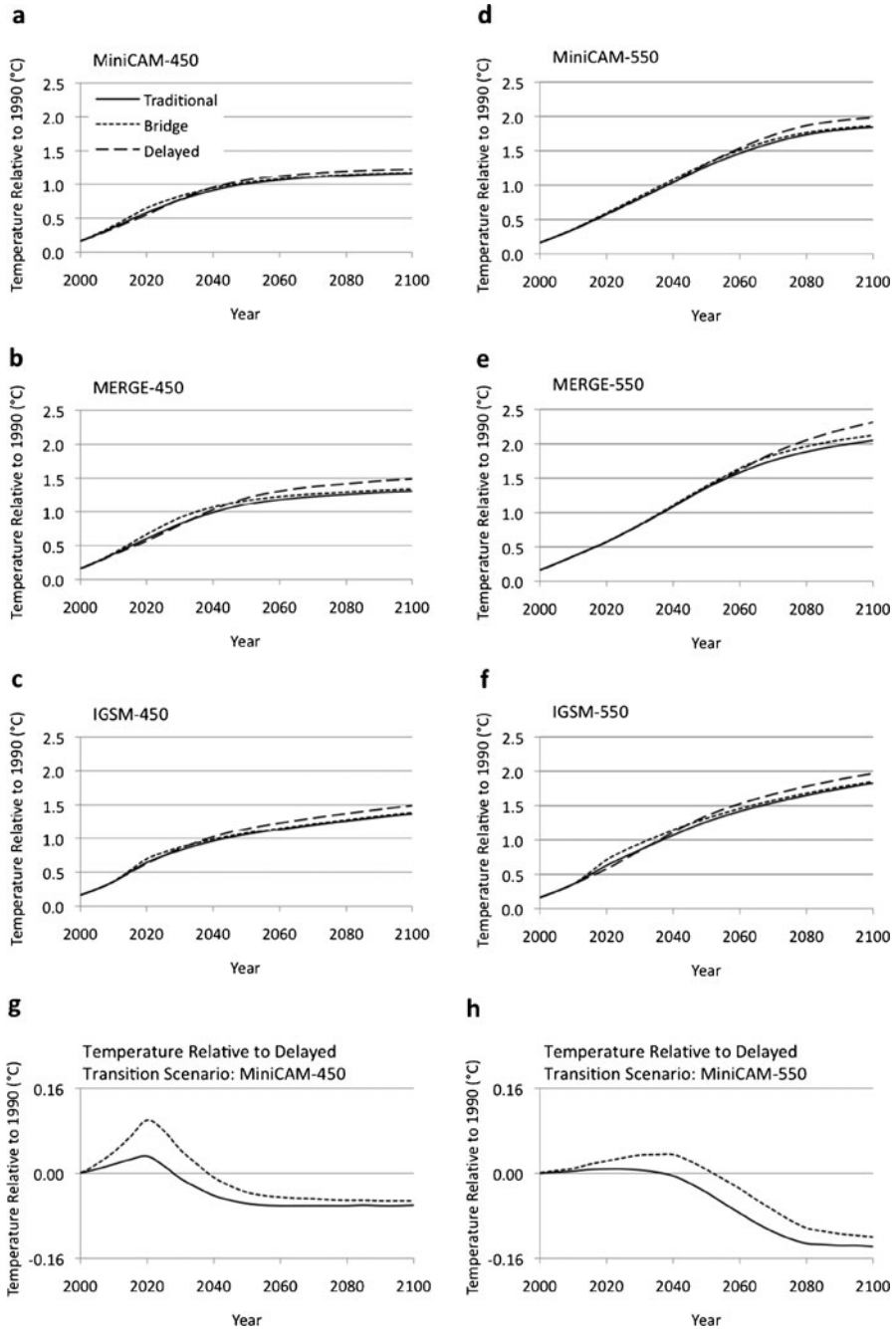
$$SO_2(3)^i(Y) = 0.027k_3(k_{SO_2}(Y)Coal^i(Y) - k_{SO_2}(2000)Coal^i(2000)) - C_3 \quad (10)$$

where  $C_1$ ,  $C_2$ ,  $C_3$ ,  $k_1$ ,  $k_2$ , and  $k_3$  are chosen so that SO<sub>2</sub> emissions match up with those used in the well known WRE450 scenario (Wigley et al. 1996) for 1990 and 2000, and  $k_{SO_2}$  is the quantity of sulfur dioxide emissions per unit carbon emissions from coal combustion, which, following (Wigley 2011), we take as 12 GtS/GtC in 2000, declining linearly to 2 GtS/GtC in 2060, and remaining constant thereafter. We set CO<sub>2</sub> emissions from deforestation in all scenarios equal to the corresponding values from the WRE450 scenario (Wigley et al. 1996). (Deforestation emissions in WRE450 and WRE550 are both the same.)

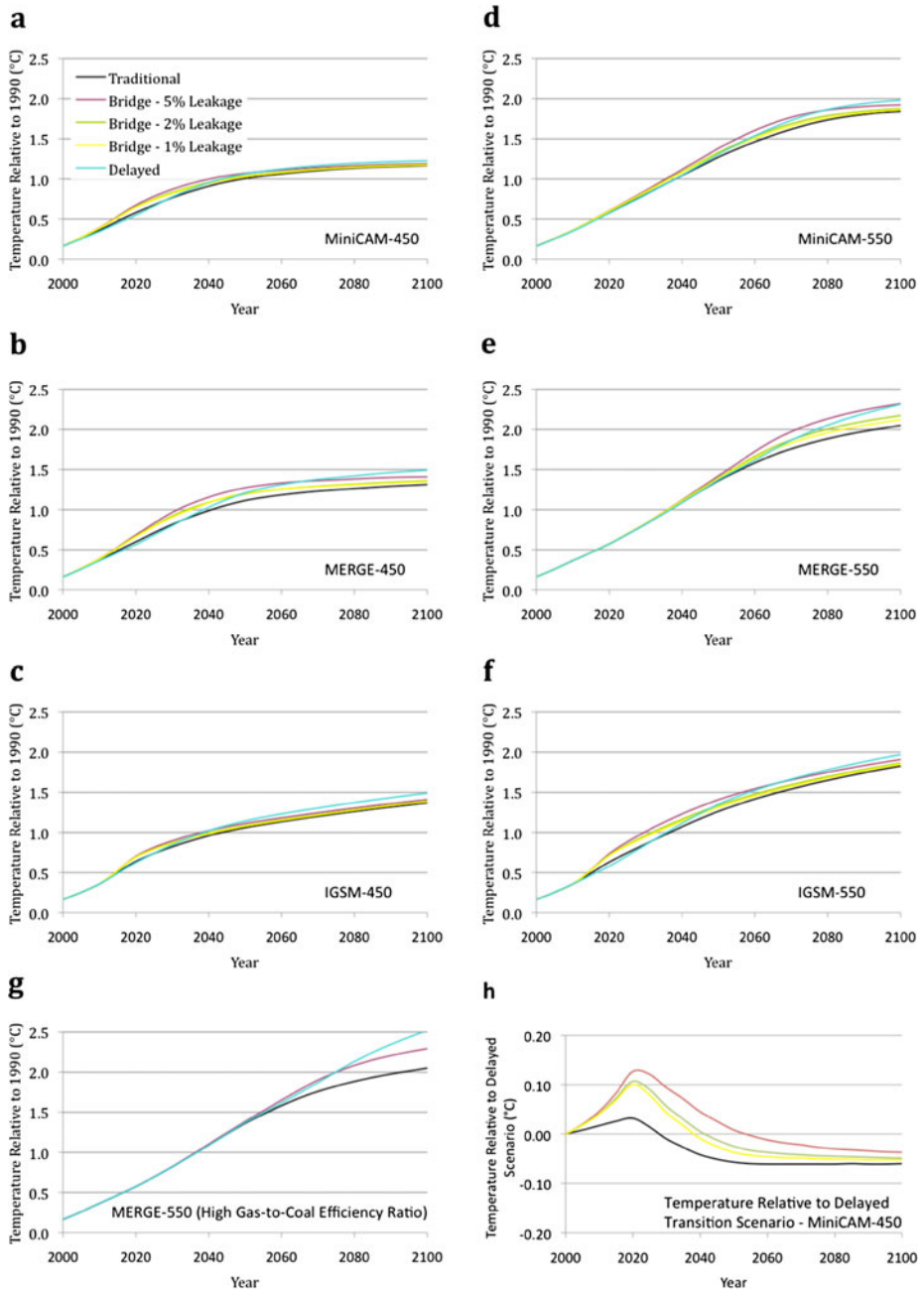
In order to isolate the impact of CO<sub>2</sub>, we assume for now that replacing one unit of final energy produced from coal with one produced from gas, or vice-versa, does not alter total methane emissions, an assumption that we will relax later. Note that the bridge and delayed scenarios still have higher methane emissions than the traditional stabilization scenarios, since they involve more total coal and gas use.

Figure 3a–f compare expected temperature pathways for our six triplets of traditional, bridge, and delayed emissions scenarios. To make it possible to distinguish the different paths, the figure does not show projected temperature rises for the reference cases, which exceed 2 °C relative to 2000 levels by 2050 and approach 6 °C by 2100, at which point they are still rising steeply (Prinn et al. 2008). In order to make the impact of the different scenarios on peak temperatures and warming rates transparent, most of the panels in this figure (along with those in Fig. 4) show absolute temperature changes relative to 2000, rather than changes relative to a baseline case. To help the reader distinguish between the different paths, Fig. 3g and h show temperature rises in the traditional stabilization and bridge scenarios relative to those for the delayed scenario, with all scenarios grounded in MiniCAM; qualitative results are similar for scenarios grounded in MERGE and IGSM.

It is readily apparent that bridge scenarios offer greater climate advantage (measured as the difference in peak temperature rise prior to 2100) over delayed ones in the context of less ambitious stabilization targets. Specifically, the difference in expected temperature increases in 2100 between bridge and delayed scenarios ranges from 0.052 to 0.149 °C for stabilization targets near 450 ppm CO<sub>2</sub> but from 0.119 to 0.189 °C for targets near 550 ppm CO<sub>2</sub>. (CO<sub>2</sub> emissions are, by construction, higher in the delayed case than in the others, leading to stabilization at somewhat higher CO<sub>2</sub> concentrations.) Why is this so? For scenarios with outcomes near the most stringent stabilization target investigated (450 ppm), coal and gas must both be phased out relatively quickly; any natural gas bridge is thus short, and can offer only limited advantage over burning coal for a similarly short additional period. The penalty



**Fig. 3** (a–f) are projected temperature rises for traditional, bridge, and delayed scenarios, relative to 1990, in Celsius degrees. (a) shows projected temperatures for scenarios grounded in MiniCAM aimed at stabilizing CO<sub>2</sub> concentrations near 450 ppm; (b) and (c) do the same for scenarios grounded in MERGE and IGSM respectively. (d), (e), and (f) parallel (a), (b), and (c) respectively expect with stabilization in the neighborhood of 550 ppm CO<sub>2</sub>. (g) and (h) show temperature relative to the MiniCAM-based delayed-transition scenarios for stabilization near 450 and 550 ppm CO<sub>2</sub> respectively



**Fig. 4** How methane assumptions affect temperature. (a–g) show projected temperature rises (°C) relative to 1990 with different rates of methane leakage. (a) shows scenarios grounded in MiniCAM aimed at stabilizing CO<sub>2</sub> concentrations near 450 ppm; (b) and (c) do the same for scenarios grounded in MERGE and IGSM respectively. (d), (e), and (f) parallel (a), (b), and (c), except with stabilization near 550 ppm. (g) shows results for scenarios similar to those in (e), but assuming coal combustion is 53 % as efficient as gas combustion. (h) shows expected temperatures relative to those in the delayed transition case, for scenarios grounded in MiniCAM aimed at stabilization near 450 ppm CO<sub>2</sub>

for delay is much greater in the scenario grounded in MERGE than for those scenarios grounded in MiniCAM and IGSM, because MERGE features far more coal in its reference case, and hence in the scenario with a delayed transition.

In contrast, less stringent but still pressing stabilization targets (e.g. 550 ppm CO<sub>2</sub>) can be consistent with longer natural gas bridges (as can be seen from Fig. 2), which offer commensurately greater advantages over simply delaying a transition away from coal for a similarly long time, as can be seen from Fig. 3d–f. In the scenarios produced by MiniCAM, MERGE, and IGSM for the CCSP, even laxer targets, like 650 ppm CO<sub>2</sub>, do not require much immediate substitution of either gas or zero-carbon energy for coal (Clarke et al. 2007), making discussion of bridge scenarios largely irrelevant.

In contrast with their consequences for peak temperature rise, scenarios with delayed transitions exhibit lower temperatures than the bridge (and traditional) scenarios for several decades in the immediate future. This owes to the fact that their greater coal combustion initially raises sulfur dioxide emissions and thus lowers temperatures (Wigley 1991). Ultimately, though, all stabilization scenarios see traditional coal use decline to near zero, largely removing this effect. The timing of these effects depends on assumptions regarding the level of sulfur dioxide emissions from marginal coal plants, but the qualitative results are insensitive to this choice.

The pattern is less consistent for peak warming rates, which, independently from absolute temperature changes, are associated with elevated climate risks (O'Neill and Oppenheimer 2004). In the context of stabilization near 450 ppm, scenarios that feature natural gas bridges consistently show higher peak warming rates than ones that feature delayed transitions away from coal. In contrast, in the context of stabilization near 550 ppm, the stabilization path (gas bridge or delayed transition) that shows the highest peak warming rate depends on the underlying model (MiniCAM, MERGE, or IGSM), i.e. on the broader features of the energy system.

#### 4 Consequences of methane leakage

Several authors have recently suggested that methane emissions from natural gas production and distribution will severely reduce or entirely negate the climate benefits of the lower CO<sub>2</sub> emissions associated with a transition from coal to gas (Howarth et al. 2011). One recent study (Wigley 2011) has argued in detail that substantial CH<sub>4</sub> leakage could imply that a transition from coal to gas would not be of much or any climate benefit. Others (Alvarez et al. 2012) have come to more mixed conclusions. None of these, though, examine scenarios in which natural gas use is eventually phased out, i.e. bridge scenarios.

We address this gap by refining our bridge scenarios to reflect CH<sub>4</sub> emissions associated with a range of assumptions (1 %, 2 %, and 5 % leakage) about CH<sub>4</sub> leakage rates. Most recent publications have indicated that leakage in the United States is likely to be 1–2 %, and have all but rejected the possibility of leakage on the order of 5 % (e.g. Jiang et al. 2011; Cathles et al. 2011). We include the 5 % case here for completeness, however, given the existence of at least one outlier in the literature (Howarth et al. 2012), the possibility of greater leakage overseas than in the United States, and continuing uncertainty given the paucity of field observations.

Figure 4a–f show expected temperature rises for a range of bridge fuel scenarios including different methane leakage rates along with traditional and delayed transition scenarios for comparison. The bridge scenarios with 1–2 % methane leakage consistently yield temperatures in 2100 that are much closer to those produced in the traditional

stabilization scenarios than to those that result from a delayed transition from coal. The same is true for those bridge scenarios that feature 5 % leakage and aim to stabilize near 450 ppm CO<sub>2</sub>. This contradicts recent suggestions that such leakage rates make natural gas worse for climate change than coal.

The bridge scenarios with 5 % leakage that aim to stabilize CO<sub>2</sub> concentrations around 550 ppm yield more varied results. In all cases, they produce temperatures in 2100 that are lower than those that result from a delayed transition from coal. In many of the cases, though, the resulting temperatures in 2100 are closer to those generated by a delayed transition from coal than to those produced by the traditional stabilization scenarios (which emphasize a more rapid transition to zero-carbon energy). These are generally cases where fossil fuel use of some sort will persist at a high level well into this century. (One should also note, though, that even in these cases, temperatures in the delayed transition scenarios remain on a steep upward trajectory in 2100, while temperatures in the bridge scenarios, even with high leakage, have at least begun to plateau.)

This last feature disappears if one assumes that natural gas combustion is substantially more efficient than coal combustion, as recent studies often do (Wigley 2011; Cathles et al. 2011). Figure 4g shows projected temperature pathways for several scenarios grounded in MERGE that aim to stabilize concentrations near 550 ppm CO<sub>2</sub>, with methane leakage of 5 %, and assuming that coal combustion is only 53 % as efficient as gas combustion (Wigley 2011). (The proper comparison here is between Fig. 4b and g; the only difference between them is the relative efficiency of coal and gas combustion.) Now, even with 5 % methane leakage, the bridge fuel scenarios yield substantially lower temperatures in 2100 than the delayed transition scenarios do. (One should note, though, that the ratio of coal-to-gas efficiency used in this sensitivity analysis may be lower than what is plausible given current and prospective coal and natural gas combustion technologies.) The scenario grounded in MERGE that stabilized CO<sub>2</sub> concentrations near 550 ppm previously produced the greatest projected temperature penalty for methane leakage, and hence provides the most challenging case for natural gas.

The consequences for peak warming rates are similar to those in the previous section, with bridge scenarios delivering greater peak warming rates than the others. More leakage raises peak warming rates further.

Though the method for including methane leakage here follows Wigley (2011), the results are different, with leakage resulting in a much more modest penalty in the present study. This is because the two analyses differ fundamentally in the types of scenarios they examine. Wigley (2011) studies a scenario in which greatly expanded use of natural gas continues indefinitely, resulting in methane emissions (and consequent radiative forcing) that also continue indefinitely. In contrast, the scenarios studied here ultimately phase out natural gas, and hence accompanying methane emissions, leading to lower long-term temperature impacts.

## 5 Conclusions and discussion

Beginning with well known stabilization scenarios that feature direct transitions from a coal-dominated world to one featuring zero-carbon energy (“traditional stabilization scenarios”), we have constructed scenarios that feature a natural gas “bridge” to a zero-carbon world while leaving carbon dioxide emissions the same at all points in time, and ones that differ from those only by replacing that bridge with coal.

Comparing bridge and traditional stabilization scenarios aimed at stabilizing CO<sub>2</sub> concentrations near 450 ppm with closely related scenarios in which a transition from coal is

delayed, we find that the differences in peak temperatures between the various scenarios is relatively small. This remains true regardless of methane leakage rates. The greatest differences occur for those scenarios where coal use in the reference case is highest.

In contrast with the 450 ppm cases, in the scenarios explored here, pathways that stabilize CO<sub>2</sub> concentrations near 550 ppm using natural gas as a bridge fuel promise substantially lower peak temperatures than similar ones that differ only by delaying the transition away from coal until zero carbon energy rises in its place.

Moreover, in most cases where stabilization is near 550 ppm CO<sub>2</sub>, even high rates of methane leakage do not fundamentally alter the conclusion that replacing coal with gas can substantially lower peak temperatures relative to what they would be if a transition away from coal were instead delayed. In particular, if so-called “tipping points” can be triggered by exceeding particular temperature thresholds, methane leakage in the context of bridge fuel scenarios will have at most a very small impact on the odds that those thresholds will be crossed. This is true even if steps to reduce methane leakage can yield benefits exceeding costs.

Collectively, these results suggest that it may be useful to think of a natural gas bridge as a potential hedging tool against the possibility that it will be more difficult to move away from coal than policymakers desire or can achieve, rather than merely (or primarily) as a way to achieve particular desired temperature outcomes.

In addition, the results show that scenarios featuring natural gas as a bridge fuel can, in principle, result in precisely the same CO<sub>2</sub> concentrations, and similar warming rates, to scenarios in which a transition to zero-carbon energy from coal is direct and begins sooner. This does not mean that the various scenarios have identical climatic results or that they are equally plausible, nor does it mean that other plausible scenarios might not have superior climate outcomes.

The use of multiple scenarios, loosely grounded in different energy-economy models, suggests that these results are robust to different assumptions. Examination of additional scenarios could further reinforce, or challenge, this result.

None of this means that a near-term transition from coal to natural gas would not present other advantages or disadvantages, whether in terms of air or water pollution, land impacts, economic consequences, infrastructural inertia, altered innovation in low-carbon technologies, or changed political dynamics. These should be assessed on their own merits.

## References

- Alvarez RA, Pacala SW, Winebrake JJ, Chameides WL, Hamburg SP (2012) Greater focus needed on methane leakage from natural gas infrastructure. *PNAS*. doi:10.1073/pnas.1202407109
- Brenkert AJ, Kim SH, Smith AJ, Pitcher HM (2003) Model Documentation for the MiniCAM. PNNL Pub. 14337
- Brown SPA, Krupnick A, Walls MA (2009) Natural gas: a bridge to a low-carbon future? RFF Issue Brief 09–11. Resources for the Future, Washington, DC
- Cathles LM (2012) Assessing the greenhouse impact of natural gas. *Geochem Geophys Geosyst* 13:Q06013
- Cathles LM III, Brown L, Taam M, Hunter A (2011) A commentary on “The greenhouse-gas footprint of natural gas in shale formations” by R.W. Howarth, R. Santoro, and Anthony Ingraffea. *Clim Chang*. doi:10.1007/s10584-011-0333-0
- Clarke L, Edmonds J, Jacoby H, Pitcher H, Reilly J, Richels R (2007) Scenarios of greenhouse gas emissions and atmospheric concentrations. U.S. Climate Change Science Program, Washington, DC
- Clarke L, Edmonds J, Krey V, Richels R, Rose S, Tavoni M (2009) International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics* 31(2):S64–S81
- Editorial (2012) Gas and air. *Nature* 428: 131–132 (2012)

- Howarth RW, Santoro R, Ingraffea A (2012) Venting and leaking of methane from shale gas development: response to Cathles et al. *Clim Chang*. doi:10.1007/s10584-012-0401-0
- Howarth RW, Santoro R, Ingraffea A (2011) Methane and the greenhouse-gas footprint of natural gas from shale formations. *Clim Chang*. doi:10.1007/s10584-011-0061-5
- International Energy Agency (2011) Special Report: Are We Entering a Golden Age of Gas?
- International Energy Agency (2011) World Energy Outlook 2011
- Jiang M, Griffin WM, Hendrickson C, Jaramillo P, VanBriesen J, Venkatesh A (2011) Life cycle greenhouse gas emissions of Marcellus shale gas. *Environ Res Lett* 6
- Kerr RA (2010) Natural gas from shale bursts onto the scene. *Science* 328:1624–1626
- Manne A, Mendelsohn R, Richels R (1995) MERGE: A model for evaluating regional and global effects of GHG reduction policies. *Energy Policy* 23:17–34
- Massachusetts Institute of Technology (2011) The future of natural gas: An interdisciplinary MIT study. Cambridge, MA
- Myhrvold NP, Caldeira K (2012) Greenhouse gases, climate change and the transition from coal to low-carbon electricity. *Environ Res Lett* 7
- O'Neill BC, Oppenheimer M (2004) Climate change impacts are sensitive to the concentration stabilization path. *Proc Natl Acad Sci USA* 101:16411–16416
- Podesta JD, Wirth TE (2009) Natural gas: a bridge fuel for the 21st century. Center for American Progress
- Prinn R, Paltsev S, Sokolov A, Sarofim M, Reilly J, Jacoby H (2008) The influence on climate change of differing scenarios for future development analyzed using the MIT integrated global system model. MIT Joint Program Report Series 163
- Prinn R, Jacoby H, Sokolov A, Wang C, Xiao X, Yang Z, Eckhaus R, Stone P, Ellerman D, Melillo J et al (1999) Integrated global system model for climate policy assessment: Feedbacks and sensitivity studies. *Clim Chang* 41:469–546
- Skone TJ, Littlefield J, Marriott J (2011) Life cycle greenhouse gas inventory of natural gas extraction, Delivery and Electricity Production. DOE/NETL-2011/1522
- Wigley TML (2011) Coal to gas: The influence of methane leakage. *Clim Chang*. doi:10.1007/s10584-011-0217-3
- Wigley TML (1991) Could reducing fossil-fuel emissions cause global warming? *Nature* 349:503–506
- Wigley TML (2008) MAGICC/SCENGEN 5.3: User Manual ver. 2.
- Wigley TML, Richels R, Edmonds JA (1996) Economic and environmental choices in the stabilization of atmospheric CO<sub>2</sub> concentrations. *Nature* 379:240–243