


# Leakage risks of geologic CO<sub>2</sub> storage and the impacts on the global energy system and climate change mitigation

Hang Deng<sup>1,2</sup>  · Jeffrey M. Bielicki<sup>3,4</sup> ·  
Michael Oppenheimer<sup>5,6</sup> · Jeffrey P. Fitts<sup>1</sup> ·  
Catherine A. Peters<sup>1</sup>

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**Abstract** This study investigated how subsurface and atmospheric leakage from geologic CO<sub>2</sub> storage reservoirs could impact the deployment of Carbon Capture and Storage (CCS) in the global energy system. The Leakage Risk Monetization Model was used to estimate the costs of leakage for representative CO<sub>2</sub> injection scenarios, and these costs were incorporated into the Global Change Assessment Model. Worst-case scenarios of CO<sub>2</sub> leakage risk, which assume that all leakage pathway permeabilities are extremely high, were simulated. Even with this extreme assumption, the associated costs of monitoring, treatment, containment, and remediation resulted in minor shifts in the global energy system. For example, the reduction in CCS deployment in the electricity sector was 3% for the “high” leakage scenario, with replacement coming from fossil fuel and biomass without CCS, nuclear power, and renewable energy. In other words, the impact on CCS deployment under a realistic leakage scenario is likely to be negligible. We also quantified how the resulting shifts will impact atmospheric CO<sub>2</sub> concentrations. Under a carbon tax that achieves an atmospheric CO<sub>2</sub> concentration of 480 ppm in 2100, technology shifts due to leakage costs would increase this concentration by

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✉ Hang Deng  
hangdeng310@gmail.com

<sup>1</sup> Department of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA

<sup>2</sup> Present address: Energy Geosciences Division, Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

<sup>3</sup> Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, Columbus, OH, USA

<sup>4</sup> The John Glenn College of Public Affairs, The Ohio State University, Columbus, OH, USA

<sup>5</sup> Department of Geosciences, Princeton University, Princeton, NJ, USA

<sup>6</sup> Woodrow Wilson School of Public and International Affairs, Princeton University, Princeton, NJ, USA

less than 5 ppm. It is important to emphasize that this increase does not result from leaked CO<sub>2</sub> that reaches the land surface, which is minimal due to secondary trapping in geologic strata above the storage reservoir. The overall conclusion is that leakage risks and associated costs will likely not interfere with the effectiveness of policies for climate change mitigation.

**Keywords** Carbon capture, utilization and storage · Geologic CO<sub>2</sub> storage · Leakage risk · Climate change mitigation · Integrated assessment modeling · GCAM · Carbon tax · Representative concentration pathways

## 1 Introduction

Transitions to carbon-neutral economies to reduce climate change risks require that energy systems worldwide be decarbonized. CO<sub>2</sub> Capture and Storage (CCS) technologies are important components of the energy technology portfolios that facilitate this transformation because they can mitigate CO<sub>2</sub> emissions while meeting energy demand with carbon-intensive energy technologies (IPCC 2014a; Schleussner et al. 2016). CCS comprises CO<sub>2</sub> capture from large stationary sources (e.g., coal or natural gas power plants) and transport to locations where it is injected into porous geologic formations deep underground to isolate it from the atmosphere (Benson and Surles 2006). The latter part is referred to as Geologic CO<sub>2</sub> Storage (GCS). The worldwide potential capacity of GCS has been estimated at 2000 to 4000 GtCO<sub>2</sub> (IPCC 2014a; Metz et al. 2005), which is equivalent to 60 to 120 years of the global emissions of CO<sub>2</sub> from the consumption of energy in 2012.

Integrated assessment models (IAMs), incorporating the physical and cost characteristics of energy technologies and the interactions between climate and energy systems, enable evaluation of the timing and magnitude of decarbonization of the energy system and of how policy instruments may incentivize the deployment of CO<sub>2</sub> mitigation technologies (Calvin et al. 2012; Edenhofer et al. 2010; Edmonds et al. 2004; Fawcett et al. 2015; IPCC 2014a; Kriegler et al. 2014; van Vuuren et al. 2011). Specifically, IAMs have been used to analyze CCS deployment for various scenarios of technological availability and options for regulatory control (Bosetti et al. 2012; Griffin et al. 2014; Kalkuhl et al. 2015; Kanudia et al. 2014; Koelbl et al. 2014; Muratori et al. 2016, 2017; Smith et al. 2015; van der Zwaan and Gerlagh 2009, 2016; van der Zwaan and Smekens 2009). In most of these analyses, CCS technologies are used for 20–80% of primary energy production under various scenarios. These analyses also show that stringent climate goals can be met without CCS technologies, but doing so increases estimated mitigation costs by 50–250% (e.g., IPCC 2014a). CCS may become more attractive with the potential of “negative emissions” by coupling it with bioenergy and air capture (Lackner et al. 2012).

There are potential obstacles to large-scale CCS deployment, including the possibility of leakage from GCS reservoirs (Bielicki et al. 2014, 2015; Blackford et al. 2013; Fitts and Peters 2013; Hepple and Benson 2005; Herzog 2011; Leung et al. 2014). The economic implications of leakage have been investigated, some using integrated assessment models, by considering the economic burden that would fall on future generations or lost carbon credits when leaked CO<sub>2</sub> returns to the atmosphere (Gerlagh and van der Zwaan 2012; Ha-Duong and Keith 2003; Keller et al. 2008; Teng and Tondeur 2007; van der Zwaan and Gerlagh 2009, 2016; van der Zwaan and Smekens 2009). While these normative studies provide valuable insights on “acceptable” rates of leakage to the atmosphere, they do not consider the geophysical processes that control the outcomes and economic consequences of leakage.

In fact, an abundance of field and modeling studies have illuminated the subsurface systems and geophysical processes associated with GCS, especially in deep saline aquifers (for a review, see (Celia et al. 2015)). The data and the practical models resulting from these studies have enabled quantitative analysis of leakage risk and the associated costs (Bielicki et al. 2016). For example, previous work has investigated leakage risk in sedimentary basins by simulating worst-case scenarios of reservoir siting and leaking-well permeabilities (Bielicki et al. 2015, 2016). One major finding is that, even at unrealistically high well permeability, leaked CO<sub>2</sub> is very unlikely to be released to the atmosphere because of the interception by overlying geologic strata (Bielicki et al. 2016), which was termed as “secondary trapping.”

Previous studies have also examined the unique economic consequences that can result from four leakage outcomes (Bielicki et al. 2014, 2016): leaked fluids may (1) accumulate in formations overlying the storage reservoir, but remain isolated from other subsurface activities; (2) interfere with another subsurface activity (e.g., natural gas storage, deep-well injection of wastes); (3) cause groundwater contamination; or (4) reach the land surface and escape into the atmosphere. The first outcome could be considered “benign leakage”. Even though it has no negative physical effects, regulatory requirements may involve costly remedial actions and incur economic consequences that need to be considered with those of other leakage outcomes.

To date, however, the wealth of knowledge in the GCS community has rarely been integrated into IAM analyses. Existing integrated assessment analyses of leakage have accounted for only seepage to the atmosphere using assumed leakage rates, while the *subsurface* outcomes of leakage, and their expected costs, have not been addressed. This study bridges this research gap and answers the question: How could the economic consequences of leakage, which arise from the geophysical processes of the subsurface system, affect the deployment of CCS in the global energy system?

We developed a model framework that uses the Leakage Risk Monetization Model (LRiMM) to estimate CO<sub>2</sub> leakage and its expected costs (Bielicki et al. 2016) and then modifies the costs for GCS in the Global Change Assessment Model (GCAM) (Calvin et al. 2012). As a demonstration, leakage was simulated using a geophysical representation of the Michigan sedimentary basin and injection scenarios into the Mt. Simon sandstone. While offshore storage is a potentially important option for GCS (van der Zwaan and Gerlagh 2016), we focused on onshore GCS. An array of leakage scenarios was examined by considering multiple geographic locations of injection. Consistent with the prior work (Bielicki et al. 2015), we used permeability values for the potential leakage pathways that represent worst-case leakage scenarios. The resulting monetized leakage risk curves were extrapolated to represent onshore GCS opportunities worldwide. Although there have been no comparative studies of worldwide storage opportunities, and it is thus difficult to state with certainty that our basin and formation are representative of GCS opportunities worldwide, they are considered to be typical targets for CO<sub>2</sub> storage. For example, their geophysical properties are comparable to those of the sites chosen for current onshore GCS projects (Celia et al. 2015) and are consistent with the geophysical properties that are required to meet the capacity, injectivity, and containment of suitable geologic CO<sub>2</sub> storage sites. In addition, oil and gas activities tend to be co-located with the areas that are suitable for GCS (Metz et al. 2005), which is the case with the basin that we studied. Here, we investigated the impacts of leakage risk on CCS deployment in the energy sector and the resulting changes in stored CO<sub>2</sub> under four mitigation scenarios: two CO<sub>2</sub> tax scenarios and two Representative Concentration Pathways (RCP) (Moss et al. 2010). Changes in CO<sub>2</sub> atmospheric concentrations and CO<sub>2</sub> allowance prices are also examined under the CO<sub>2</sub> tax and RCPs scenarios, respectively.

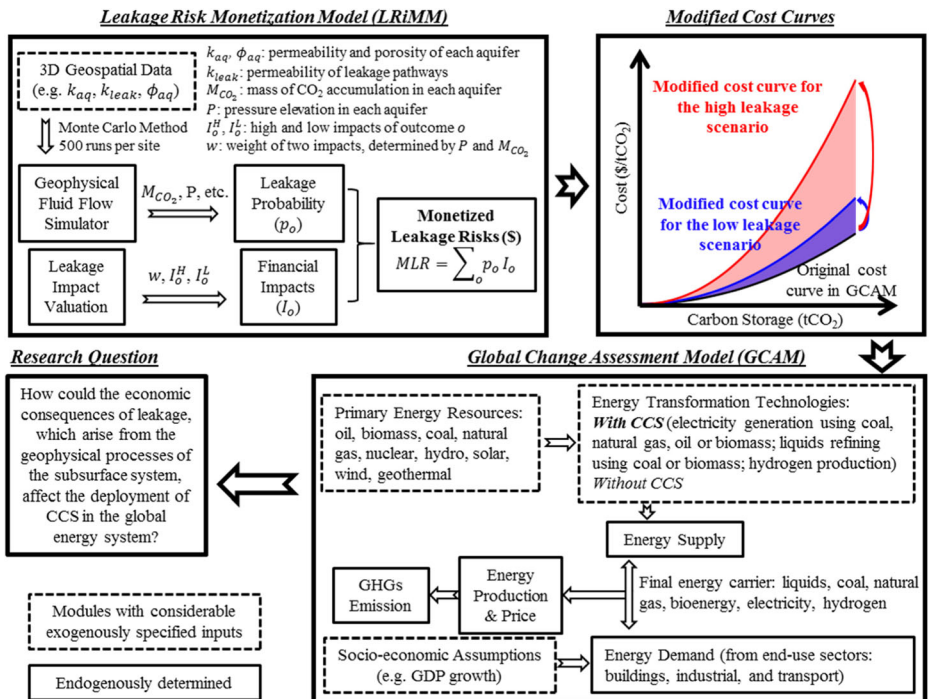
## 2 Model framework and simulation conditions

Figure 1 depicts the model framework. The following sections describe the components of the framework and the simulation conditions. More details are provided in the [Supplementary Materials](#).

### 2.1 The leakage risk monetization model and study area

LRiMM quantifies the Monetized Leakage Risk (MLR)—the expected cost of leakage—for a given injection scenario (Bielicki et al. 2016). LRiMM includes a three-dimensional geospatial representation of the sedimentary basin, a semi-analytical model for estimating leakage (Celia et al. 2011), and the Leakage Impact Valuation (LIV) method that estimates the economic consequences of leakage (Bielicki et al. 2014). For detailed model descriptions, we refer readers to the original paper (Bielicki et al. 2016).

In this application, the 3D geospatial model was limited to the Michigan sedimentary basin due to data availability. It represents a sedimentary basin that has multiple subsurface uses (Bielicki et al. 2015), with a deep saline aquifer (Mt. Simon sandstone) that has potential (6–95 GtCO<sub>2</sub>) for commercial-scale GCS (Medina et al. 2011). The 3D geophysical characterization of the Michigan sedimentary basin, the range of leakage pathway permeabilities (10<sup>-10</sup>, 10<sup>-12</sup>, 10<sup>-14</sup>, and 10<sup>-16</sup> m<sup>2</sup>), the information on other subsurface activities (e.g., natural gas storage,



**Fig. 1** The framework for assessing the effect of leakage risk on the deployment of CCS. The cost curves in GCAM for geologic CO<sub>2</sub> storage are modified by adding cost curves that are derived from estimates of Monetized Leakage Risk (MLR) by LRiMM. These modified cost curves are then substituted for the original cost curves in GCAM

deep-well waste injection), and the probabilistic approach used to account for uncertainty in critical geophysical parameters in the current study have been detailed in previous investigations (Bielicki et al. 2015, 2016). It should be noted that we used a range of leakage pathway permeability values that are much higher than those reported for properly plugged wells ( $10^{-14}$  to  $10^{-18}$  m<sup>2</sup> (Tao and Bryant 2014)) or abandoned oil and gas wells ( $10^{-13}$  to  $10^{-21}$  m<sup>2</sup> (Kang et al. 2015)). We advance the prior work by sampling many different sites within the basin (see [Supplementary Materials](#) for details of the 42 injection sites) to create an array of possible leakage outcomes and interactions with other subsurface resources.

At each site, we simulated injection of 1 MtCO<sub>2</sub>/year continuously for 50 years, following the common practices envisioned for commercial-scale GCS (National Energy Technology Laboratory 2012), and the subsequent CO<sub>2</sub> migration, brine displacement, and pressure propagation throughout the geologic formations. As a result, a probabilistic representation of different leakage outcomes was generated.

For each leakage outcome, the LIV method constructs low- and high-cost storylines that describe the financial exposure of various stakeholders. These costs are weighted by the pressure buildup and CO<sub>2</sub> plume size at the site and then multiplied by the probability of the leakage outcome to compute the MLR. The total MLR is the sum of the MLRs for all possible leakage outcomes and stakeholders. This expected cost (in 2010 USD) is only calculated for the operational period because the probabilities and consequences of leakage decrease as pressure buildup dissipates after injection ends and is divided by 1.5 to represent the 1990 USD used in GCAM.

## 2.2 The global change assessment model

GCAM identifies the least-cost portfolio of energy technologies for a CO<sub>2</sub> emissions mitigation target. It models the interactions between the global climate, economic, and energy systems and uses a partial equilibrium, recursive, dynamic, and deterministic approach to solve the entire system at 5-year intervals up to the year 2100. Detailed model descriptions and a list of GCAM publications are available at <http://www.globalchange.umd.edu/gcam/>. Here, we highlight the energy system and the attributes associated with CCS (Fig. 1).

In GCAM, CCS can be applied to cement production facilities and to three types of energy technologies: (1) liquids refining, using coal, or biomass, (2) hydrogen production, and (3) electricity generation using coal, natural gas, oil, or biomass. The costs of CCS in GCAM include those that are specific to each energy technology (Muratori et al. 2017), and those that are generic across technologies (i.e., the costs associated with GCS). Our approach was to modify the GCS costs by adding the cost of leakage risk.

The global onshore GCS capacity in GCAM totals 5800 GtCO<sub>2</sub>.<sup>1</sup> This capacity is divided into four grades with increasing cost: 0.5, 10, 60, and 29.5%, and each grade has a unique GCS cost curve. The unmodified costs range from \$0.03 to \$55.90/tCO<sub>2</sub> (in 1990 USD), and the majority of the CO<sub>2</sub> storage capacity is available at a price between \$3.74 to \$7.47/tCO<sub>2</sub>, which is consistent with the range of costs in the literature (Herzog 2011). The unlimited

<sup>1</sup> GCAM uses units of carbon (e.g., GtC). Here, we report these values in units of mass of CO<sub>2</sub>, with the conversion that 1 GtC equals 3.67 GtCO<sub>2</sub>. We also note that the total CO<sub>2</sub> storage capacity in GCAM is greater than the estimated technical storage potential in (Metz et al. 2005).

offshore GCS capacity is available at a cost of \$96 /tCO<sub>2</sub> (1990 USD), which is higher than the majority of the onshore GCS costs.

### 2.3 Modifying cost curves

A total of 2100 MtCO<sub>2</sub> was injected at the 42 sites. The unique MLR for each tonne of CO<sub>2</sub> was rank-ordered so that each incremental tonne of CO<sub>2</sub> goes to the site that has the lowest MLR. To upscale the marginal cost curve of leakage risk that was determined for the Michigan basin to GCS opportunities worldwide, this rank-ordered curve was divided into four grades in accordance with the onshore GCS capacity percentages in GCAM. Within each grade, the marginal cost curve of leakage risk was added to the original GCS cost curve, under the assumption that leakage risk increases with GCS cost. While there is little evidence on the correlation between leakage risk and GCS costs, this assumption generates modified cost curves that are similar to those that are generated with no correlation between GCS costs and leakage risk (see [Supplementary Materials](#)).

We did not modify the cost curves for offshore GCS storage because LRiMM was developed for onshore GCS. Even if LRiMM results were applicable to offshore GCS, the large offshore GCS capacity in GCAM implies that effectively unlimited capacity is available at negligible risk. In addition, because offshore GCS is available at a higher cost in GCAM, adding costs of leakage risk is unlikely to significantly alter GCS deployment.

### 2.4 Climate change mitigation scenarios

Simulating the effect of a CO<sub>2</sub> tax provides the opportunity to assess two mechanisms by which leakage can increase CO<sub>2</sub> in the atmosphere: (i) the *direct effects* of leaked CO<sub>2</sub> released to the atmosphere and (ii) the *indirect effects* of how the economic costs of managing leakage in the subsurface alter the deployment of energy technologies. We considered two CO<sub>2</sub> tax levels provided in GCAM. The taxes were applied starting 2020 and increased 5%/year until 2100:

- (1) Ctax1: \$2.73/tCO<sub>2</sub> in 2020 and reaches \$135/tCO<sub>2</sub> by 2100 (in 1990 USD).
- (2) Ctax2: \$6.82/tCO<sub>2</sub> in 2020 and reaches \$338/tCO<sub>2</sub> by 2100 (in 1990 USD).

The Ctax1 scenario is much less effective in mitigating CO<sub>2</sub> emissions than the Ctax2 scenario, in which atmospheric CO<sub>2</sub> peaks at 520 ppm around 2070 and decreases below 480 ppm by 2100.

The two RCP scenarios (RCP2.6 and RCP4.5) provide the opportunity to investigate the responses of the energy system to leakage under different CO<sub>2</sub> emissions mitigation scenarios. To implement an RCP scenario in GCAM, a trajectory of radiative forcing is specified, and the CO<sub>2</sub> allowance price is solved at every time step from the year 2020 such that the resulting energy production, economic activities, and GHGs emissions satisfy the radiative forcing constraint (Muratori et al. 2017). In the stringent RCP2.6 scenario, the radiative forcing reaches ~3.0 W/m<sup>2</sup>, atmospheric CO<sub>2</sub> peaks around 490 ppm, and then both metrics decline by 2100 (van Vuuren et al. 2011). The RCP4.5 scenario models a radiative forcing that never exceeds 4.5 W/m<sup>2</sup> (~600 ppm CO<sub>2</sub> equivalent) (Thomson et al. 2011).



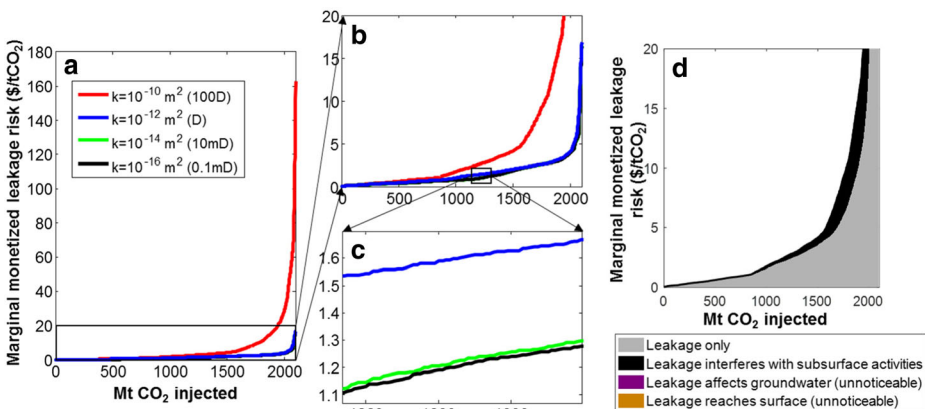
### 3 Results and discussion

#### 3.1 Marginal cost curves of leakage risk

Figure 2a plots the marginal leakage cost for each incremental tonne of CO<sub>2</sub> injected, referred to as the MLR curves. The MLR increases because less ideal sites are used. The convex shape of the curves suggests that most of the basin can be used for GCS at a low cost of leakage risk, and only a small portion of the injection sites would have very large leakage costs. For the two largest modeled leakage pathway permeabilities (10<sup>-10</sup> and 10<sup>-12</sup> m<sup>2</sup>), 75 and 96% of the basin has MLR below \$5/tCO<sub>2</sub>, respectively (Fig. 2b).

Because the MLR curves for leakage pathway permeabilities of 10<sup>-12</sup> to 10<sup>-16</sup> m<sup>2</sup> are essentially the same (differ by < \$0.5/tCO<sub>2</sub>, Fig. 2c), we only implemented in GCAM the MLR curves for two leakage cases: “high” and “extremely high,” which correspond to leakage pathway permeability of 10<sup>-12</sup> and 10<sup>-10</sup> m<sup>2</sup>, respectively. These cases are worst-case scenarios because (a) the permeability values are very high compared to reported field measurements and (b) these values are assigned to all of the 45,000 leakage pathways within the basin (Bielicki et al. 2015). The results are compared with those for a “no leakage” case in which all leakage pathways are assumed impervious.

The majority of the leakage costs result from leakage that does not reach groundwater or the land surface (Fig. 2d). On average, 74% of the MLR in the extremely high leakage case and 90% in the high leakage case are attributed to cost that arises from the benign leakage that undergoes secondary trapping. The remaining costs are incurred when leakage interferes with other subsurface activities—mostly with oil and gas production; the costs due to groundwater contamination and surface seepage are negligible. Even in the extremely high leakage case, only 0.005% of the total amount of injected CO<sub>2</sub> migrates into the groundwater aquifer after 50 years of simulated injection over all of the 42 injection sites.



**Fig. 2** The marginal cost curves of leakage risk that are compiled from applying LRiMM to the 42 hypothetical CO<sub>2</sub> storage sites in the Michigan sedimentary basin. **a** The marginal cost curves for each leakage pathway permeability that was modeled; **b** and **c** are insets of **a**; **d** shows the break down for the highest leakage case (10<sup>-10</sup> m<sup>2</sup>) according to the four leakage outcomes. The costs of leakage that affect groundwater or reaches the land surface do not show on **d** because they are negligibly small

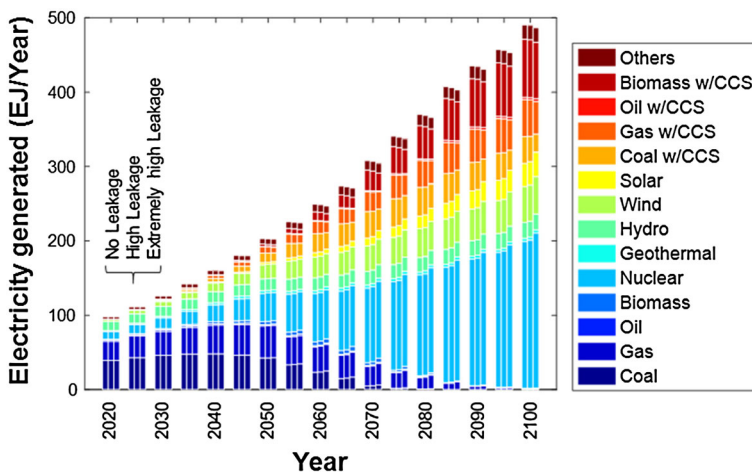
### 3.2 Impact on CCS deployment and the global energy system

The GCS costs in GCAM, and the increased costs due to leakage risk, do not vary across the fuels and sectors that deploy CCS (see [Supplementary Material](#)). Here, we focus on the electricity sector, which has more CO<sub>2</sub> stored than others. We quantify the projected changes in CCS deployment in terms of the amount of electricity that is generated by CCS technologies: coal, natural gas, oil, and biomass facilities with CCS.

Figure 3 shows the projected mix of the electricity generation technologies for the “no,” “high,” and “extremely high” leakage cases with Ctax2. Leakage risk reduces the deployment of CCS technologies because of the increase in electricity generation costs. In the “no leakage” case, the 5482 EJ of cumulative electricity generation by CCS technologies between 2020 and 2100 is equivalent to 67 years of the ~82 EJ global electricity generation in 2012 (IEA 2014). Relative to the no leakage case, there is a decrease of 143 EJ (3%) and 658 EJ (12%) in the high and extremely high leakage cases, respectively. The results for the Ctax1 and the two RCPs scenarios show similar reductions (see [Supplementary Material](#)): The cumulative electricity generation from CCS technologies decreases 10–14% in the extremely high leakage case and 2–4% in the high leakage case. The reduction is smaller with a lower CO<sub>2</sub> emissions mitigation target (e.g., lower CO<sub>2</sub> tax, RCP4.5), but the percentage changes are higher because of less reliance on electricity as a final energy carrier.

The decrease in the electricity generated by CCS technologies does not produce an equivalent decrease in the total electricity generation, partly because of the increase in the use of fossil fuels and biomass without CCS. In the extremely high leakage case with Ctax2, the cumulative electricity production using fossil fuels and biomass decreases by only 106 EJ. There are smaller increases in the use of fossil fuels and biomass without CCS under the more stringent climate goal (e.g., RCP2.6).

The shift to energy technologies that do not emit CO<sub>2</sub>, mostly nuclear, further reduces the impact of leakage risk on electricity generation. For all of the leakage cases and mitigation



**Fig. 3** Projected electricity generation by different technologies under the climate change mitigation scenario of Ctax2. Each cluster shows the yearly results for the no leakage (*left*), high leakage (*middle*), and extremely high leakage (*right*) cases. The GCAM simulations run at a 5-year interval, and the results reported are for the corresponding year



scenarios that we investigated, the reduction in cumulative electricity generation is within 1% of the no leakage case.

Overall, total primary energy production is essentially unaffected across the scenarios (<1% difference, see [Supplementary Material](#)). Accordingly, the energy end-use sectors are not noticeably affected by leakage risk. For example, the use of different types of fuels (e.g., delivered gas, electricity, refined liquids) in the transportation sector for the leakage cases changes <0.1% from the no leakage case under all CO<sub>2</sub> emissions mitigation scenarios (see [Supplementary Material](#)).

### 3.3 Impact on atmospheric CO<sub>2</sub> concentrations

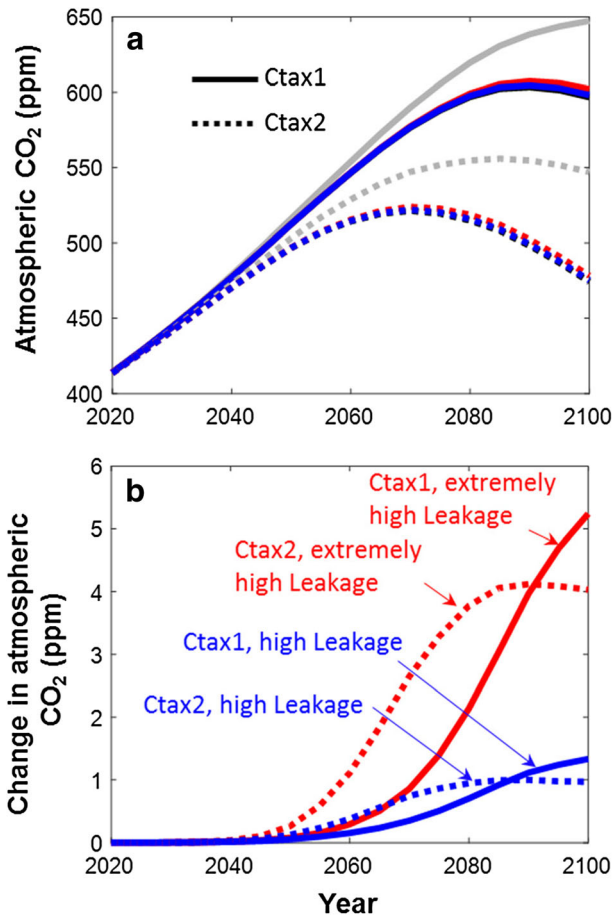
The indirect effects of leakage risk have two opposing effects on CO<sub>2</sub> emissions and thus the atmospheric CO<sub>2</sub> concentration under carbon taxes: (1) The amount of CO<sub>2</sub> *produced* decreases because of shifts away from fossil fuel and biomass in primary energy production, and (2) the amount of CO<sub>2</sub> *stored* decreases because of the reduced CCS deployment (see [Supplementary Material](#)). Everything else held equal, the first effect decreases CO<sub>2</sub> emissions, whereas the second effect increases CO<sub>2</sub> emissions. Figure 4 shows that the second effect is larger. The atmospheric CO<sub>2</sub> concentration in 2100 for the extremely high leakage case is approximately 4 and 5 ppm higher than the no leakage case with Ctax2 and Ctax1, respectively. For the high leakage case, the corresponding differences are about 1 and 1.5 ppm for the respective taxes. These differences increase faster with Ctax2 in both leakage cases because CO<sub>2</sub> storage is consistently higher, and riskier and costlier storage reservoirs are used sooner. However, this difference plateaus around 2085, while the differences under Ctax1 continue to increase because CO<sub>2</sub> emissions mitigation is more elastic under the less stringent climate mitigation targets.

For the atmospheric CO<sub>2</sub> concentration, the indirect effects of the increased cost of GCS with leakage are greater than the direct effects of CO<sub>2</sub> seepage. The surface seepage of CO<sub>2</sub> that would increase the atmospheric CO<sub>2</sub> concentration by 1 ppm (~2.2 GtC) amounts to 0.7 and 1.2% of the CO<sub>2</sub> that is stored under Ctax2 (1104 GtCO<sub>2</sub>, no leakage) and Ctax1 (649 GtCO<sub>2</sub>, no leakage), respectively. These values are orders of magnitude greater than the seepage of CO<sub>2</sub> to the atmosphere for the worst-case scenarios considered here. Even if secondary trapping is ineffective and all of the leaked CO<sub>2</sub> eventually reaches the surface, which is ~0.003 and ~0.2% for the high and extremely high leakage cases, respectively, the resulting increase in the atmospheric CO<sub>2</sub> concentration would be much less than 1 ppm.

For the RCP scenarios, the goal is to achieve a desired trajectory of radiative forcing, and thus, the atmospheric CO<sub>2</sub> concentration is not affected by the leakage risk. Instead, CO<sub>2</sub> prices for the leakage cases increase in addition to some shifts in the energy system (see the [Supplementary Material](#)).

### 3.4 Uncertainties and implications

Our primary finding is that leakage risk is likely to have a negligible effect on CCS deployment in the global energy system and the effectiveness of climate change mitigation policies—especially for more stringent climate mitigation targets. Here, we discuss this finding in the context of uncertainties generated by the model framework's assumptions, approaches, and abstractions.



**Fig. 4** Projected concentration of CO<sub>2</sub> in the atmosphere with Ctax1 (solid lines) and Ctax2 (dashed lines) over the three leakage cases. **a** Projected atmospheric CO<sub>2</sub> concentration for the reference “no leakage” case (black; co-aligned with the high leakage case), high leakage case (blue), extremely high leakage case (red), and for a technological scenario with no CCS (gray), and **b** difference in the atmospheric CO<sub>2</sub> concentration for the leakage cases relative to the reference no leakage case

The GCAM projections of the effects of leakage are expected to be greater than from other IAMs because inter-model comparison studies have shown that GCAM tends to deploy CCS more than other IAMs (van der Zwaan et al. 2013; Wilkerson et al. 2015). The increase in CO<sub>2</sub> storage costs from the worst-case leakage cases considered here leads to at most a small reduction in the deployment of CCS, which is negligible compared with the inter-model discrepancies. Further, the projected atmospheric CO<sub>2</sub> concentrations under the two CO<sub>2</sub> tax scenarios are higher than those for the no leakage case by only a few ppm. Such differences are within the uncertainties in climate modeling (IPCC 2014b) and are negligible when compared to the increase in atmospheric CO<sub>2</sub> concentration that would result from not using CCS (Fig. 4a). In addition, since the impact of the worst-case scenario assumption on the overall leakage costs is far greater than that may arise from other geophysical modeling options (e.g., the choice of target formation, see Supplementary Materials), we feel confident that the primary finding of our study would hold for a wide range of sedimentary basin conditions.

This is not to say that leakage risk is not important in CCS deployment and operational decision-making. It will always be important to carefully site GCS reservoirs, monitor CO<sub>2</sub> movement in the subsurface, and track the potential for environmental damage (Herzog 2011, Pawar et al. 2015). Furthermore, the costs of leakage may still be substantial for some stakeholders at individual storage reservoirs (Bielicki et al. 2016).

Our second major finding is that the indirect effects of leakage risk are greater than the direct effects of surface seepage on CO<sub>2</sub> emissions mitigation. As such, it is important to ensure a twofold assessment, i.e., for potential GCS reservoirs to be assessed on the probability for leaked CO<sub>2</sub> to reach the atmosphere *and* on the consequences of leakage that remains in the subsurface. The twofold assessment can guide GCS siting to minimize leakage costs from interferences with subsurface activities. The benign CO<sub>2</sub> leakage that is contained in the subsurface by secondary trapping may account for the majority of the expected cost of leakage risk. If secondary trapping was to be considered a reliable backup trapping mechanism, then relaxing the requirements to address leakage could further reduce costs and the effect of leakage on CCS deployment and on the atmospheric CO<sub>2</sub> concentration could be even smaller than what was predicted by our GCAM simulations.

## 4 Conclusions

This work is the first to develop a model framework that quantifies the extent to which the physical processes of secondary trapping and the economic costs of leakage from GCS reservoirs affect the deployment of CCS and other CO<sub>2</sub> emissions mitigation technologies in the global energy system. In some respects, our results are similar to those from past IAM studies of leakage from GCS reservoirs that consider only seepage of leaked CO<sub>2</sub> to the atmosphere. However, we conclude that twofold assessment of surface seepage and of subsurface leakage is needed for GCS siting. Such a framework provides critical information regarding secondary trapping and its associated costs, which are substantial but may be reduced if secondary trapping were to be considered a reliable backup trapping mechanism. Our study gives further confidence that CCS has the potential to become an important technology for achieving climate goals, even with the expected costs of leakage risk and the seepage of CO<sub>2</sub> to the atmosphere. While acknowledging the uncertainties in quantifying leakage rates and risks, and recognizing the limitations and uncertainties in the integrated assessment modeling framework, we conclude that, from the perspective of energy system level least-cost simulation and modeling, the expected cost of leakage risk is unlikely to significantly hinder global CCS deployment or the effectiveness of policy for mitigating climate change.

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