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Policy implications of Monetized Leakage Risk from Geologic CO_2 Storage Reservoirs

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Abstract

Geological storage of carbon dioxide (CO_2) as a part of the CO_2 capture and storage (CCS) process has a large potential to mitigate greenhouse gas emissions, but its deployment will require accurate assessment of both the possibility and cost of leakage. In this study, we took the Michigan sedimentary basin as an example to investigate the monetized risks associated with leakage, using the Risk Interference of Subsurface CO_2 Storage (RISCS) model. The monetized leakage risks derived from the RISCS model were then used to modify existing cost curves in GCAM (Global Change Assessment Model). With the modified cost curves, the model provided policy-relevant results to help inform the potential role of CCS in future energy systems when carbon mitigation targets and incentives are in place. The results showed that leakage risks from geologic storage reservoirs can reduce the deployment of CCS as much as 60%. The extent of this impact is sensitive to the permeability of potential leakage pathways, the regulations governing leakage interferences with other subsurface activities, and the stringency of climate policies. With low well leakage permeability, the costs of leakage will be manageable, and under more stringent carbon mitigation policies such as a high carbon tax, higher leakage risks can be afforded and incorporating leakage risks will have a smaller impact on CCS deployment. Our results also show that if the leakage risks were accounted for by charging a fixed premium - similar to how the risk of nuclear waste disposal is treated - the projected scale of CCS deployment in the energy mix is less affected.

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Keywords: Carbon Capture and Storage; Geologic Storage of CO_2; Leakage Risk; Integrated Assessment Model

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1. Introduction

CO_2 Capture and Storage (CCS) has been consistently identified as a necessary technology to stabilize atmospheric CO_2 concentrations while meeting future energy demand [1-3]. Numerous studies have concluded that deployment of CCS can achieve given climate targets at lower mitigation costs relative to a technology portfolio without CCS [4-8]. Among CCS technologies, geologic storage of CO_2 has a practical worldwide capacity estimated at 2000~4000 $GtCO_2$ [2,3]. In addition, coupling geologic storage with bio-energy has been proposed as an approach to remove historical CO_2 from the atmosphere [3,7]. However, large-scale deployment of geologic CO_2 storage is often clouded by the possibility of leakage and the associated financial consequences [9].

Integrated Assessment Models (IAMs) have been used extensively to evaluate the technical and economic viability of energy technology deployment under certain climate goals [3,6]. For example, the DICE-(Dynamic Integrated model of Climate and the Economy) family models, and Global Change Assessment Model (GCAM) have been adapted to investigate the interactions between technological advancements, economic development and climate mitigation [8,10]. Although it has been acknowledged that consideration of long term security of CO_2 storage and leakage risks is important [4,6], current IAMs fail to adequately account for the costs of leakage risks of geologic storage. In previous studies, leakage is simply included as additional sources of CO_2 emissions into the atmosphere [11]. However, the costs arise from leaked CO_2/brine interfering with other valuable subsurface resources (e.g., natural gas and groundwater), which can introduce significant financial risks [9], are overlooked.

The goal of this study is to fill this research gap. We ran geophysical fluid flow model to simulation leakage probability, derived costs that comprehensively reflect the financial consequences of possible leakages, and incorporated the monetized leakage risks into GCAM. With modified cost curves, GCAM enabled us to improve our understandings of how costs associated with leakage risks will affect the extent of geologic CO_2 storage deployment. The modified model was also used to compare different policy scenarios and inform regulatory decisions that will shape the role of CCS in our future energy system.

2. Methods

To derive monetized leakage risks, the Risk Interference of Subsurface CO_2 Storage (RISCS) model [12] was used, which provides a detailed probabilistic monetization of possible outcomes of CO_2 and brine leakage. RISCS is composed of three modules: a three-dimensional model of the subsurface that includes spatial distributions of wells and subsurface activities, a geophysical fluid flow model, and the Leakage Impacts Valuation (LIV) module. The LIV module is a systematic scenario-based framework that identifies the stakeholders affected by a leakage event, and evaluates the financial consequences of a single leakage event that may lead to four outcomes or combinations of outcomes: leakage only, leakage that interferes with other subsurface activities, leakage that affects groundwater, and leakage reaches the surface and is emitted to the atmosphere [12,13]. For each outcome, a low- and high-cost storylines were devised, and weighted based on the leakage probabilities derived from the geophysical fluid flow simulations.

The Michigan sedimentary basin was selected because of its high potential storage capacity and representative subsurface activities. The Mt. Simon Sandstone has been identified as a suitable reservoir and selected as the target storage formation both in both Michigan and Illinois sedimentary basins [14,15]. Its total storage capacity has been estimated to be between 11-150 $GtCO_2$ depending on the storage efficiency factor [15], while its capacity in Michigan alone is between 6-95 $GtCO_2$ [14]. Eleven injection sites, 100km apart, were selected, forming a grid covering Michigan's Lower Peninsula (Fig. 1). At each site, site-specific subsurface information, including formation depth and thickness were used for the geophysical flow simulations. Social-economic inputs for LIV, such as population density, were averaged over the counties that the plume of injected CO_2 affects. Given the large documented variations of hydrodynamic properties of the Mt Simon formation [16], porosity and permeability were sampled from joint distributions derived from well data. To estimate the probabilities of leakage, 500 flow simulations were conducted at each of the eleven sites. Well leakage permeability is highly uncertain; in this study, four different permeabilities were assumed, to provide a bounding analysis. The injection rate at each site was held constant at 1 $MtCO_2$/yr for 50 yrs, following common design of large commercial storage projects. The leakage risks calculated for each site were compiled following the approach of electricity dispatch models, in order to generate marginal leakage cost curves (Fig. 2).

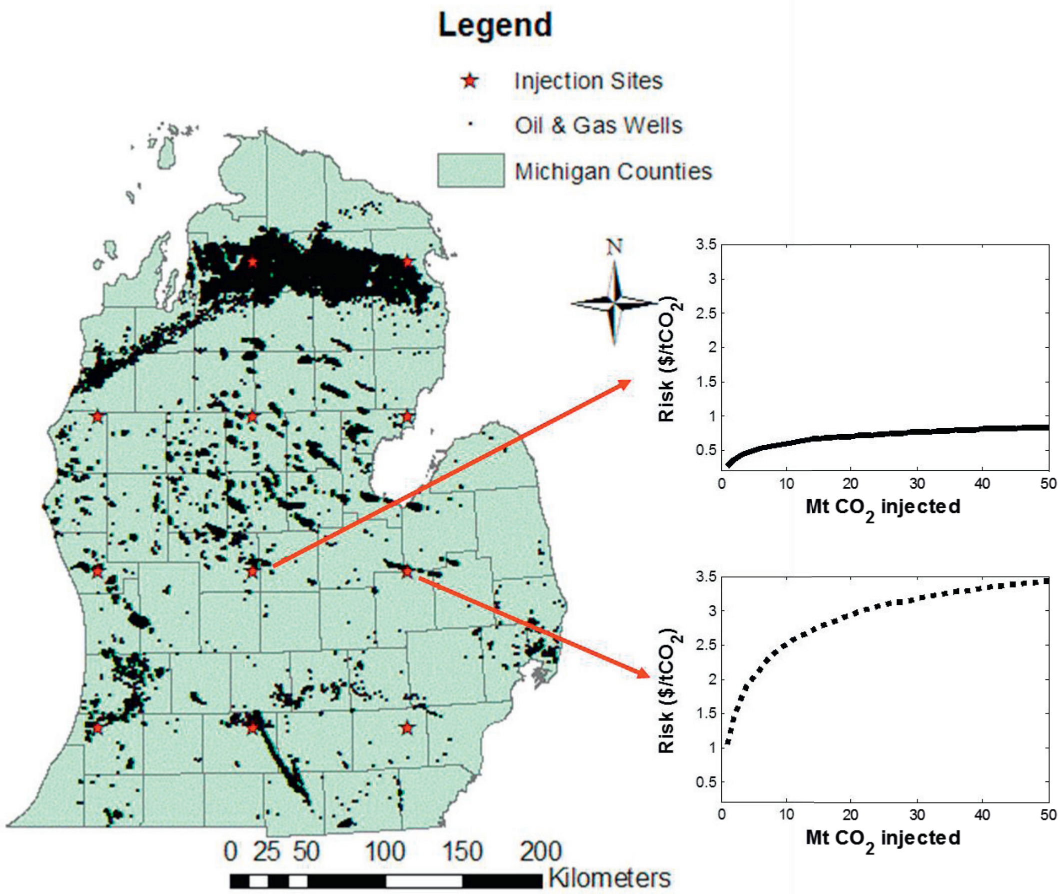

Fig. 1. Geography of the study area and injection sites, and illustration of site-specific leakage risk profile.

The marginal leakage cost curves were incorporated into GCAM, which is an integrated assessment model capturing the interactions between global climate, economics, energy, technology systems, agricultural and land use [17]. It takes a partial equilibrium, recursive, dynamic and deterministic approach to solve the system at a 5 year interval. GCAM was chosen for our study, because it incorporates 'bottom-up' technology details into 'top-down' economic structures. Furthermore, GCAM conducts cost-effective analyses, and identifies the least costly portfolio of energy technologies given a predefined mitigation target, and therefore is useful in determining the value of a technology and how it changes with regulations.

In the energy module of GCAM, three conversion technologies - liquids refining using coal and biomass, hydrogen production using coal, natural gas and biomass, and electricity generation – have CCS as an option. The costs of CCS in GCAM include three components: the capital and operation costs associate with capturing CO_2, costs incurred by venting CO_2 that is not captured, and the cost associated with transport and storage. CO_2 storage is modelled as a resource in GCAM, where the costs of available storage capacity are represented by a supply curve. In GCAM, the storage space was divided into four grades, accounting for the 0.5%, 10%, 60% and 29.5% of the total capacity. The cost of per ton CO_2 stored increases from grade 1 to grade 4, reflecting primarily the transportation cost generated by matching CO2 sources and storage sites [18].

To investigate how regulatory decisions regarding CCS will affect the monetized risks of CO_2 geologic storage and thereby, impact its importance in the energy system, we devised the following cases that incorporate the monetized leakage risks into GCAM's storage supply curves.

Table 1. Case designs for leakage cost incorporation.

	Well permeability	Leakage outcome considered	Tech maturity	Premium value
Leakage risks of each grade were added on the corresponding storage cost in GCAM*	10^{-10} m^2	With interferences	NOAK	
	10^{-12} m^2	With interferences	NOAK	
	10^{-10} m^2 (10^{-12} m^2)	Without interferences	NOAK	
	10^{-10} m^2 (10^{-12} m^2)	With interferences	FOAK for the first grade	
Leakage risks were incorporated by charging a fixed premium	10^{-10} m^2 (10^{-12} m^2)	With interferences	NOAK	Average leakage risk

*Note: The storage capacity of Mt Simon in Michigan Basin was divided into four grades according to the percentage in GCAM, and leakage costs of each grade were added on the corresponding storage cost. As mentioned above, the capacity estimates are highly dependent on the efficiency factor. In this study, a conservative value of 15 $GtCO_2$ was assumed. Given that the currently used operation parameters only generates results up to 550 $MtCO_2$ (grade 2), the same risk as for grade 2 was assumed for grade 3 and grade 4.

3. Results and Discussions

Numerous studies into how the global energy economy needs to change in order to stabilize atmospheric CO_2 concentrations in the 21st century have concluded that meaningful mitigation of CO_2 emissions will only occur when a climate policy introduces and supports a carbon tax or cap-and-trade system [19-21]. Running GCAM without a climate policy, CCS is not deployed, as there is not enough economic incentive. Therefore, in our study, two climate policies are assumed, representing two levels of stringency. One imposes a carbon tax of \$10 per ton of carbon (Ctax10) starting at 2020, while the other starts with a \$25/tC tax (Ctax25). In both scenarios, the carbon tax increases at a rate of 5% per year. The Ctax10 scenario stabilizes the atmospheric CO_2 concentration below 600 ppm by year 2100, whereas the concentration peaks at 520 ppm and mostly stays under 500 ppm under the Ctax25 scenario (Fig. 3(b)). In the presence of carbon taxes, carbon sequestration occurs across industries. The largest contribution comes from electricity generation, with 30.4% and 34.1% of the sequestration made possible by technologies with CCS, for the Ctax10 and Ctax25 scenarios, respectively. The technologies that can be coupled to CCS include electricity generation using biomass, oil, natural gas and coal. Therefore, in the rest of the paper, we focus on the electricity generation sector and examine how incorporation of the monetized leakage risks of geologic storage affects CCS deployment in this sector.

The leakage risk profile of an injection site depends on the hydrodynamic properties of the injection formation, operational parameters such as injection rate, and the proximity of the injection site to potential leakage pathways and subsurface activities. Fig. 1, shows the importance of site-specific parameters, where neighboring injection sites can exhibit significantly different leakage risk profiles. The injection site to the east possessed relatively higher risks because of its proximity to a series oil and gas wells. In addition, permeability of the potential leakage pathways plays a critical role in determining the leakage risks (Fig. 2). Given a well leakage permeability of 10^{-10} m^2, the monetized leakage risk can reach \$72.7 / tCO_2, an approximately twenty-fold greater risk than the highest risk for well permeability of 10^{-12} m^2. For well permeability of 10^{-12} m^2 (Leake12), 10^{-14} m^2 (Leake14), and 10^{-16} m^2 (Leake16), the leakage risks are quite comparable, and therefore case Leake14 and Leake16 will not be discussed further.

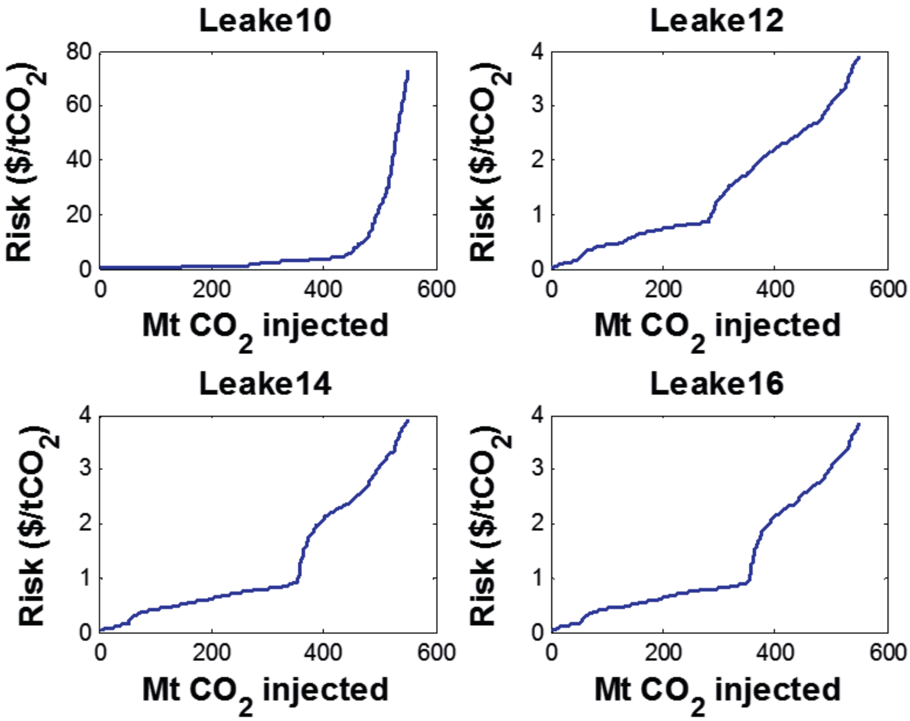

Fig. 2. Compiled leakage risk of all eleven injection sites over cumulative CO_2 injected for well leakage permeability of 10^{-10} m^2 (Leake10), 10^{-12} m^2 (Leake12), 10^{-14} m^2 (Leake14), and 10^{-16} m^2 (Leake16).

Incorporating monetized leakage risk into GCAM reduces CCS deployment within the electricity generation sector throughout all time periods. With high well leakage permeability, the reduction is far more substantial than in the low well leakage permeability case. The extent of the impact also depends on the stringency of the climate policy. Under the high carbon tax scenario, electricity generated by technologies coupled to CCS in the year 2100 decreases from 167 EJ to 105 EJ and 164 EJ for the high and low well leakage permeability cases respectively, representing a 37% and 2% reduction (Fig. 3(a)). By comparison, under the low carbon tax scenarios, the decreases in the year 2100 are 78 EJ (59.6%) and 5 EJ (3.5%) for the high and low well leakage permeability cases (Fig. 3(a)). As a result of reduced CCS deployment resulting from the inclusion of monetized leakage risks, carbon mitigation is less efficient given the same climate policy. For example, in the case of Ctax25 scenario, both the peak atmospheric

CO_2 concentration and CO_2 concentrations by the year 2100 are approximately 30 ppm higher after accounting for leakage risks with high well leakage permeability, while it is only ~2 ppm higher for the low well leakage permeability case (Fig. 3(b)).

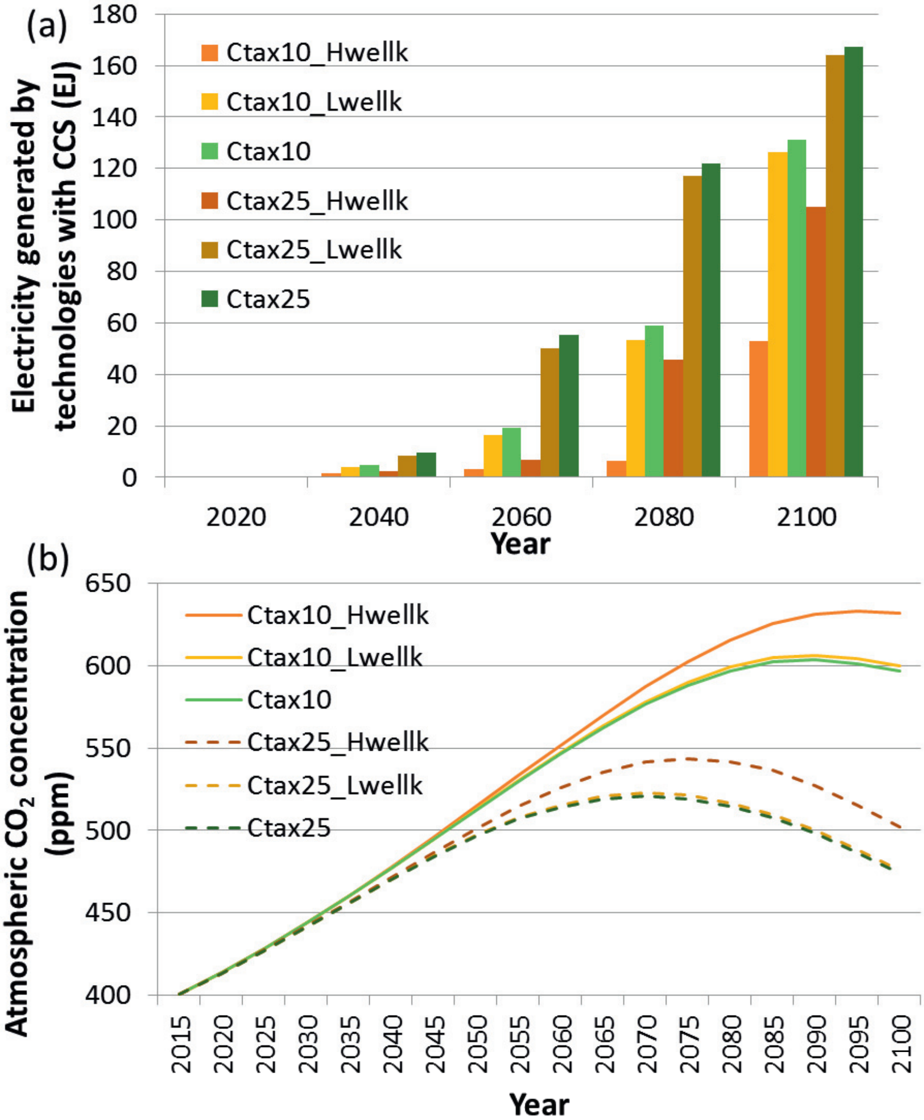

Fig. 3. (a) Electricity generated by technologies with CCS for the reference case (no leakage risks considered Ctax10, Ctax25), high and low well leakage permeability cases (_Hwellk and _Lwellk) under the two climate policy scenarios; and (b) atmospheric CO_2 concentration for each case.

For the high well leakage permeability case, the monetized leakage risks and the subsequent impacts on CCS deployment also depend on whether leakage costs incurred by interferences with subsurface activities and resources are considered. Under the Ctax25 scenario, not considering interferences reduces the risks substantially and increases the amount of electricity generated by technologies with CCS by 24 EJ, approximately 20% higher than the case for which interferences are included (Fig. 4(b)). Similarly, under the Ctax10 scenario, electricity generated by technologies with CCS is 29 EJ, approximately 54.5% higher without interferences (Fig. 4(b)). In contrast, for the low well permeability case, monetized risks incurred by interferences with other subsurface activities and groundwater are so small that the effect on CCS deployment is negligible (Fig. 4(a)).

Our results suggest that regulations should require assessments of the permeability of active and abandoned wells whose location and depth have the potential to serve as a leakage pathway. Studies of properly plugged abandoned wells report relatively low permeabilities (10^{-14} to 10^{-18} m^2) [22], and therefore, our results suggest that the costs of leakage will be manageable, and likely closer to our low cost scenarios. These field observations, however, come from a handful of wells, and therefore, we do not currently have a representative measure of well permeability, which will require a major undertaking given the huge number, type and age of wells. In addition, operational parameters, such as injection rate and injection duration will also affect the migration of CO_2 and brine, and thus the probabilities of leakage. These factors need to be studied in the future to examine their impacts on monetized leakage risks and CCS deployment. Comparisons between these parameters, including well permeability and injection rate will allow us to identify the primary versus secondary factors that affect CCS deployment in general.

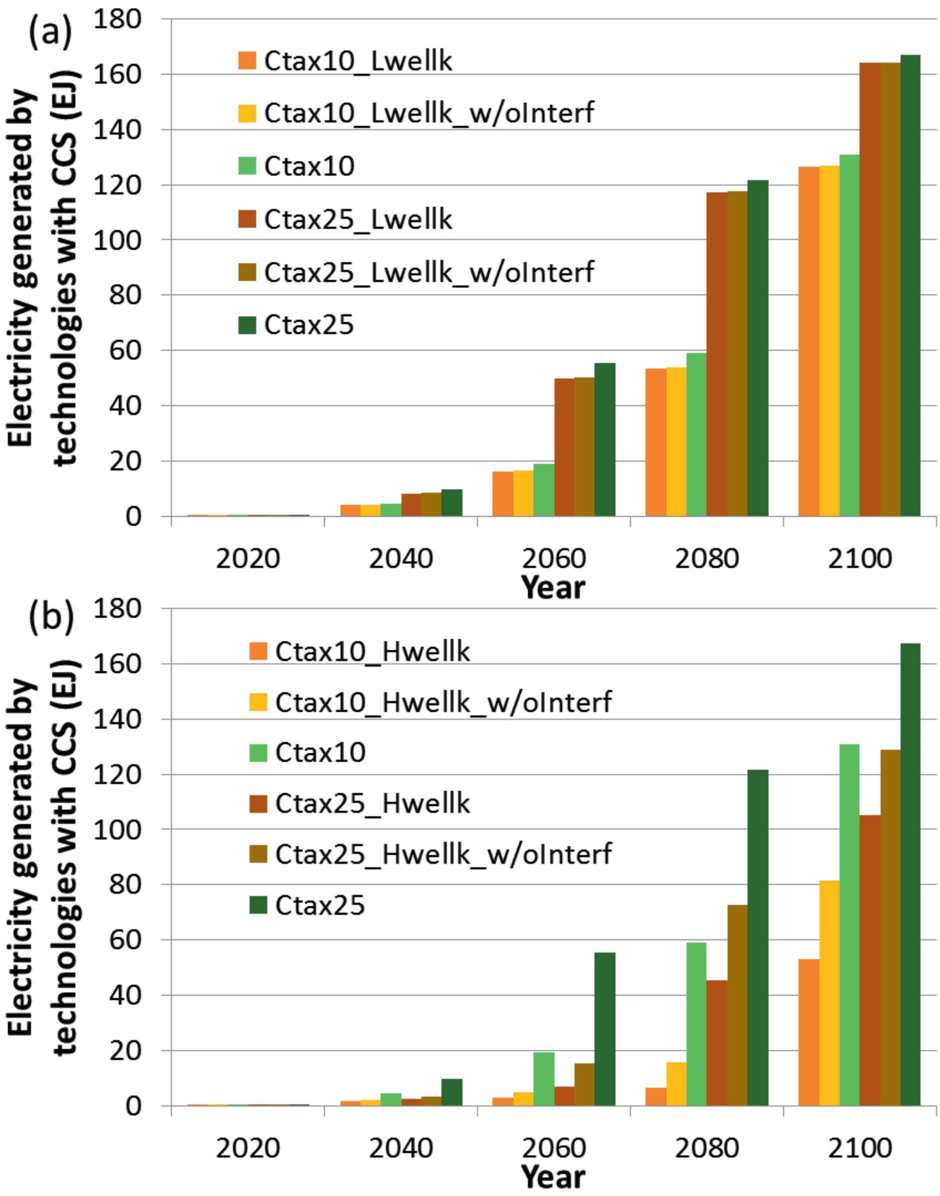

Fig. 4. Electricity generated by technologies with CCS for leakage risks with and without interferences with subsurface activities and groundwater for (a) low and (b) high well leakage permeability.

At the early stage of geologic CO_2 storage deployment, when First-Of-A-Kind (FOAK) projects are launched, leakage events will likely result in prolonged interruptions that incur higher costs. However, in this study, substituting the leakage risk of grade 1 storage space with the value of the FOAK set-up does not produce results significantly different from the Nth-Of-A-Kind (NOAK) set-up. It implies that the impacts of the costs of leakage the early stage technology development may not be important over the long run.

In addition, we studied the impact of charging a fixed premium per ton of CO_2 stored to cover the anticipated costs of leakage, similar to the case of nuclear waste disposal. Assuming perfect information, the premium can be set to the average of the leakage risks so that all leakage risks are accounted for. In this case, incorporating the leakage risks has a much weaker impact on the overall CCS deployment in the electricity sector than the case with an escalating risk profile. This effect is more evident for the high well permeability case and the less stringent climate policy scenario. Under the Ctax10 scenario with high well permeability, the premium case only reduces the electricity generation by ~8 EJ, which is small relative to a 78 EJ reduction when an escalating risk profile is considered. In contrast, the low well permeability scenario results in changes in CCS deployment of ~2 EJ and ~5 EJ for the fixed premium and increasing risk profile case, respectively (Fig. 5). The fixed premium approach does mitigate the impact of accounting for leakage risks on CCS deployment, and the extent of this effect is sensitive to the value of the premium charged. Our study indicates the necessity of such sensitivity analysis in the future for detailed comparisons of the two approaches of including monetized leakage risks and their respective influences on CCS deployment.

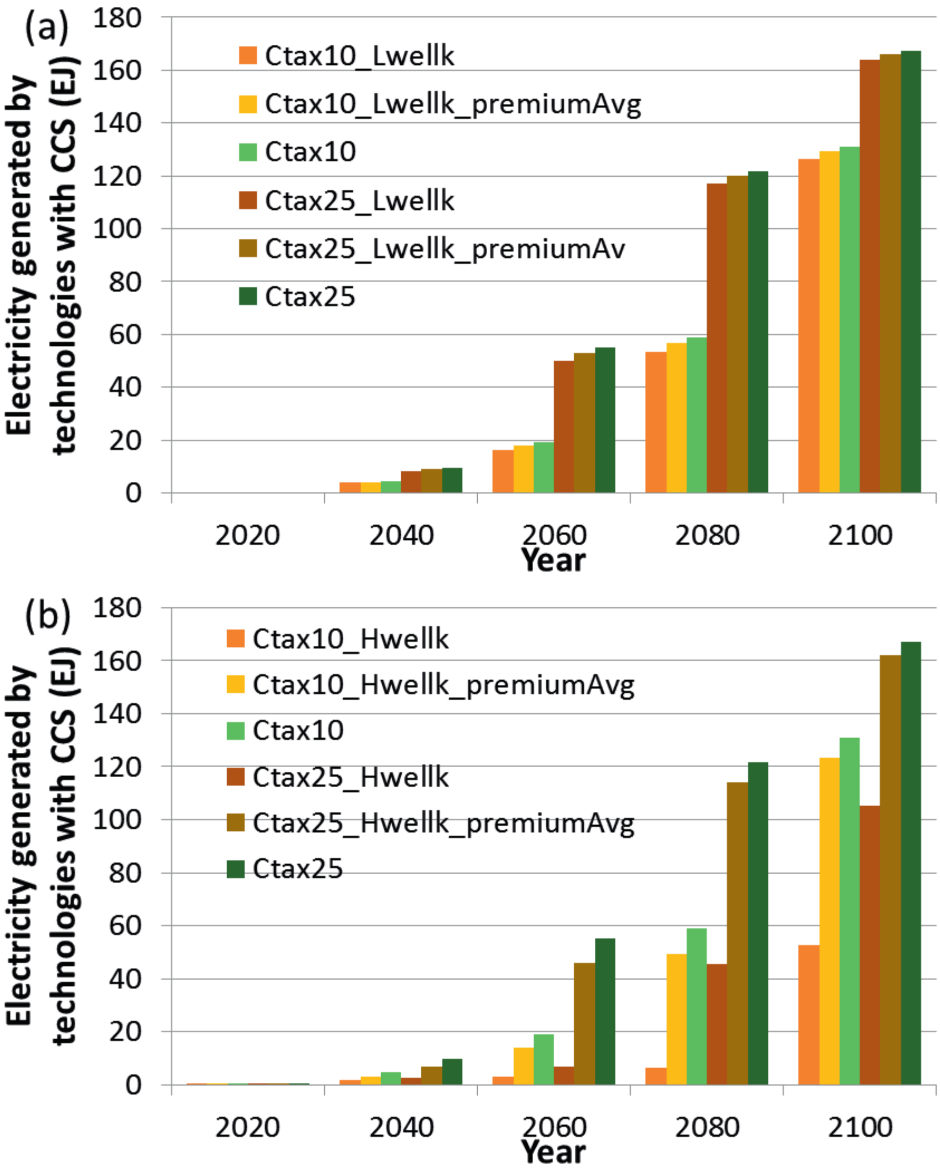

Fig. 5. Electricity generated by technologies with CCS for risks incorporated as an increasing variable over injection and as a fixed premium for (a) low and (b) high well leakage permeability.

4. Conclusions

Considerations of leakage risks from geologic CO_2 storage reservoirs increase storage cost, and therefore reduce deployment of technologies with CCS in the electricity sector. Such reduction is more significant when regulations account for interferences with other subsurface activities such as natural gas and groundwater. Under a relatively low carbon tax scenario and assuming high well leakage permeability, the reduction of CCS deployment can reach 60%, resulting in approximate ~30ppm higher atmospheric CO_2 concentration given the same policy scenario. Regulations that require assessments that ensure low permeability of all active and abandoned wells that may potentially come in contact with a stored CO_2 plume should effectively reduce the impacts of leakage risks on CCS deployment. Covering the anticipated costs incurred by CO_2 leakage by charging a fixed premium per ton of CO_2 stored, instead of including an escalating risk profile where monetized leakage risk increases over the amount of CO_2 stored, can also mitigate the impact of accounting for monetized leakage risks from geologic storage reservoirs on CCS deployment.

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References

[1] Pacala S, Socolow R. Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. Science 2004; 305:968-72.

[2] Metz B, Davidson O, de Coninck H, Loos M, Meyer L. *IPCC special report on carbon dioxide capture and storage*. Cambridge, United Kingdom, and New York, NY, USA: Cambridge University Press; 2005.

[3] IPCC. Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge, United Kingdom, and New York, NY, USA: Cambridge University Press; 2014.

[4] Edmonds JA, Clarke J, Dooley J, Kim SH, Smith SJ. Modeling greenhouse gas energy technology responses to climate change. Energy 2004; 29:1529-36.

[5] Scott MJ, Edmonds JA, Mahasenan N, Roop JM, Brunello AL, Haites EF. International emission trading and the cost of greenhouse gas emissions mitigation and sequestration. Clim Change 2004; 64:257-87.

[6] Edenhofer O, Knopf B, Barker T, Baumstark L, Bellevrat E, Chateau B et al. The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. Energy J 2010; 31:11-48.

[7] Luckow P, Wise MA, Dooley JJ. Deployment of CCS technologies across the load curve for a competitive electricity market as a function of CO2 emissions permit prices. 2011; 4:5762-9.

[8] McJeon HC, Clarke L, Kyle P, Wise M, Hackbarth A, Bryant BP et al. Technology interactions among low-carbon energy technologies: What can we learn from a large number of scenarios? Energy Econ 2011; 33:619-31.

[9] Bielicki JM, Pollak MF, Fitts JP, Peters CA, Wilson EJ. Causes and financial consequences of geologic CO_2 storage reservoir leakage and interference with other subsurface resources. International Journal of Greenhouse Gas Control 2014; 20:272-84.

[10] Popp D. ENTICE-BR: The effects of backstop technology R&D on climate policy models. Energy Econ 2006; 28:188-222.

[11] Keller K, McInerney D, Bradford D. Carbon dioxide sequestration: how much and when? Clim Change 2008; 88:267-91.

[12] Bielicki JM, Pollak MF, Wilson EJ, Fitts JP, Peters CA. A Methodology for Monetizing Basin-Scale Leakage Risk and Stakeholder Impacts. Energy Procedia; GHGT-11 2013; 37:4665-72.

[13] Pollak MF, Bielicki JM, Dammel JA, Wilson EJ, Fitts JP, Peters CA. The Leakage Impact Valuation (LIV) Method for Leakage from Geologic CO_2 Storage Reservoirs. Energy Procedia; GHGT-11 2013; 37:2819-27.

[14] Medina C, Rupp J, Barnes D. Effects of reduction in porosity and permeability with depth on storage capacity and injectivity in deep saline aquifers: A case study from the Mount Simon Sandstone aquifer. International journal of greenhouse gas control 2011; 5:146.

[15] NACSA 2012 First Edition (http://www.netl.doe.gov/technologies/carbon_seq/refshelf/NACSA2012.pdf).

[16] Leetaru HE, McBride JH. Reservoir uncertainty, Precambrian topography, and carbon sequestration in the Mt. Simon Sandstone, Illinois Basin. Environmental Geosciences 2009; 16:235-43.

[17] Kim SH, Edmonds J, Lurz J, Smith SJ, Wise M. The ObjECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation. Energy J 2006; 27:63-91.

[18] Dooley JJ, Kim SH, Edmonds JA, Friedman JS, Wise MA. A First Order Global Geologic CO_2 Storage Potential Supply Curve and its Application in a Global Integrated Assessment Model. 2005; 1.

[19] GEA. Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012.

[20] IEA. *Redrawing the Energy Climate Map.* WEO Special Report. 2013.

[21] IPCC. Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge, United Kingdom, and New York, NY, USA: Cambridge University Press; 2014, p. 1-32.

[22] Tao Q, Bryant SL. Well permeability estimation and CO_2 leakage rates. International Journal of Greenhouse Gas Control 2014; 22:77-87.