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A Global but Regionally Disaggregated Accounting of CO2 Storage Capacity: Data and Assumptions for Compiling Regional CO2 Storage Capacity Supply Curves for Incorporation within ObjECTS->MiniCAM

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A Global but Regionally Disaggregated Accounting of CO_2 Storage Capacity: Data and Assumptions for Compiling Regional CO_2 Storage Capacity Supply Curves for Incorporation within ObjECTS→MiniCAM

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ABSTRACT
This technical working paper lays out the assumptions and data sources used to calculate a regionally disaggregated assessment of the carbon dioxide (CO2) storage capacity of various geologic reservoirs. We present estimates of CO2 storage capacity in the following classes of reservoirs: depleted oil plays, coal beds, depleted gas basins, deep saline formations, and off-shore deep saline formations. CO2 storage capacity for each of these classes of candidate geologic reservoirs were estimated by consulting the technical literature or through our own technical judgment for the following regions of the globe: USA, Canada, Western Europe, Japan, Australia and New Zealand, the Former Soviet Union, China, the Middle East, Africa, Latin America, Southeast Asia, Eastern Europe, Korea, and India. Within each of these regions and for each class of candidate CO2 storage reservoir we have disaggregated the regional CO2 capacity into five grades of the resource. Each grade is described by its own cost of storage supply schedule. These data have been assembled so that we can employ a new version of the MiniCAM Integrated Assessment Model, known as ***ObjECTS→MiniCAM.*** It is our intent to update this dataset describing the regional distribution of candidate CO2 geologic storage capacity as new information and also to bring this new knowledge into the evolving *ObjECTS* Integrated Assessment Model.

KEY WORDS
Geologic CO2 storage reservoirs; integrated assessment; climate change.

Introduction

This technical working paper lays out the assumptions and data sources used to calculate a regionally disaggregated assessment of the carbon dioxide (CO2) storage capacity of various geologic reservoirs. We present estimates of CO2 storage capacity in the following classes of reservoirs: depleted oil plays, coal beds, depleted gas basins, deep saline formations, and off-shore deep saline formations. CO2 storage capacity for each of these classes of candidate geologic reservoirs were estimated by consulting the technical literature or through our own technical judgment for the following regions of the globe: USA, Canada, Western Europe, Japan, Australia and New Zealand, the Former Soviet Union, China, the Middle East, Africa, Latin America, Southeast Asia, Eastern Europe, Korea, and India.

These data have been assembled so that we can employ a new version of the MiniCAM Integrated Assessment Model, which is embedded in an object oriented modeling framework. This new modeling framework is known as ***ObjECTS→MiniCAM***, where ObjECTS refers to the **Obj**ect-oriented **E**nergy-**C**limate-**T**echnology **S**ystem. ***ObjECTS*** is a flexible model embodiment framework, coded in C++, capable of representing and solving alternative model equation formulations (e.g., ObjECTS can also be used to represent and solve the equation structure of the Second Generation Model as well). ObjECTS→MiniCAM version 2004.04 solves the equation structure for MiniCAM, described in Edmonds, et. al. (2004). The MiniCAM equation structure has been enhanced to include regional representations for the cost of CO2 storage in five alternative reservoirs: depleted oil plays, coal beds, depleted gas basins, deep saline formations, and off-shore deep saline formations. Each of these types in turn is disaggregated into five grades of the resource. Each grade is described by its own cost of storage supply schedule and a maximum extent of potential storage.

It is our intent to update this dataset describing the regional distribution of candidate CO2 geologic storage capacity as new information and also to bring this new knowledge into the evolving *ObjECTS* Integrated Assessment Model.

United States:

- Data for depleted oil, depleted gas, coal seams and deep saline formations are taken from Dooley, et. al. 2004 which was a detailed multi-year study of geologic sequestration potential in the United States and Canada.
- Distributing the overall CO2 storage capacities across the four grades for each reservoir class was estimated by examining the more detailed cost curves that are the basis of the Dooley, et. al. 2004 study and looking for "natural" breaks in the cost curve.
- The authors have assumed that the storage capacity for offshore deep saline formations in the United States is one-third the size of the onshore deep saline formation potential. We assume that this capacity is distributed across the four grades in a way that mirrors the distribution of the capacity across the four grades for onshore deep saline formations in the United States contained in Dooley, et. al. 2004.

Canada:

- Data for Canada (with the exception of off-shore deep saline formations) are representative of the CO2 storage capacity of candidate CO2 storage reservoirs in Alberta and Saskatchewan only. These two provinces are believed to contain the majority of Canada's CO2 storage potential.
- Data for depleted oil, depleted gas, coal seams and deep saline formations are taken from Dooley, et. al. 2004 which was a detailed multi-year study of geologic sequestration potential in the United States and Canada.
- The large capacity for deep saline formations (on shore) is the estimated capacity of the very large deep saline formations contained within the Alberta Basin. The massive capacity of this formation was divided evenly among the four grades. This was simply a guess on our part.
- The large capacity for depleted gas basins comes from an assessment of a number of smaller depleted gas basins contained in Dooley et. al. 2004. While there are numerous data points along this supply curve for Canadian depleted gas basins, they all fall in a very narrow price range. This large capacity was divided evenly among the four grades. Once again this was simply a guess on our part.
- Data on coal bed storage capacity and depleted oil plays were all taken from Dooley, et. al. 2004 and were divided into the four grades by looking for natural breaks in the cost of storage in their individual supply price curves.
- Offshore deep saline formations were assumed by the authors to be ¼ the capacity of the onshore deep saline formation capacity with the majority of this capacity being in the grades 3 and 4 as relatively few large Canadian CO2 point sources lie near the coastal areas. The distribution across the four grades is as follows: grade 1 (10%), grade 2 (10%), grades 3 and 4 (40% each).

Western Europe:

- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- The IEAGHG (1998) estimates that there is potentially 1.9 Gt CO2 storage capacity in the Saar coal basin in France and Germany. We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- We estimate that the storage capacity of onshore deep saline formations is equal to 1.5 times the capacity of all depleted oil and gas fields. We assume that grades 1 and 2 each contain 25% of the storage potential, grade 3 contains 40% of the capacity and grade 4 contains 10% of the total storage potential.

Japan:

- Akimoto et. al. (2003) identify 378.5 MtC of storage capacity in offshore deep saline formations capacity. Akimoto asserts that their assumptions for capacity in offshore fields is conservative and that they only assessed regions with known anticline structures and with high quality data. The distribution of these offshore deep saline formations across the grades is based upon our estimates of the proximity of major CO2 point sources to these offshore deep saline formations. These are based upon our assessment of Figure 8 in the Akimoto et al. 2003 paper.
- We assume that useable on-shore deep saline reservoirs are 1/10 the size of offshore reservoirs and are distributed among the grades in the same way that the offshore deep saline reservoir are.
- We assume that useable depleted gas fields are the same capacity and as on-shore deep saline reservoirs and are distributed among the grades in the same way that the offshore deep saline reservoir are.
- Komaki (2004) states that the CO2 storage capacity of coals in Japan is "10 billon tons." Given that most of the coal is in Hokkaido which is far from the population and industrial centers of Honshu, we will assume that grades 1 and 2 each contain 5% of the storage potential, grade 3 contains, 10% and grade 4 contains 80% of the storage potential. It should be said that given the extremely small volumes of coal in Japan relative to other nations and coal basins, there is reason to suspect this to be a significant overestimate.
- We assume that there are for all practical purposes no depleted oil reservoirs in Japan that are suitable for storing CO2 on a commercial basis.

Textbox 1: Key Assumptions for CO2 Storage Capacity in Depleted Oil and Gas Formations

Many of our data draw heavily on IEAGHG 2000 and in particular Appendices 1A, 1B and 1C of this report. These appendices list estimated reserves, production, EOR potential and CO2 storage potential for the most prolific 155 basins in the world (see refs below). We chose the following criteria to determine how to allocate this storage capacity across the four grades we are using to subdivide the CO2 storage capacity in each region. We used the following rules to allocate this storage capacity:

- Grade 1 = storage capacity in onshore oil and gas fields in and where CO2 point sources are in close proximity
- Grade 2 = storage capacity in onshore oil and gas fields in and where CO2 point sources are medium to far away
- Grade 3 = storage capacity in offshore oil and gas fields and where CO2 point sources are in close proximity
- Grade 4 = storage capacity in offshore oil and gas fields and whereCO2 point sources are medium to far away.

These simple rules for allocating the capacity among the grades based upon the authors' knowledge about the location and character of the basins (see cited General References). There is clearly a need for an international, more comprehensive, basin- and formation-based capacity estimate.

Assumptions for Australia and New Zealand:

- Bradshaw et al. (2003) identifies 720 $GtCO_2$ as the total theoretical storage capacity for Australia.
- IEAGHG (1998) identify 29.9$GtCO_2$ storage capacity contained within the Bowen (11.2 $GtCO_2$), Sydney (7.8 $GtCO_2$), Clarnce/Moreton (3.4 $GtCO_2$), Gunnedah (3.2 $GtCO_2$), and Gailee(4.3 $GtCO_2$) coal basins. We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1. This amounted to 960 $MtCO_2$ in depleted oil fields and 10,100 $MtCO_2$ in depleted gas fields.
- This leaves 679$GtCO_2$ of the original Bradshaw estimate of the nation's storage capacity unallocated. We assume that 70% of this capacity is contained in offshore deep saline formations and the remaining 30% is in onshore deep saline formations. We assume this is evenly divided among the various grades for each reservoir class.
- Given the large uncertainties in the above estimates we will simply assume that New Zealand's CO_2 storage capacity is contained within these estimates for Australia.

Former Soviet Union:

- The IEAGHG (1998) identifies an estimated 18.9 $GtCO_2$ of CO_2 storage capacity in the Kunetsk coal basin (13.6 $GtCO_2$) and the Donetsk coal basin (5.3 $GtCO_2$). We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evely divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- For onshore deep saline reservoirs, we assume that their storage capacity is equal to the five times the sum of the capacity of the depleted oil and gas fields for each corresponding grade.
- We were unable to find published information on the storage capacity of offshore deep saline formations for the Former Soviet Union and therefore we simply estimated these amounts. Estimated amounts correspond to the capacity for the Caspian (grades 1&2) and Sakhalin, Baikal, and the arctic ocean deep saline formations (grades 3&4). The storage volume is equal to five times the onshore oil & gas capacity for each corresponding grade. We believe this to be a conservative estimate

China:

- The IEAGHG (1998) identified an estimated 12.7 GtCO2 of CO2 storage capacity in China contained within the Ordos coal basin (8.4 GtCO2) and various other coal basins in China (4.3 GtCO2). We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- The total capacity of onshore deep saline formations is assumed to be 25 times the capacity of the total capacity of all of the identified depleted oil and gas fields. This capacity was divided among the four grades as follows: grades 1 and 2 each hold 25% of the capacity, grade 3 holds 40% of the capacity and the remaining 10% is in grade 4.
- For offshore deep saline reservoirs, we assume that their storage capacity is equal to the five times the sum of the capacity of the depleted oil and gas fields for each corresponding grade.

Middle East:

- We believe that for all practical purposes, there is no effective CO2 storage capacity for coal seams in the Middle East. It should be mentioned, however, that coal basins in Iran (EIA, 2001; WEC, 2001) and subsurface coal identified in Kuwait suggest that there is non-negligible volumes in the Middle East.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- For onshore deep saline reservoirs, we assume that their storage capacity is equal to the sum of the total capacity of the depleted oil and gas fields. The distribution of this onshore deep saline formation storage capacity is weighted towards grades 1 (20% of the total) and 2 (40%) because of the exceptional reservoir quality and low drilling costs likely to be encountered in the Middle East. Grade 3 is assumed to contain 30% of the capacity while grade 4 contains the remaining 10%.
- Offshore acreage in the Middle East is roughly 12% of the onshore acreage. The offshore has received considerably less characterization as a whole than the onshore, so there is reasonable potential for increases in all grades. However, due to downstream fining away from the Arabian craton, we have assumed a very conservative estmate of 6% of the onshore deep saline aquifer volume.

Africa:

- The IEAGHG (1998) identified an estimated 6.8 GtCO2 of CO2 storage capacity in South Africa and Zimbabwe contained within the Karoo coal basin (1.7 GtCO2) and the Zambez coal basin (5.1 GtCO2). We used the "CBM Resource

Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4. This may represent an underestimation, since it does not account for recognized coal seams in Ethiopia, Eritrea, Chad, Niger, and Mauritania.

- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- Africa's onshore deep saline formations capacity is assumed to be 1.5 times the combined total storage capacity of depleted oil and gas fields. We assume grades 1 and 2 each hold 25% of the capacity, grade 3 holds 40% of the capacity and the remaining 10% is in grades 4.
- The authors have estimated offshore deep saline formation CO2 storage capacity based upon the values for on-shore storage capacity as follows:
    - the storage capacity for grade 1 and grade 2 offshore DSF capacity is 1.5 times that of the corresponding onshore DSF capacity,
    - the storage capacity for grade 3 is equal to twice the storage capacity of the corresponding grade 3 onshore storage capacity plus ½ the storage capacity of onshore DSF contained in grade 1,
    - the storage capacity for grade 4 is equal to twice the storage capacity of the corresponding grade 4 onshore storage capacity plus ½ the storage capacity of onshore DSF contained in grade 2.

The capacity of these offshore deep saline formations is weighted heavily towards grades 3 and 4 due to a lack of infrastructure and very high drilling costs. Since most of Africa's basins and reserves lie offshore (e.g., Niger delta shelf and slope, Gabon and Angolan basins), even a conservative rendering produces high volumes.

Latin America:

- We were unable to find any information in the literature on the CO2 storage capacity of coals in Mexico, Central and South America . However, the region contains many large volume coal basins, especially in Brazil, Columbia, and Mexico (WEC 2001). Since Latin American reserves are approximately 8% of US reserves, we have used that percentage as a crude scaling agent and assigned 5000 MM tons capacity to be conservative. Most of this lies in grades 1 and 2 (1500 and 2000 MM tons respectively) given the relative proximity of these basins to infrastructure and population.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- The total capacity of Latin American onshore deep saline formations is assumed to be three times the combined total capacity of the depleted oil and gas reservoirs in this region. This capacity is divided up among the grades as follows: 25% in Grade 1, 25% in Grade 2, 35% in Grade 3, and 15% in Grade 4

- For each grade, offshore deep saline formations were assumed to contain 30% of the capacity of the onshore deep saline formation capacity in the corresponding grade.

South East Asia:

- The IEAGHG (1998) identified an estimated 23.9 $GtCO_2$ of CO_2 storage capacity in Indonesia contained within the Sumatra coal basin (13 $GtCO_2$) and various other coal basins in Indonesia (10.9 $GtCO_2$). We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- Onshore deep saline formations were assumed to be 5 times as large as the coal basin CO_2 storage capacity. This scaling factor was used for all grades.
- Offshore deep saline formations were assumed to be 1.5 times as large as the onshore deep saline formations' CO_2 storage capacity. This scaling factor was used for all grades.

Eastern Europe:

- The IEAGHG (1998) 1.6 $GtCO_2$ storage capacity in the coal seams of Poland/Czech specifically with in the Upper Silesian coal basin. We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- On-shore deep saline formations in Eastern Europe are assumed to be 1.5 times as large as the capacity of onshore deep saline reservoirs in Western Europe.
- Off-shore deep saline formations in Eastern Europe are assumed to be only 10% the capacity of the onshore deep saline formations in Eastern Europe.

Korea:

- We believe that for all practical purposes, there is no CO_2 storage capacity within Korea in coal seams, depleted oil and gas fields, and deep saline formations.
- The authors have included a total of 0.4$GtCO_2$ storage capacity in offshore deep saline aquifers for Korea. This is split evenly between Grades 3 and 4 given the adjacent western basins. This is roughly 1% of China's saline aquifer storage, and Korea has about 1% of China's coal volume so it seems reasonable. Given

Korea's very limited storage, even this small amount of very expensive storage might matter.

India:

- The IEAGHG (1998) identified an estimated 5.5 $GtCO_2$ of CO_2 storage capacity in India contained within the Cambay coal basin (3.8 $GtCO_2$) and the Damodan coal basins (1.7 $GtCO_2$). We used the "CBM Resource Type" classifications provided in this publication to subdivide this capacity among the four grades for the coal seam sequestration storage resource as follows: "CBM Resource Type A" = grade 1, "CBM Resource Type B" = grade 2, and "CBM Resource Type C" = was evenly divided among grades 3 and 4.
- Data for depleted oil and gas fields are taken from (IEAGHG, 2000) and were tabulated following the methodology spelled out in Textbox 1.
- The authors have assumed that the storage capacity of onshore deep saline formations in India is 25 times the capacity of the total for all grades for depleted oil and depleted gas fields. We assume that the majority of this capacity will be in the higher grades and as a result have allocated this total capacity as follows: 10% in Grade 1, 10% in Grade 2, 40% in Grade 3, and 40% in Grade 4
- The authors have assumed that the storage capacity of offshore deep saline formations in India (e.g., Bengal Fan & Indus Cone) is a function of the on shore deep saline formation capacity as follows:
    - the capacity of Grade 1 off-shore deep saline formations is equal to 75% of the onshore deep saline formation capacity for that grade,
    - the capacity of Grade 2 off-shore deep saline formations is equal to 75% of the onshore deep saline formation capacity for that grade,
    - the capacity of Grade 3 off-shore deep saline formations is equal to the some of 100% of the Grade 3 onshore deep saline formation capacity plus 25% of the capacity of Grade 1 on shore deep saline formations, and
    - the capacity of Grade 3 off-shore deep saline formations is equal to the some of 100% of the Grade 3 onshore deep saline formation capacity plus 25% of the capacity of Grade 1 on shore deep saline formations,

  It should be said that these two sediment accumulations contain over 13 km of strata that have received very little direct or indirect study.

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