Estimation of Emissions from CO_2 Capture and Storage: the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

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1 INTRODUCTION

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories (2006GL)[1] include guidance on how to treat CO_2 capture and geologic storage (CCS). This paper summarises the methods provided in the 2006GL. The approach adopted is consistent with the remainder of the guidelines, in particular a fundamental principle that the inventory methods reflect the estimated actual emissions in the year in which they occur, and in line with the approach used for the treatment of biogenic material. These Guidelines can also be used with the revised 1996 IPCC guidelines[2] and subsequent good practice guidance[3].

CCS is one potential option that could be used to reduce greenhouse gas emissions. CCS consists of the following steps: the capture and compression of CO2 (usually at a large industrial installation); its transport to a storage location; injection into the geological reservoir; and its subsequent long-term isolation from the atmosphere. CO_2 capture is most likely to take place at stationary combustion sites (Sector 1A) and in the Industrial Process and Product Use sector (IPPU, Sector 2). The IPCC has produced a Special Report on Carbon Dioxide Capture and Storage[4] (SRCCS), from which additional technological information on CCS can be obtained. The 2006 Guidelines are consistent with the information in the SRCSS and have been produced in consultation with the relevant authors

Geological storage uses natural geological barriers to isolate the CO_2 from the atmosphere and can take place in natural underground reservoirs such as oil and gas fields, coal seams and saline water-bearing formations. Geological CO_2 storage may take place either at sites where the sole purpose is CO_2 storage, or in association with enhanced oil recovery, enhanced gas recovery or enhanced coal-bed methane recovery operations (EOR, EGR and ECBM respectively).

The 2006GLs provide emission estimation guidance for the capture and transport of CO_2 and for geological storage. No emissions estimation methods are provided for any other type of storage option such as ocean storage or conversion of CO_2 into inert inorganic carbonates.

2 METHODS

The 2006GL provide good practice methods for estimating national emissions of greenhouse gases. Therefore emissions are estimated in the sector where this is most easily, and accurately, achieved. Hence, emissions resulting from the additional fossil fuels used for capture, compression, transport, and injection of CO_2, are included and reported in the national inventory where the energy is used, in the appropriate stationary or mobile energy use categories. Fuel use by ships engaged in international transport will be treated as international bunker fuels. Fugitive emissions from surface facilities at EOR, EGR and ECBM sites (with or without CO_2 storage) are classified as oil and gas operations

Emissions from CO_2 transported, injected and stored are reported in sector 1C (see Table 1). Emissions from plant with CO_2 capture are estimated by subtracting the measured amount captured from the emissions without capture. As emissions of CO_2 from biomass are reported as zero in the Energy, IPPU and

[1] IPCC (2006) *IPCC Guidelines on National Greenhouse Gas Emission Inventories*, In press 2006
[2] IPCC (1997). *Revised 1996 IPCC Guidelines for National Greenhouse Inventories*. IPCC/OECD/IEA, Paris, France
[3] IPCC (2000). *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. IPCC/OECD/IEA/IGES, Hayama, Japan; and IPCC (2003), *Good Practice Guidance for Land Use, land-Use Change and Forestry*, IPCC/IGES, Hayama, Japan
[4] IPCC 2005, *IPCC Special Report in Carbon Dioxide Capture and Storage,* CUP, UK.

Waste sectors[5] this can lead to negative emission estimates where plant use fuels or feedstock that are totally or partially made up of biomass. This approach is consistent with the treatment in the Agriculture, Forestry and Other Land Use (AFOLU) volume for emissions and removals associated with the use of biomass and avoids any complex, and probably impractical, separate accounting of captured biogenic and fossil CO_2. Any subsequent leakage of biogenic CO_2 represents an additional release of CO_2 to the atmosphere and so no distinction need be made between any subsequent leakage of this CO_2 and that of CO_2 from fossil sources.

Carbon dioxide emissions from transport, injection and storage include both fugitive losses from CO_2 transport stages plus any losses from CO_2 accumulated underground. The inventory estimates reflect the actual emissions in the year in which they occur.

Table 1 Source Categories for Carbon Dioxide Transport, Injection and Geological Storage

1C		Carbon dioxide (CO_2) capture and storage (CCS) involves the capture of CO_2, its transport to a storage location and its long-term isolation from the atmosphere. Emissions associated with CO_2 transport, injection and storage are covered under category 1C. Emissions (and reductions) associated with CO_2 capture should be reported under the IPCC sector in which capture takes place (e.g. Stationary Combustion or Industrial Activities).
1C1	Transport of CO_2	Fugitive emissions from the systems used to transport captured CO_2 from the source to the injection site. These emissions may comprise fugitive losses due to equipment leaks, venting and releases due to pipeline ruptures or other accidental releases.
1C1a	Pipelines	Fugitive emissions from the pipeline system used to transport CO_2 to the injection site.
1C1b	Ships	Fugitive emissions from the ships used to transport CO_2 to the injection site.
1C1c	Other (please specify)	Fugitive emissions from other systems used to transport CO_2 to the injection site.
1C2	Injection and Storage	Fugitive emissions from activities and equipment at the injection site and those from the end containment once the CO_2 is placed in storage.
1C2a	Injection	Fugitive emissions from activities and equipment at the injection site.
1C2b	Storage	Fugitive emissions from the end containment once the CO_2 is placed in storage.
1C3	Other	Any other emissions from CCS not reported elsewhere

2.1 CO_2 CAPTURE

Anthropogenic CO_2 emissions that can be feasibly captured arise mainly from combustion of fuels in large stationary combustion plant and some non-combustion sources in certain industrial processes such as cement manufacture, natural gas processing and hydrogen production. Technology is generally deployed in a way that captures around 85-95 percent of the CO_2 processed in a capture plant (see Chapter 3 of the SRCCS). CO_2 capture compression and any dehydration or other conditioning of the CO_2 that takes place before transportation produces a high pressure, concentrated stream of CO_2

Capturing CO_2 from an emission source can, in general, result in two sources of CO_2. Firstly the capture process usually will result in increased energy consumption. CO_2 emissions from this energy use will be included in the energy consumption statistics and the emissions calculated in the usual way. Secondly, the capture process will not be 100% efficient. As all the CO_2 from the plant will be either emitted or captured the emissions from the plant can be estimated from the unabated emissions and the amount captured.

[5] In general, the AFOLU sector uses stock change approaches to produce estimates of net CO2 emissions from agriculture, forestry and other land uses, and from biogenic products such as fuels. Therefore the CO2 emissions from the use of biofuels is already included in the AFOLU sector estimates and reporting it in Energy, IPPU or Waste would double count the emissions.

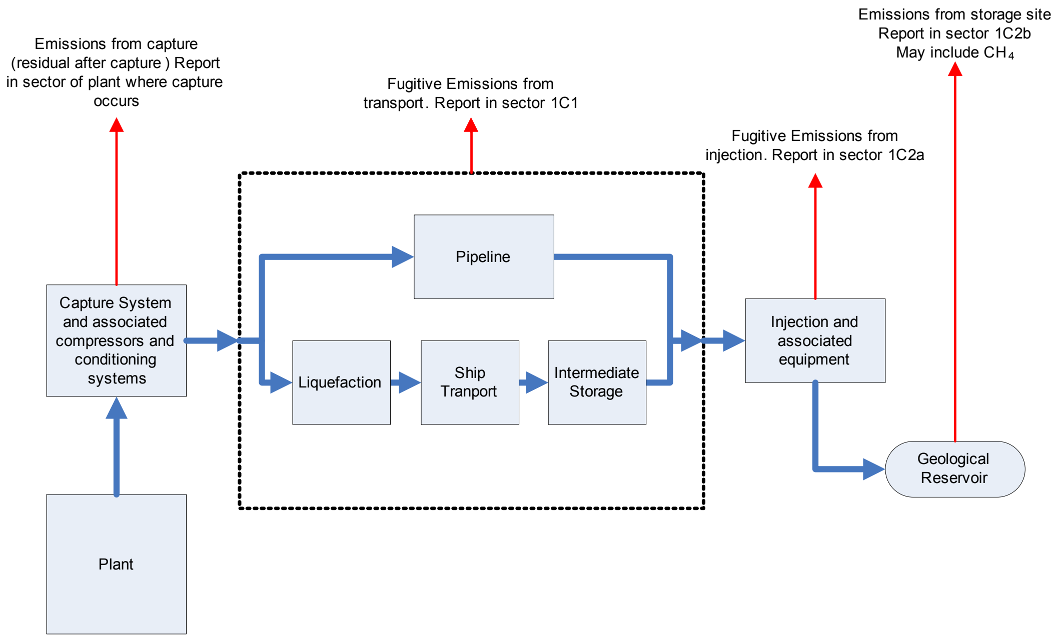
$$Emission = [Potential\ Emission] - [Amount\ Captured]$$

Where:

Potential Emission = the amount that would be emitted without CO_2 capture plus CO_2 form any additional fuel used to run the CCS. This can either be estimated from the carbon contents of the fuel (or from inputs into an industrial process) or be measured using a continuous emission monitoring system (CEMS) in the appropriate gas streams.

Amount Captured = the measured amount captured and sent into a transport system for long term geological storage.

Figure 1 Schematic representation of the carbon capture and storage process.



Basing the emissions on measurements in this way does not need to make assumptions about capture efficiency.

One source that needs extra consideration is enhanced hydrocarbon recovery operations. In these operations, CO_2 is injected into the hydrocarbon reservoir, but a proportion of the amount injected is commonly produced along with the product. This CO_2 can either be separated and re-injected or emitted to the atmosphere through combustion of high CO_2 fuels or through venting. Oil and gas reserves underground often include natural CO_2 that can be released in the same way. Re-injection of this CO_2 gas should not be accounted for as additional CO_2 storage, but all emissions to the atmosphere are real emissions. Guidance is given in the appropriate chapter of the 2006GL for these specific sources.

2.2 CO_2 TRANSPORT

CO_2 pipelines are the most common means of bulk CO_2 transport and are a mature market technology in operation today. Bulk transport of CO_2 by ship also takes place, though on a relatively minor scale. This occurs in insulated containers at temperatures well below ambient, and much lower pressures than pipeline transport. Transport by truck and rail is possible, but unlikely to be significant in CCS because of the very large masses likely to be captured. Therefore no methods of calculating emissions from truck and rail transport are given in the 2006 Guidelines.

To estimate emissions from pipeline transport of CO2, default emission factors can be derived from the emission factors for transmission (pipeline transport) of natural gas. Fugitive emissions from pipeline transport are largely independent of the throughput, but depend on the type and size of equipment installed in the pipeline systems. Since it is good practice to both treat capture and storage on a site by site basis, the length of the transporting CO_2 pipeline system will be known and should be used to estimate emissions from transport. Emissions are reported under category 1C1a.

Better estimates depend on knowledge of the number and type of equipment components and the type of service. Most of the equipment tends to occur at the facilities connected to the pipeline rather than with the pipeline itself. Therefore, in a more detailed approach, the leakage emissions from the transport pipeline can be obtained from data on number and type of equipment and equipment-specific emission factors.

Default emission factors for fugitive emissions from CO_2 transport by ship are not available. The amounts of gas should be metered during loading and discharge using flow metering and losses reported as fugitive emissions of CO_2 resulting from transport by ship under category 1C1b.

If there is a mismatch between supply and transport or storage capacity, a CO_2 buffer (above ground or underground) may be used to store the CO_2 temporarily. f the buffer is a tank, fugitive emissions should be estimated as part of the transport system and reported under category 1C1 c (other). If buffer is a geological storage reservoir, fugitive emissions from it can be treated in the same way as for any other geological storage reservoir and reported under category 1C3.

Where CO2 is exported each of the countries involved is responsible for reporting the associated emissions within its jurisdiction. If CO2 is injected in one country and travels underground from the storage site and leaks in a different country, then the first country is responsible for reporting the emissions from the geological storage site.

2.3 CO_2 INJECTION

The injection system comprises surface facilities at the injection site, e.g. storage facilities, any distribution manifold at the end of the transport pipeline, distribution pipelines to wells, additional compression facilities, measurement and control systems, wellhead(s) and the injection wells.

Meters at the wellhead measure the flow rate, temperature and pressure of the injected fluid. Thus the amount of CO_2 injected into a geological formation through a well can be monitored by equipment at the wellhead, just before it enters the injection well. The composition of the imported CO_2 commonly shows little variation and can be analyzed periodically using a gas chromatograph. The mass of CO_2 passing through the wellhead can then be calculated from the measured quantities. It is good practice to calculate and report the mass of CO_2 injected from direct measurements.

If the pressure of the CO_2 arriving at the storage site is not as high as the required injection pressure, compression will be necessary. Any emissions from compression of the stored gas at the storage site should also be estimated and reported.

2.4 GEOLOGICAL STORAGE OF CO_2

Most of the CO_2 stored in geological reservoirs may remain there for centuries to millennia. Therefore potential emissions pathways created or activated by slow or long-term processes need to be considered as well as those that may act in the short to medium term.

Pathways that need to be considered are both CO_2 leakage to the ground surface and to the seabed[6]. There is a possibility that methane emissions, as well as CO_2 emissions, could arise from geological storage reservoirs that contain hydrocarbons. Although there is insufficient information to provide guidance for estimating CH_4 emissions, it is good practice to undertake appropriate assessment of the potential for CH_4

[6] Emissions of CO_2 may occur as free gas or gas dissolved in groundwater that reaches the surface e.g. at springs.

emissions from such reservoirs and, if necessary, include any such emissions attributable to the CO_2 storage process in the inventory.

Geological conditions vary widely, and there are currently only a few published studies of monitoring programmes that identify and quantify fugitive anthropogenic carbon dioxide emissions from geological storage operations. Thus, it is not feasible to produce default emission factors that could be applied to leakage from geological storage reservoirs. Consequently, the 2006GL does not include a Tier 1 or Tier 2 methodology[7]. There are Tier 3 monitoring technologies available, which have been developed and refined over the past 30 years in the oil and gas, groundwater and environmental monitoring industries. The suitability and efficacy of these technologies can be strongly influenced by the geology and potential emissions pathways at individual storage sites, so the choice of monitoring technologies will need to be made on a site-by-site basis. Monitoring technologies are advancing rapidly and it would be good practice to keep up to date on new technologies.

In order to understand the fate of CO_2 injected into geological reservoirs it is necessary to:

i. Properly and thoroughly characterise the geology of the storage site and surrounding strata

ii. Model the injection of CO_2 into the storage reservoir and the future behaviour of the storage system.

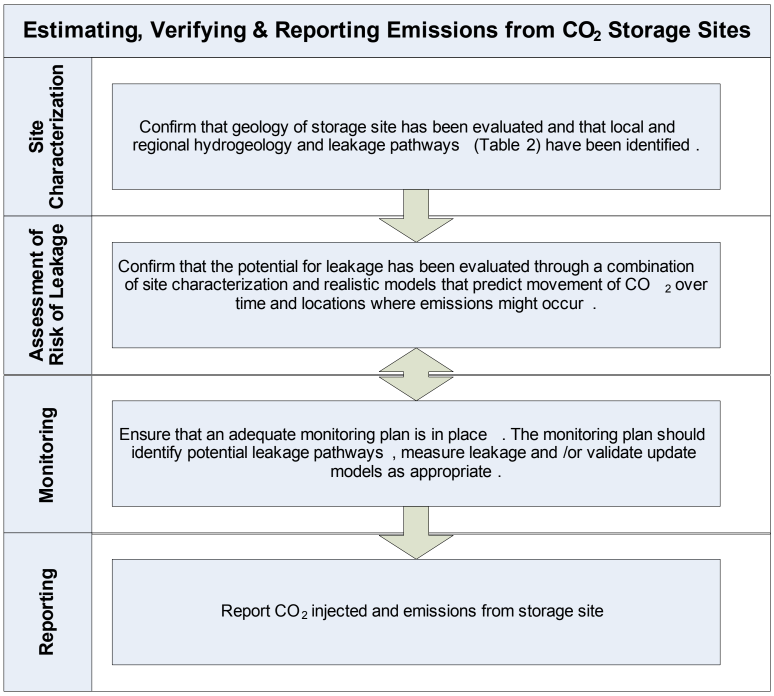
iii. Monitor the storage system.

iv. Use the results of the monitoring to validate and/or update the models of the storage system.

The Tier 3 procedures for estimating and reporting emissions from CO2 storage sites are summarised in Figure 2. Many factors could be considered: changes in temperature and pressure; mixing of the injected gas with the fluids initially present in the reservoir; the type and rate of carbon dioxide immobilization mechanisms; and fluid flow through the geological environment. These can be modelled successfully with numerical modelling tools known as reservoir simulators. These are widely used in the oil and gas industry and have proved effective in predicting movement of gases and liquids, including CO_2, through geological formations.

[7] In the 2006GL methodologies are categorised as Tier 1, 2 or 3 (in increasing complexity). Tier 1 methods typically are based on default emission factors, Tier 2 are still based on emission factors but use county-specific data while modelling and measurements are Tier 3. Higher Tier methods should be used for significant sources or sinks while Tier 1 methods can be used for very small sources or sinks (see guidance on *Key Categories* in the 2006GL).

Figure 2 Procedures for estimating emissions from CO_2 storage sites



Reservoir simulation coupled where necessary to additional numerical modelling techniques to analyze particular aspects of the geology are used to predict the likely location, timing and flux of any emissions which should be periodically checked using direct monitoring techniques.

Numerical simulations should be validated by direct measurements from the storage site, where possible. These measurements should be part of a monitoring programme, and comparison between monitoring results and expectations used to improve the geological and numerical models. Expert opinion is needed to assess whether the geological and numerical modelling are valid representations of the storage site and surrounding strata and whether subsequent simulations give an adequate prediction of site performance.

Monitoring should take place at leakage locations predicted by the modelling, Site managers will typically be responsible for installing and operating carbon dioxide storage monitoring technologies. Regulatory authorities and/or inventory compilers will need to ensure that they have sufficient information from each storage site to assess annual emissions. To make this assessment, there should be a formal arrangement with each site operator that will allow for annual reporting, review and verification of site-specific data.

Note that as CCS becomes more commonplace, countries may put in place domestic permitting systems and other regulations that are relevant to inventory steps covered in the 2006 Guidelines. For example, risk assessment, site-specific modelling and monitoring may be required as part of groundwater protection measures.

3 QA/QC

The 2006GL specify site-specific QA/QC and reporting and documentation procedures as well as more general national reporting and QA/QC. Given the detailed nature of the Tier 3 methods extensive site-specific documentation is anticipated. However as this is likely to be required by any regulatory regime, and given the fact that these sites are like to be large and represent significant financial investments this is not considered to be a significant additional burden.

Inventory compilers should also check that they have a complete and consistent national overview of all captured, imported and exported CO_2, as well as its storage and any fugitive emissions. For example, ideally:

$$[total\ captured] + [net\ imports] - [total\ injection] = [total\ leakage]$$

Any discrepancy large compared to the uncertainties should be checked.[8]

4 CONCLUSION

The 2006GL provide a methodology for including CCS in national greenhouse gas inventories.

- This method is consistent with the remainder of the 2006 Guidelines (and the 1996 Guidelines).
- The method makes no assumptions about the efficiency of capture or of storage sites. No assumptions are made about the length of time the gas can be stored.
- The method is based on detailed modelling and measurements for storage sites and more conventional emission factors for transport where the technologies are in use today. Thus it is based on existing knowledge where this is available for mature technologies and on measurements and simulation for new technologies.
- The method can deal with the use of biomass as fuel or feedstock.

[8] Small discrepancies may arise from a number of factors such as uncertainties in the measurements of amounts captured, injected and of any leaks, or from intermediate storage.