Supplementary Materials: Integrated Assessment of Carbon Capture and Storage (CCS) in South Africa's Power Sector

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For further information, reference is made to project report [1] on which this article is based.

ad Section 1. Introduction

Table S1. List of organizations interviewed in South Africa (face-to-face interviews).

Organization	Date of interview
Industry	
Sasol	24/10/2011
Eskom	27/10/2011
Anglo American	27/10/2011
Civil society	
Fossil Fuel Foundation (FFF)	25/10/2011
Greenpeace Africa	31/10/2011
Science, consultancies and think-tanks	
South African Centre for Carbon Capture and Storage (SACCCS)	24/10/2011 25/10/2011
IMBEWU – Sustainability Legal Specialists	27/10/2011
Council for Geoscience	28/10/2011
School of Chemical and Metallurgical Engineering at University of Witwatersrand	31/10/2011

Questionnaire (research interviews)

Your General Position on CCS

1. Please describe your function and how you are involved in the debate on CCS in South Africa.
2. What do you think about carbon capture and storage (CCS) in general and its potential in South Africa?
3. In which way are you and your organization dealing with CCS technologies?

CCS Stakeholders in South Africa

4. Which stakeholders are most important with regard to the prospects of CCS in South Africa, both within the government and industry?
5. Is there a public opinion on CCS and CO_2 storage in South Africa in particular? Is public acceptance an important determinant for the deployment of CCS?

CCS in South Africa's Energy Sector

6. Which technological and economic parameters are of decisive meaning for a possible market introduction and diffusion of CO_2 capture technologies in South Africa?
7. What are the most important CO_2 capture activities (demonstration projects, policy initiatives *etc.*) going on in South Africa at the time being?
8. Which technology path is most relevant for South Africa and globally (post-combustion, pre-combustion, oxyfuel)?
9. Is CCS primarily considered for the power sector or also for other industrial CO_2 large-point sources?

10. What share of South Africa's power plant fleet could be equipped with CCS until 2030 or 2050?
11. To which degree do you expect the costs of CCS plants in South Africa to be different from the international level? Why?
12. Does the proximity of South Africa's CO_2 sources or storage sites inhibit or support CCS?
13. Is there a problem regarding increased water needs for CO_2 capture in water scarce regions?

Energy Scenarios

14. What are the most relevant scenario projections (until 2050) for energy and power demand in South Africa?
15. Which of these scenario projections could be used as a basis for a conservative, moderate and ambitious development of CCS in South Africa?
16. How far can CO_2 be transported in South Africa for geological storage in a feasible manner? Is there a maximum value (e.g., 500 km)?

CO_2 storage

17. What are the most important CO_2 storage activities (demonstration projects, policy initiatives *etc*.) going on in South Africa at the time being?
18. Which storage estimates seem to be most realistic for South Africa?
19. Do you know other estimates of or research projects on South Africa's underground storage capacity?
20. Which formations seem most promising in South Africa for CO_2 storage: Coal fields (ECBM), depleted oil or gas fields, deep saline aquifers or basalt formations?
21. Regarding CO_2 sequestration in aquifers: Is a production of water needed to increase the amount of space? If this is the case, what should be done with the produced water to avoid environmental hazard?
22. Do you see a potential conflict of interest between groundwater supply, geothermal energy production and CO_2 storage projects?
23. Could CO_2-EOR help to boost CCS in South Africa and increase oil production? Are there new EOR operations being planned?
24. Is there a limit to the amount of CO_2 that can be injected safely in the subsurface per year and site (injection rate)?
25. Does seismic activity exclude formations and regions from being potential CO_2 storage sites? Which regions?

Political Aspects of CCS

26. Which political developments are decisive for CCS deployment in South Africa?
27. In which way are South Africa's governments supporting the development and deployment of CCS?
28. Do regulatory frameworks and incentives exist or are they being developed?
29. Would the integration of CCS into the CDM foster CCS development and deployment?

ad Section 3.2. Long-term usable CO_2 storage potential for South Africa's power sector Energy

Scenario Analysis

Table S2. Overview of existing long-term energy scenarios for South Africa and assessment of their suitability for this study arranged by year of publication.

Year	Scenario	Target year	Coal capacity given	CCS for …	Installed CCS capacity	Cumulative stored CO_2 up to target year	CCS share of electricity generation	Decision	Remark
World Bank Sources: [2,3] (compiled by Vito [Belgium]; Energetski Institut Hrvoje Požar [Hungary]; Cape Town University's Energy Research Centre [South Africa]) *1)									
2011	Reference	*2030*	Yes	---	---	---	---	n.c.	
	Baseline (IRP revised balance scenario)	*2030*	Yes	Natural gas (2025)	Figures for 2020/25/30 0.2–2.4 GW	19 Mt *1)	2%	n.c.	
	Baseline with EOR/ECBM	*2030*	Yes	Natural gas	Only figure for 2030: 2.4 GW	23 Mt *1) + 4 Mt retrofit	2%	n.c.	
	CO_2 Price Scenarios	*2030*	Yes	Coal: 2025 or (mainly) 2030	Figures for 2025/30 5.9–7.3 GW	162/177/283 Mt *1) + 15.4/0/0 Mt retrofit	10–16%	n.c.	
EREC and Greenpeace International Sources: [4] (compiled by German Aerospace Center and ecofys [the Netherlands])									
2011	Reference	2050	Yes	---	---	---	---	**Taken as pathway E2: middle**	Up to 2030 based on [5] and updated with figures from IRP (May 2011) (committed and newly built options); updated up to 2050
	Energy [R]evolution	2050	Yes	---	---	---	---	**Taken as pathway *E3: low***	Up to 2030 based on IRP (May 2011) (committed power plants only); updated up to 2050

Table S2. *Cont.*

Year	Scenario	Target year	Coal capacity given	CCS for …	Installed CCS capacity	Cumulative stored CO_2 up to target year	CCS share of electricity generation	Decision	Remark
WWF South Africa Source: [6] (compiled by Cape Town University's Energy Research Centre [South Africa])									
2010	Reference Case	*2030*	Yes	---	---	---	---	n.c.	Uses LTMS framework
	Alternative Scenario	*2030*	Yes	---	---	---	---	n.c.	Uses LTMS framework
Department of Environment Affairs and Tourism South Africa Sources: [7,8] (compiled by Cape Town University's Energy Research Centre [South Africa]) *2)									
2007	LTMS Scenario 1 "Growth without constraints"	2050	Yes	---	---	---	---	**Taken as pathway E1: high**	5 new CTL plants each 80,000 bbl/d=½ Secunda
	LTMS Scenario 2 "Required by Science"	2050							*Storylines*
	"Start now"	*???*	---	Synfuels	*No figures*	2 Mt/a	---	n.c.	*3)
	"Scale up"	*???*	---	Synfuels	*No figures*	23 Mt/a or 20 Mt/a	---	n.c.	*2), *3)
	"Use market"		---	---	---	---	---	n.c.	
	"Reach goal"		---	---	---	---	---	n.c.	

Figures in italics: exclusion criteria; n.c. = not considered. *1) Whole of the Southern Africa Region; *2) Starting figure for 2010 is too low (32.8 GW instead of currently installed 38 GW); IRP figures not given at that time; *3) The low CCS application seems to be a contradiction to the statement that CCS is "included as a major component of energy security strategy" (p. 29).

Main conclusions drawn from the assessment of existing energy scenarios and roadmaps (Table S2):

- No scenarios exist that go up to 2050 and that include use of CCS for power plants;
- Only one scenario applies CCS for coal-to-liquid plants (20 or 23 Mt CO_2/a), but considers the existing Secunda plant only;
- Two scenarios attempt to achieve climate goals in 2030 and 2050 without using CCS or nuclear energy [4,6], respectively);

Only one study is up-to-date compared with the current power plant development plan of the South African government. [4] adapted both the *Energy [R]evolution Scenario* and the *IEA WEO 2010 scenario*, which is taken as the *Reference Scenario*, to the May 2011 *Policy Adjusted Scenario* of the Integrated Resource Plan (IRP) for Electricity [9]. Since IRP only covers the period up to 2030, the figures were updated to 2050.

CCS Deployment

Table S3. Conventional and CCS-based coal-fired power plant capacity installed in South Africa in the three pathways *E1*–*E3* for the base case (CCS from 2030).

Type of capacity	2010	2020	2030	2040	2050
E1: high					
Currently installed	37	42	28	10	5
Newly built without CCS			23	16	16
Newly built with CCS				34	58
Retrofitted with CCS			4	12	12
CCS penalty load newly built				6	139
CCS penalty load retrofitted			1	2	2
Total CCS newly built + penalty				40	67
Total CCS retrofitted + penalty			5	14	14
Total CCS			5	54	81
Total	37	42	56	80	102
E2: middle					
Currently installed	37	42	28	10	5
Newly built without CCS		7	12	10	10
Newly built with CCS				19	24
Retrofitted with CCS			4	6	6
CCS penalty load newly built				3	4
CCS penalty load retrofitted			1	1	1
Total CCS newly built + penalty				22	28
Total CCS retrofitted + penalty			5	7	7
Total CCS			5	29	35
Total	**37**	**49**	**45**	**49**	**50**
E3: low					
Currently installed	37	42	28	10	5
Newly built without CCS					
Newly built with CCS				8	8
Retrofitted with CCS			4	4	4
CCS penalty load newly built				2	2
CCS penalty load retrofitted			1	1	0
Total CCS newly built + penalty				10	10
Total CCS retrofitted + penalty			5	5	5
Total CCS			5	15	15
Total	**37**	**42**	**33**	**24**	**20**

All quantities are given in Gt CO_2

Power Plant Analysis

Table S4. Overview of parameters assumed for future coal-fired power plants in South Africa.

	Unit	2010	2020	2030	2040	2050
Share of power plants in newly built coal fired power plants						
Supercritical	%		100	90	70	60
Integrated Gasification Combined Cycle	%		0	10	30	40
Efficiencies for newly built coal-fired power plants						
Supercritical	%	38	39	41.5	42	42
Integrated Gasification Combined Cycle	%		44	46.5	47	47
Efficiency losses through CCS						
Efficiency penalty post-combustion	%-pt	12	8.5	7	6	5
Efficiency penalty pre-combustion	%-pt	8	6.5	6	6	6
Additional efficiency penalty for retrofitting	%-pt	1.5	1.5	1.5	1.5	1.5
Other parameters						
Origin of hard coal: import share	%	0				
Net calorific value for medium-quality South African coal	MJ/kg_{coal}	19.6				
Price of hard coal mix (100% domestic)	$\$_{2011}/kwh$	1.33	1.73	2.20	2.67	3.15
Technical lifetime of newly built coal-fired plants	a			50		
Plant load factor (PLF)	%			80		
	h/a			7,000		
CO_2 capture rate	%			90		
Average/maximum CO_2 transport distance	km			550		
CO_2 leakage of storage sites	%/a			0		
Cost parameter						
Coal-fired power plants without CCS						
Capital cost	$\$_{2011}/kW_{el}$	2,297	Further development depends on installed capacities within pathways E1–E3			
O&M cost (4% of capital cost)	$\$_{2011}/kW_{el}$	92				
Learning rate capital cost	%			1.7		
Learning rate O&M cost	%			3.9		
Interest rate	%			8		
Depreciation period	a			25		
Resulting annuity factor	%/a			9.37		
Coal-fired power plants with CCS						
Capital cost (175% of capital cost w/o CCS)	$\$_{2011}/kW_{el}$			Development from 2030 depends on installed capacities in pathways E1-E3		
O&M cost (183% of O&M cost w/o CCS)	$\$_{2011}/kW_{el}$					
Learning rate capital cost	%			2.5		
Learning rate O&M cost	%			5.8		
CO_2 transportation costs via pipeline	$\$_{2011}/(t_{CO2},100\ km)$			5.5		
Average/maximum CO_2 transport distance	km			550		
Other parameters						
CO_2 costs	$\$_{2011}/t_{CO2}$		42	49	56	63

Source-Sink Matching

Table S5 shows the comparison of the *high storage scenario* $S1_{600km}$ with coal development pathways *E1–E3*. First, the onshore Zululand basin is filled with 0.4 Gt of CO_2 in each scenario. The offshore Durban & Zululand basin is then filled until all emissions have been stored. The matched capacity amounts to 22.0, 9.3 and 4.0 Gt of CO_2 for pathways *E1*, *E2* and *E3*, respectively.

Table S5. Source-sink match of effective storage scenario *$S1_{600km}$: high* with coal development pathways *E1–E3* in South Africa (authors' calculation with data from [10]).

Basin	Formation	$S1_{600km}$: high	E1: high (22.0)	E2: middle (9.3)	E3: low (4.0)
Zululand	Onshore basin	0.4	0.4	0.4	0.4
Durban & Zululand	Offshore basin	42.3	21.6	8.9	3.6
Total		42.7	22.0	9.3	4.0
All quantities are given in Gt CO_2					

Matching the *intermediate storage scenario $S2_{600km}$* with the identified emissions, a similar picture can be seen for the combination with *E2* and *E3* (Table S6) as for *$S1_{600km}$*. All captured emissions in these two pathways (9.3 and 4.0 Gt of CO_2) can be stored. Regarding pathway *E1*, the available storage capacity is insufficient for storing the entire amount of captured emissions. Hence 17.1 Gt of CO_2 is the matched capacity for *E1*.

Table S6. Source-sink match of effective storage scenario *$S2_{600km}$: intermediate* with coal development pathways *E1–E3* in South Africa (authors' calculation with data from [10]).

Basin	Formation	$S2_{600km}$: intermediate	E1: high (22.0)	E2: middle (9.3)	E3: low (4.0)
Zululand	Onshore basin	0.2	0.2	0.2	0.2
Durban & Zululand	Offshore basin	16.9	16.9	9.2	3.9
Total		17.1	17.1	9.3	4.0
All quantities are given in Gt CO_2					

In contrast to *$S1_{600km}$* and *$S2_{600km}$*, low storage scenario $S3_{600km}$ does not include onshore capacity; hence only 4.2 Gt of CO_2 is available in the offshore Durban & Zululand basin (**Table S7**). The total estimated emissions captured therefore exceed the storage space available for *E1* and *E2*. Thus the matched capacity for *$S3_{600km}$* equals the total storage capacity of 4.2 Gt of CO_2 in these two cases. For *E3*, it was possible to store the entire quantity of emissions of 4.0 Gt of CO_2.

Table S7. Source-sink match of effective storage scenario *$S3_{600km}$: low* with coal development pathways *E1–E3* in South Africa (authors' calculation with data from [10]).

Basin	Formation	*$S3_{600km}$: low*	*E1: high* (22.0)	*E2: middle* (9.3)	*E3: low* (4.0)
Zululand	Onshore basin	0.0	0.0	0.0	0.0
Durban & Zululand	Offshore basin	4.2	4.2	4.2	4.0
Total		4.2	4.2	4.2	4.0
All quantities are given in Gt CO_2					

ad Section 3.4. Environmental impacts of CCS-based power plants from a life cycle assessment perspective

Table S8. Parameters used in the LCA of future coal-fired power plants in South Africa.

Parameter	**Unit**	**PC power plant**	**IGCC power plant**
Coal-fired power plants without CCS			
Installed capacity	MW_{el}	600	451
Net efficiency	%	41.5	46.5
Plant load factor (PLF)	%	85	
	h/a	7,500	
Plant lifetime	a	25	
Type of cooling		Dry	
Net calorific value of coal	MJ_{th}/kg_{coal}	19.59	
Methane emissions from coal mining	kg CH_4/kg_{coal}	0.0012	
CO_2 emissions from coal	kg/MJ_{th}	0.0962	
CO_2 capture			
Type of capture process		Post-comb.	Pre-comb.
Concentration of solvent	kg/t of CO_2	1.958	0.011
Energy required for capture	kWh_{el}/t of CO_2	178	119
Energy required for compression	kWh_{el}/t of CO_2	92.84	
CO_2 capture rate	%	90	
CO_2 transportation and storage			
Average CO_2 transport distance	km	550	
Energy required for recompressor	kWh/tkm	0.011	
Energy required for CO_2 injection into 800 metre deep saline aquifer	kWh/kg CO_2	0.00668	

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