Appendix 3A: Levelized Cost of Electricity and Competition between Natural Gas and CCS

This appendix provides the details for calculating levelized cost of electricity (LCOE) and an illustrative calculation of a required carbon price to make carbon capture and storage (CCS) technology competitive. LCOE is the cost per kilowatt-hour (kWh) that over the life of the plant fully recovers operating, fuel, capital and financial costs. Figures in the table are at point of generation and transmission, and additional distribution cost is $0.02/kWh for all technologies except wind with backup for which the cost is $0.03/kWh. The cost numbers and heat rate for the Nth plant are taken from the U.S. DOE Energy Information Administration (EIA)[1], with a correction for the way the EPPA model represents wind and solar[2]. Estimates of CCS transmission and storage cost (line 24) are taken from Hamilton (2009)[3].

Table 3A.1 Details of Levelized Cost of Electricity (2005 cents/kWh)

	Units	Pulverized Coal	NGCC	NGCC with CCS	IGCC with CCS	Advanced Nuclear	Wind	Biomass	Solar Thermal	Solar PV	Wind Plus Biomass Backup [a]	Wind Plus Gas Backup [a]
[1] "Overnight" Capital Cost	$/kW	2049	892	1781	3481	3521	1812	3548	4731	5688	5360	2705
[2] Total Capital Requirement	$/kW	2377	964	1995	4177	4930	1957	4116	5109	6144	5789	2921
[3] Capital Recovery Charge Rate	%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
[4] Fixed O&M	$/kW	25.9	11.0	18.8	43.5	84.8	28.6	60.7	53.5	11.0	89.2	39.6
[5] Variable O&M	$/kWh	0.0043	0.0019	0.0028	0.0042	0.0005	0.0000	0.0063	0.0000	0.0000	0.0063	0.0019
[6] Project Life	years	20	20	20	20	20	20	20	20	20	20	20
[7] Capacity Factor	%	85%	85%	80%	80%	85%	35%	80%	35%	26%	42%	42%
[8] (Capacity Factor Wind)											35%	35%
[9] (Capacity Factor Biomass/NGCC)											7%	7%
[10] Operating Hours	hours	7446	7446	7008	7008	7446	3066	7008	3066	2277.6	3679.2	3679.2
[11] Capital Recovery Required	$/kWh	0.03	0.01	0.03	0.06	0.07	0.07	0.0621	0.1761	0.2850	0.1663	0.0839
[12] Fixed O&M Recovery Required	$/kWh	0.003	0.001	0.00	0.0062	0.01	0.01	0.01	0.02	0.00	0.02	0.01
[13] Heat Rate	Btu/kWh	8740	6333	7493	8307	10488	0	7765	0	0	7765	6333
[14] Fuel Cost	$/MMBtu	1.40	6.08	6.08	1.40	0.63	0.00	1.03	0.00	0.00	1.03	6.08
[15] (Fraction Biomass/NGCC)	%										8.8%	8.2%
[16] Fuel Cost per kWh	$/kWh	0.0122	0.0385	0.0456	0.0116	0.0066	0.0000	0.0080	0.0000	0.0000	0.0007	0.0032
[17] Levelized Cost of Electricity	**$/kWh**	**0.054**	**0.056**	**0.085**	**0.092**	**0.088**	**0.077**	**0.085**	**0.194**	**0.290**	**0.198**	**0.100**
[18] Markup Over Coal		**1.00**	**1.03**	**1.57**	**1.71**	**1.64**	**1.43**	**1.58**	**3.60**	**5.39**	**3.67**	**1.85**

For CCS

[19] Amount Fossil Fuel	EJ/KWh	9.221E-12	6.68E-12	7.905E-12	8.76E-12
[20] Carbon Content	MtC/EJ	24.686	13.700	13.700	24.686
[21] Carbon Emissions	MtC/KWh	2.276E-10	9.153E-11	1.083E-10	2.163E-10
[22] CO_2 Emissions	tCO_2/KWh	0.0008	0.0003	0.0004	0.0008
[23] CO_2 Emissions after 90% Capture	tCO_2/KWh			3.971E-05	7.93E-05
[24] Cost of CO_2 T&S	$/$tCO_2$			10	10
[25] CO_2 Transportation & Storage Cost	$/KWh			0.0036	0.0071

[a] A combined wind and biomass plant (or wind and natural gas plant) assumes that there is 1 KW installed capacity of biomass (or natural gas) for every 1 KW installed capacity of wind, and assumes the wind plant has a capacity factor of 35% and the biomass (or natural gas) plant has a capacity factor of 7%, operating only as needed to eliminate the variability of the wind resource.

[1] Input, from EIA 2010

[2] [1]+([1]*0.4*y) where y=construction time in years: coal=4, NGCC=2, IGCC with CCS=5, NGCC with CCS=3, nuclear=5, wind=2, biomass=4, solar=2, wind with biomass=2, wind with NGCC=2. For nuclear there is additional cost of ([1]*0.2) for the decommission cost.

[3] =r/(1-(1+r)^(-[6])) where r is discount rate. The discount rate is 8.5%.

[4] Input, from EIA 2010

[5] Input, from EIA 2010

[6] Input, assumption

[7] Input, standard assumptions

[8] Input, assumption

[9] Input, assumption

[10] =8760*[7] (8760 is the number of hours in a year)

[11] =([2]*[3])/[10]

[12] =[4]/[10]

[13] Input, from EIA 2010

[14] Input, from EIA data, 5-year average price from 2002-2006

[15] =[9]/80% for wind plus biomass; =[9]/85% for wind plus NGCC

[16] =[13]*[14]/1000000; for wind with backup =([13]*[14]/1000000)*[15]

[17] =[5]+[11]+[12]+[16]; for CCS technologies this also includes CO_2 T&S costs from [25]

[18] =[17]/([17] for coal)

[19] =[13]*(1.055*10^-15)

[20] Input, from EPPA model

[21] =[19]*[20]

[22] =[21]*(44/12)*1000000

[23] =[22]*(1-0.9), assuming 90% capture

[24] Input, from Hamilton (2009)

[25] =([22]-[23])*[24]

Table 3A.1 can also be used for calculating a carbon price that is required to make CCS technology competitive. The resulting price is driven by a relative difference in LCOE and carbon emissions. Current designs for a CCS technology envision 90% carbon capture, leaving 10% of CO_2 emitted. Based on information provided in Table 3A.1, a difference between LCOE for pulverized coal and coal with CCS is 0.038$/kWh. Considering the coal carbon content of 24.686 MtC/EJ, a pulverized coal technology emits 0.835kg CO_2 per kWh (shown in row 22), while coal with CCS emits 0.079 kg CO_2 per kWh (shown in row 23). Therefore, it costs 0.038$/kWh to avoid 0.755kg CO_2 per kWh. Converting this last result to a cost per ton of CO_2 leads to a required carbon price of 50.79$/t$CO_2$ to make coal with CCS competitive with pulverized coal technology.

Applying the fuel prices in Table 3A.1 (line 14) the required carbon price increases if CCS has to compete with natural gas-based electricity instead of coal-based electricity. In this case, NGCC emissions are 0.3356 kg CO_2 per kWh, while gas with CCS emits 0.0397 kg CO_2 per kWh. Considering the difference in LCOE for these technologies of 0.037$/kWh, a carbon price of 98.40$/t$CO_2$ is required to make natural gas with CCS economic when it competes with NGCC technology. A similar calculation results in a carbon price of 142.77/tCO_2 that is required when coal with CCS competes with NGCC. These simple calculations illustrate that a higher carbon price is needed to justify CCS when electricity is based on natural gas in comparison to a coal-based electricity. Figure 3A.1 shows LCOE for coal and natural gas technologies with and without CCS for different carbon prices.

Figure 3A.1 Levelized Cost of Electricity at Different Carbon Prices

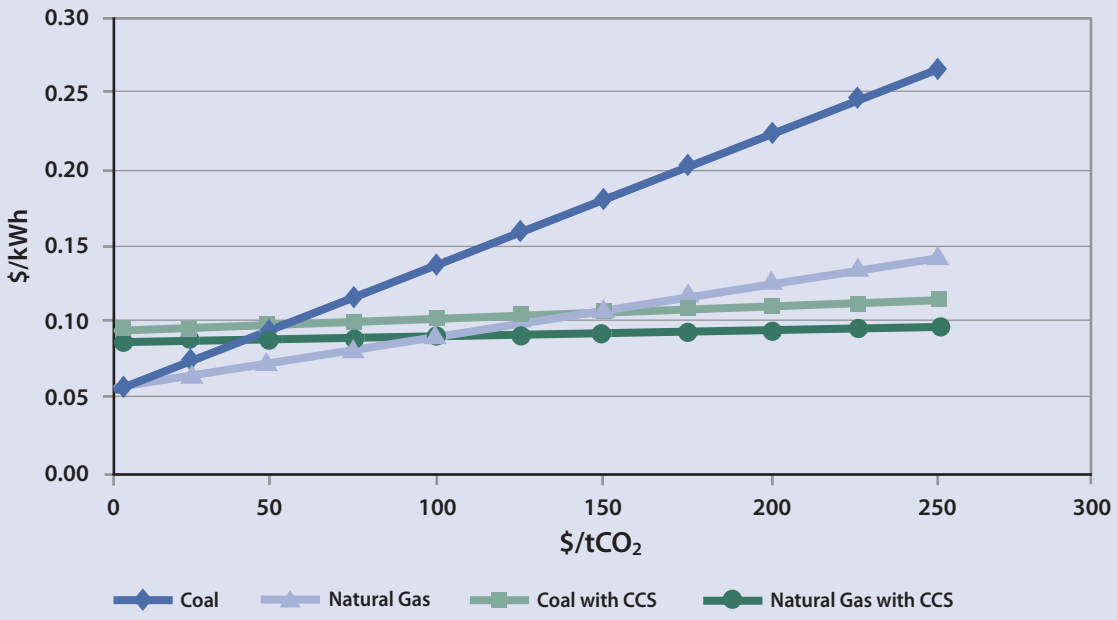

Figure 3A.2 Least-Cost Generation Technology Zones for Coal and Natural Gas with and without CCS for Different Natural Gas Prices and Carbon Prices

Gas Price $/MMBtu									
12	coal	coal	coal	coal_CCS	coal_CCS	coal_CCS	coal_CCS	coal_CCS	coal_CCS
10	coal	coal	coal	coal_CCS	coal_CCS	coal_CCS	coal_CCS	coal_CCS	coal_CCS
8	coal	coal	gas	gas	coal_CCS	coal_CCS	coal_CCS	gas_CCS	gas_CCS
6	coal	gas	gas	gas	gas_CCS	gas_CCS	gas_CCS	gas_CCS	gas_CCS
4	gas	gas	gas	gas	gas_CCS	gas_CCS	gas_CCS	gas_CCS	gas_CCS
2	gas	gas	gas	gas	gas_CCS	gas_CCS	gas_CCS	gas_CCS	gas_CCS
	0	25	50	75	100	125	150	175	200
	Carbon Price $/tCO2								

Estimates of the heat rates for CCS technologies have a wide range. For example, assuming the heat rates from Hamilton (2009) instead of EIA (2010), the required carbon prices are 63.48$/$tCO_2$ a coal with CCS vs. coal competition and 196.80$/$tCO_2$ for a coal with CCS vs. natural gas competition.

Similar recalculations of the required carbon prices can be done for alternative fuel prices. Figure 3A.2 shows the zones of the least cost generation for coal and natural gas with and without CCS for a range of different natural gas and carbon prices and assuming the coal price fixed at the level shown in Table 3A.1 (line 14). Based on the costs of coal, capital, and labor in Table 3A.1, natural gas with CCS becomes economic at the prices of higher than 100$/$tCO_2$ for a range $2–6$/MMBtu natural gas prices. At the higher natural gas prices, coal with CCS becomes economic. A similar comparison has been developed by personnel at ExxonMobil.[4]

In the projections reported in Chapter 3, the EPPA model endogenously determines the prices for capital, labor, energy and other intermediate inputs. The relative economics of CCS is therefore changing over time based on a change in prices. CCS penetration in the model is also influenced by an additional factor that is used to limit the penetration rate of a new technology. This penetration-limiting factor allows economic rents to accrue to economic agents with knowledge to build a technology when it is still new and when there is no widespread technical knowledge to build cheaply at large scale. Initially, it leads to higher costs to represent first of the kind plants. As cumulative production increases (and experience is gained), the costs gradually decrease to the Nth plant cost.

NOTES

[1] The EIA source is the U.S. Energy Administration *Assumptions to the Annual Energy Outlook, 2010 Early Release*. The EIA presents costs in $2008, which are converted here to $2005 (by a factor of 0.9218 using data from the U.S. Bureau of Economic Analysis (http://www.bea.gov)).

[2] The EIA wind and solar costs shown in the table are for a typical plant. In the EPPA model wind and solar are distinguished by scale. At low penetration levels they enter as imperfect substitutes for conventional electricity generation. The LCOE for wind without backup is reduced to $0.06/kWh in this study to reflect higher quality wind resources. Through the elasticity of substitution the model imposes a gradually increasing cost of production. The extension of wind capacity into lower quality resources is represented by wind plus biomass or NGCC backup technologies. The model does not distinguish between solar thermal and solar PV and the LCOE of $0.19/kWh is applied.

[3] Hamilton, M.R., 2009. An Analytical Framework for Long-Term Commercial Deployment and Innovation in Carbon Capture and Sequestration Technology in the United States, Master of Science Thesis, Technology and Policy Program, Massachusetts Institute of Technology.

[4] Kheshgi, H.S., N.A. Bhore, R.B. Hirsch, M.E. Parker, G.F. Teletzke and H. Thomann, 2010. Perspectives on CCS Cost and Economics, presented to Society of Petroleum Engineers, International Conference on CO_2 Capture, Storage and Utilization (SPE 139716) New Orleans, LA.

Appendix 3B: Details of Simulation Results

No Policy								
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Economy Wide Indicators								
Population (million)	326	341	357	373	390	406	422	439
GDP (trillion 2005$)	15	17	19	22	25	28	32	36
% Change GDP from Reference	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GDP per capita (thousand 2005$)	45	49	53	58	63	69	76	83
Welfare (trillion 2005$)	10	11	13	15	17	19	21	24
% Change Welfare from Reference (EV)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO_2-E Price (2005$/t$CO_2$-e)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Prices (2005$)								
Exclusive of Carbon Charge								
Oil Product ($/barrel)	75.70	84.10	94.32	106.29	118.08	127.05	137.31	148.16
Natural Gas ($/thousand cubic feet)	6.39	6.86	7.40	8.05	8.63	9.16	9.76	10.37
Coal ($/short ton)	24.77	26.41	28.25	30.50	32.79	34.87	37.06	39.41
Inclusive of Carbon Charge								
Oil Product ($/barrel)	75.70	84.10	94.32	106.29	118.08	127.05	137.31	148.16
Natural Gas ($/thousand cubic feet)	6.39	6.86	7.40	8.05	8.63	9.16	9.76	10.37
Coal ($/short ton)	24.77	26.41	28.25	30.50	32.79	34.87	37.06	39.41
Electricity ($/kWh)	0.10	0.11	0.12	0.12	0.13	0.13	0.14	0.14
GHG Emissions (mmt CO_2-e)								
GHG Emissions	7282.3	7543.5	7820.8	8179.7	8571.1	8956.1	9340.2	9754.9
CO_2 Emissions	6252.2	6488.5	6726.2	7042.8	7378.8	7706.1	8028.8	8363.1
CH_4 Emissions	520.8	528.1	538.5	552.5	571.7	589.2	607.4	631.0
N_2O Emissions	386.1	393.5	402.6	413.6	435.5	459.3	484.3	520.3
Fluorinated Gases Emissions	123.3	133.4	153.5	170.8	185.1	201.6	219.6	240.5
Primary Energy Use (qBtu)								
Coal	21.3	22.5	23.7	25.2	26.9	28.4	29.9	31.5
Oil	41.4	42.2	43.1	44.4	45.8	47.2	48.6	50.1
Natural Gas	24.0	25.2	26.3	27.8	29.4	30.8	32.3	33.8
Nuclear (primary energy eq)	7.7	7.9	8.0	8.2	8.4	8.6	8.9	9.1
Hydro (primary energy eq)	2.5	2.5	2.4	2.3	2.3	2.3	2.4	2.5
Renewable Elec. (primary energy eq)	3.2	3.4	3.6	3.8	4.1	4.4	4.7	5.0
Biomass Liquids	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Primary Energy Use	100.1	103.6	107.1	111.7	116.7	121.7	126.7	132.0
Reduced Use from Reference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Electricity Production (TkWh)								
Coal w/o CCS	2.2	2.3	2.5	2.7	2.9	3.1	3.3	3.6
Oil w/o CCS	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Natural Gas w/o CCS	0.6	0.7	0.7	0.7	0.8	0.8	0.9	1.0
Nuclear	0.8	0.8	0.9	0.9	0.9	0.9	1.0	1.0
Hydro	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.3
Renewables	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5
Natural Gas with CCS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal with CCS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Electricity Production	4.4	4.6	4.8	5.1	5.4	5.8	6.1	6.5

Price Policy								
	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Economy Wide Indicators								
Population (million)	326	341	357	373	390	406	422	439
GDP (trillion 2005$)	15	17	19	21	24	27	31	35
% Change GDP from Reference	-0.49	-0.82	-1.20	-1.66	-2.06	-2.43	-2.88	-3.45
GDP per capita (thousand 2005$)	45	48	52	57	62	68	74	80
Welfare (trillion 2005$)	10	11	13	14	16	19	21	24
% Change Welfare from Reference (EV)	-0.18	-0.42	-0.72	-1.10	-1.51	-1.90	-2.41	-3.04
CO_2-E Price (2005$/t$CO_2$-e)	34.00	53.59	76.98	105.51	135.62	156.62	178.11	238.40
Prices (2005$)								
Exclusive of Carbon Charge								
Oil Product ($/barrel)	74.29	81.64	89.17	97.97	104.85	107.32	109.65	113.42
Natural Gas ($/thousand cubic feet)	6.15	6.51	6.91	7.51	8.23	8.61	8.99	8.77
Coal ($/short ton)	22.14	21.96	20.93	19.64	17.92	17.70	17.83	18.95
Inclusive of Carbon Charge								
Oil Product ($/barrel)	89.65	105.86	123.95	145.65	166.12	178.09	190.13	221.14
Natural Gas ($/thousand cubic feet)	8.03	9.47	11.16	13.33	15.71	17.25	18.82	21.93
Coal ($/short ton)	91.77	131.71	178.61	235.74	295.68	338.48	382.62	507.23
Electricity ($/kWh)	0.13	0.15	0.17	0.19	0.21	0.22	0.24	0.26
GHG Emissions (mmt CO_2-e)								
GHG Emissions	5797.3	5457.5	5117.0	4776.5	4436.1	4095.5	3754.8	3413.4
CO_2 Emissions	5197.3	4866.6	4534.9	4211.5	3888.9	3553.7	3216.0	2870.4
CH_4 Emissions	319.7	313.4	306.7	291.1	270.7	270.4	272.1	271.6
N_2O Emissions	274.5	271.9	270.0	268.4	271.5	266.5	262.0	266.7
Fluorinated Gases Emissions	5.9	5.6	5.4	5.5	5.0	4.9	4.8	4.7
Primary Energy Use (qBtu)								
Coal	15.1	12.3	9.2	5.4	0.7	0.4	0.6	0.8
Oil	37.0	35.9	34.9	33.8	32.3	24.3	16.2	13.0
Natural Gas	21.2	21.5	22.1	24.5	29.0	28.7	27.7	23.8
Nuclear (primary energy eq)	8.1	8.3	8.6	9.1	9.5	10.3	11.8	16.0
Hydro (primary energy eq)	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.7
Renewable Elec. (primary energy eq)	3.6	4.0	4.4	4.9	5.2	5.4	5.7	6.2
Biomass Liquids	0.0	0.0	0.0	0.0	0.1	4.1	8.2	9.5
Total Primary Energy Use	87.9	85.0	82.4	80.9	80.1	76.6	73.6	72.9
Reduced Use from Reference	12.2	18.6	24.7	30.8	36.5	45.1	53.1	59.0
Electricity Production (TkWh)								
Coal w/o CCS	1.6	1.5	1.2	0.7	0.0	0.0	0.0	0.0
Oil w/o CCS	0.2	0.2	0.2	0.1	0.0	0.0	0.0	0.0
Natural Gas w/o CCS	0.6	0.8	1.0	1.5	2.3	2.3	2.2	1.7
Nuclear	0.9	0.9	0.9	1.0	1.0	1.1	1.3	1.7
Hydro	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
Renewables	0.4	0.4	0.5	0.5	0.6	0.6	0.6	0.7
Natural Gas with CCS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal with CCS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Electricity Production	4.0	4.1	4.1	4.1	4.2	4.4	4.5	4.5

Regulatory Policy								
	2015	2020	2025	2030	2035	2040	2045	2050
Economy Wide Indicators								
Population (million)	326	341	357	373	390	406	422	439
GDP (trillion 2005$)	15	17	19	21	24	28	32	36
% Change GDP from Reference	-0.01	-0.26	-0.53	-0.74	-0.87	-0.99	-1.04	-1.05
GDP per capita (thousand 2005$)	45	49	52	57	63	69	75	82
Welfare (trillion 2005$)	10	11	13	14	16	19	21	24
% Change Welfare from Reference (EV)	0.03	-0.14	-0.38	-0.61	-0.78	-0.91	-1.00	-1.04
CO_2-E Price (2005$/t$CO_2$-e)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Prices (2005$)								
Exclusive of Carbon Charge								
Oil Product ($/barrel)	75.31	83.00	92.02	102.64	112.83	119.76	127.44	135.13
Natural Gas ($/thousand cubic feet)	6.34	6.74	7.20	7.83	8.43	9.03	9.67	10.69
Coal ($/short ton)	22.80	22.08	21.98	22.18	22.45	22.62	22.89	23.16
Inclusive of Carbon Charge								
Oil Product ($/barrel)	75.31	83.00	92.02	102.64	112.83	119.76	127.44	135.13
Natural Gas ($/thousand cubic feet)	6.34	6.74	7.20	7.83	8.43	9.03	9.67	10.69
Coal ($/short ton)	22.80	22.08	21.98	22.18	22.45	22.62	22.89	23.16
Electricity ($/kWh)	0.11	0.14	0.17	0.19	0.19	0.20	0.21	0.21
GHG Emissions (mmt CO_2-e)								
GHG Emissions	6831.3	6515.2	6424.3	6476.8	6654.6	6870.6	7143.4	7466.9
CO_2 Emissions	5810.8	5484.8	5362.0	5376.6	5500.6	5663.9	5871.4	6120.0
CH_4 Emissions	512.9	508.9	513.0	522.6	540.3	554.4	573.1	591.2
N_2O Emissions	384.9	389.8	398.2	409.7	432.2	455.0	484.1	520.5
Fluorinated Gases Emissions	122.7	131.7	151.2	167.9	181.5	197.3	214.9	235.3
Primary Energy Use (qBtu)								
Coal	16.7	12.6	10.3	8.6	7.6	7.1	7.3	7.4
Oil	41.4	41.9	42.7	44.2	45.8	47.6	49.4	51.4
Natural Gas	23.9	24.6	25.2	26.6	28.6	30.2	31.2	33.1
Nuclear (primary energy eq)	7.9	8.3	8.6	9.1	9.2	9.4	9.8	9.9
Hydro (primary energy eq)	2.7	3.0	3.1	3.2	3.3	3.3	3.4	3.5
Renewable Elec. (primary energy eq)	4.4	6.7	8.5	10.0	11.0	11.9	12.7	12.4
Biomass Liquids	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Primary Energy Use	97.1	97.1	98.5	101.7	105.4	109.5	113.9	117.8
Reduced Use from Reference	3.0	6.5	8.6	10.0	11.3	12.1	12.8	14.1
Electricity Production (TkWh)								
Coal w/o CCS	1.9	1.5	1.3	1.1	1.0	0.9	0.9	0.9
Oil w/o CCS	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
Natural Gas w/o CCS	0.7	0.7	0.7	0.9	1.1	1.3	1.4	1.6
Nuclear	0.9	0.9	0.9	1.0	1.0	1.0	1.1	1.1
Hydro	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
Renewables	0.5	0.7	0.9	1.1	1.2	1.3	1.4	1.3
Natural Gas with CCS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal with CCS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Electricity Production	4.3	4.3	4.4	4.6	4.9	5.1	5.4	5.6

NOTES

Changes in Welfare are measured as equivalent variation (EV).

Oil numbers in primary energy use include the current generation biofuels (ethanol, biodiesel).

Biomass liquids refer to the second generation biofuels.

In Price Policy scenario, Natural Gas with CCS and Coal with CCS enter in 2045–2050 and produce 0.01–0.03 TkWh of electricity. See text of Chapter 3 for a sensitivity test with less costly CCS assumptions.