Update Electricity Generation Assumptions (Proposal 210)
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Objective

Update the assumptions pertaining to the electricity generation sector in GCAM 4.0 and resolve issues related to sudden variations in demand due to sudden technology adoption or price variations.

Background

GCAM currently includes 22 technologies competing for the generation of electricity. The competition is based on a logit-share algorithm comparing levelized electricity generation cost (COE, in $/MWh), currently computed as:

$$COE = \underbrace{\frac{C_f}{\eta}}_{\text{Fuel Cost}} + \underbrace{\frac{1000 \cdot C_I}{8766 \cdot CF} \cdot i}_{\text{Capital cost}} + \underbrace{\frac{C_{O\&Mfix}}{8766 \cdot CF} + C_{O\&Mvar}}_{\text{O\&M Costs}}$$

where:
C_f is the fuel cost, expressed in $/MWh;
η is the power plan efficiency;
C_I is the investment cost, expressed in $/kW
CF is the capacity factor, namely the ratio of operating hours out of the total 8766 hours in a year;
i is the fixed charge rate;
$C_{O\&M\ fix}$ is the annual fixed O&M cost, expressed in $/MW per year; and
$C_{O\&M\ var}$ is the variable O&M cost, expressed in $/MWh.

For each technology a set of parameters are assumed for each simulated time-step: fixed charge rate, capacity factor, lifetime, capital cost, fixed and variable O&M costs, energy conversion efficiency, and CO_2 capture efficiency. Moreover, intermittent sources include an added cost for backup when their market share exceeds 25% of the total market.

Motivation

The electricity generation sector has last been updated in 2008. Since then significant changes affected the costs of electricity-generating technologies. In particular, a significant cost increase is noted in general for capital-intense projects; IGCC technologies are now estimated to be significantly more expensive than they used to be in 2008; use of biomass for electricity production is reported to be much less efficient and more costly; and PV systems experienced a significant cost reduction.

Approach

A decision has been made to review the current assumption without changing the modeling structure, even if some possible improvements are suggested at the end of this proposal. Two technologies are introduced: pulverized coal plant and conventional biomass plant, both with post combustion CCS. A complete review of the assumptions in the electricity generation sector has been made based on relevant literature published in the last two years. First, we review GCAM assumptions for 2015.

Table 1. Fixed Charge Rates.

TECHNOLOGY	Currently in GCAM	Revised Assumptions
coal (conv pul)	0.15	0.13
coal (conv pul CCS)	-	0.13
coal (IGCC)	0.15	0.13
coal (IGCC CCS)	0.15	0.13
gas (steam/CT)	0.15	0.13
gas (CC)	0.15	0.13
gas (CC CCS)	0.15	0.13
refined liquids (steam/CT)	0.15	0.13
refined liquids (**CC**)	0.15	0.13
refined liquids (**CC** CCS)	0.15	0.13
biomass (conv)	0.15	0.13
biomass (conv CCS)	-	0.13
biomass (IGCC)	0.15	0.13
biomass (IGCC CCS)	0.15	0.13
Gen_II_LWR	0.15	0.13
Gen_III	0.15	0.13
wind (on-shore)	0.125	0.13
wind_storage	0.125	0.13
PV	0.125	0.13
PV_storage	0.125	0.13
CSP	0.125	0.13
CSP_storage	0.125	0.13
geothermal	0.125	0.13
rooftop_pv	0.1	**0.10**

Main literature sources:
Iyer *et al.* "Improved representation of investment decisions in assessments of CO_2 mitigation." *Nature Climate Change* (2015).

DISCUSSION POINT:
Charge/Discount rate: GCAM currently uses a fixed charge rate approach that is currently set to be 15% for fossil-fuel and nuclear plants, 12.5% for renewable sources, and 10% for residential rooftop PVs.
Such an approach does not consider the lifetime of specific technologies, which a tradition discount rate would consider.

$$COE = \underbrace{\frac{C_f}{\eta}}_{\text{Fuel Cost}} + \underbrace{\frac{1000 \cdot C_I}{8766 \cdot CF} \cdot \frac{i}{1 - \frac{1}{(1+i)^{PL}}}}_{\text{Capital cost}} + \underbrace{\frac{C_{O\&Mfix}}{8766 \cdot CF} + C_{O\&Mvar}}_{\text{O\&M Costs}}$$

<u>Decision</u>: **<u>fix charge</u>** rate Vs. discount rate. The numerical difference is minimal.

Table 2. Capacity Factors.

TECHNOLOGY	Currently in GCAM capacity.factor	Revised Assumptions capacity.factor
coal (conv pul)	0.8	0.85
coal (conv pul CCS)	-	0.8
coal (IGCC)	0.8	0.8
coal (IGCC CCS)	0.8	0.8
gas (steam/CT)*	0.8	0.85
gas (CC)	0.8	0.85
gas (CC CCS)	0.8	0.8
refined liquids (steam/CT)*	0.8	0.85
refined liquids (CC)	0.8	0.85
refined liquids (CC CCS)	0.8	0.8
biomass (conv)	0.8	0.85
biomass (conv CCS)	-	0.8
biomass (IGCC)	0.8	0.8
biomass (IGCC CCS)	0.8	0.8
Gen_II_LWR	0.9	0.9
Gen_III	0.9	0.9
wind (on-shore)	SC	SC
wind_storage	SC	SC
PV	0.25	**0.2 +SC**
PV_storage	0.25	**0.2 + SC**
CSP	0.31	**0.25 + SC**
CSP_storage	0.73	**0.65**
geothermal	0.9	0.9
rooftop_pv	0.25	**0.2 + SC**

*Note that we are assuming a higher capacity factor than typically realized in practice for combustion turbines here as we do not have demand segments separated in this version of GCAM. Instead, we are modeling an average annual electricity demand, and a lower capacity factor assumption would distort the relative economics of these plants unfairly.

Main literature sources:
Transparent Cost Database (http://en.openei.org/apps/TCDB/): including DOE, Black and Veatch, and Lazard estimates.

Table 3. Lifetime.

TECHNOLOGY	Currently in GCAM years	Revised Assumptions years
coal (conv pul)	60	60
coal (conv pul CCS)	-	60
coal (IGCC)	60	60
coal (IGCC CCS)	60	60
gas (steam/CT)	45	45
gas (CC)	45	45
gas (CC CCS)	45	45
refined liquids (steam/CT)	45	45
refined liquids (CC)	45	45
refined liquids (CC CCS)	45	45
biomass (conv)	60	60
biomass (conv CCS)	-	60
biomass (IGCC)	60	60
biomass (IGCC CCS)	60	60
Gen_II_LWR	60	60
Gen_III	60	60
wind (on-shore)	30	30
wind_storage	30	30
PV	30	30
PV_storage	30	30
CSP	30	30
CSP_storage	30	30
geothermal	30	30
rooftop_pv	30	30

Main literature sources:
Transparent Cost Database (http://en.openei.org/apps/TCDB/): including DOE, Black and Veatch, and Lazard estimates.

Table 4. Capital Cost, 2020. In 2010$.

TECHNOLOGY	Currently in GCAM $/kW	Revised Assumptions $/kW	DIFFERENCE
coal (conv pul)	1616	2900	79.46%
coal (conv pul CCS)	-	5800	
coal (IGCC)	1873	4000	113.52%
coal (IGCC CCS)	2470	6600	167.25%
gas (steam/CT)	531	750	41.23%
gas (CC)	759	1050	38.32%
gas (CC CCS)	1179	2100	78.05%
refined liquids (steam/CT)	531	750	41.23%
refined liquids (CC)	1684	1050	-37.66%
refined liquids (CC CCS)	2414	2499	3.52%
biomass (conv)	1665	4000	140.26%
biomass (conv CCS)	-	6443	
biomass (IGCC)	1929	6000	211.08%
biomass (IGCC CCS)	2486	8190	229.48%
Gen_II_LWR	2020	2020	0.00%
Gen_III	2202	5500	149.72%
wind (on-shore)	1192	2000	67.72%
wind_storage	2694	5300	96.70%
PV	6220	3000	-51.77%
PV_storage	7722	6300	-18.41%
CSP	3242	4800	48.07%
CSP_storage	6487	8000	23.33%
Geothermal*	1580	5200	229.08%
rooftop_pv	9116	4700	-48.44%

* $800/kW of this cost is already included in the supply curve

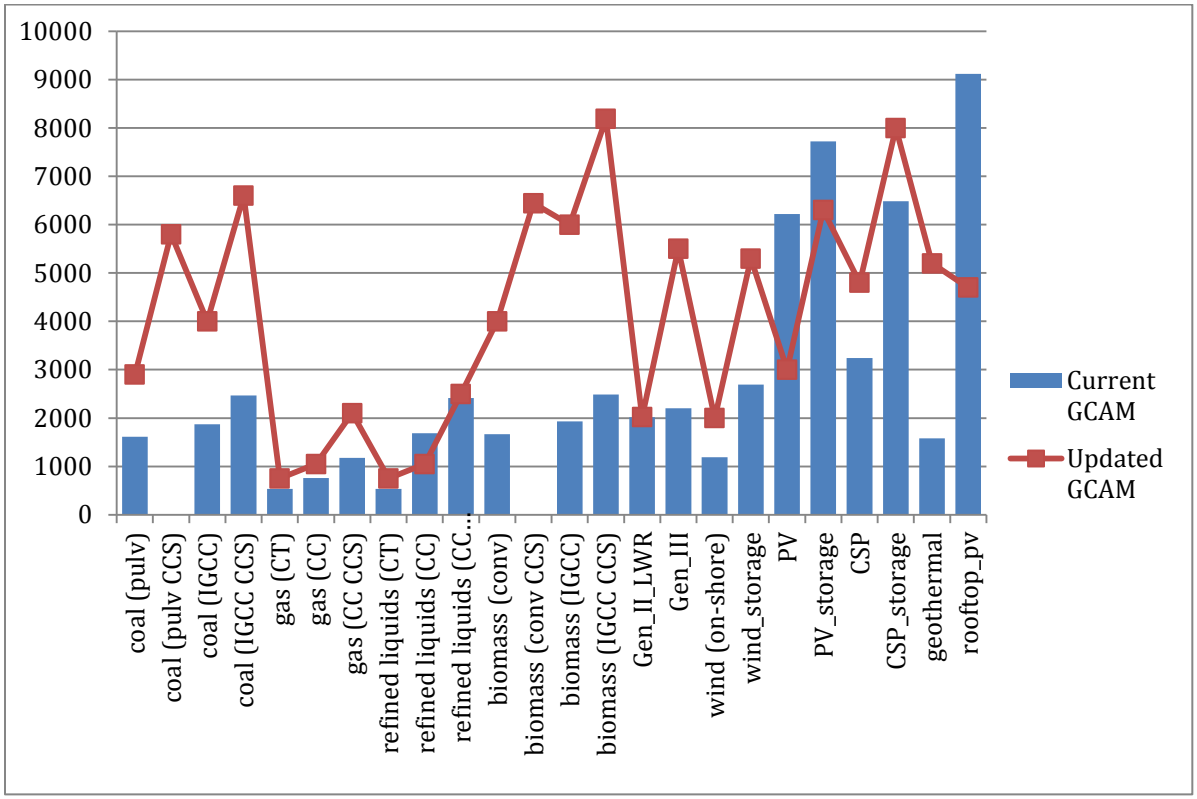
Main literature sources:

B&V: Black and Veatch for U.S. Department of Energy - National Renewable Energy Laboratory, *Cost and Performance Data for Power Generation Technologies*, 2012.

EIA: U.S. Department of Energy - Energy Information Administration, *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants*, 2013.

IRENA: International Renewable Energy Agency (IRENA), Concentrating Solar Power - Technology Brief, 2013.

U.S. DOE: *Photovoltaic System Pricing Trends. Historical, Recent, and Near-Term Projections.* 2014 Edition (http://www.nrel.gov/docs/fy14osti/62558.pdf)


10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
coal (pulv)
coal (pulv CCS)
coal (IGCC)
coal (IGCC CCS)
gas (CT)
gas (CC)
gas (CC CCS)
refined liquids (CT)
refined liquids (CC)
refined liquids (CC...
biomass (conv)
biomass (conv CCS)
biomass (IGCC)
biomass (IGCC CCS)
Gen_II_LWR
Gen_III
wind (on-shore)
wind_storage
PV
PV_storage
CSP
CSP_storage
geothermal
rooftop_pv
Current GCAM
Updated GCAM

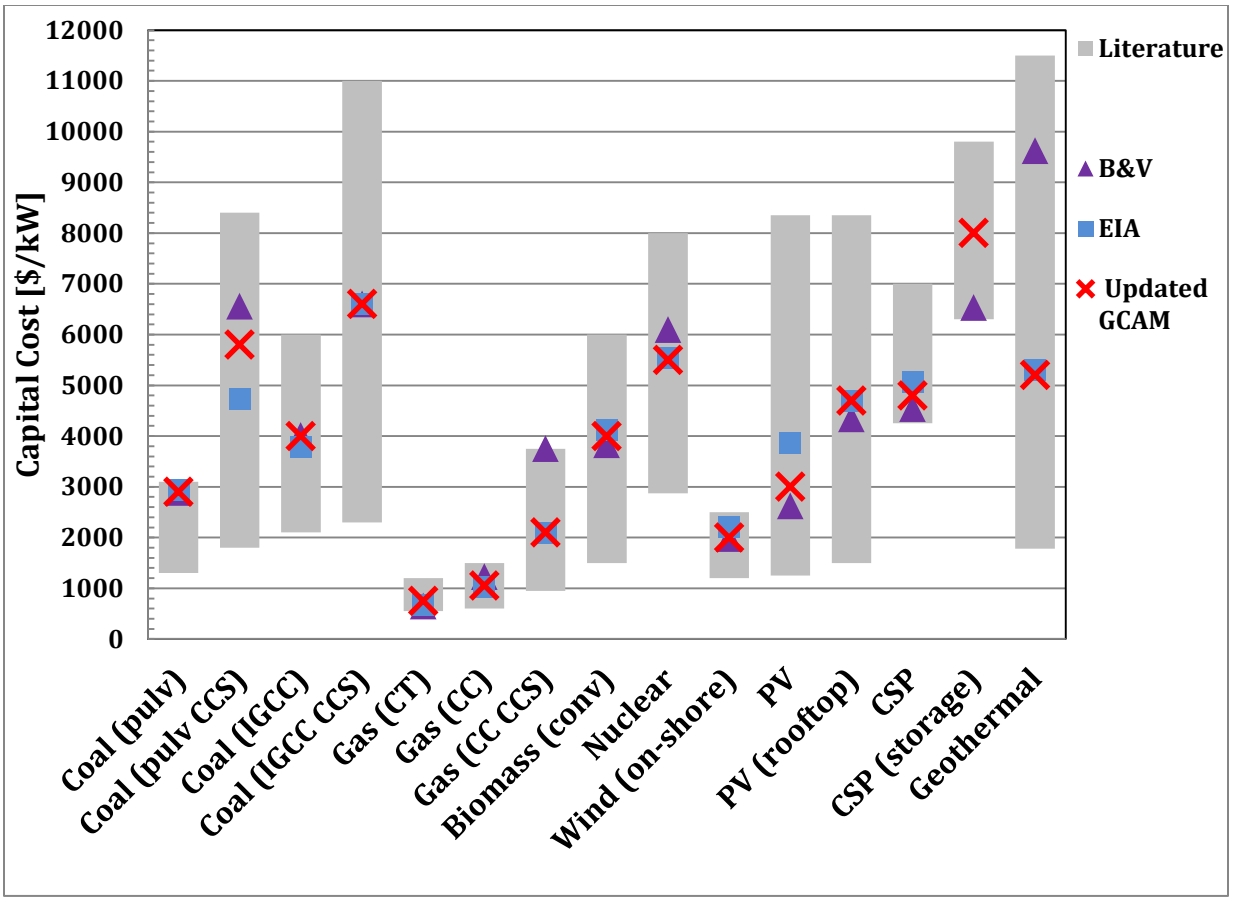


Table 5. O&M costs.

TECHNOLOGY	Currently in GCAM $/kW/year	Revised Assumptions $/kW/year	DIFFERENCE
coal (conv pul)	28.77	25	-13.10%
coal (conv pul CCS)	-	50	-
coal (IGCC)	40.40	35	-13.37%
coal (IGCC CCS)	46.33	70	51.09%
gas (steam/CT)	12.22	6	-50.89%
gas (CC)	12.64	10	-20.89%
gas (CC CCS)	13.98	20	43.09%
refined liquids (steam/CT)	12.22	6	-50.89%
refined liquids (CC)	36.36	10	-72.50%
refined liquids (CC CCS)	39.16	24	-39.22%
biomass (conv)	29.62	95	220.77%
biomass (conv CCS)	-	116	-
biomass (IGCC)	41.61	140	741.24%
biomass (IGCC CCS)	46.69	170	756.75%
Gen_II_LWR	71.74	105	46.36%
Gen_III	70.93	95	33.94%
wind (on-shore)	12.22	50	309.24%
wind_storage	28.12	60	113.39%

PV	29.09	40	37.48%
PV_storage	52.88	48	-9.23%
CSP	50.24	55	9.48%
CSP_storage	50.24	65	29.38%
geothermal	71.38	100	40.09%
rooftop_pv	73.27	60	-18.12%

TECHNOLOGY	Currently in GCAM $/kWh	Revised Assumptions $/kWh	DIFFERENCE
coal (conv pul)	4.79	4	-16.48%
coal (conv pul CCS)	-	8	-
coal (IGCC)	3.06	6.5	112.24%
coal (IGCC CCS)	5.60	10	78.45%
gas (steam/CT)	3.65	10	174.05%
gas (CC)	2.12	3.5	65.27%
gas (CC CCS)	2.70	7	158.86%
refined liquids (steam/CT)	3.65	10	174.05%
refined liquids (CC)	2.74	3.5	27.89%
refined liquids (CC CCS)	3.94	8	111.33%
biomass (conv)	4.85	10	105.99%
biomass (conv CCS)	-	13.4	-
biomass (IGCC)	3.10	15	384.63%
biomass (IGCC CCS)	5.28	18	337.22%
Gen_II_LWR	0.16	2.2	1250.50%
Gen_III	0.52	2	283.66%
wind (on-shore)	4.89	0	-100.00%
wind_storage	10.20	0	-100.00%
PV	0.00	0	0
PV_storage	0.00	0	0
CSP	0.00	0	0
CSP_storage	0.00	0	0
geothermal	0.00	0	0
rooftop_pv	0.00	0	0

Table 6. CO_2 sequestration efficiency.

	Currently in GCAM					
TECHNOLOGY	1971	2020	2035	2050	2065	2100
coal (IGCC CCS)	0.91	0.91	0.92	0.93	0.94	0.94
gas (CC CCS)	0.91	0.91	0.92	0.93	0.94	0.94
refined liquids (IGCC CCS)	0.91	0.91	0.92	0.93	0.94	0.94
biomass (IGCC CCS)	0.91	0.91	0.92	0.93	0.94	0.94

	Revised Assumptions					
TECHNOLOGY	**1971**	**2020**	**2035**	**2050**	**2065**	**2100**
coal (conv pul CCS)	0.85	0.85				0.95
coal (IGCC CCS)	0.85	0.85				0.95
gas (CC CCS)	0.85	0.85				0.95
refined liquids (IGCC CCS)	0.85	0.85				0.95
biomass (conv CCS)	0.85	0.85				0.95
biomass (IGCC CCS)	0.85	0.85				0.95

Table 7. HHV Efficiency.

TECHNOLOGY	Currently in GCAM	Revised Assumptions	DIFFERENCE
coal (conv pul)	0.37	0.38	1.4%
coal (conv pul CCS)	-	0.28	
coal (IGCC)	0.41	0.39	-4.4%
coal (IGCC CCS)	0.35	0.32	-8.3%
gas (steam/CT)	0.35	0.34	-1.9%
gas (CC)	0.50	0.52	4.0%
gas (CC CCS)	0.44	0.42	-5.2%
refined liquids (steam/CT)	0.36	0.34	-5.5%
refined liquids (CC)	0.40	0.52	30.2%
refined liquids (CC CCS)	0.34	0.39	14.8%
biomass (conv)	0.36	0.25	-30.3%
biomass (conv CCS)	-	0.18	
biomass (IGCC)	0.39	0.30	-23.2%
biomass (IGCC CCS)	0.34	0.25	-27.9%
Gen_II_LWR	0.33	0.33	0.0%
Gen_III	0.33	0.33	0.0%
wind (on-shore)	1.00	1.00	0.0%
wind_storage	0.96	0.96	0.0%
PV	1.00	1.00	0.0%

PV_storage	0.96	0.96	0.0%
CSP	1.00	1.00	0.0%
CSP_storage	1.00	1.00	0.0%
geothermal	0.10	0.10	0.0%
rooftop_pv	1.00	1.00	0.0%

Table 8. LCOE, in 2010$/kWh.

TECHNOLOGY	Cost of fuel [$/MWh]	Currently in GCAM	Revised Assumptions
coal (conv pul)	7.62	63	78
coal (conv pul CCS)	7.62	-	150
coal (IGCC)	7.62	67	105
coal (IGCC CCS)	7.62	86	166
gas (steam/CT)	20.53	70	85
gas (CC)	20.53	57	63
gas (CC CCS)	20.53	72	98
refined liquids (steam/CT)	40.58	122	144
refined liquids (CC)	40.58	139	101
refined liquids (CC CCS)	40.58	173	162
biomass (conv)	22.98	105	185
biomass (conv CCS)	22.98	-	274
biomass (IGCC)	22.98	106	223
biomass (IGCC CCS)	22.98	128	287
Gen_II_LWR	2.72	56	57
Gen_III	2.72	60	113
wind (on-shore)	0.00	62	98
wind_storage	0.00	140	237
PV	0.00	379	251
PV_storage	0.00	478	507

CSP	0.00	172	317
CSP_storage	0.00	138	199
geothermal	0.00	35	101
rooftop_pv	0.00	475	319

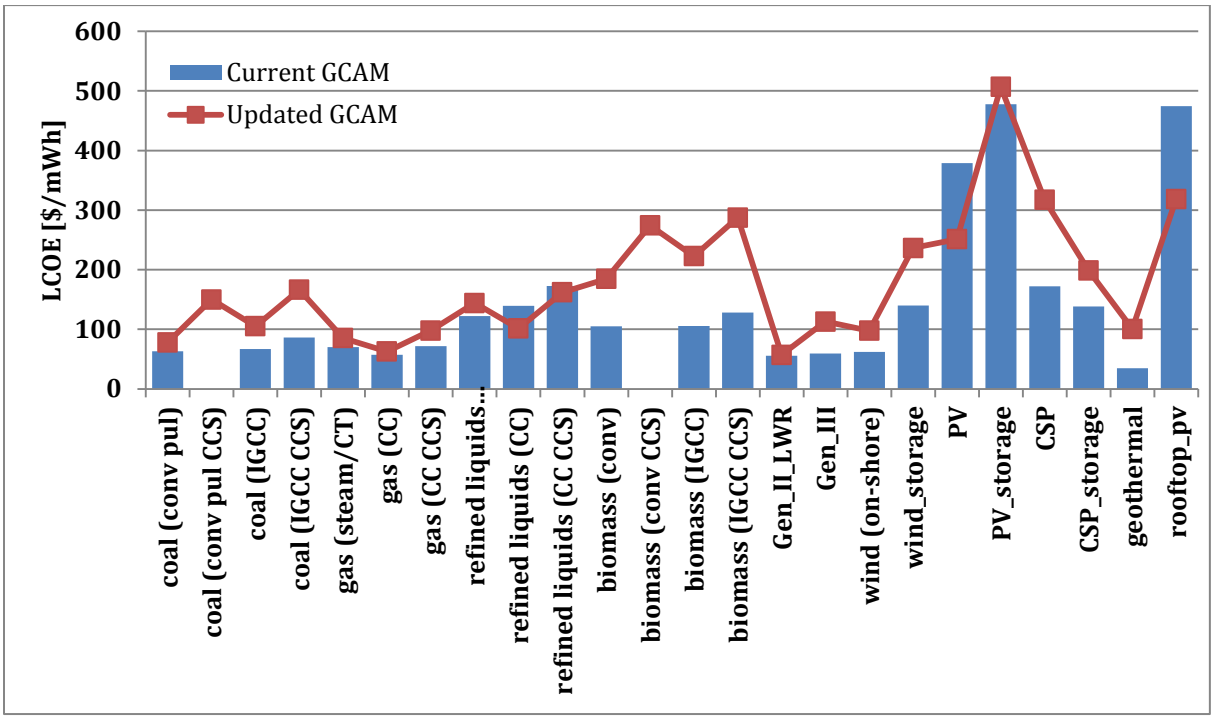
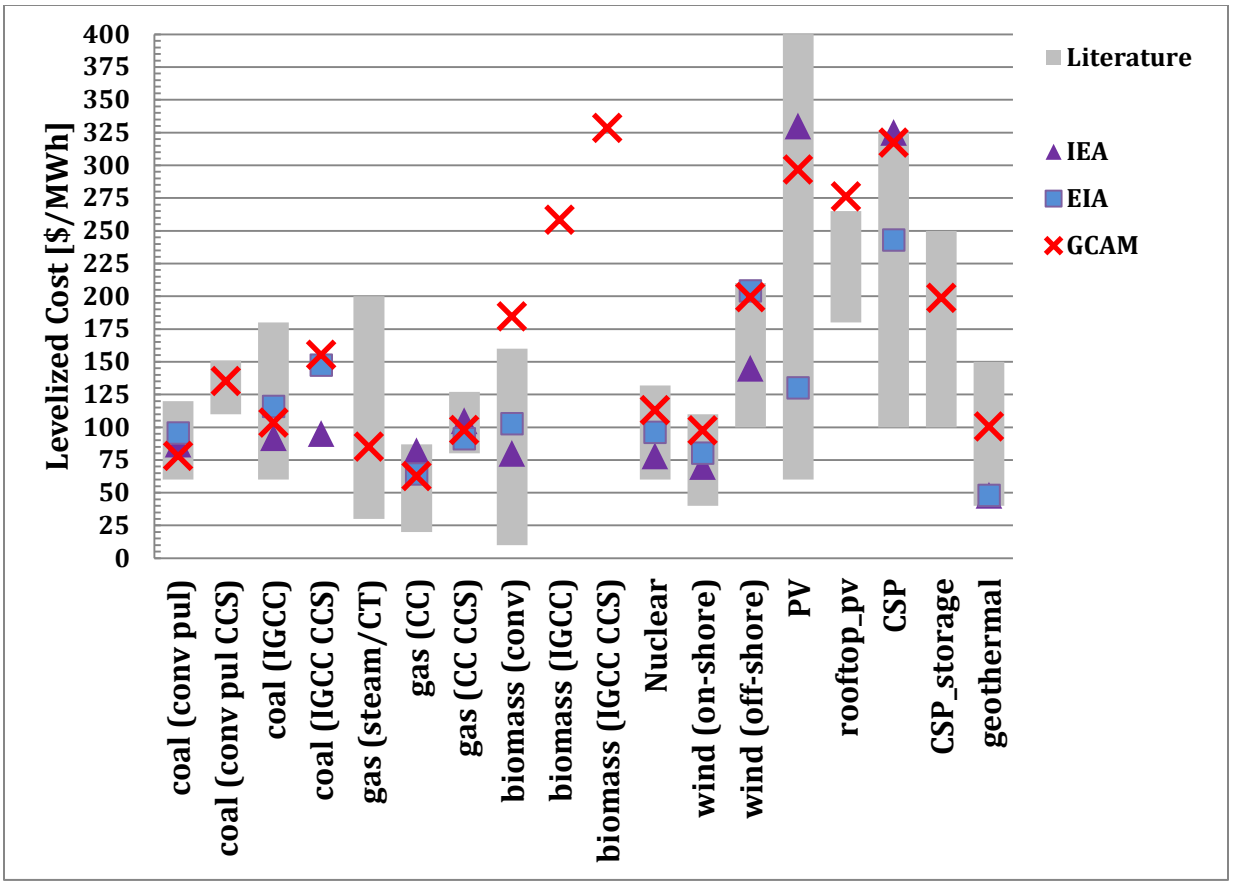


Table 9. LCOE breakdown, in 2010$/kWh

TECHNOLOGY	Cost of fuel [$/MWh]	Levelized Fuel Cost	Levelized Capital Cost	Levelized O&M Cost
coal (conv pul)	7.62	20.1	50.6	7.4
coal (conv pul CCS)	7.62	27.2	107.6	15.1
coal (IGCC)	7.62	19.5	74.2	11.5
coal (IGCC CCS)	7.62	23.8	122.4	20.0
gas (steam/CT)	20.53	60.4	14.0	10.9
gas (CC)	20.53	39.5	18.4	4.8
gas (CC CCS)	20.53	48.9	39.1	9.9
refined liquids (steam/CT)	40.58	119.4	14.0	10.9
refined liquids (CC)	40.58	78.0	18.4	4.8
refined liquids (CC CCS)	40.58	103.7	46.5	11.7
biomass (conv)	22.98	91.9	69.8	22.7
biomass (IGCC)	22.98	124.8	119.5	29.9
biomass (IGCC CCS)	22.98	76.6	111.3	35.0
Gen_II_LWR	2.72	93.4	151.9	42.1
Gen_III	2.72	8.2	33.3	15.5
wind (on-shore)	0.00	8.2	90.7	14.0
wind_storage	0.00	0.0	82.3	15.4
PV	0.00	0.0	218.0	18.5
PV_storage	0.00	0.0	228.3	22.8
CSP	0.00	0.0	479.4	27.4
CSP_storage	0.00	0.0	292.2	25.1
geothermal	0.00	0.0	187.3	11.4
rooftop_pv	0.00	0.0	87.9	12.7

Table 10. Carbon capture cost adders, in $/tCO$_2$.

	CCS Cost [$/tCO2]		
	2015	**2050**	**2100**
coal (conv pul CCS)	66	54	52
coal (IGCC CCS)	64	53	51
gas (CC CCS)	93	67	61
refined liquids (CC CCS)	108	69	61
biomass (conv CCS)	64	54	52
biomass (IGCC CCS)	62	51	49



Main literature sources:

IEA: International Energy Agency, *Projected Costs of Generating Electricity*, 2010. Assumptions: U.S. costs, 10% discount rate.

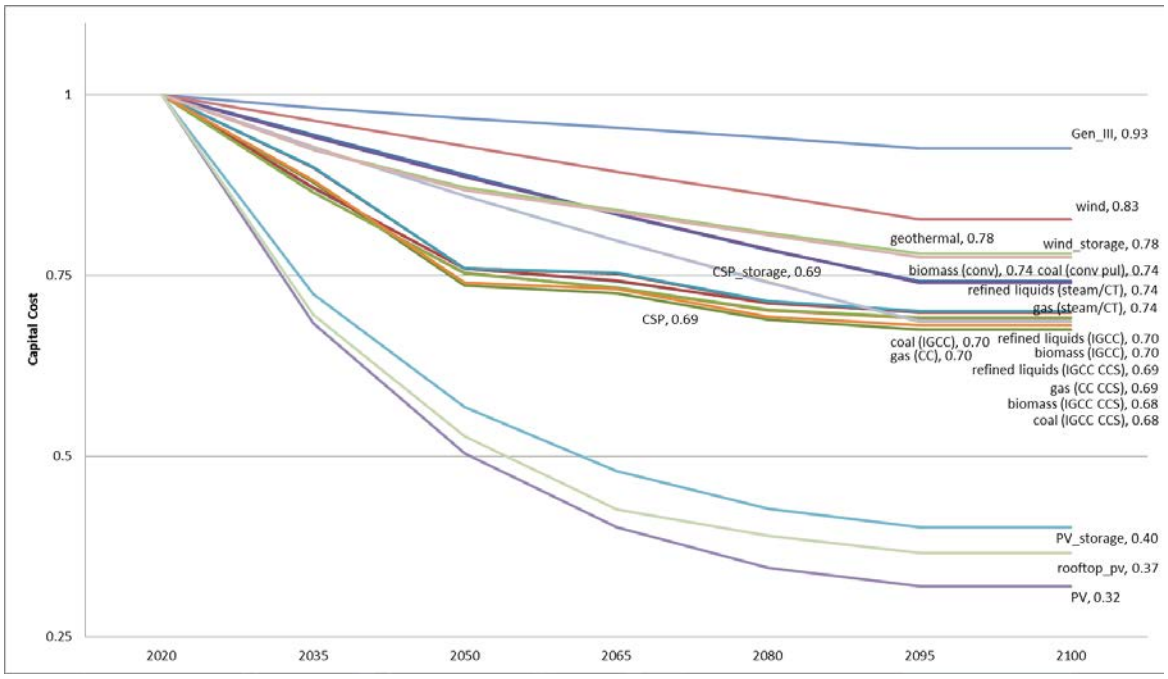
EIA: U.S. Department of Energy - Energy Information Administration, *Annual Energy Outlook 2014*. Assumptions: real after tax weighted average cost of capital of 6.5% (9.5% for greenhouse gas (GHG) intensive technologies, like coal)

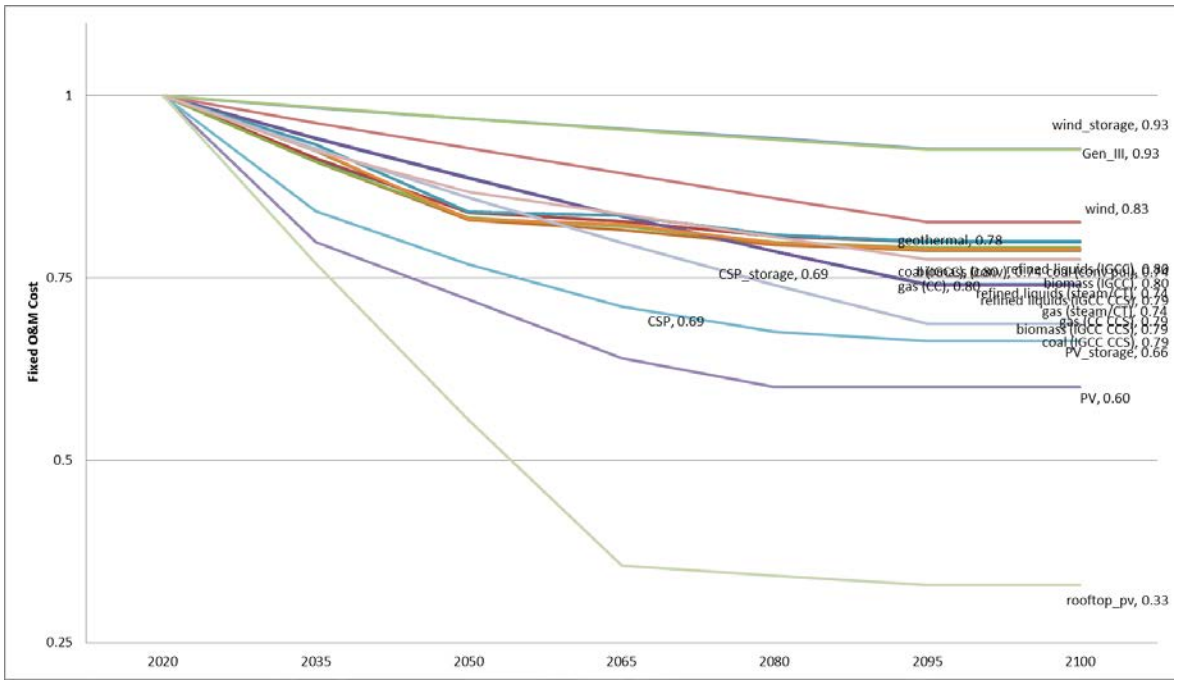
N.B. LCOE for biomass power plants results to be high compared to the literature. The cost of capital and of fuel are in line with assumptions in the literature. Main reason for this high LCOE might be:

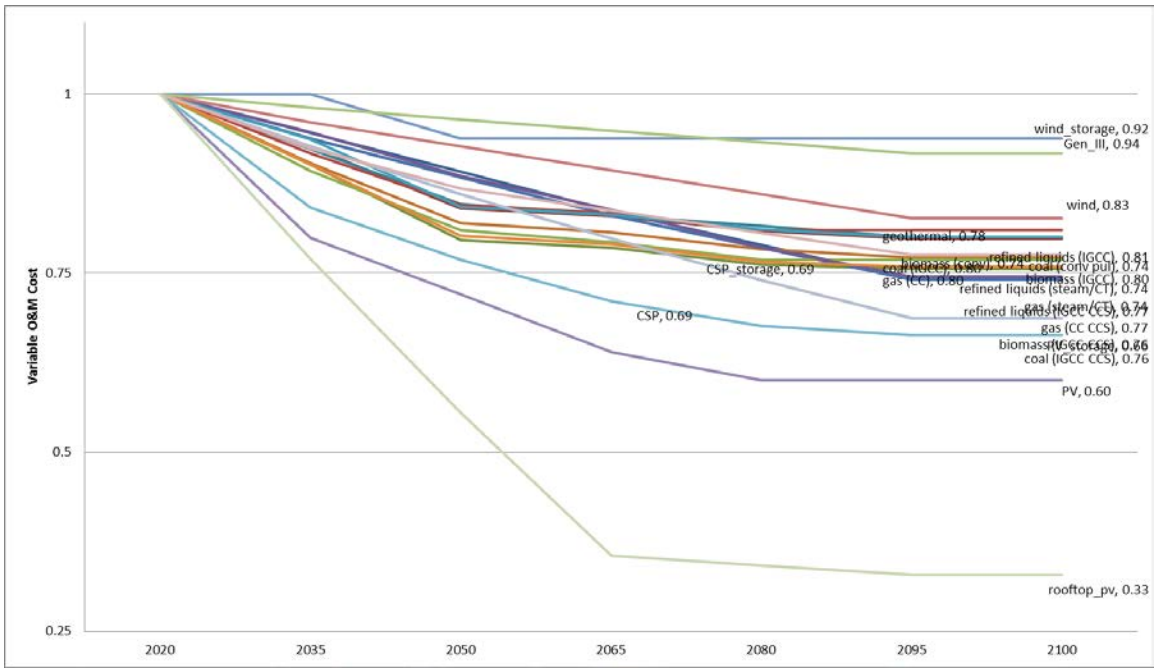
1) Recent increases in the cost of biomass power plants, which might not have been adjusted in the studies reporting LCOE, which are older.

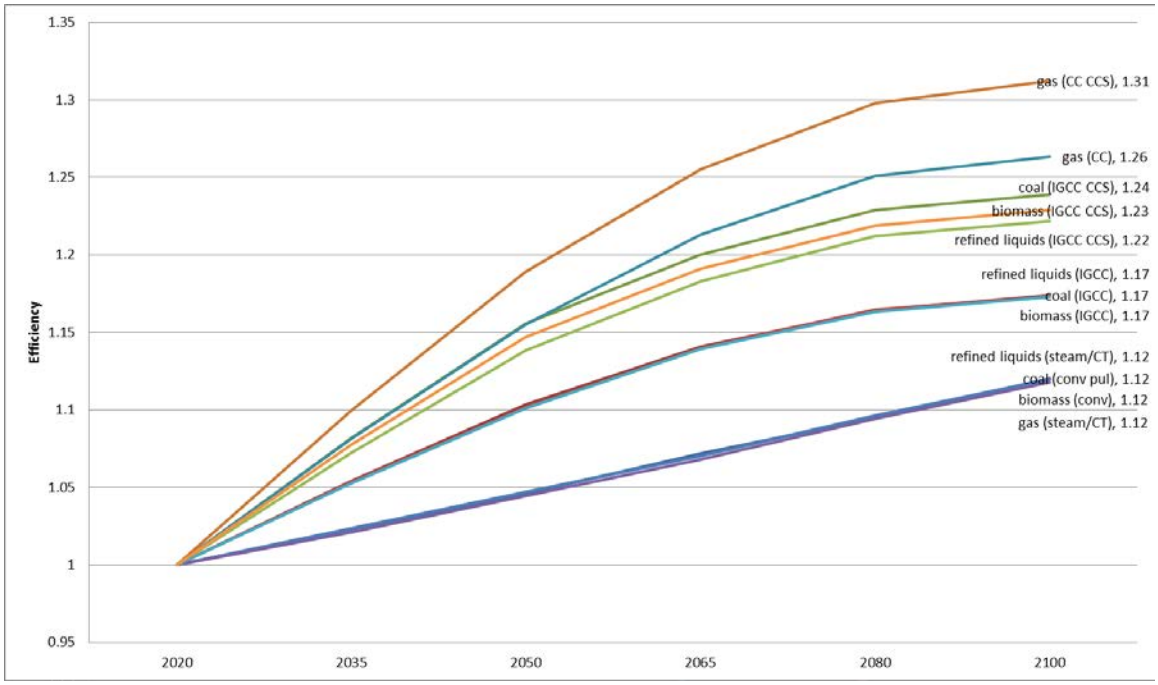
2) A significantly higher cost of biomass compared to coal, taken from GCAM in 2010.

Second, we compare **future assumptions** currently in GCAM with proposed revised assumptions. Currently, costs and efficiency are set exogenously to improve over time.






Variable O&M Cost
1
0.75
0.5
0.25
2020
2035
2050
2065
2080
2095
2100
wind_storage, 0.92
Gen_III, 0.94
wind, 0.83
geothermal, 0.78
refined liquids (IGCC), 0.81
coal (conv pul), 0.74
biomass (IGCC), 0.80
refined liquids (steam/CT), 0.74
gas (CC CCS), 0.77
coal (IGCC CCS), 0.76
PV, 0.60
rooftop_pv, 0.33
CSP_storage, 0.69
CSP, 0.69


Efficiency
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
2020
2035
2050
2065
2080
2100
gas (CC CCS), 1.31
gas (CC), 1.26
coal (IGCC CCS), 1.24
biomass (IGCC CCS), 1.23
refined liquids (IGCC CCS), 1.22
refined liquids (IGCC), 1.17
coal (IGCC), 1.17
biomass (IGCC), 1.17
refined liquids (steam/CT), 1.12
coal (conv pul), 1.12
biomass (conv), 1.12
gas (steam/CT), 1.12

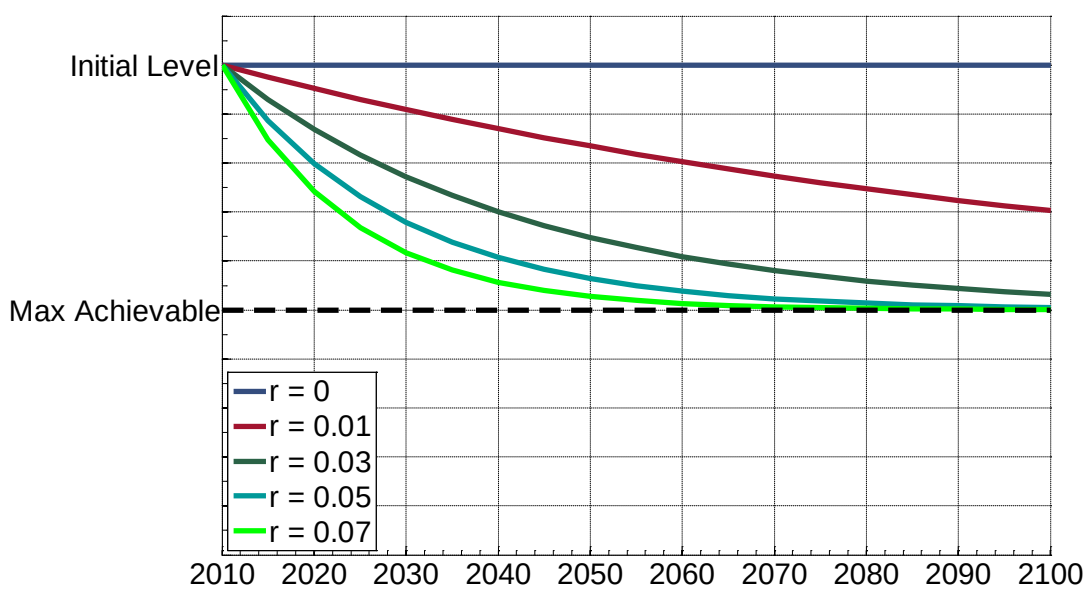
This approach requires exogenous assumptions for each time step modeled and has a series of limitations:

1) Lack on an explicit mathematical formulation.
2) Possible absurd assumption in case of extrapolation (*e.g.* linear extrapolation running GCAM until 2300 leads to negative technology costs).
3) Hard to endogenously model the impact of different technological learning processes: for example learning-by-doing translates into faster improvement rates, while R&D investments and spillovers can be seen as factors reducing the final cost achievable. These phenomena are hard to model following the current approach.

We propose to model technological and cost improvements using an **exponential growth/decay formulation with a limiting bound**. This model is characterized by two parameters: maximum achievable performance (y_{BEST}) and growth rate (r).
For example, the cost of a technology at time t ($y(t)$) is computed based on the minimum achievable cost (y_{BEST}), the initial cost (y_0), and the improvement rate ($0 \leq r \leq 1$) as:

$$y(t) = y_{BEST} + (y_0 - y_{BEST}) \cdot (1 - r)^{(t - t_0)}$$

Different decay rates allow simulating different cost-reduction paths.



The maximum achievable performance (y_{MAX}) can be parametrized as a function of the current status: for example $y_{MAX} = \alpha \cdot y_0$.

Also, the number of years needed to achieve half of the total improvement (halfway between y_0 and y_{MAX}) can be computed as:

$$t_{1/2} = \frac{\log(0.5)}{\log(1-r)}$$

Moreover, we propose to categorize all the technologies into three groups:

1) Mature
2) Evolutionary
3) Revolutionary

TECHNOLOGY	Mature	Evolutionary	Revolutionary
coal (conv pul)	x		
coal (conv pul CCS)			x
coal (IGCC)		x	
coal (IGCC CCS)			x
gas (steam/CT)	x		
gas (CC)	x		
gas (CC CCS)			x
refined liquids (steam/CT)	x		
refined liquids (CC)	x		
refined liquids (CC CCS)			x
biomass (conv)	x		
biomass (conv CCS)			x
biomass (IGCC)		x	
biomass (IGCC CCS)			x
Gen_II_LWR	x		
Gen_III	x		
wind (on-shore)		x	
wind_storage		x	
PV		x	
PV_storage		x	
CSP			x
CSP_storage		x	
geothermal	x		
rooftop_pv		x	

N.B. for CCS technologies only the CCS portion will be considered "revolutionary" (as well as for the storage portion of CSP_storage).

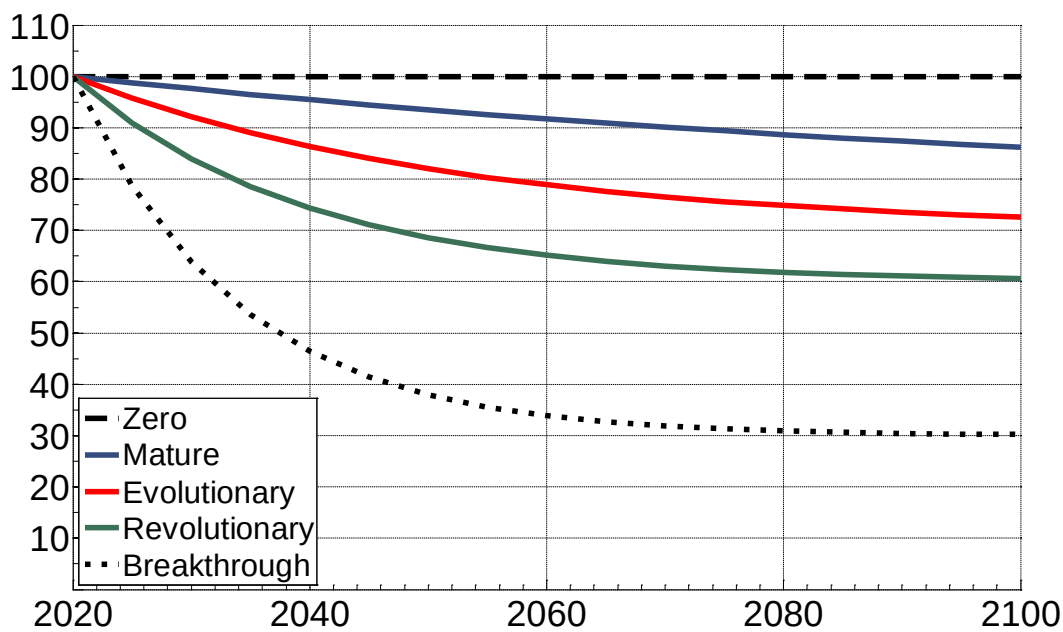
Main literature sources:

EIA: U.S. Department of Energy - Energy Information Administration, *Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants*, 2013.

Technologies in the same group will experience the same improvement over time. The basic idea is that mature technologies experience a constant and slow cost reduction and efficiency increase. Evolutionary technologies experience a faster improvement during an initial period, and then transition to mature improvement rates. Revolutionary technologies experience an even faster initial improvement rates.
This approach allows for differentiating the evolution of different technologies. Moreover, different technologies might have a different "Revolutionary stage", both in terms of duration and in terms of starting date (*e.g.* PV might start improving in 2015, while CCS technologies remain stable until 2025).

COST

TECHNOLOGY CLASS	y_{MAX}	r	$t_{1/2}$
Zero	y_o	0	∞
Mature	$0.75 \cdot y_o$	-0.01	69 years to reach $0.875 \cdot y_o$
Evolutionary	$0.70 \cdot y_o$	-0.03	23 years to reach $0.85 \cdot y_o$
Revolutionary	$0.60 \cdot y_o$	-0.05	14 years to reach $0.80 \cdot y_o$
Breakthrough	$0.30 \cdot y_o$	-0.07	10 years to reach $0.65 \cdot y_o$



The "Zero" and "Breakthrough" classes can be used as starting point for scenario analysis.

EFFICIENCY

Table 11. HHV efficiency, 2015-2100.

TECHNOLOGY CLASS	η_{BEST}	r	η_{2015}	η_{2050}	η_{2100}
coal (conv pul)	0.56	0.015	38%	45%	51%
coal (conv pul CCS)	-0.08	0.05	28%	38%	43%
coal (IGCC)	0.57	0.02	39%	48%	54%
coal (IGCC CCS)	-0.05	0.05	32%	43%	49%
gas (steam/CT)	0.49	0.015	34%	38%	42%
gas (CC)	0.66	0.015	51%	57%	62%
gas (CC CCS)	-0.05	0.05	42%	52%	57%
refined liquids (steam/CT)	0.51	0.015	34%	39%	44%
refined liquids (CC)	0.68	0.015	52%	59%	64%
refined liquids (CC CCS)	-0.05	0.05	39%	53%	59%
biomass (conv)	0.40	0.015	25%	31%	36%
biomass (conv CCS)	-0.08	0.05	18%	24%	29%
biomass (IGCC)	0.47	0.02	30%	39%	44%
biomass (IGCC CCS)	-0.05	0.05	25%	34%	39%

N.B. for CCS technologies the η_{BEST} indicates the efficiency penalty compared to the corresponding plant without CCS.

The maximum achievable efficiencies are approximated by the efficiencies at maximum power output (Chambadal – Novikov –Curzon – Ahlborn efficiency) computed according to finite-time thermodynamics theory [Durmayaz, Ahmet, et al. "Optimization of thermal systems based on finite-time thermodynamics and thermoeconomics." *Progress in Energy and Combustion Science* 30.2 (2004): 175-217].[1] The cold heat sink is assumed to be at 298K, and the temperature of the hot heat source is assumed to reach 70% of the adiabatic combustion flame temperature of each specific fuel.
r factors are set to mimic efficiency predictions available in the literature:

- Machteld van den Broek *et al.* "Effects of technological learning on future cost and performance of power plants with CO 2 capture." *Progress in Energy and Combustion Science* 35.6 (2009): 457-480.
- EPRI 2003 Electricity Technology Roadmap
- U.S. National Energy Technology Laboratory, "Cost and Performance Baseline for Fossil Energy Plants", 2013.
- IEA, Energy Technology Systems Analysis Programme. http://www.iea-etsap.org/web/e-techds/pdf/e02-gas_fired_power-gs-ad-gct.pdf

[1] For this application, similar results are obtained following the approach proposed in: Denton, Jesse C. "Thermal cycles in classical thermodynamics and nonequilibrium thermodynamics in contrast with finite time thermodynamics." Energy conversion and management 43.13 (2002): 1583-1617.

ISSUE

Sudden deployment of natural gas combined cycles: boom in 2015 and rebound in 2060

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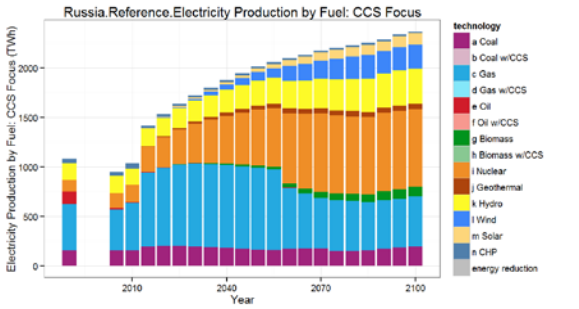	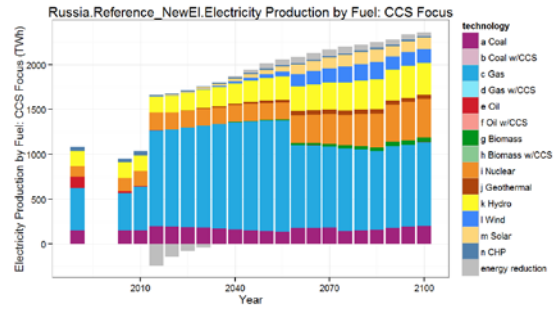

In 2015 CC natural gas plants become available in some regions where they haven't been used previously, for a variety of reasons. Currently, there is not technology-level share weight assumption: the share weight goes from 0 in 2010 to 1 in 2015.

CC are cheaper than technology used in 2010 in those regions, thus are largely built leading to two effects: 1) drop in electricity cost → abrupt increase in consumption; 2) rebound peak at the end of the plants life, 45 years later (2060).

This issue was already present and appears in several regions, the more evident being Russia.

SOLUTION :

Gradual adoption of CC. We treat the competition within the subsector using the same approach used for competition among different sub-sectors by setting the CC share weight to converge to 1 in 2100 following an s-shape (starting from whatever value we find in the calibration year).

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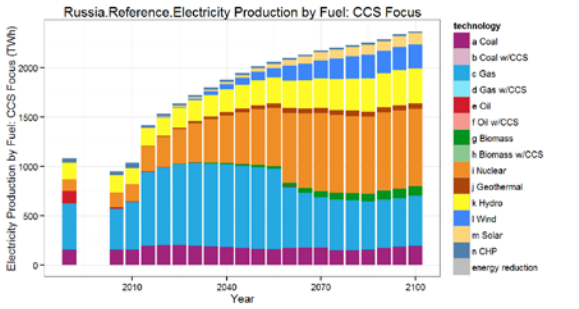	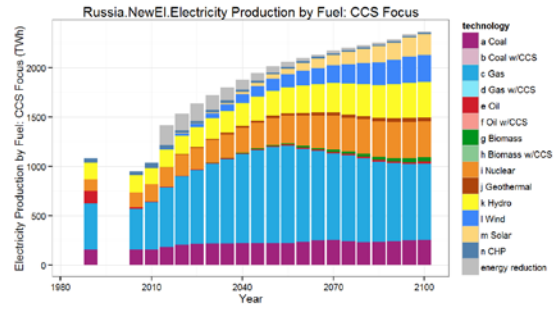

This allows for a gradual market penetration of CC in those regions where CC is not currently used, without impacting other regions (if CC share weight is already 1 in 2010 it simply stays constant at 1), solving the issue.

ISSUE

Currently, nuclear gen II and hydro power plants are modeled using a "fixed output" approach, which does not associate any price to those technologies. In some regions, where nuclear is a key technology for electricity generation in the calibration period or after, the review of electricity generation cost leads to a spike in the electricity price in the first modeled period, leading to reduction in demand.

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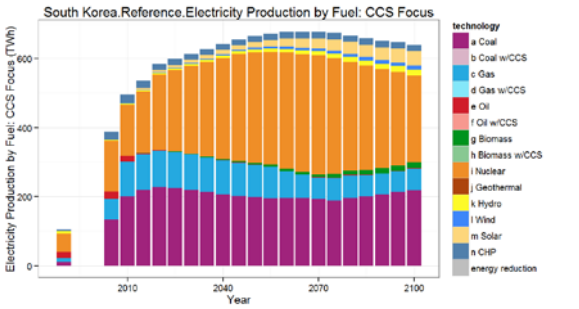	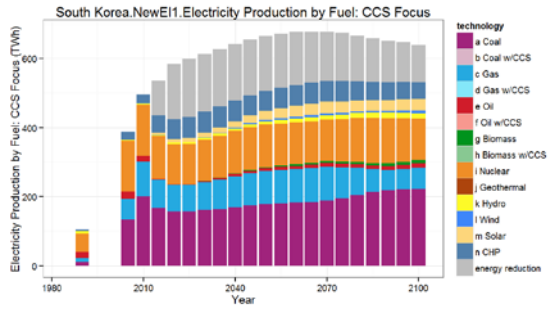

SOLUTION :

Nuclear is modeled as "output" technology, thus gen II contributes to the price determination in the calibration period. Also, the cost of nuclear gen II is aligned with nuclear gen III in the calibration year.

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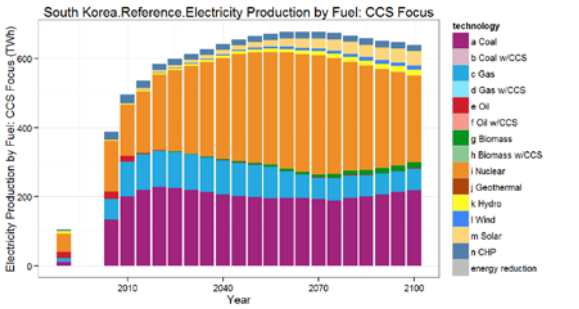
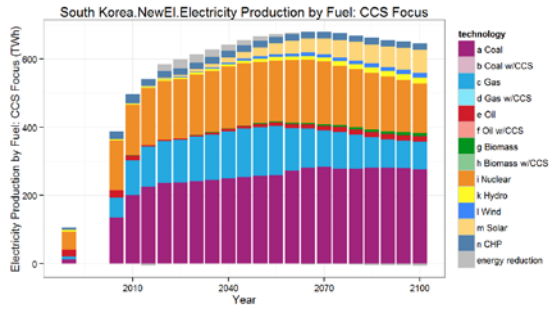
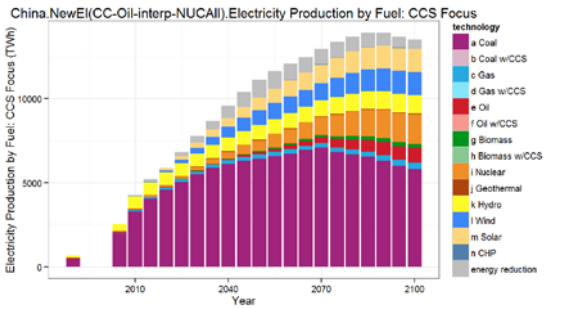
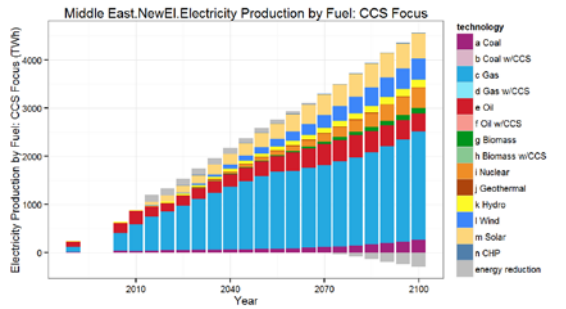
	

ISSUE

Oil-fire power plants, regardless their higher cost, are still significantly used in some regions. This reflects a series of aspects not modeled in GCAM, such as political preference for domestic fossil fuels (*e.g.* in the Middle East), use in remote locations (small and portable diesel generators), infrastructure barriers (oil procurement is easier for archipelagos and small islands). The result is that share weight for the use of liquid fuels in the electricity sector vary from very small values (<0.2) in some regions (*e.g.* USA, EU) to very high number (>7) in other regions (*e.g.* Africa, South America, Middle East).

- Setting the share weights for the liquid fuel subsector to converge to a common global value introduces oil in countries that have not used it for electricity production before and removes it from countries that show a significant use of oil (oil-fired combined cycle are operated in the Middle East, for example).

Introduction of oil in China	Lack of oil in Middle East
	

- Setting the share weights for the liquid fuel subsector to remain constant at the calibration year level leads to oil-fired combined cycles being largely deployed in some regions, even if producing electricity with natural-gas fired combined cycle would be significantly cheaper.

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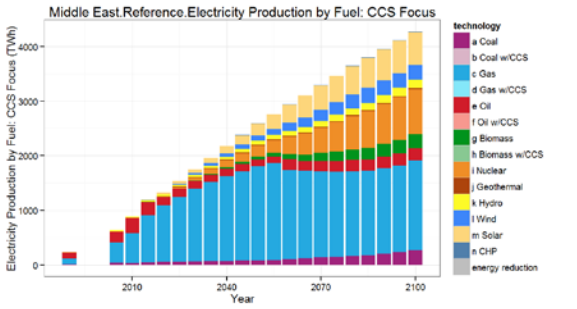	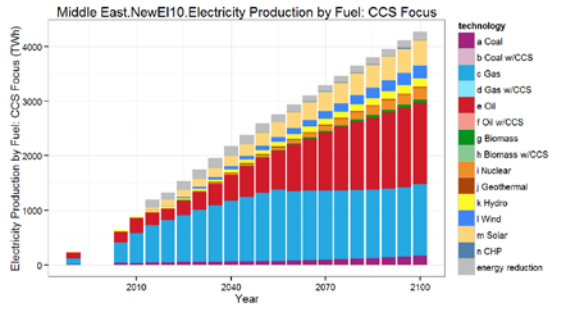

SOLUTION :

To solve this issue the share weight for the liquid fuel subsector in the electricity sector are maintained constant at the calibration level for countries that have a calibration share weight <1 (long-term share weight for renewables, also in line with coal and gas share weight in 2100), and are set to linearly converge to 1 in 2100 for those regions where the calibration share weights are >1.

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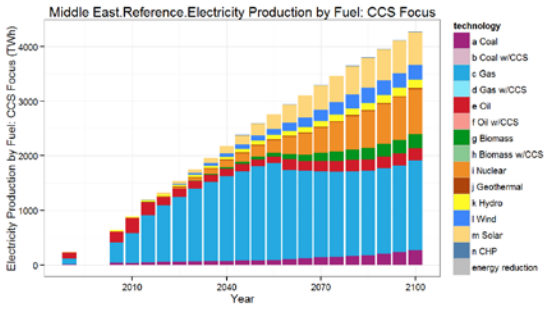	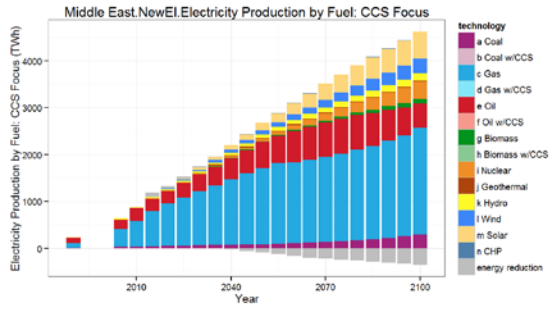

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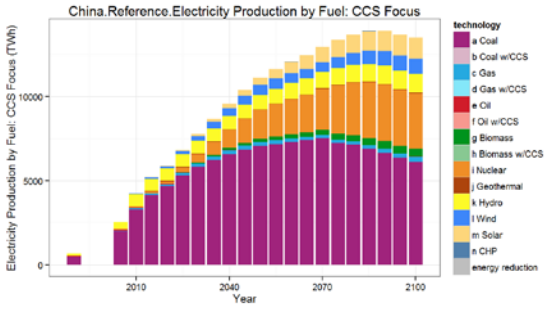	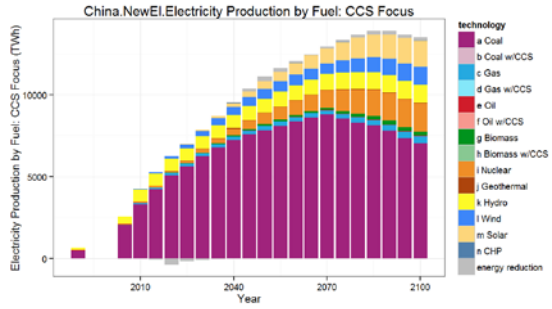

ISSUE: Near-term share weights for renewables

Short-term share weights for nuclear and renewable sources are currently calibrated to match near-term installations planned and approved. This was done in 2011 (Proposal 91: Renewable deployment as a fraction of total generation appears to be more aggressive than several other integrated assessment models for several regions. We will adjust share-weights to improve this behavior). In the long term they reach 0.5.

This proposal (200) changes the calibration share-weights (cost is now updated) and the share weights set to mimic short-term behavior are now inappropriate (fast deployment of renewables in the near-term).

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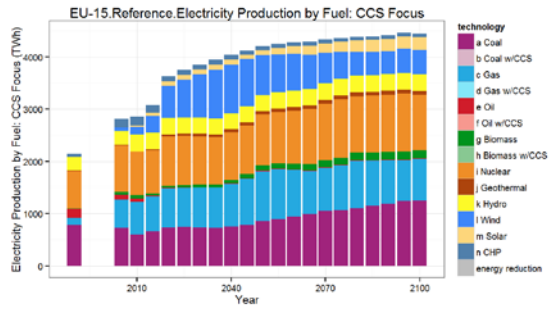	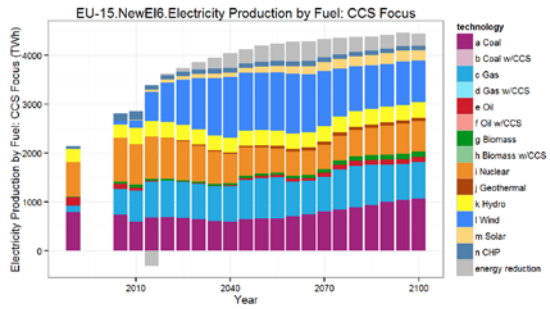

SOLUTION :

To solve this issue the share weights for renewable are set to linearly interpolate from the calibration value to 1 in 2100. Now renewables deployment is more paced (in line with previous reference case, and a policy can be easily introduced to push for early deployment: incentives).

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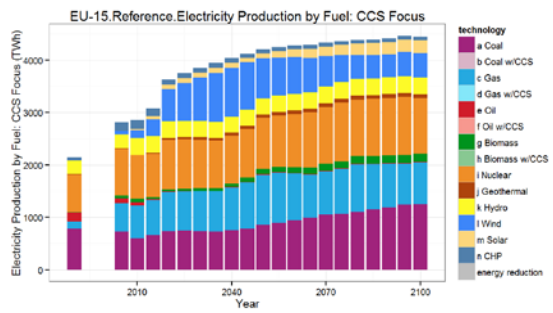	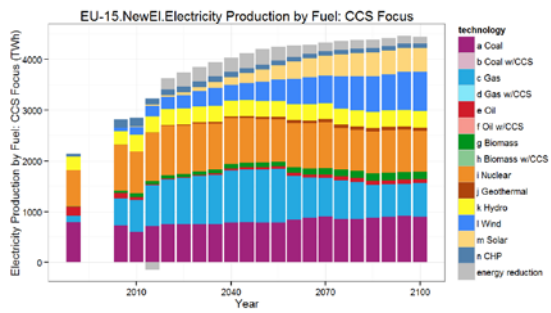

Similarly, short-term share weights are set for nuclear, and were reviewed to reflect current under construction/planned/proposed nuclear power plants. After 2050 nuclear share weights converge to 1 in 2300 with an s-curve interpolation.

Calibrated share weight change every time that the electricity sector is reviewed, and should not be used to calibrate short-term behavior. Rather than setting share-weight in

the near term to mimic approved and under construction plants, this should be done fixing the nuclear output in the near-future.

SHARE WEIGHTS SUMMARY:

Starting from the values calibrated in 2010:

- COAL: converge to 1 in 2300, s-curve
- NATURAL GAS: converge to 1 in 2300, s-curve
- WIND: linearly converge to 1 in 2100
- SOLAR: linearly converge to 1 in 2100
- BIOMASS: linearly converge to 1 in 2100
- OIL: if calibration share weight >1 → converge to 1 in 2100;
  if calibration share weigh <1 → constant.
- NUCLEAR: short- medium-term share weights (2020, 2035, 2050) fixed to model current under construction/planned/proposed nuclear power plants. After 2050 converge to 1 in 2300, s-curve.

POSSIBLE FUTURE MODELING IMPROVEMENTS:

1) Improve renewable supply curves. Revisit competition between PV and rooftop PV. Review wind capacity factors and include off-shore wind (a more efficient – higher CF – and more expensive technology, corresponding to CSP in the solar subsector)
2) Explicitly model the electricity backup sector. In this way different back-up solutions (e.g. back-up natural gas power plants, batteries, pumped hydro, demand response) could compete in a separate subsector. Currently intermittent resources are coupled to a natural gas back-up technology that adds on the cost of wind, CSP, and PV. This would also remove the PV_storage and Wind_storage technology options, which are conceptually misleading.
3) Add Hydro technologies (we currently model this technology as a fixed output, and don't let it compete in the market)
4) Improve CHP modeling → we expect an increasing trend
5) Model load segments to have a better depiction of different technologies use, and better calculate actual LCOE.
6) Calibration: we currently calibrate on the average existing stock. In the future modeling periods we compute electricity prices based on the new capacity installed in each period, introducing a discontinuity in the electricity price that might results in abrupt changes in the demand in the first modeled period. We could vintage the existing stock and calculate price in the calibration year based on new additional capacity installed, thus using a homogeneous approach.
7) Short-term behavior calibration to mimic regional trends.
8) Endogenously model regional differences in capital costs, which could be explained by different wages, regulatory processes, cost of energy, etc.

Staffing

Matteo Muratori, Haewon McJeon, Sonny Kim, Page Kyle, Pralit Patel, Leon Clarke.

Verification

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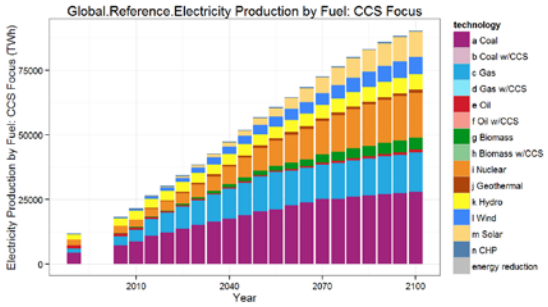	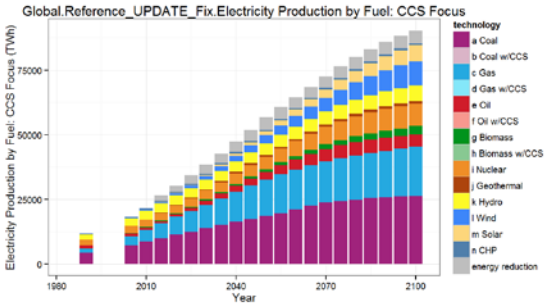
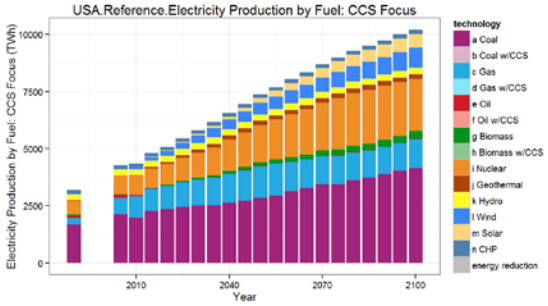	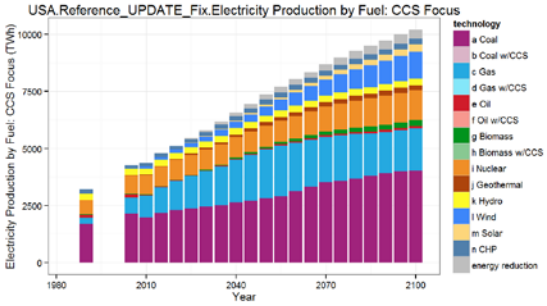
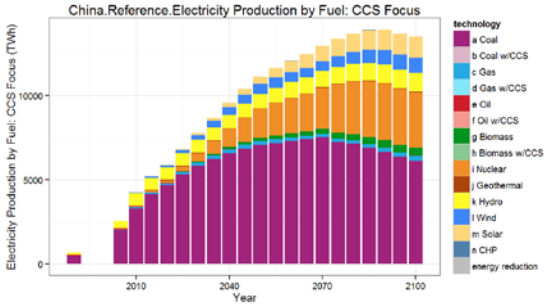	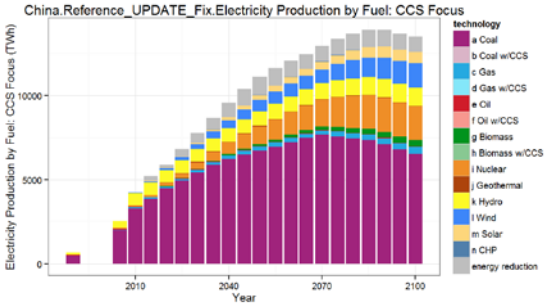
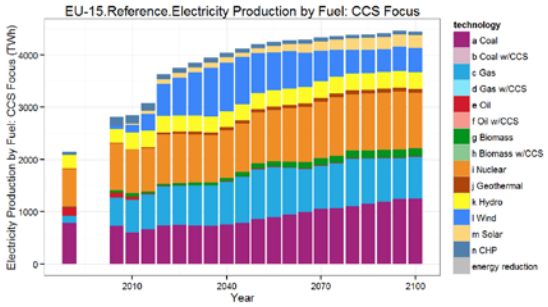	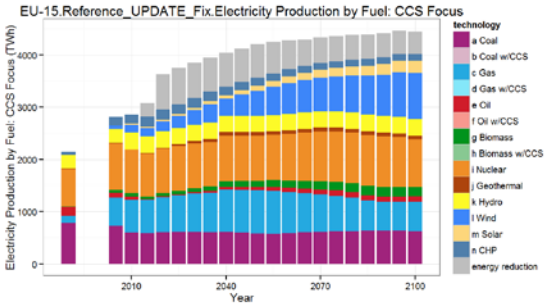

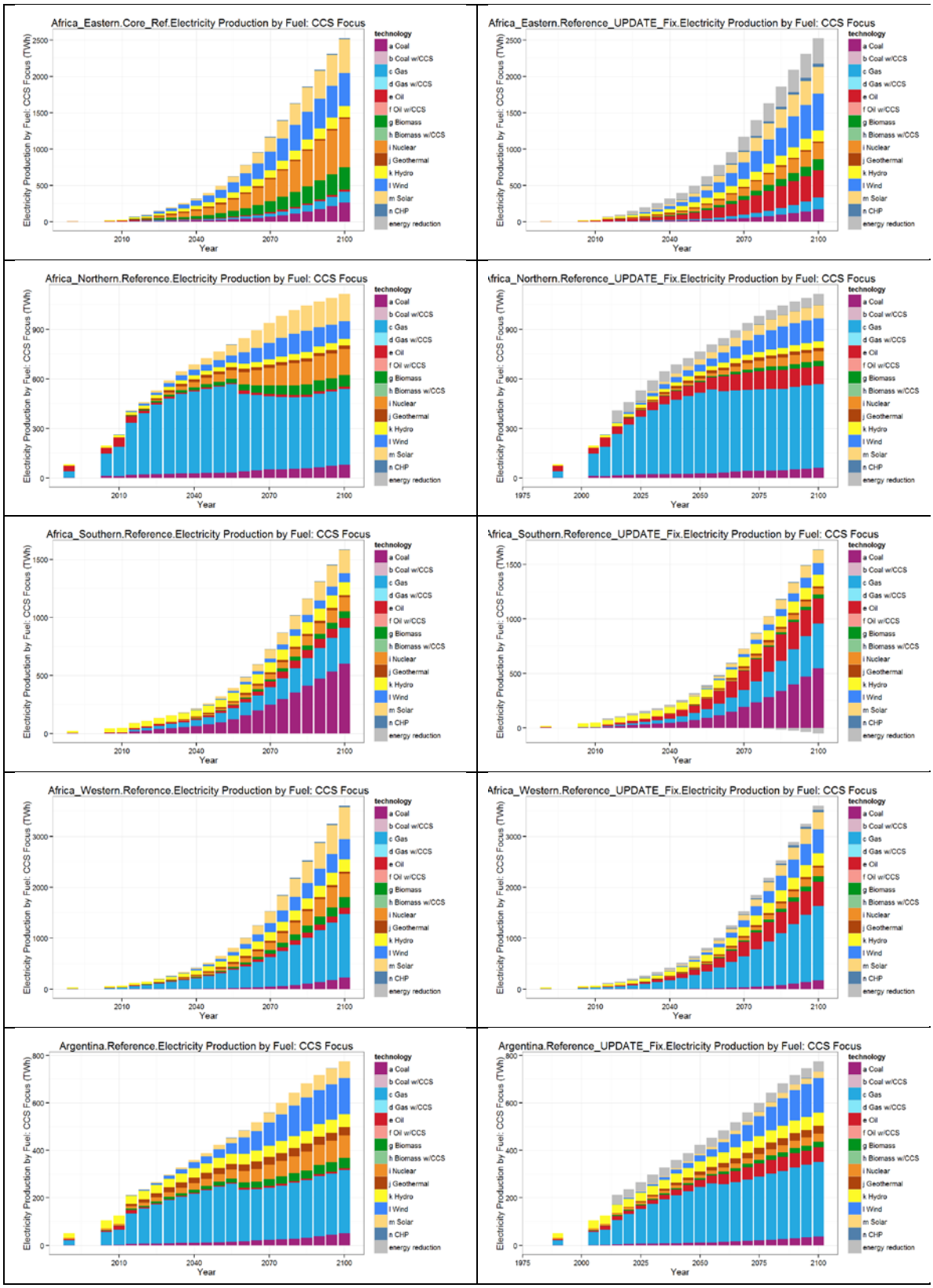
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Year
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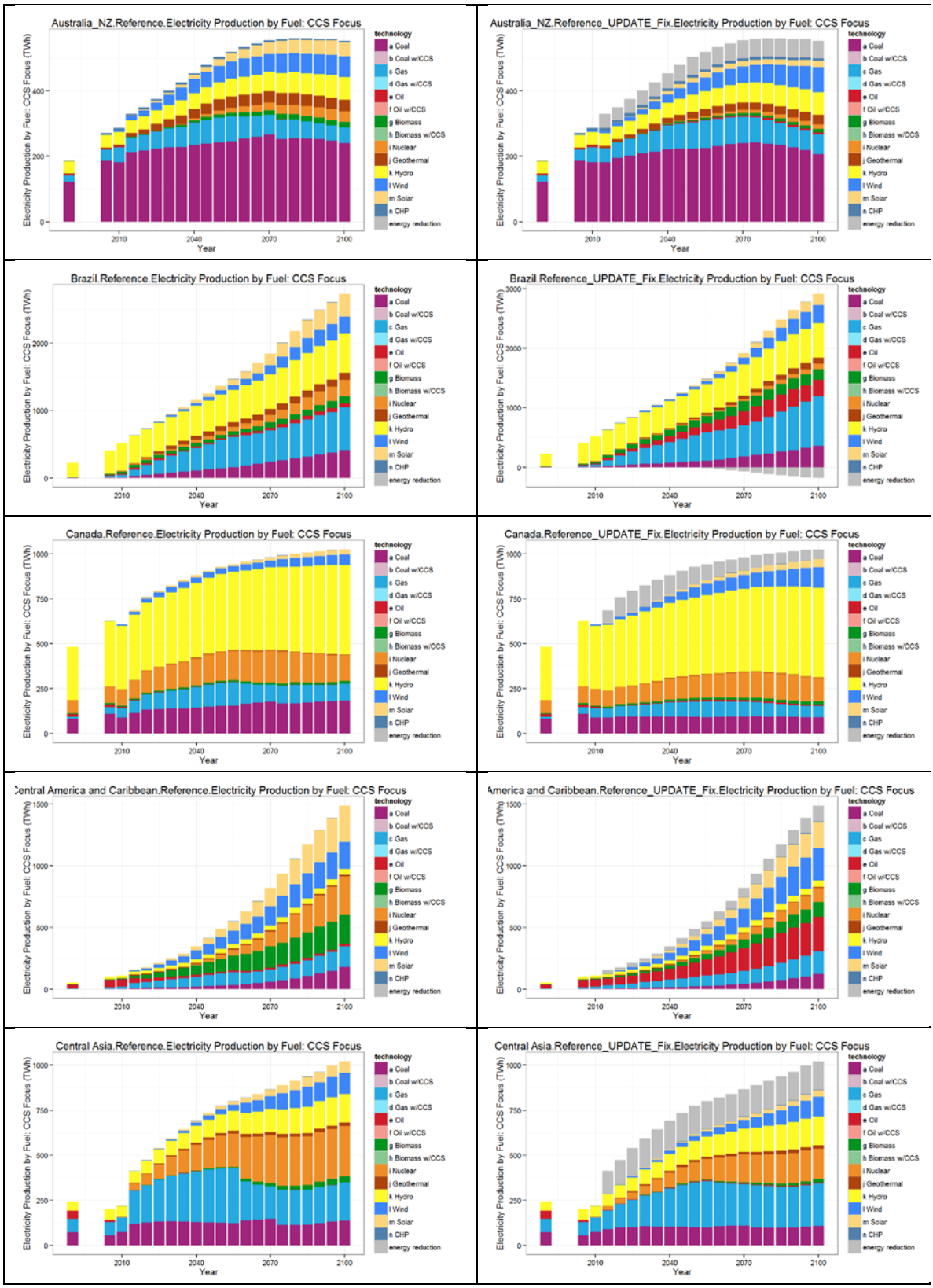
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction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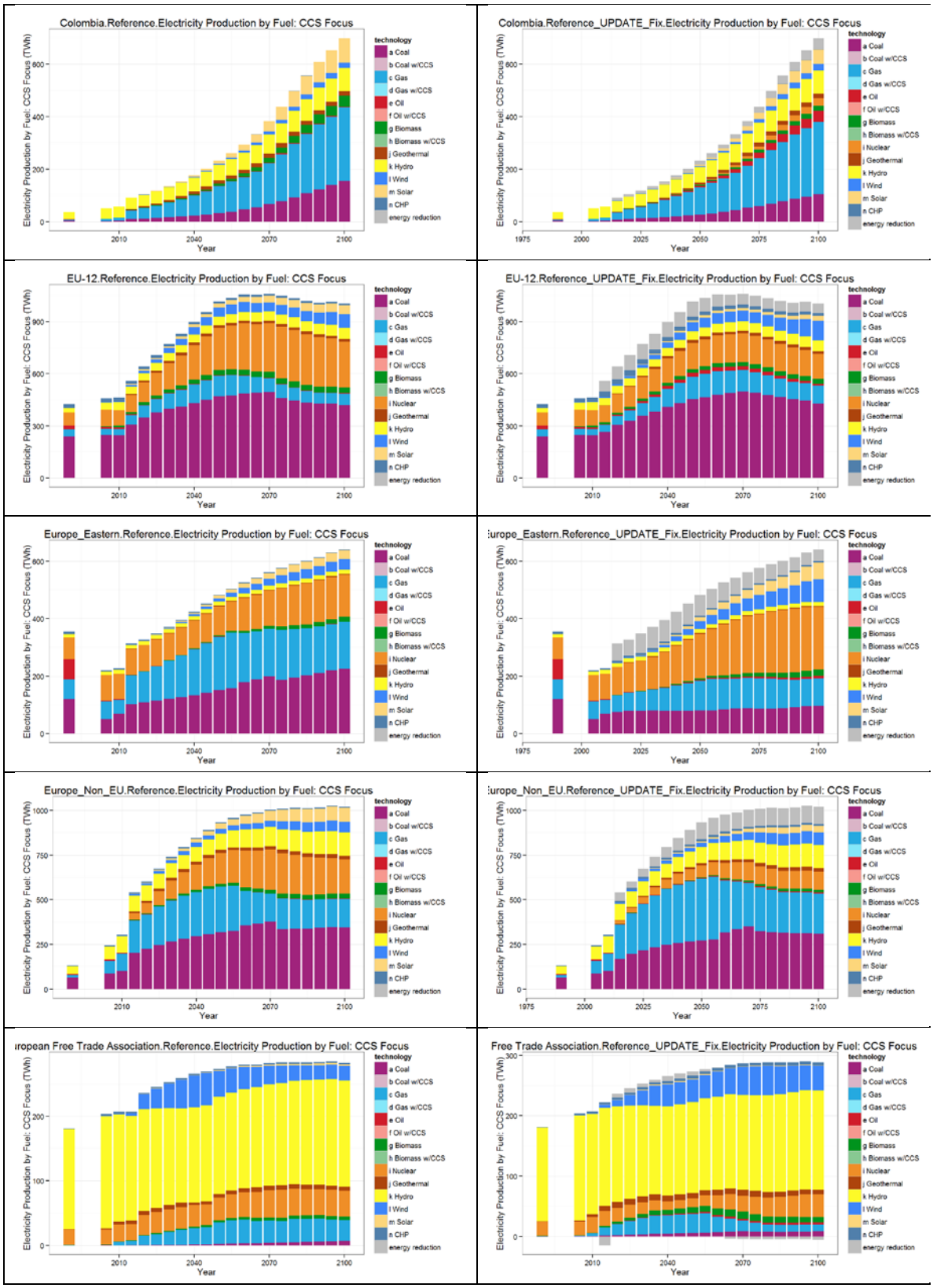
Central Asia.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction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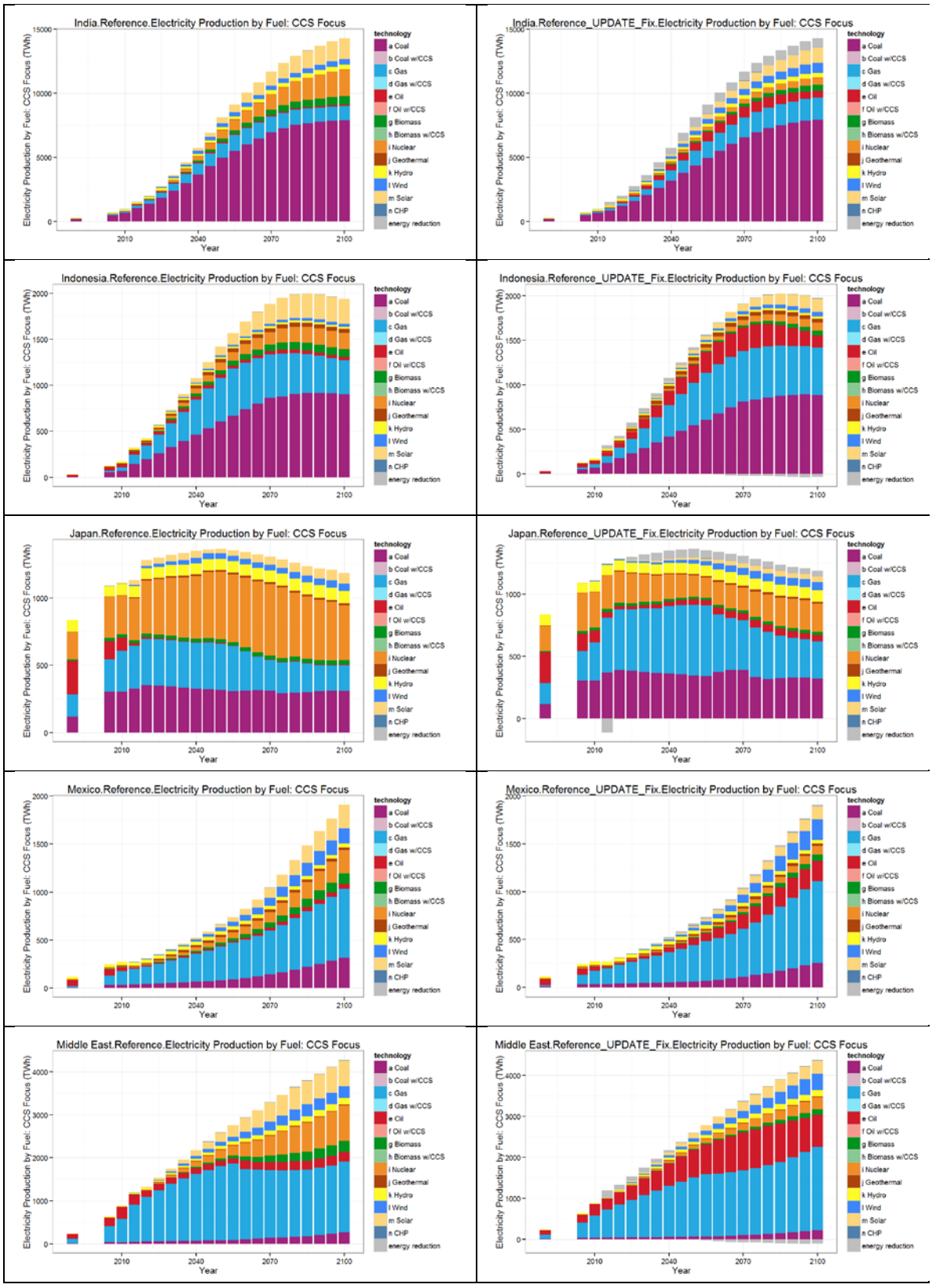
ıropean Free Trade Association.Reference.Electricity Production by Fuel: CCS Focus
Free Trade Association.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction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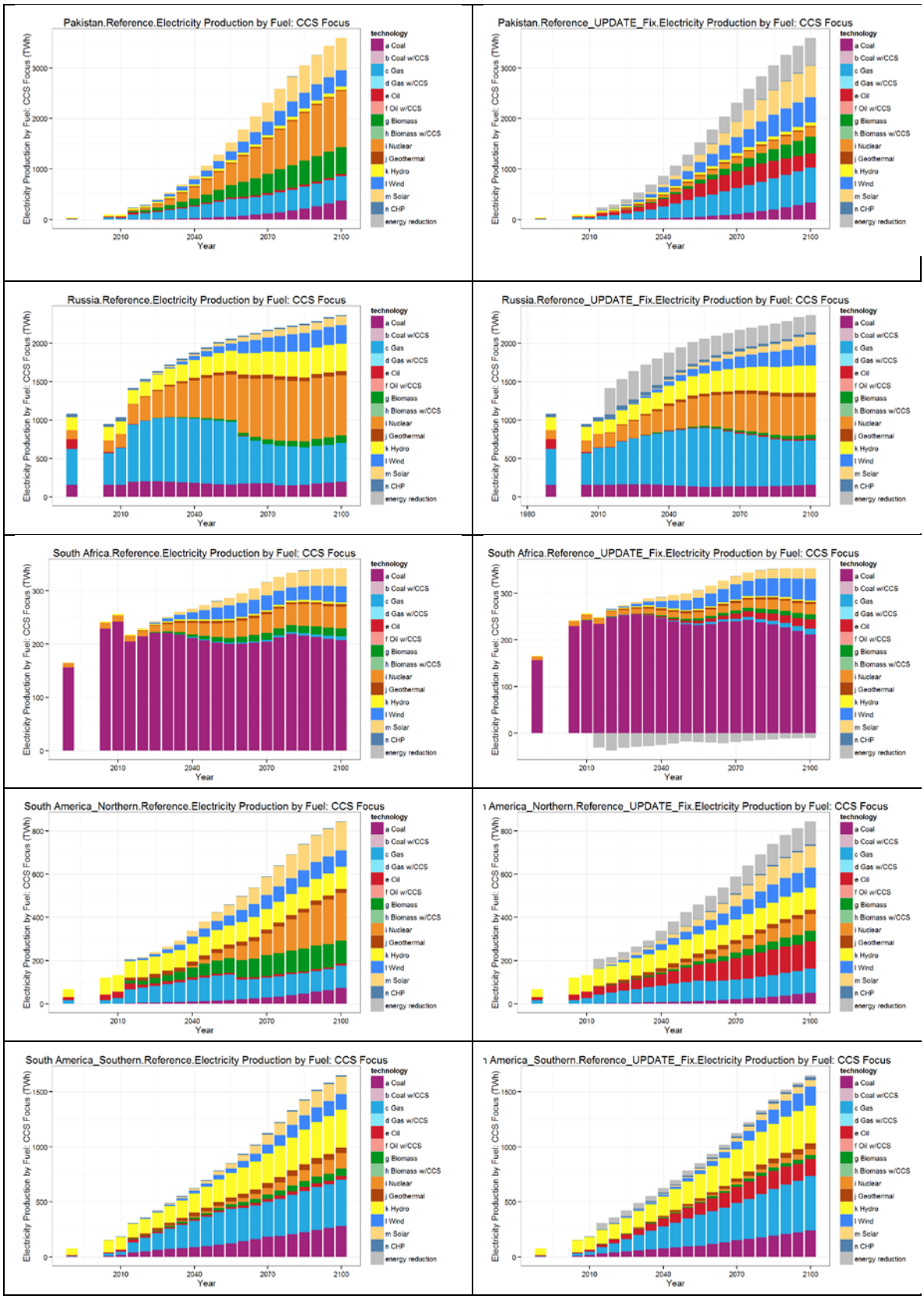
Mexico.Reference.Electricity Production by Fuel: CCS Focus
Mexico.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Middle East.Reference.Electricity Production by Fuel: CCS Focus
Middle East.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction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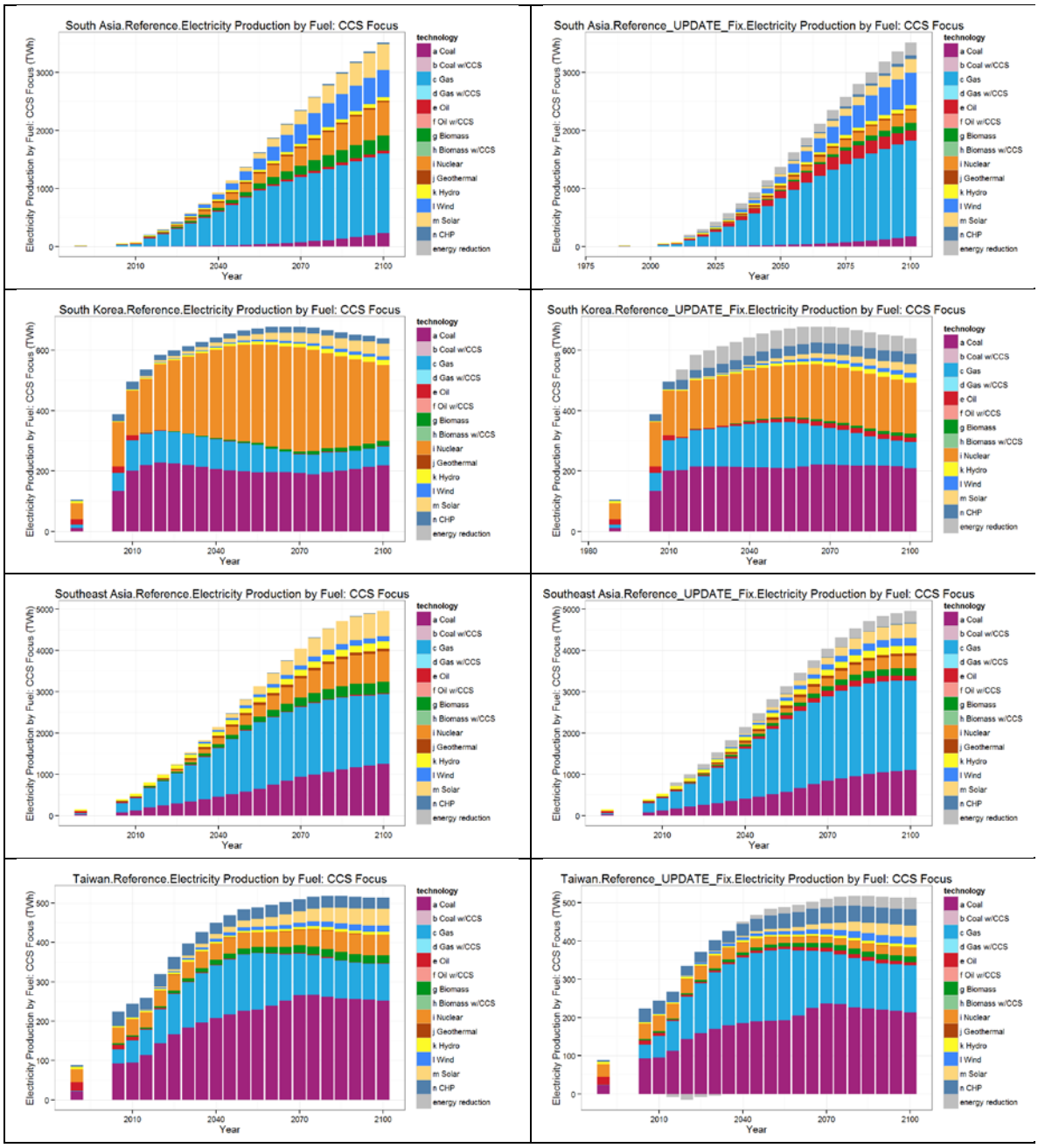
South Africa.Reference.Electricity Production by Fuel: CCS Focus
South Africa.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
South America_Northern.Reference.Electricity Production by Fuel: CCS Focus
America_Northern.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
South America_Southern.Reference.Electricity Production by Fuel: CCS Focus
America_Southern.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction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South Asia.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
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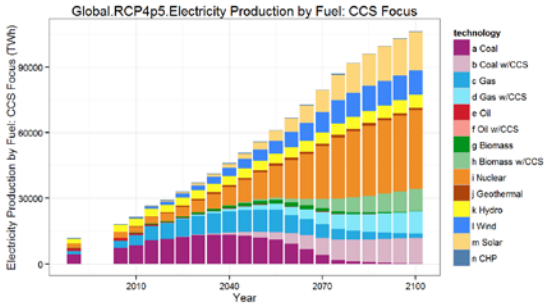
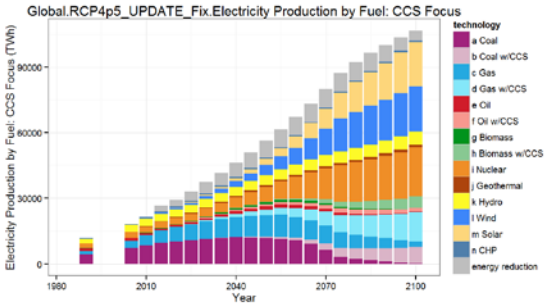
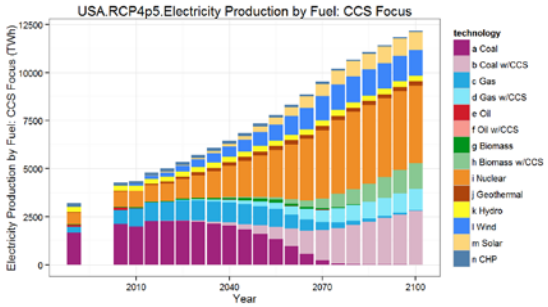
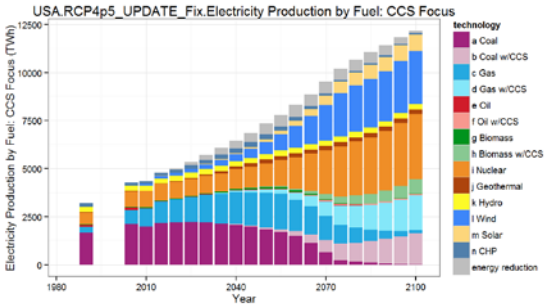
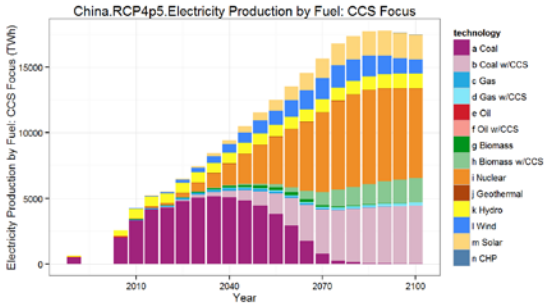
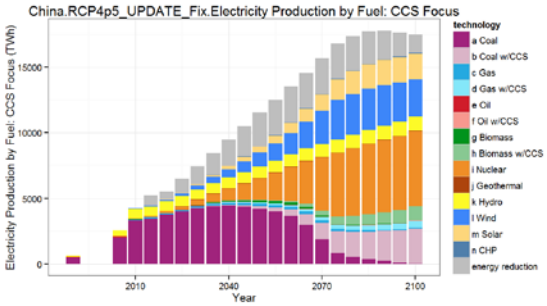
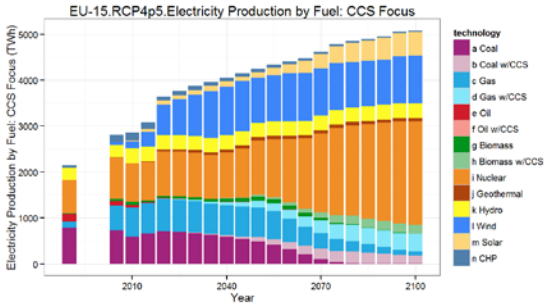
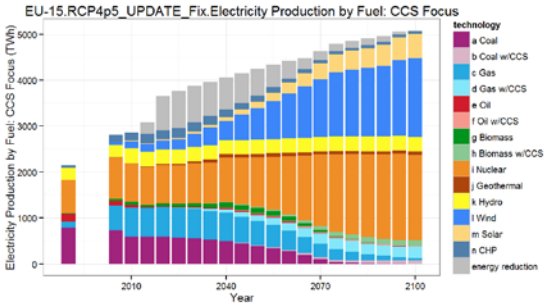
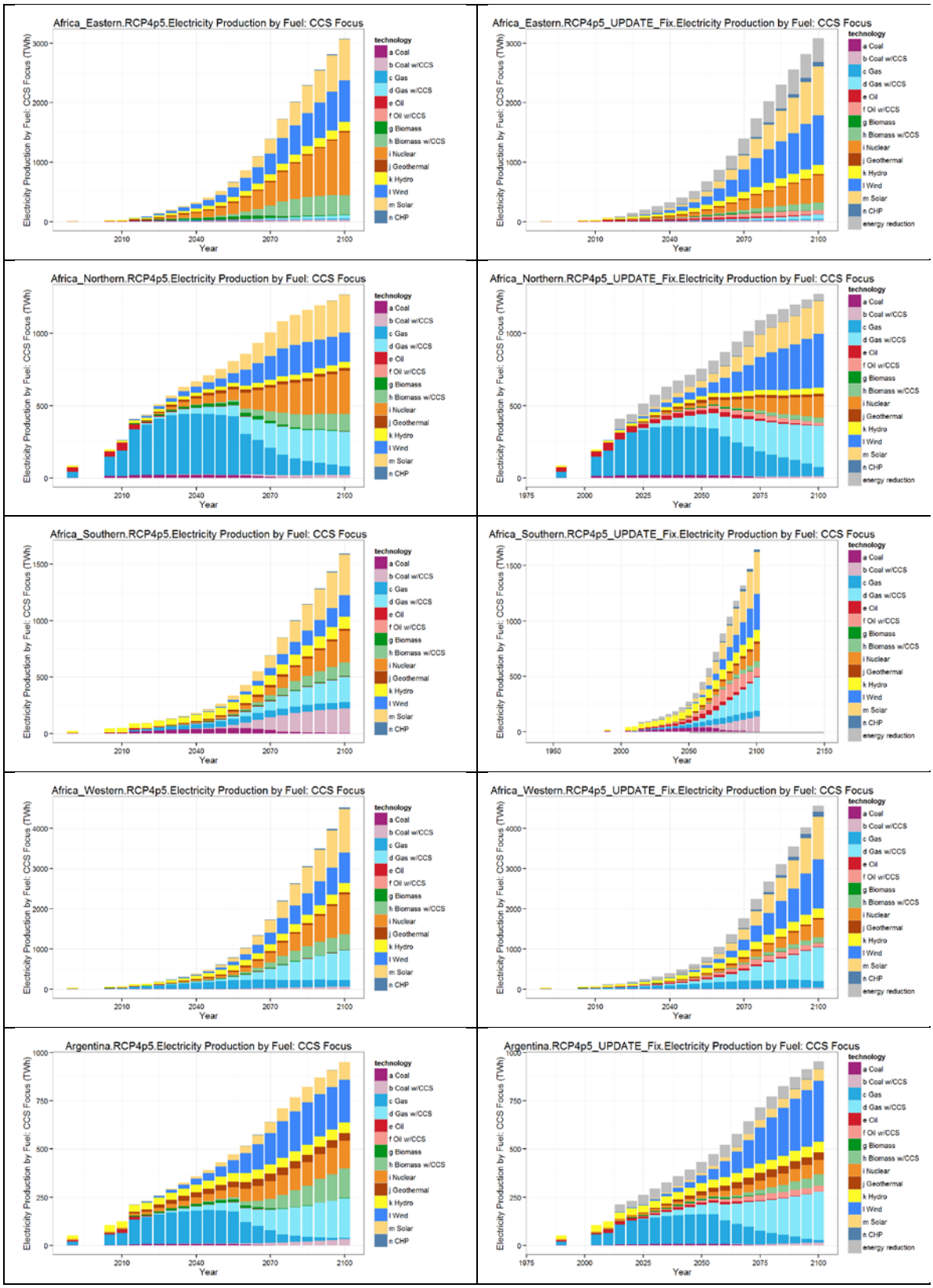
Southeast Asia.Reference.Electricity Production by Fuel: CCS Focus
Southeast Asia.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Taiwan.Reference.Electricity Production by Fuel: CCS Focus
Taiwan.Reference_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction

CLIMATE POLICY SCENARIO

CURRENT GCAM RCP 4.5 SCENARIO	UPDATED GCAM RCP 4.5 SCENARIO
	
	
	
	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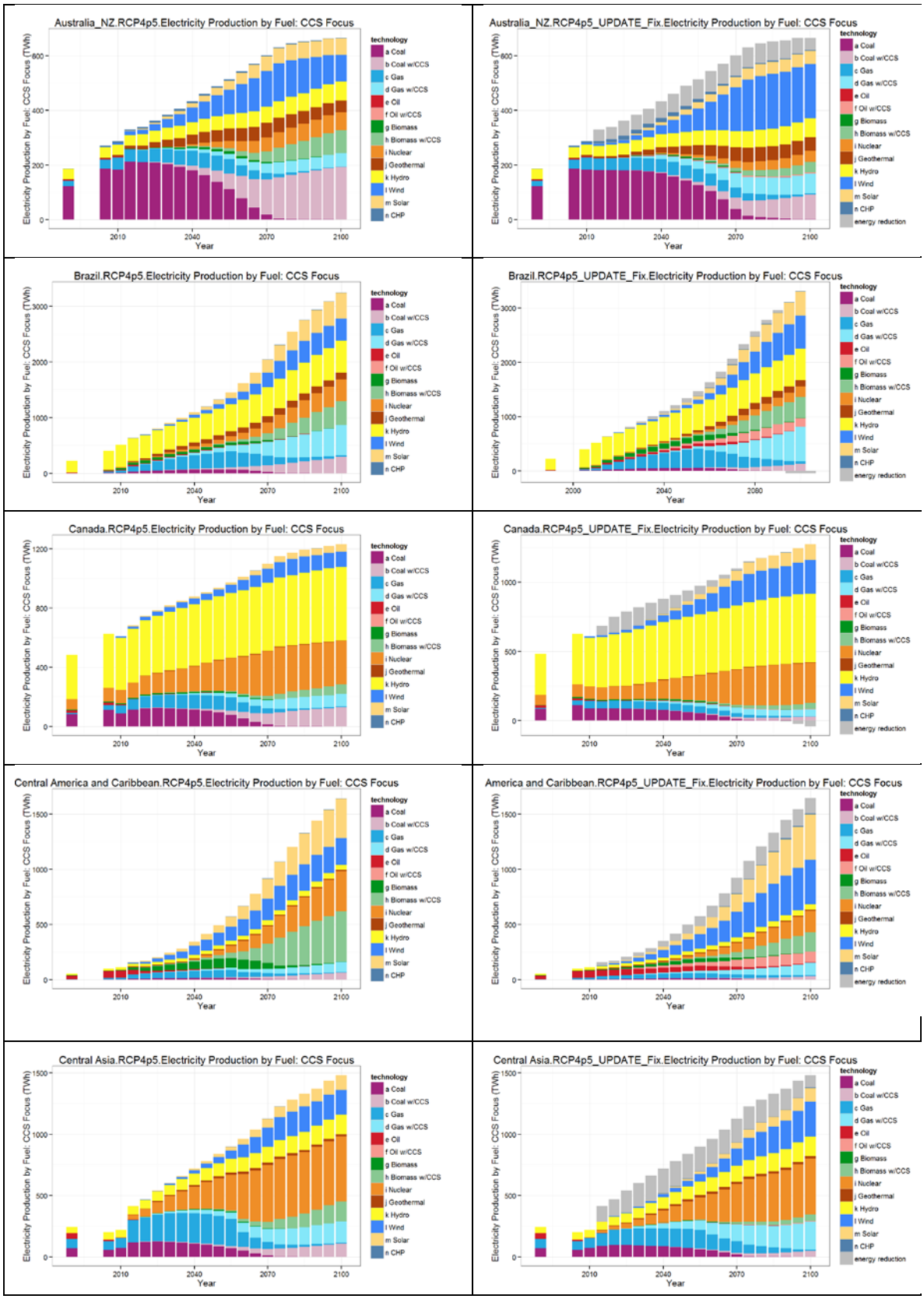
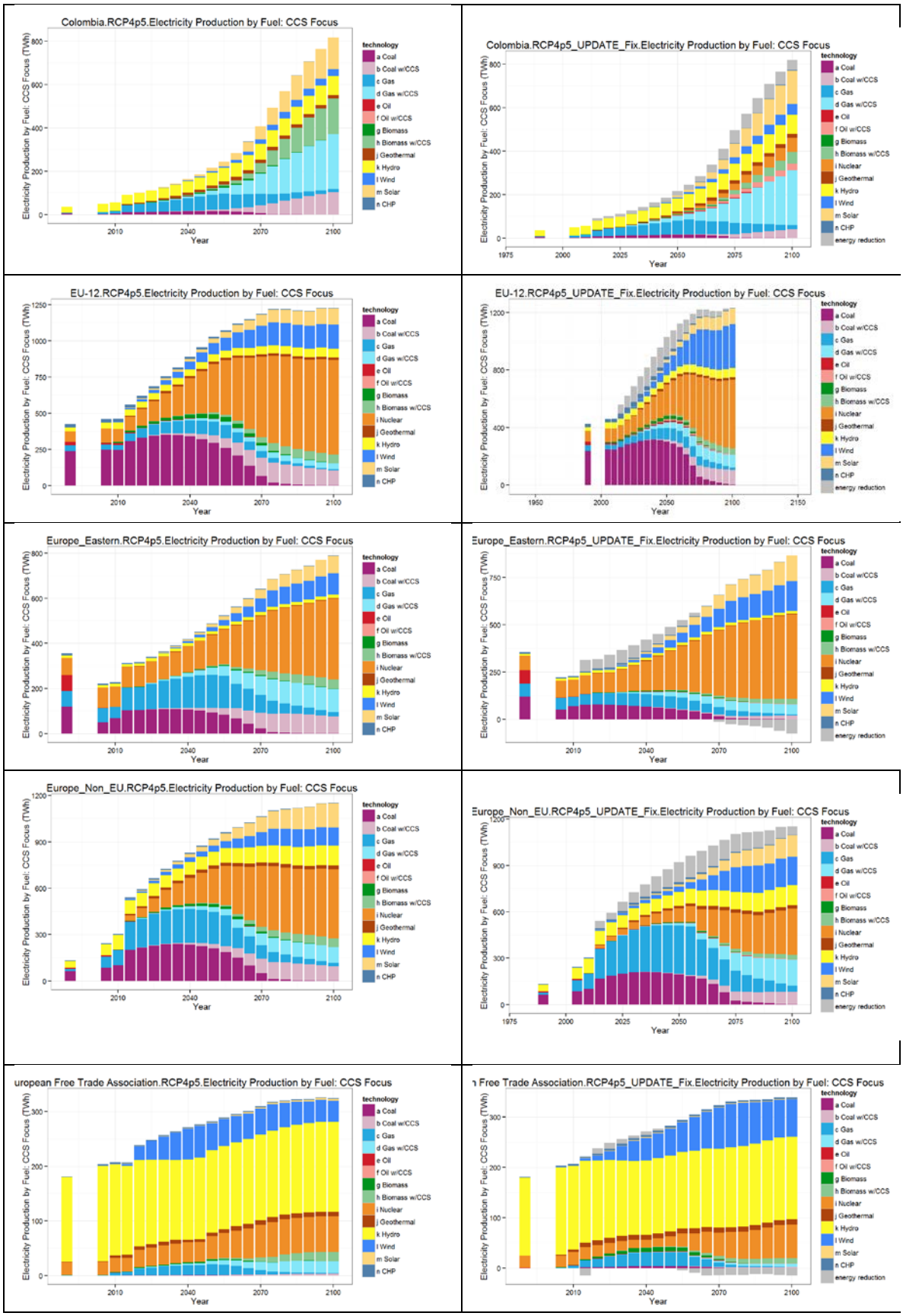
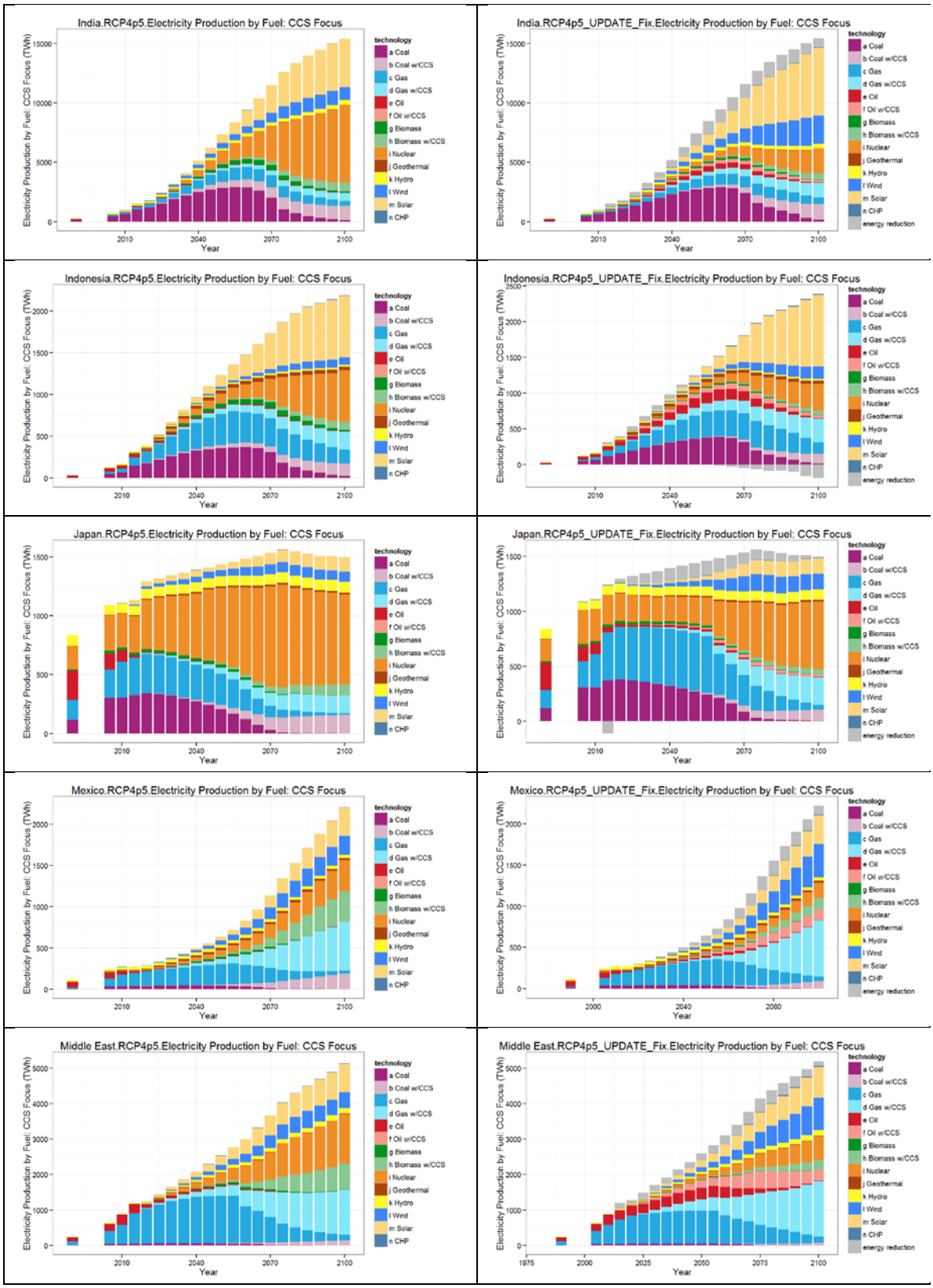
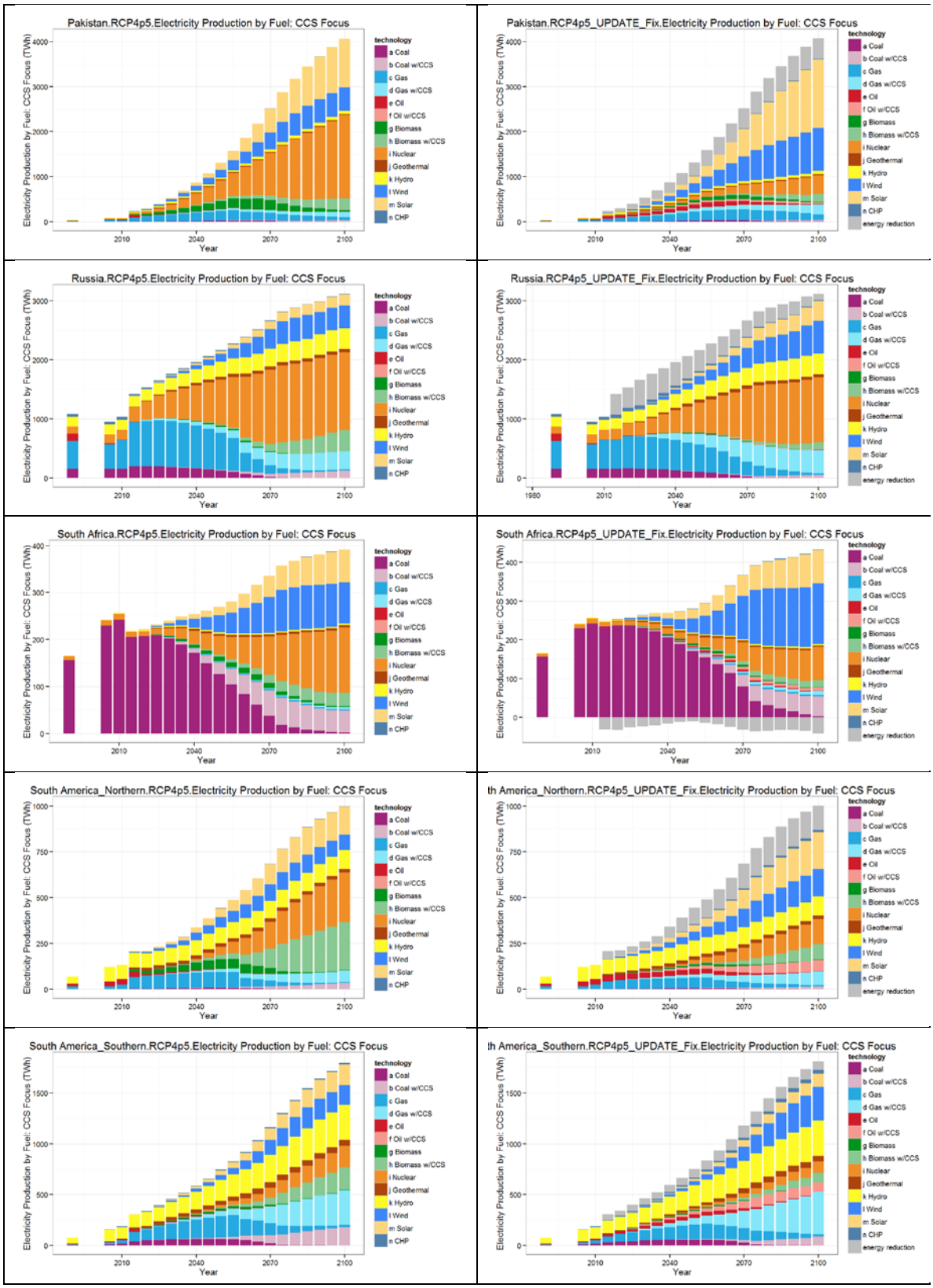
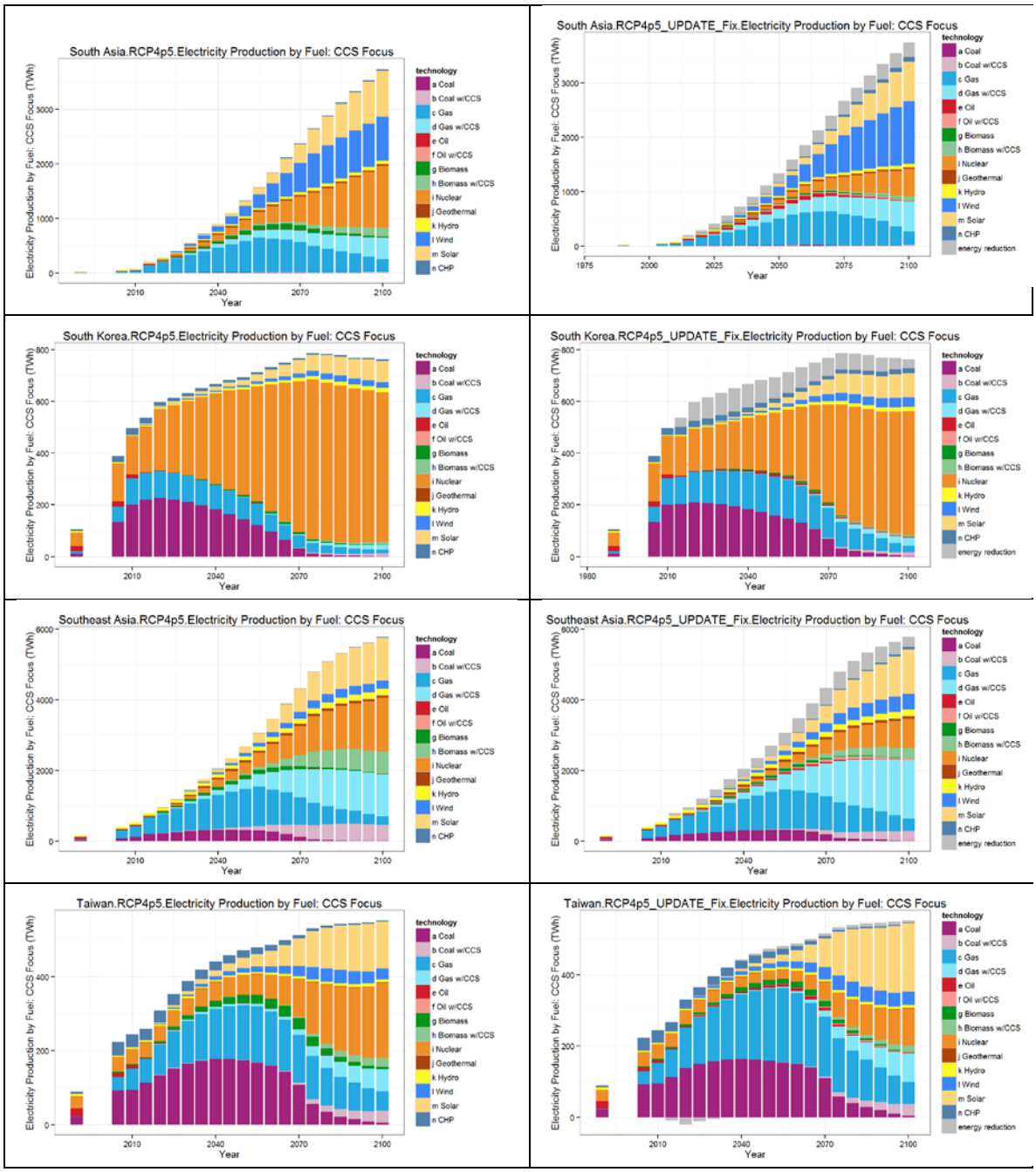
Africa_Eastern.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Africa_Northern.RCP4p5.Electricity Production by Fuel: CCS Focus
Africa_Northern.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Africa_Southern.RCP4p5.Electricity Production by Fuel: CCS Focus
Africa_Southern.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Africa_Western.RCP4p5.Electricity Production by Fuel: CCS Focus
Africa_Western.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Argentina.RCP4p5.Electricity Production by Fuel: CCS Focus
Argentina.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction


Australia_NZ.RCP4p5.Electricity Production by Fuel: CCS Focus
Australia_NZ.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Brazil.RCP4p5.Electricity Production by Fuel: CCS Focus
Brazil.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Canada.RCP4p5.Electricity Production by Fuel: CCS Focus
Canada.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Central America and Caribbean.RCP4p5.Electricity Production by Fuel: CCS Focus
America and Caribbean.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Central Asia.RCP4p5.Electricity Production by Fuel: CCS Focus
Central Asia.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction


Colombia.RCP4p5.Electricity Production by Fuel: CCS Focus
Colombia.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
EU-12.RCP4p5.Electricity Production by Fuel: CCS Focus
EU-12.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Europe_Eastern.RCP4p5.Electricity Production by Fuel: CCS Focus
Europe_Eastern.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Europe_Non_EU.RCP4p5.Electricity Production by Fuel: CCS Focus
Europe_Non_EU.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
uropean Free Trade Association.RCP4p5.Electricity Production by Fuel: CCS Focus
n Free Trade Association.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction


India.RCP4p5.Electricity Production by Fuel: CCS Focus
India.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Indonesia.RCP4p5.Electricity Production by Fuel: CCS Focus
Indonesia.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Japan.RCP4p5.Electricity Production by Fuel: CCS Focus
Japan.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Mexico.RCP4p5.Electricity Production by Fuel: CCS Focus
Mexico.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Middle East.RCP4p5.Electricity Production by Fuel: CCS Focus
Middle East.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction


Pakistan.RCP4p5.Electricity Production by Fuel: CCS Focus
Pakistan.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Russia.RCP4p5.Electricity Production by Fuel: CCS Focus
Russia.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
South Africa.RCP4p5.Electricity Production by Fuel: CCS Focus
South Africa.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
South America_Northern.RCP4p5.Electricity Production by Fuel: CCS Focus
th America_Northern.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
South America_Southern.RCP4p5.Electricity Production by Fuel: CCS Focus
th America_Southern.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction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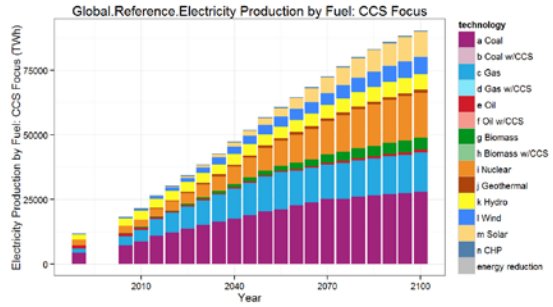
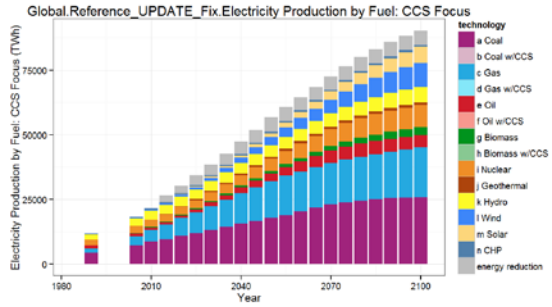
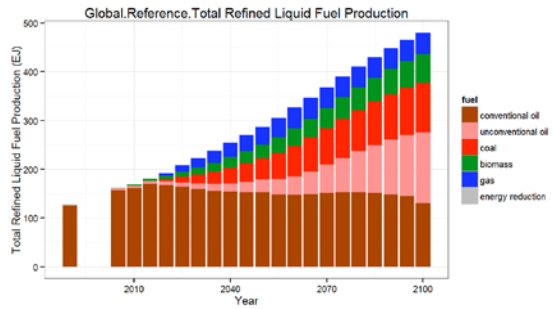
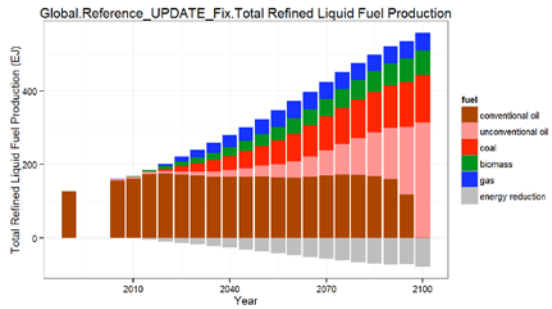
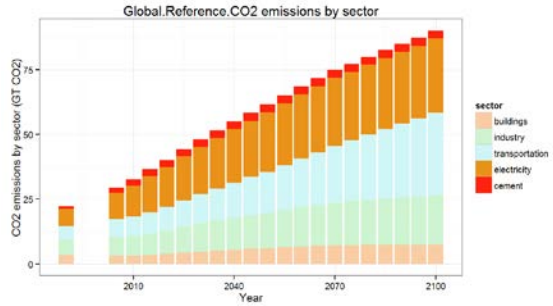
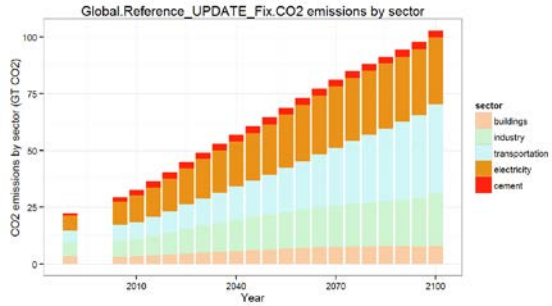
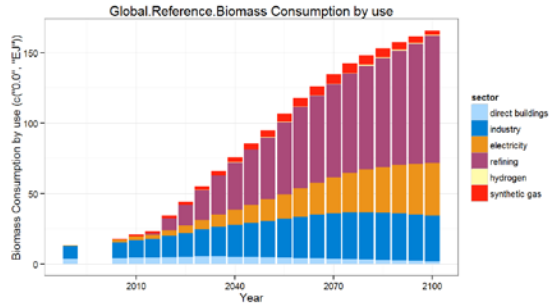
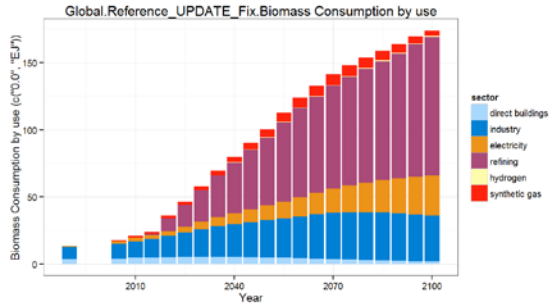
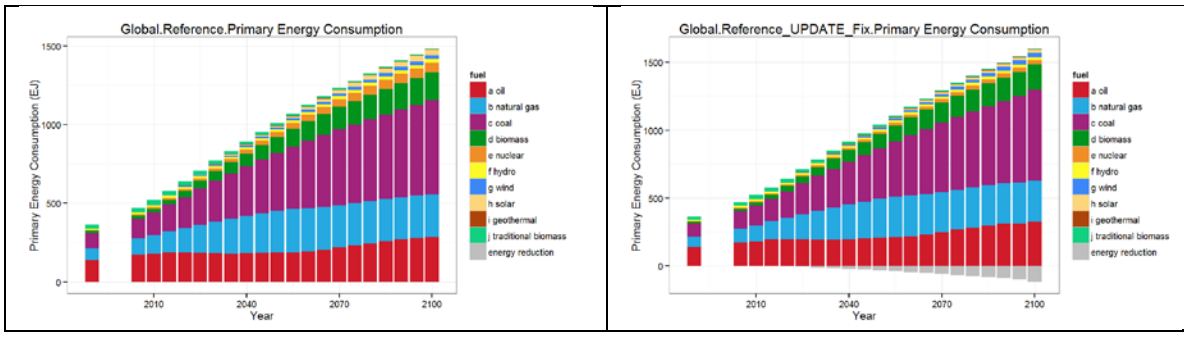
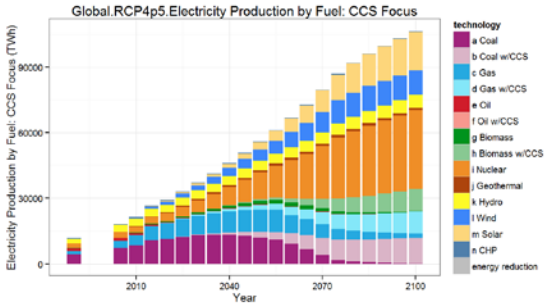
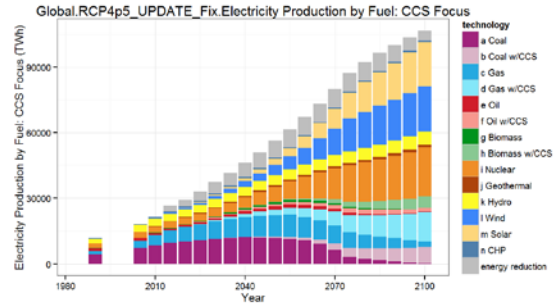
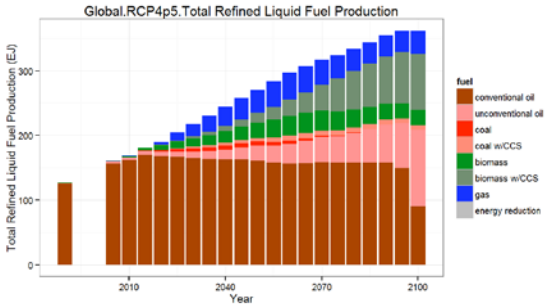
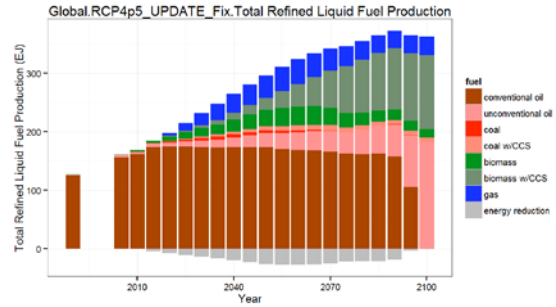
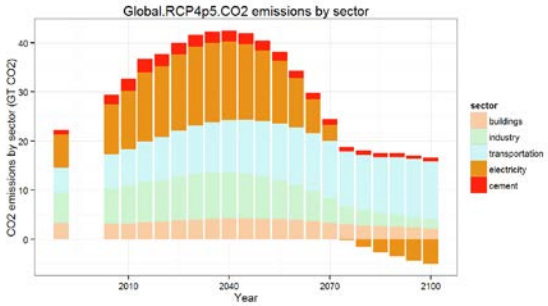
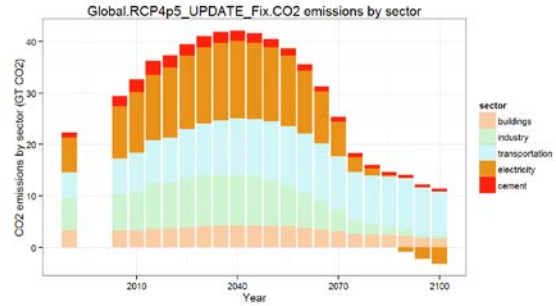
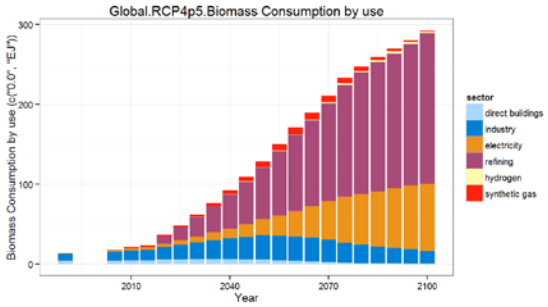
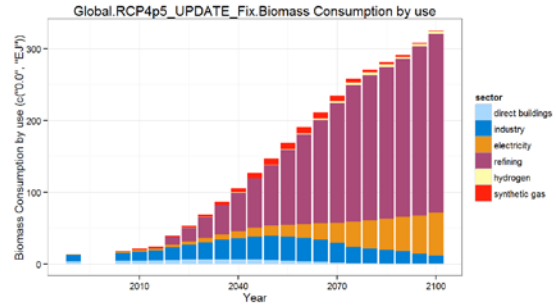
South Asia.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
South Korea.RCP4p5.Electricity Production by Fuel: CCS Focus
South Korea.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Southeast Asia.RCP4p5.Electricity Production by Fuel: CCS Focus
Southeast Asia.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Taiwan.RCP4p5.Electricity Production by Fuel: CCS Focus
Taiwan.RCP4p5_UPDATE_Fix.Electricity Production by Fuel: CCS Focus
Electricity Production by Fuel: CCS Focus (TWh)
Year
technology
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m Solar
n CHP
energy reduction

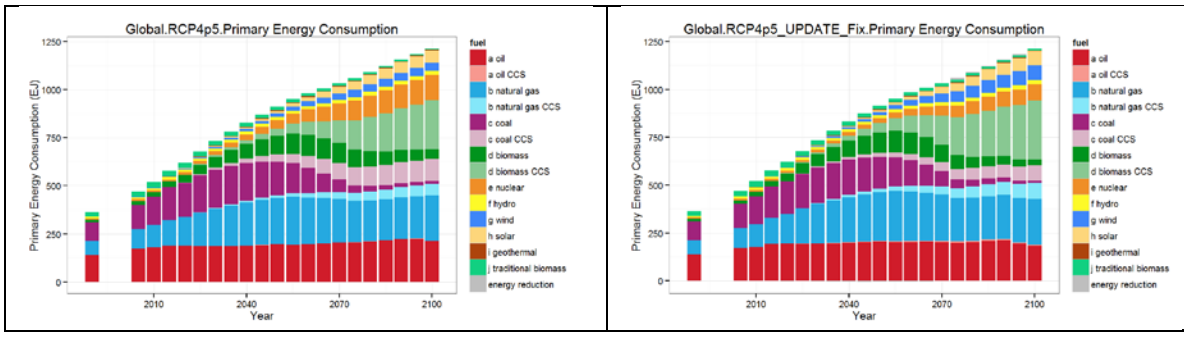
REFERENCE SUMMARY

CURRENT GCAM REFERENCE SCENARIO	UPDATED GCAM REFERENCE SCENARIO
	
	
	
	

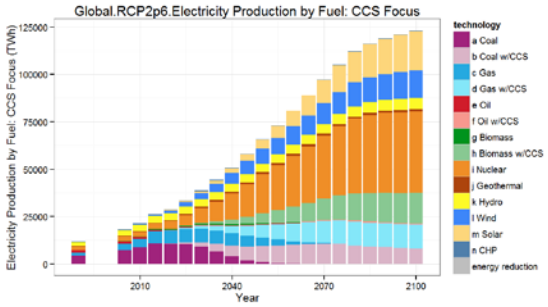
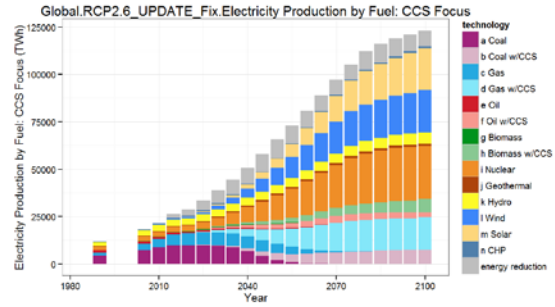
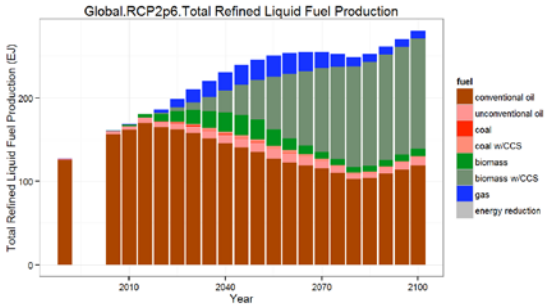
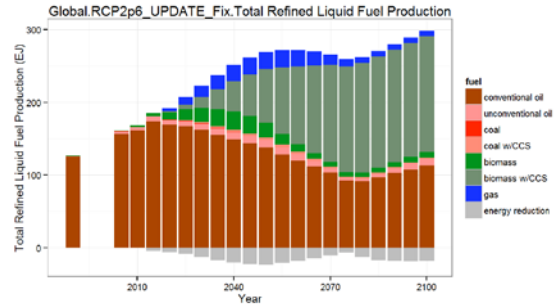
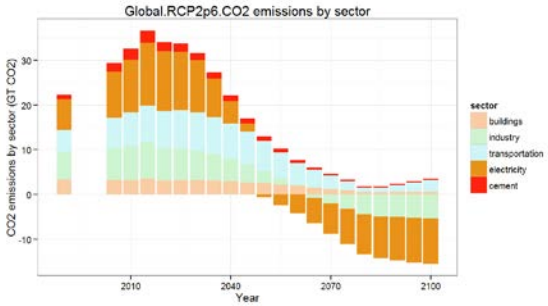
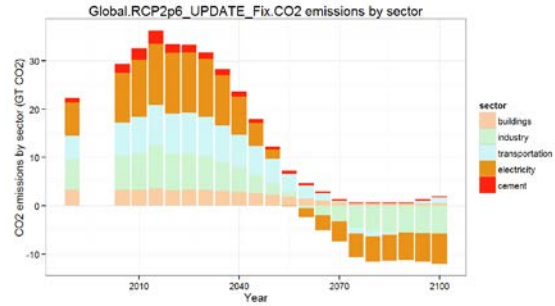
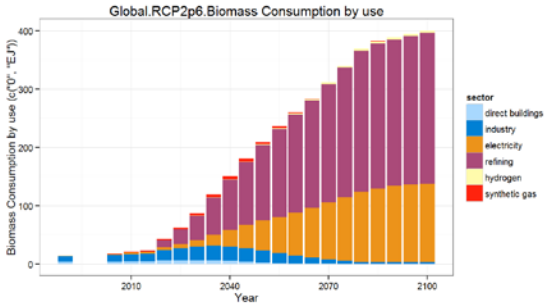
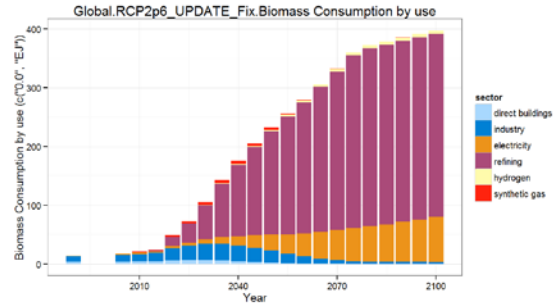

Global.Reference.Primary Energy Consumption
Primary Energy Consumption (EJ)
1500
1000
500
0
2010
2040
2070
2100
Year
fuel
a oil
b natural gas
c coal
d biomass
e nuclear
f hydro
g wind
h solar
i geothermal
j traditional biomass
energy reduction
Global.Reference_UPDATE_Fix.Primary Energy Consumption
Primary Energy Consumption (EJ)
1500
1000
500
0
2010
2040
2070
2100
Year
fuel
a oil
b natural gas
c coal
d biomass
e nuclear
f hydro
g wind
h solar
i geothermal
j traditional biomass
energy reduction

RCP 4.5 SUMMARY

CURRENT GCAM RCP 4.5 SCENARIO	UPDATED GCAM RCP 4.5 SCENARIO
	
	
	
	


Global.RCP4p5.Primary Energy Consumption
Primary Energy Consumption (EJ)
1250
1000
750
500
250
0
2010
2040
2070
2100
Year
fuel
a oil
a oil CCS
b natural gas
b natural gas CCS
c coal
c coal CCS
d biomass
d biomass CCS
e nuclear
f hydro
g wind
h solar
i geothermal
j traditional biomass
energy reduction
Global.RCP4p5_UPDATE_Fix.Primary Energy Consumption
Primary Energy Consumption (EJ)
1250
1000
750
500
250
0
2010
2040
2070
2100
Year
fuel
a oil
a oil CCS
b natural gas
b natural gas CCS
c coal
c coal CCS
d biomass
d biomass CCS
e nuclear
f hydro
g wind
h solar
i geothermal
j traditional biomass
energy reduction

RCP 2.6 (with limited negative emissions) SUMMARY

CURRENT GCAM RCP 2.6 SCENARIO	UPDATED GCAM RCP 2.6 SCENARIO
	
	
	
	

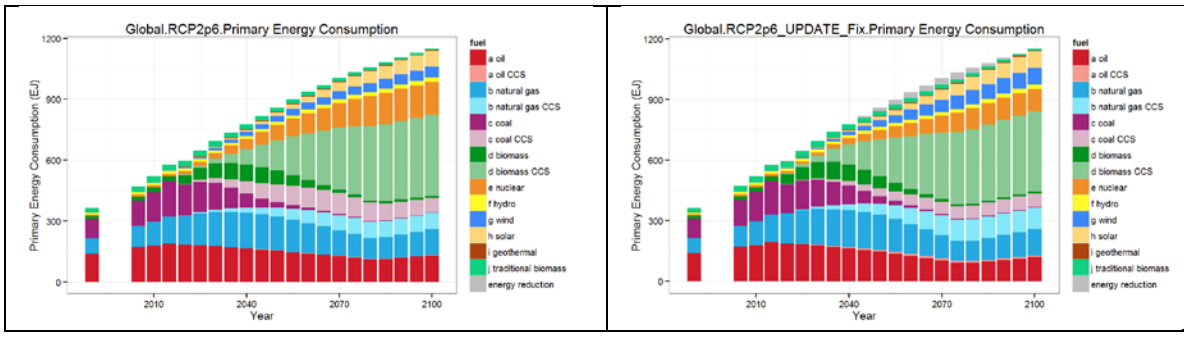


Table 12. Primary energy consumption shares in 2100 (direct equivalent).

	Reference		RCP4.5		RCP2.6	
	Old	**New**	**Old**	**New**	**Old**	**New**
Oil	19%	20%	18%	16%	12%	11%
Natural gas	18%	19%	25%	27%	18%	21%
Coal	41%	42%	11%	8%	7%	6%
Biomass	11%	11%	24%	27%	36%	35%
Nuclear	4%	2%	11%	7%	14%	9%
Hydro	1%	1%	2%	2%	2%	2%
Wind	2%	2%	3%	6%	5%	7%
Solar	2%	1%	5%	6%	7%	7%
Geothermal	0%	0%	0%	0%	0%	0%
Traditional Biomass	0%	0%	1%	1%	1%	1%

FINAL OBSERVATIONS:

Overall, here the key effects of this proposal:

1) Electricity is less used in the reference scenario (-7% globally in 2100), due to its generally higher cost.
2) **Nuclear** is significantly less used (in the reference scenario -50% in 2100 compared to the current version of GCAM; -38% in the RCP4.5 scenario). Still, electricity production from nuclear power plants increases monotonically in the revised scenarios, increasing by 25% by 2030, 75% by 2050, and three-fold by 2100 in the reference scenario; and by 31% by 2030, 247% by 2050, and 8.1 fold by 2100 in the RCP4.5 scenario.
3) **Wind** is more widely deployed in policy scenarios. In the RCP4.5 scenario solar accounts for 5.4% and wind for 10% of the market in 2050. Both reach 20% by 2100 (compared to 16% and 11% in the current version of GCAM). RCP4.5 saturates the solar and wind deployment, no significant increase in RCP2.6.
4) **Natural gas** is more widely used to produce electricity. Coupled to CCS in the climate change mitigation scenarios.
5) **Biomass** is less used for electricity production, but its share of primary energy is not significantly changed.
6) In **stringent climate policy scenarios** the electricity sector takes on less negative emissions, which come from the production of refined liquids using BECCS. Some of these biomass-generated liquids are then used to produce electricity in CC plants.