Supplementary Materials: A Sketch of Bolivia's Potential Low-Carbon Power System Configurations. The Case of Applying Carbon Taxation and Lowering Financing Costs

Jenny Gabriela Peña Balderrama [1,2,*], Thomas Alfstad [3], Constantinos Taliotis [4], Mohammad Reza Hesamzadeh [5] and Mark Howells [1]

Annex A

Gas export price projections.

Contractual natural gas export prices are indexed to international reference oil prices; and consequently, volatile to any fluctuation that this might entail. The quarterly export prices for the current contract with Brazil follows Equation (S1).

$$P_{G,t} = P_{B,i}\left(0{,}5 \cdot \frac{FO_{1,t-1}}{FO_{1,0}} + 0{,}25 \cdot \frac{FO_{2,t-1}}{FO_{2,0}} + 0{,}25 \cdot \frac{FO_{3,t-1}}{FO_{3,0}}\right) \quad \text{(S1)}$$

Where: $P_{G,t}$ is the gas export price in the quarter t, US$/MMBTU, $P_{B,i}$ is the reference price in US$/MMBTU, FO_1, FO_2 and FO_3 refer to three reference oil prices (Fuel oil 35% sulphur FOB Med Cargoes Italy, fuel oil 1% sulphur U.S. Gulf Coast Waterborne and fuel oil 1% sulphur Cargoes FOB NEW respectively.) , $FO_{1,t-1}$, $FO_{2,t-1}$, $FO_{3,t-1}$ are the average fuel oil prices from the quarter immediately to *t* and $FO_{1,0}$, $FO_{2,0}$, $FO_{3,0}$ values are the average fuel oil prices for the period 1990-1992. The price is re-calculated each quarter following Equation (S2):

$$P_{t} = 0.5 \cdot P_{G,t-1} + 0.5 \cdot P_{G} \quad \text{(S2)}$$

Where: P_t is the gas price for the quarter t and P_G is the gas price calculated by Equation (S1).

For sake of simplicity and due similar historical trends between international oil prices with the West Texas International oil price, the later was used as exogenous variable to project the Bolivian gas export price. Historical (quarterly) WTI oil prices from 1999–2015 and annual projections to 2050 (Reference Oil Scenario) were used from the Annual Energy Outlook 2016, EIA.

A Vector Error Correction model was used to estimate the long-run relationship between the WTI oil price and the gas export price Equation (S3). The estimated equation and relevant statistics are presented in Table S1. Projections are illustrated on Figure S1.

$$\Delta y_{t-1} = \gamma \cdot (y_{t-1} - a - b \cdot x_{t-1}) + c + \beta \cdot \Delta x_{t-1} + \varepsilon_t \quad \text{(S3)}$$

Where: y_t is the logarithm of the gas export price, x_t is the logarithm of the WTI oil price, γ is the long-term error correction factor, a and b are cointegrating coefficients, c is the intercept, β is the short-term correction factor, ε_t are the error terms and t represent each observation in quarterly basis.

Table S1. VECM regression results.

Coefficients	Value	Std. Error	p-Value
A	−1.273	0.061	0.061
B	1.557	0.000	0.000
c	0.029	0.008	0.001
γ	−0.247	0.028	0.000
β	-	-	-
Cointegration Regression	**Value**	**Model Validation Tests**	**p-Value**
R-Squared	0.542	Normality test, Jarque-Bera stat.	0.087
Durbin-Watson stat.	1.213	VEC Residual Heteroskedasticity, Chi-sq	0.012
Sum sq. resids	0.303	VEC Residual Portmanteau, Lag1	0.002
Observations	67	Granger Causality	1.00E-11

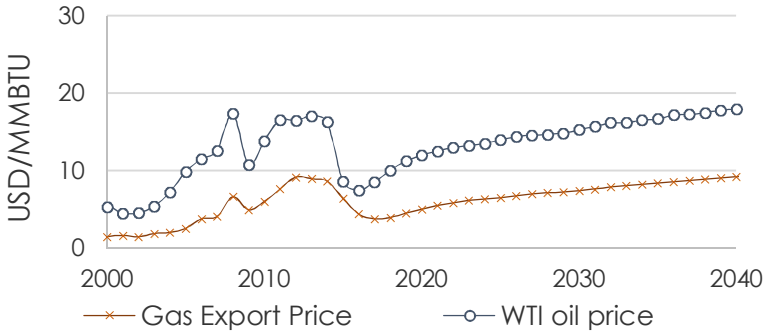

Figure S1. Gas export price and WTI projections.

Annex B

Table S2. Cost and technical input data. References: (*) [2], (**) [21].

Technologies	Scenario	Overnight capital cost				Fixed cost	Variable cost	Construction Time	Capacity factor [b]	Efficiency [a]	Economic lifetime
		USD/kW				USD/kW	USD/MWh	years	%	%	years
		2012	2020	2030	2040	2012–2040	2012–2040	2012–2040	2012–2040	2012–2040	2012–2040
**Diesel centralized, base 5MW	All	590	590	590	590	10	33	2	85	35	20
**HFO, Sub-critical Oil-fired, base 300 MW	All	1180	1180	1180	1180	21	33	2	85	35	20
**OCGT, base 150 MW	All	480	480	480	480	7	0.45	2	85	42	30
**CCGT, base 140 MW	All	1140	1140	1140	1140	17	1	3-2	85	52	30
*Pulverized Coal Power plant, base 300 MW	All	2920	2920	2920	2920	44	4	4	85	45	40
**Hydropower run of river small scale	All	3350	3300	3300	3300	35	7	2	[a]	100	50
**Hydropower dam medium scale	All	2100	2100	2100	2100	45	1	5-4	[a]	100	50
**Hydropower dam large scale	All	2100	2100	2100	2100	30	1	5	[a]	100	50
*Biomass steam turbine, base 50 MW	High	2250	2200	2100	2050	80-75	3	3	34	35	30
	Ref	2250	2200	2150	2150	80-75	3	3	34	35	30
	Low	2250	2200	2200	2220	80-75	3	3	34	35	30
*Geothermal incineration, base 50 MW	High	5218	5088	4696	4305	78	5	4	85	35	20
	Ref	5218	5218	5218	5218	78	5	4	85	35	20
	Low	5218	5218	5218	5218	78	5	4	85	35	20
*Wind onshore, base 50 MW	High	1380	1300	1240	1220	38–36	0	3–2	[a]	100	30

	Ref	1380	1320	1280	1280	38–36	0	3–2	[a]	100	30
	Low	1380	1320	1280	1280	38–36	0	3–2	[a]	100	30
*Solar PV, Buildings, base 5kW	High	2680	1740	1280	1080	30–26	0	1	[a]	25	25
	Ref	2680	1780	1400	1240	30–26	0	1	[a]	25	25
	Low	2680	2230	2116	2068	30–26	0	1	[a]	25	25
*Solar PV, large scale, base 100 MW	High	1980	1340	980	840	24–20	0	2	[a]	25	30
	Ref	1980	1360	1080	960	24–20	0	2	[a]	25	30
	Low	1980	1670	1530	1470	24–20	0	2	[a]	25	30
*Concentrated solar power	High	5350	4700	3500	2950	210–140	4	3	[a]	35	40
	Ref	5350	4850	4050	3550	210–140	4	3	[a]	35	40
	Low	5350	5100	4860	4710	210–140	4	3	[a]	35	40
**Overhead Transmission 230 kV, connecting same nodes, [c]	All	140	140	140	140	0	0	3	na	93–97	60
**Overhead Transmission 230 kV, connecting different nodes, [c]	All	306	306	306	306	0	0	3	na	93–98	60
**Overhead Transmission 500 kV, connecting large power plants to nodes, [c]	All	131	131	131	131	0	0	5	na	93–99	60
**Overhead Transmission 69 kV, connecting North off-grid, [c]	All	489	489	489	489	0	0	3	na	93–100	60
**Overhead Transmission 69 kV, connecting **Oriental off-grid, [c]	All	381	381	381	381	0	0	3	na	93–101	60
**Overhead Transmission 69 kV, connecting South off-grid, [c]	All	195	195	195	195	0	0	3	na	93–102	60
**Distribution lines	All	1300	1300	1300	1300	0	0	2	na	85–91	60

[a] Capacity factor for renewable technology are specific for each region. [b] Altitude corrections were applied to thermal efficiency.

Table S3. Altitude correction factor for thermal efficiency. Reference: [21].

Region	Correction	Gas Open Cycle	Gas Combined Cycle	Diesel Generator
	Factor	Efficiency (%)	Efficiency (%)	Efficiency (%)
North	0.99	42.4%	53.4%	34.6%
Central	1.01	41.6%	52.4%	35.2%
West	1.02	40.9%	51.5%	35.8%
South	1.02	41.1%	51.8%	35.7%

Table S4. Assumptions to calculate finance costs during construction.

Technology	Years Before Commercial Operation (% of Total overnight cost in given Year)					
	−5	**−4**	**−3**	**−2**	**−1**	**0**
Diesel centralized					20	80
HFO, Sub-critical Oil-fired					35	65
OCGT					25	75
CCGT				10	60	30
Pulverized Coal Power plant					20	80
Hydropower run of river small scale			20	30	20	80
Hydropower dam medium scale		0	10	25	35	30
Hydropower dam large scale	10	15	20	20	25	10
Biomass steam turbine			20	30	35	15
Geothermal			10	25	35	30
Wind onshore					25	75
Solar PV, buildings						100
Solar PV, large scale					25	75
Concentrating solar power				10	60	30
Transmission and distribution lines						100%

Table S5. Data used for calculating solar capacity factors.

Technical Data for Model					
Dataset		MERRA- 2 (global)			
Capacity		5 MW			
Tilt:		35			
Azimuth		180			
Sub-region		Point 1	Point 2	Point 3	Point 4
North	Lat	−17.728	−17.424	−16.941	−17.34
	Long	−66.841	−68.324	−68.994	−68.917
Central	Lat	−17.728	−17.508	−17.214	−17.853
	Long	−66.05	−66.237	−66.292	−65.841
East	Lat	−18.334	−18.615	−18.386	−18.782
	Long	−63.402	−62.996	−62.963	−63.358
South	Lat	−17.665	−17.497	−21.474	−21.943
	Long	−68.071	−68.73	−68.247	−65.413
Off-grid	Lat	−17.728	−17.424	−16.941	−17.34
	Long	−66.841	−68.324	−68.994	−68.917

Table S6. Data used for calculating wind capacity factors.

Technical Data for Model					
Turbine capacity		30 MW			
Hub height		80 m			
Turbine model		Vestas V90 3000			
Sub-region		Point 1	Point 2	Point 3	Point 4
North	Lat	−17.665	−17.497	−17.623	−17.372
	Long	−68.071	−68.73	−68.247	−68.906
Central	Lat	−17.728	−17.508	−17.214	−17.853
	Long	−66.05	−66.237	−66.292	−65.841
East	Lat	−18.313	−18.688	−17.853	−18.188
	Long	−63.281	−63.127	−63.237	−63.259
South	Lat	−22.004	−21.31	−20.345	−22.167
	Long	−64.006	−63.94	−63.94	−64.094
Off-grid	Lat	−17.665	−17.497	−17.623	−17.372
	Long	−68.071	−68.73	−68.247	−68.906

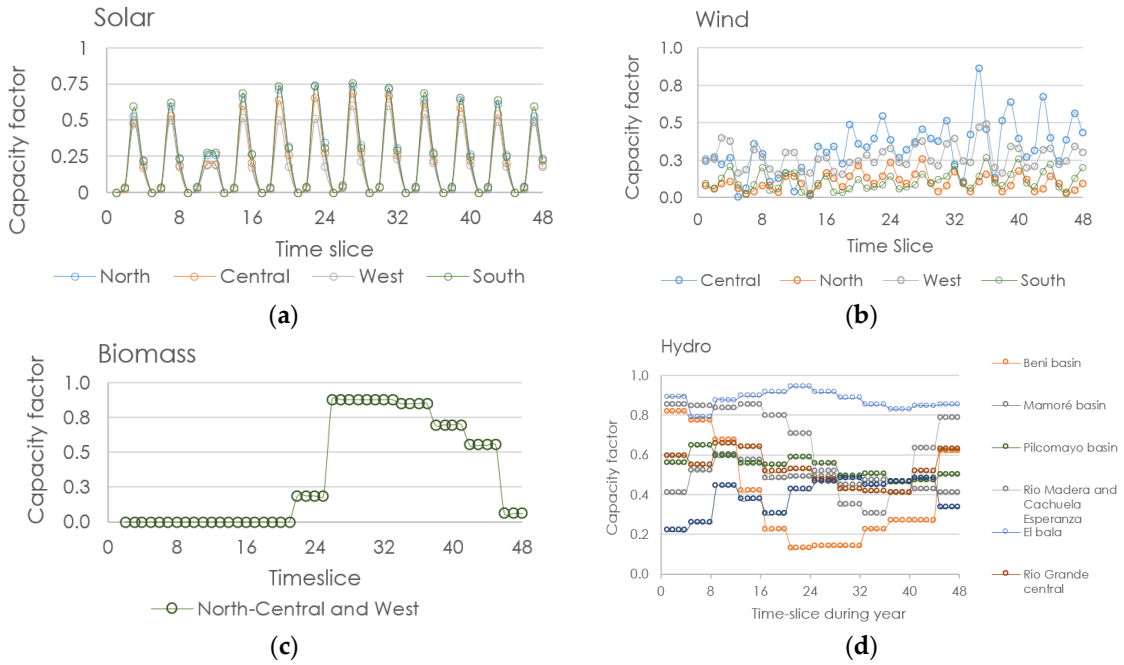

Figure S2. Capacity factors for Solar, Wind, Hydro and Biomass.

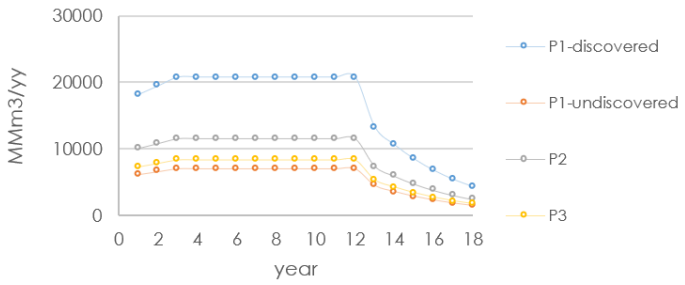

Figure S3. Reservoir Production Estimates.

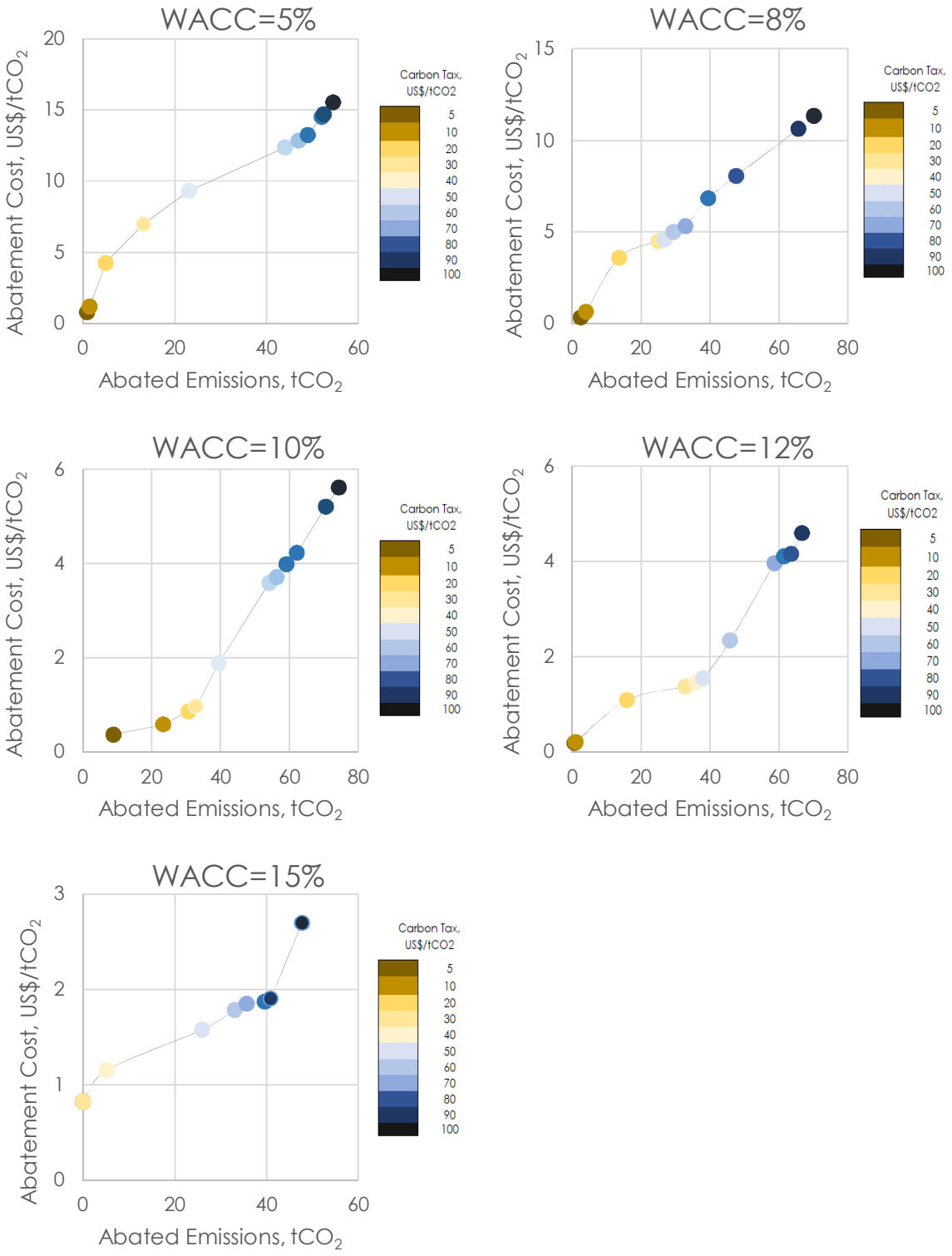

Figure S4. Discounted abatement costs, USD/avoided tCO_2 e for all discount rate scenarios.