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A Report for NWPCC

Forecasting the Future Value of Carbon

A Literature Review of Mid- to Long-Term Carbon Price Forecasts

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1 Introduction

The Northwest Power and Conservation Council (NWPCC) is currently developing its next Northwest Power Plan. As part of this process, NWPCC is considering the impacts of climate change policy on its resource planning. This report is designed to deliver insight into how CO_2 liability costs may evolve in a carbon-constrained world, so as to assist NWPCC in incorporating potential future CO_2 liabilities into its planning process for the power system in the Pacific Northwest.

Climate change mitigation policy is evolving relatively rapidly both internationally and domestically, and the cost of complying with future greenhouse gas (GHG) emissions constraints is becoming an increasingly important consideration in evaluating the financial performance of companies, projects and investments that have significant exposure to potential GHG mandates.

As pollutants, GHGs are notable for several reasons. First, they mix effectively in the atmosphere and, indeed, any given molecule of CO_2 emitted through human activities can be shifted anywhere in the atmosphere within a matter of days. Second, GHGs tend to have long atmospheric residence times and do not quickly precipitate out of the atmosphere as do pollutants like sulfur dioxide (SO_2). Moreover, GHG emissions do not pose local health risks as do criteria pollutants (i.e. there is no risk of GHG “hot spots.”)

This combination of characteristics means that GHGs are uniquely suited to market-based approaches that achieve least-cost compliance with emission reduction mandates. This is precisely the reason emissions trading has received so much attention during the development of both domestic and international climate change policy. Properly structured, emissions trading can significantly cut the costs of achieving any given reduction target.

Emissions trading can in principle occur at multiple levels, and it is possible to envision simultaneous domestic, regional, and international trading programs. Each of these programs could, in theory, have different market clearing prices owing to different operating rules and differing access to cost-effective emissions reduction opportunities. From the standpoint of projecting carbon prices in a carbon-constrained world, however, trying to anticipate the range of potential geography- or sector-specific trading markets simply adds too much complexity to an analysis of future carbon prices, and the uncertainty bands around such projections would render the projections themselves of questionable value.

For these reasons, a relatively high-level look at GHG markets is likely to generate the most useful insight into the economic implications of future carbon constraints. An international GHG market-clearing price, for example, reflecting a market that is able to take advantage of the broadest array of emission reduction options, will reflect a conservative estimate of the economic impacts associated with any given level of carbon emissions constraint. This makes political sense since political pressures, given enough time, will likely shrink any major differential between the market-clearing prices in domestic and international GHG trading systems

There remains a good deal of uncertainty regarding the manner through which GHGs will be regulated and how the markets will respond as a result. Policy options such as cap-and-trade programs and carbon taxes offer regulatory options with distinct costs and benefits.

Debating the use of carbon taxes versus cap-and-trade programs is popular among policymakers wishing to address the issue of climate change. On the one hand, a carbon tax sets a price that regulated emitters must pay for every ton of GHG they release into the atmosphere above a given level. A cap-and-trade program, in contrast, sets a limit on GHG emissions themselves. Under a cap-and-trade, the regulating body issues “allowances” to capped entities, representing the right to emit a certain amount of GHGs. Allowance holders that reduce their emissions below this amount may sell their allowances to those who exceed their cap. Thus, a carbon tax fixes the *price* of carbon while leaving the environmental results uncertain, while a cap-and-trade program fixes the *quantity* of emissions while letting price be determined by the market.

Those who support a carbon tax consider price reliability to be of key importance. If the costs of regulation are certain, decision-makers can make investments based on predictable, long-term energy prices. They also argue that taxes are more easily implemented and more transparent than cap-and-trade systems. Cap-and-trade advocates, on the other hand, point to the political challenges associated with imposing a carbon tax significant enough to materially influence GHG emissions. Given the short window of time we have to address the climate change problem, they argue, it is better to be certain of the environmental result than of the cost.

Politicians historically favor cap-and-trade systems; the current regulatory climate—both in the United States and abroad—generally favors the development of such programs. Established systems include emissions trading under the Kyoto Protocol, the European Union Emission Trading Scheme (EU ETS), and the New South Wales (NSW) Greenhouse Gas Abatement Scheme. Within the US, two cap-and-trade systems—the Regional Greenhouse Gas Initiative (RGGI) and the Western Climate Initiative (WCI)—are in advanced stages of development, while the proposed Boxer-Lieberman-Warner bill would establish a comprehensive federal program. The Chicago Climate Exchange (CCX), a voluntary but legally-binding cap and trade program, has been trading emission allowances among participating entities since 2003.

Despite the popularity of cap-and-trade systems as a regulatory means of managing GHGs, forecasting the future value of carbon in a carbon-constrained world is usually done through GHG price forecasting models that use a carbon tax proxy to forecast carbon prices even in a cap-and-trade scenario. This is the case because macro-economic models are the most useful way to forecast long-term carbon costs given the complexity of the impacts of a carbon constraint on national and global economies, and the many feedbacks that are involved. That said, the use of a carbon tax proxy in most modeling represents yet another complicating variable in confidently forecasting future GHG prices.

The models profiled in this review were chosen based on their relative transparency and credibility, and to reflect a range of models and approaches in order to provide a wider perspective on the forecasting of GHG prices.

2 GHG Price Forecasting Introduced

This section of the report attempts to highlight the key attributes of a variety of GHG price forecasting approaches.

2.1 The Various Approaches to GHG Price Forecasting

Many studies and observers have projected or are projecting GHG prices. These projections are commonly based on several approaches:

- *Top-down models* are usually macroeconomic in structure. Their estimates are highly influenced by economic growth, energy mix, and compliance system flexibilities assumed by the modeler. These models generally do not specifically incorporate supply and demand for carbon offsets, but instead rely on a carbon-tax proxy for purposes of estimating mitigation costs. As a result, a specific GHG “commodity” is generally not defined for purposes of these models. Top-down models often generate price projections ranging from $1 to $30 per ton, although some predict costs well in excess of $100 per ton.

- *Bottom-up models* are usually project- or technology- specific. They often utilize mitigation cost curves that suggest that large-scale mitigation is available cheaply, often less than $5/ton. These estimates, however, tend to be based on social costing rather than private cost methodologies (i.e., benefits such as the dollar savings associated with energy efficiency are included in the calculation, even though they don’t actually accrue to the private entity funding the mitigation project to generate a carbon credit). Thus, they are often hard to translate into GHG market price forecasts.

- *“By analogy” forecasting* extrapolates from experience with other environmental commodities to the GHG market. Many observers, for example, have argued that because SO_2 allowance prices were much lower than anticipated when a trading system was implemented, GHG credit prices will also fall from current levels once a formal trading system is implemented. Unfortunately, the conclusions commonly drawn from an analogy-based approach fundamentally mischaracterize the relationship between SO_2 and CO_2 emission reduction potentials. SO_2 allowance price projections, for example, were based on technology-based market clearing prices (e.g., FGD construction). Most CO2 price projections, however, are already based on assuming access to the lowest cost mitigation options, as opposed to assuming that mitigation will be accomplished through carbon capture and sequestration (CCS) or other “high tech” interventions. In terms of technologies that could cap GHG credit prices, a survey of many CO_2 avoidance technologies suggests that many technologies become available at costs of $50-100 per ton.

- *"Historical extrapolation" forecasting* is often used as the basis from which to project price trends. Given the early stages of the GHG market, however, and the fact that most of its key attributes remain to be finalized (including commodity definition, supply, and demand), looking to historical prices in voluntary or even limited regulatory markets to date is a risky approach.

- *"Expert surveys"* are often used in forecasting future GHG prices based on the premise that people familiar with the market have the most insight into where prices are likely to head. This approach, however, clearly suffers from a "groupthink" phenomenon, in which everyone tends to end up with the same forecast. In addition, it can be difficult to separate out an individual's market projections from their own self-interest. For example, the brokerage community clearly has an interest in motivating near-term transactions by arguing that prices are rising, and that now is the time to buy. Some regulated industries in Canada and Europe have also had an interest in forecasting very high credit prices in an effort to get more generous allowance allocations or other favorable policy dispensations in the near term. Neither necessarily reflects supply and demand realities in the market.

It is important when forecasting GHG prices to understand the strengths and limitations of each approach profiled above, and the source of estimates used by advocates or in the press. Furthermore, it is important to assess how each approach can contribute to constructive policy and corporate planning and decision making. Table 1 provides a short review of the strengths and weaknesses of each approach. While each forecasting approach has its advantages, in the end none of the approaches alone is likely to be able to provide a sufficient foundation for carbon price forecasting for serious policy and corporate decision-making. A key limitation of each of these approaches is that they often do not provide a clear picture of the policy scenario associated with a given price projection. In reality, carbon markets and market-clearing prices will be profoundly dependent on the details of the policy scenario that is being implemented, since these details will largely determine both the demand for emissions reductions, and the shape of the emissions reduction supply curve. Carbon markets are truly policy-based markets, and are thus fundamentally different than conventional commodity markets.

Approach	Strengths	Limitations
Top Down Analysis	Assesses the economy-wide effects of a change in energy prices.	Does not define the project-level reductions being accomplished. Unable to differentiate between BAU and non-BAU reductions at the project level.
Bottom-up Analysis	Provides detailed insight into the mitigation opportunities of specific sector(s).	Generally unable to differentiate between BAU and non-BAU reductions. Often use social cost estimates that are difficult to compare, and don't reflect private sector investment costs. Unable to incorporate feedbacks.
Experience with Current Environmental Commodity Systems	Build upon the proven ability of trading systems to help lower overall implementation costs.	Many characteristics of the GHG market and eventual GHG commodity are fundamentally different than those encountered in previous environmental markets.
Extrapolating from Current Market Trends	Based on empirical evidence of what has been happening in the GHG marketplace.	The historic GHG market is not necessarily predictive of future GHG markets, and it does not incorporate policy decisions that will define the carbon market commodity.

Table 1: Summary Assessment of Common Approaches to GHG Price Forecasting

3 GHG Market Modeling: An Overview of Results

This section of the report reviews a range of analyses that have compared modeling results in forecasting carbon costs in a carbon-constrained world. The models discussed here are publicly available.

- The EMF 16 Study
    - Macro-economic study of a variety of models primarily producing pre-2020 carbon cost projections

- The DICE Model
    - Macro-economic model which utilizes a global average figure for emissions and project prices for a variety of scenarios out to 2025

- The CCSP Report
    - Integrated assessment using three models to predict carbon costs out to 2030, assuming alternative radiative forcing targets.

- The Pew Center Analysis
    - Report on six model outcomes (all using different assumptions) projecting the carbon costs associated with the proposed Lieberman-Warner Climate Security Act.

- The EMF 21 Study
    - Macro-economic study of a variety of models producing carbon cost projections out to 2025, assuming distinct radiative forcing targets

ECL focuses on these reports and models due to their time horizons, the variety of approaches reflected, the variety of assumptions made, and the different geographical scopes included. We have highlighted the range of predicted prices, and have included summary bullets regarding key assumptions underlying different modeling results.

3.1 Key Modeling Variables

Each model reviewed in this section differs in terms of its inherent structure. Apart from structural differences, however, several variables can be identified as the most significant in influencing estimates of the cost of achieving future carbon emissions constraints.

- *Socioeconomic assumptions, GDP growth, primary energy needs, and baseline emissions.* All other things being equal, higher GDP development, higher primary energy use, and higher baseline emissions will result in higher costs associated with achieving a given CO_2 concentration target. Reference scenarios were not identical among the models, and baseline emissions projections vary substantially.

- *Primary energy mix and available technology.* The cost of CO_2 controls also depends on the assumptions regarding the composition of the primary energy mix (i.e. fossil-fuel use vs. other fuels. The different models sometimes assume very different energy mixes, as well as energy prices).

- *Carbon sequestration and other carbon control technologies.* The third core determinant of CO_2 control costs involves differences in the assumed cost of carbon capture, and the relative reliance on this technology for CO_2 mitigation. Some models assume rapid “learning” in these two areas, and end up with much lower CO_2 control costs than models now making the same assumption.

- *Discount rates and assumptions that affect the timeframe or ease of implementing reductions.* The discount rate and timeframe over which models assume reductions to occur have a significant impact on the ultimate presumed value of carbon. Those models that assume low discount rates will typically generate higher net-present-values for carbon-credit projects, than models that assume greater discount rates for similar projects within the same time period.

3.2 GHG Price Modeling Results

3.2.1 The EMF 16 Study (1999)

The most notable macroeconomic modeling studies concentrating on the pre-2020 period were featured in Stanford University's Energy Modeling Forum (EMF) 16 study, published in 1999. (See Table 2 for a summary of the study). The EMF 16 study contained a wide range of model results associated with implementation of the Kyoto Protocol. The range of results published in the EMF 16 reflects structural differences and differences in model assumptions. Although some models featured carbon taxes for the long term (e.g., AIM, RICE), most models in this study concentrated on near-term (pre-2020) price projections. The EMF study assumed that all Annex I countries would maintain their Kyoto targets throughout the analyzed period under three market scenarios: (1) without trading, (2) with trading between industrialized countries only, and (3) with global trading. The meta-analysis provided in the 1999 study uses carbon taxes as a proxy for measuring the economic costs of implementing the Kyoto Protocol. The carbon tax proxy is intended to provide a rough estimate of how much energy prices would have to be increased in order to stabilize emissions at 7 percent below 1990 emissions by 2012.

Model	2010 Carbon Price, US$1990		
	No trading	Annex I trading	Global trading
ABARE-GTEM	87.7	28.9	6.3
AIM	41.7	17.7	10.4
CETA	45.8	12.5	7.1
G-Cubed	20.4	14.4	5.4
MERGE3	71.9	36.8	23.4
MS-MRT	64.3	21.0	7.4
RICE	51.2	16.9	4.9
Median	51.2	16.9	7.1

Table 2: EMF 16 Carbon Price Forecasts

As shown in Table 3 there is a wide variance in the anticipated carbon costs between and within the models, with a price variance of nearly $70/ton in the 'no trading' scenario alone (which effectively amounts to a carbon tax, as emitters must purchase carbon permits), and similarly-high ranges in the 'Annex I' and 'global trading' model results. This range can be partially attributed to an element of the study that fixed an absolute Kyoto target relative to the 1990 base year. Different emission growth rates assumed by the different models therefore led to divergent cost estimates.

3.2.2 The DICE Model (2008)

Unlike the Regional Integrated model of Climate and the Economy (RICE) model (included in the EMF 16 study) the Dynamic Integrated model of Climate and the Economy (DICE) model aggregates emissions data from all major countries into a global average. (See Table 3 for a summary of the DICE model outputs.) DICE's near-term projections consider various scenarios for global carbon (Nordhaus, W., "A Question of Balance: Weighing the Options on Global Warming Policies," 2008), including prices for carbon where atmospheric stabilization occurs at 1.5, 2, and 2.5 times the current concentration of CO_2; various levels of increased temperature; Kyoto Protocol outcomes that include US participation and no US participation; and a number of carbon control proposals. Model results are detailed in Table 3 below.

Policy	Carbon Price, US$2005		
	2005	2015	2025
No controls			
250-year delay	0.02	0.01	0.01
50-year delay	0.02	0.01	0.01
Optimal	7.43	11.42	14.55
Concentration limits			
Limit to 1.5x CO_2	39.25	67.47	114.96
Limit to 2x CO_2	7.97	12.29	15.99
Limit to 2.5x CO_2	7.43	11.42	14.55
Temperature limits			
Limit to 1.5°C	29.02	47.60	73.28
Limit to 2°C	12.34	19.57	27.86
Limit to 2.5°C	8.53	13.21	17.45
Limit to 3°C	7.60	11.69	14.98
Kyoto Protocol			
Kyoto with US	0.02	4.09	4.28
Kyoto without US	0.02	0.43	0.29
Strengthened	0.02	5.40	14.48
Stern Review	67.84	91.66	111.36
Gore proposal	6.81	25.65	72.13
Low-cost backstop	1.36	1.33	0.75

Table 3: DICE Carbon Price Forecasts

In Table 3, the scenarios examined fall into seven general categories: no controls, optimal policy, concentration limits, temperature limits, Kyoto Protocol, ambitious proposals, and low-cost backstop technology. The following is a brief recap of the elements in Table 3:

- The 'No Controls' scenarios assume that governments take no action to stem carbon emissions.

- The 'Optimal Policy' scenario balances mitigation costs with the probable long-term damages from climate change (this scenario is based on an assumption of 100% participation and compliance).

- The ‘Concentration Limits’ and ‘Temperature Limits’ scenarios assume concentration limits of 1.5, 2, and 2.5 times preindustrial levels (420ppm, 560ppm, and 700ppm respectively) and temperature restraints of 1.5°C, 2°C, 2.5°C, and 3°C.

- The three ‘Kyoto Protocol’ scenarios profiled in this study include one in which current emission restrictions are extended out to the end of the modeling period and the United States *does* participate, one with Kyoto restrictions extended while the US does *not* participate, and one that assumes a strengthened Protocol with greater country participation (every region apart from sub-Saharan Africa) and greater emission reduction obligations (10% to start, and an additional 10% every 25 years).

- The ‘Ambitious Proposals’ scenarios (so called due to their requirement for material emission reductions within the short term) comprise suggested action plans from the *Stern Review* and from Al Gore.

- The ‘Stern Review’ scenario assumes the future damage from climate change to be material; this is reflected through a comparatively low discount rate in its model run. The Gore scenario assumes a 90% emission-control rate by 2050, and that country participation in the reduction scheme becomes universal within the same time period.
  The ‘Low-cost Backstop’ scenario models the repercussions of a climate-friendly technology that can replace fossil fuel use at comparable costs. The numbers are low given the relative “cheapness” of the technologies assumed.

3.2.3 The CCSP Report (2007)

The Climate Change Science Program’s (CCSP) “Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations” employs three integrated assessment models—the Integrated Global Systems Model (IGSM), the Model for Evaluating the Regional and Global Effects (MERGE) of GHG reduction policies, and the MiniCAM Model—to analyze the effect of four increasingly-stringent radiative forcing targets in the year 2100. (See Table 4 for a summary of the CCSP report.) The targets range from 3.4 W/m^2, 4.7 W/m^2, 5.8 W/m^2, and 6.7 W/m^2. (Watts per square meter is a measure of energy in a given area.) These targets translate roughly into CO_2 concentrations of 450, 550, 650, and 750 ppm respectively. It should be noted that these equivalencies are approximate and tend to vary among the models. Each model has different assumptions regarding the quantity and behaviour of the GHGs that would lead to these levels. The MERGE model utilized in the CCSP report is an updated version from that used in the EMF 16 study.

Model	Carbon Price, US$2000			
	6.7 W/m^2	5.8 W/m^2	4.7 W/m^2	3.4 W/m^2
2020				
IGSM	4.9	8.2	20.4	70.6
MERGE	0.3	0.5	2.2	30.0
MiniCAM	0.3	1.1	4.1	25.3
2030				
IGSM	7.1	12.0	30.5	104.6
MERGE	0.5	1.1	3.5	52.0
MiniCAM	0.5	1.9	7.1	46.3

Table 4: CCSP Carbon Price Forecasts

The range in carbon prices in the CCSP report stem from the differing assumptions that form the basis of each of the models used for the study. Each model worked with different expectations regarding probable CO_2 emissions over the next century, the role that technology will play, and the ease of mitigating non-CO_2 greenhouse gases.

3.2.4 Pew Center Analysis (2008)

A Pew Center analysis of the recent Lieberman-Warner Climate Security Act (an amended version of which was recently proposed to Congress) compares allowance price estimates derived from each of the models listed in Table 5. Lieberman-Warner would reduce emissions to 71% below the 2005 level by 2050 through caps on coal-consuming and high-emitting entities (facilities that use over 5,000 tons of coal or over 10,000 t CO_2e of GHGs per year), and those entities producing or importing certain fuels. Flexible mechanisms included in the Act include the trading, banking, and (limited) borrowing of allowances, the limited use of offsets, and limited linkages with international carbon trading systems.

Model	Carbon Price US $2005	
	2020	2030
EIA: Core Scenario	29	59
CATF	22	48
ACCF/NAM: Low Cost	52	216
ACCF/NAM: High Cost	61	257
MIT: Offsets + CCS	58	86
EPA (ADAGE): Scenario 2	37	61
EPA (ADAGE): Scenario 10	28	46
CRA: Scenario with Banking	58	84

Table 5: Lieberman-Warner Compliance Carbon Price Forecasts

Prices in Table 5 range from $22 to $61 per t CO_2 in 2020 and $48 and $257 per t CO_2 in 2030. This variation can be accounted for in a number of ways: the models each used different assumptions regarding the use of offsets, for example (the CATF model assumed that up to 30% of emissions could be covered with offsets, while the ACCF/NAM model's high-cost scenario assumed only 14%), and each used a different assumption regarding the role of technology, banking, and the use of revenues from the auctioning of allowances.

3.2.5 EMF 21 Model (2006)

Stanford University's Energy Modeling Forum (EMF) 21 study features the most relevant macro-economic studies regarding the post-2020 period (Weyant, J.P., "Overview of EMF-21: Multigas Mitigation and Climate Policy," Energy Journal, Volume 27—Multi-Greenhouse Gas Mitigation and Climate Policy Special Issue, 2006). (See Table 6 for a summary of the EMF 21.) The modeling teams in the EMF 21 study ran two main scenarios:

1. An emission target for the year 2150 that stabilizes radiative forcing at 4.5 W/m^2 using only CO_2 mitigation, and

2. An emission target for the year 2150 that stabilizes radiative forcing at 4.5 W/m^2 using multi-gas mitigation.

Model	2025 Carbon Price, US$2000	
	CO_2 only	Multigas
AIM	30.52	17.71
AMIGA	19.75	13.35
COMBAT	21.58	18.31
EDGE	1.50	0.79
EPPA	30.16	11.50
FUND	131.39	107.36
GEMINI-E3	24.22	8.58
GRAPE	3.38	1.88
GTEM	59.86	32.59
IMAGE	27.74	14.47
IPAC	23.84	10.22
MERGE	6.21	2.92
MESSAGE	11.47	3.57
MiniCAM	6.84	2.78
PACE	0.76	0.41
POLES	23.46	14.69
SGM	62.94	17.71
WIAGEM	11.31	4.41
Mean	27.60	15.75

Table 6: EMF 21 Carbon Price Forecasts for 2025

The models employed in EMF 21 each operate based on a different set of assumptions regarding future population estimates, energy prices, economic growth, technology advancements, and mitigation options. Baselines varied accordingly among the models: models such as AIM, IMAGE, IPAC, and MESSAGE project that emissions will be roughly twice their current level by 2100, while models such as FUND project emissions will be 5 times their current level within the same time period. Treatment of "natural" (i.e., non-anthropogenic) emissions was similarly varied, and led to considerable differences between carbon price projections.

4 Conclusions

The highest price projection found in this survey resulted from the ACCF/NAM model, estimating that a carbon price of $257 would be needed by 2025 to accomplish the emissions reduction objective in its “High Cost” scenario. This model’s “High Cost” scenario assumed that only 14% of GHG emissions could be offset, while the remaining emissions had to be internally mitigated. This scenario also strictly limited the rate at which technologies are developed and implemented, including a constraint on nuclear by allowing only 10-25 GW of additional capacity by 2030.

The lower price projections profiled in this report resulted from the PACE model, estimating that a carbon price of only $0.41 would be needed by 2025 to accomplish the emissions reduction objective in its “Multigas” scenario, and the MERGE and MiniCAM models, estimating a required carbon price of only $0.30 in 2020 for the “6.7 W/m2” scenario. The PACE model gave low values partially as a result of assuming a relatively low GHG emissions baseline and emissions growth over time.

This survey provides useful insight into the range of carbon values that are being talked about in the medium- to long-terms, and some of the key assumptions that contribute to this range, including:

- Socioeconomic Baseline and Associated GHG Emissions
- Emissions Reduction Target, Timeframe of Analysis, and Geographic Scope
- Covered GHG Gases
- Carbon Tax vs. Cap and Trade
- Emissions Trading Rules, Including Access to Carbon Offsets
- Technology Advancement Rates and Associated Mitigation Costs

The survey illustrates that the range of forecasts is wide, based on variations not only in the structure of the models, but in the treatment of key variables. It should not be surprising that based on widely varying inputs and assumptions, different models will give very different results. It would therefore be a mistake to draw the conclusion from this survey that carbon price forecasting is fundamentally so uncertain that we can’t learn anything from it. As one zeroes in on a specific set of assumptions, many of the model results become much more consistent.

Making GHG market modeling useful for corporate and policy planning purposes requires building a preferred policy scenario around which a market forecast can be built. With a detailed enough specification of key policy and market variables, one can often generate a Best

Available Forecast that can provide considerable insight into how carbon markets may function to generate carbon prices in such a scenario. EcoSecurities Consulting Ltd. was not asked to develop such a scenario or forecast for NWPCC, although one of the reports prepared for NWPCC does profile potential carbon prices under a variety of high-level policy scenarios.

Annex 1 GHG Price Modeling Featured in the EMF 16 and 21 Studies

Acronym	Full Model Name	Author(s)/Home Institution(s)	Featured In
ABARE-GTEM	Global Trade and Environment Model	B. Fisher and V. Tulpulé	EMF 16
AIM	Asian Pacific Integrated Model	M. Kainuma, T. Morita, T. Masui, K. Takahashi (NIES) and Y. Matsuoka (Kyoto University)	EMF 16, EMF 21, and EMF 19 (not discussed in this report)
AMIGA	All Modular Industry Growth Assessment	D. Hansen (Argonne National Laboratory, U.S.), J. Laitner (U.S. EPA)	EMF 21
COMBAT	Comprehensive Abatement	H.A. Aahaim, J.S. Fuglestvedt, and O. Godal (CICERO, Norway)	EMF 21
EDGE	European Dynamic Equilibrium Model	J. Jensen (TECA TRAINING ApS)	EMF 21
EPPA	Emissions Projection & Policy Analysis Model	J. McFarland, J. Reilly, H. Herzog (MIT)	EMF 16, EMF 21, and EMF 19 (not discussed in this report)
FUND	Climate Framework for Uncertainty, Negotiation, and Distribution	Richard Tol (Economic and Social Research Institute, Ireland and Hamburg, Vrije & Carnegie Mellon Universities)	EMF 21
GEMINI-E3	General Equilibrium Model of International Interaction for Economy-Energy-Environment	A. Bernard (Min. of Equipment, Transport, and Housing, France), M. Vielle (CEA-LERNA, France), and L. Viguier (HEC Geneva and Swiss Federal Institute of Technology)	EMF 21
GRAPE	Global Relationship Assessment to Protect the Environment	A. Kurosawa (Institute of Applied Energy, Japan)	EMF 16, EMF 21, and EMF 19 (not discussed in this report)
GTEM	Global Trade and Environment Model	G. Jakeman and B. Fisher (Australian Bureau of Agricultural and Resource Economics)	EMF 21
IMAGE	Integrated Model to Assess The Global Environment	D.P. van Vuuren, B. Eickhout, P.L. Lucas and M.G.J. den Elzen (National Institute for Public Health and the Environment, The Netherlands)	EMF 21
IPAC	Integrated Projection Assessments for China	K. Jiang, X. Hu, & S. Zhu (Energy Research Institute, China)	EMF 21
MARIA	Multiregional Approach for Resource and Industry Allocation	S. Mori (Tokyo University) and T. Saito (Hitachi)	EMF19 (not discussed in this report)
MERGE	Model for Evaluating Regional and Global Effects of GHG	A. Manne (Stanford University) and R. Richels (Electric Power Research Institute)	EMF 16, EMF 21, and EMF 19 (not

	Reductions Policies		discussed in this report)
MESSAGE	Model for Energy Supply Strategy Alternatives and Their General Environmental Impact	K. Riahi, L. Schrattenholzer (ECESP) and E. Rubin, D. Hounshell (Carnegie Mellon University) and M. Taylor (UC Berkeley)	EMF 21 and EMF 19 (not discussed in this report)
MiniCAM	Mini-Climate Assessment Model	J. Edmonds, J. Clarke, J. Dooley, S. Kim, Steven Smith (University of Maryland)	EMF 21 and EMF 19 (not discussed in this report)
PACE	Policy Analysis with Computable Equilibrium	C. Böhringer, (University of Heidelberg), A. Löschel (Centre for European Economic Research – ZEW, and T. Rutherford (University of Colorado)	EMF 21
POLES	Prospective Outlook on Long-Term Energy Systems-Global Emissions Control Strategies	P. Criqui (Institute of Energy Policy and Economics, France), Peter Russ (EC- Institute for Prospective Technological Studies, Spain), and Daniel Deybe (EC Environment DG)	EMF 21
MS-MRT	Multi-Sector – Multi-Region Trade Model	Charles River Associates, University of Colorado	EMF 16
Oxford	Oxford Economic Forecasting	Oxford Economic Forecasting	EMF 16
RICE	Regional Integrated Climate and Economy Model	Yale University	EMF 16
SGM	Second Generation Model	Batelle Pacific Northwest National Laboratory	EMF 16
TIMER	TARGETS-IMAGE Energy Regional model	D. van Vuuren, B. de Vries, B. Eickhout, T. Kram (National Institute of Public Health and the Environment)	EMF 19 (not discussed in this report)
WIAGEM	World Integrated Applied General Equilibrium Model	C. Kemfert (German Inst. of Economic Research & Humboldt University), T. P. Truong (Univ. of New South Wales, Australia) and T. Bruckner (Institute for Energy Engineering, Tech Univ, Germany)	EMF 21
WorldScan	WorldScan	Central Planning Bureau (Netherlands)	EMF 16

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A Report for NWPCC

CO2 Capture and Storage

An Overview of Information Available for the Western U.S.

30 January 2009

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1 An Introduction to CO_2 Capture and Storage

CO_2 capture and storage (CCS) is the term given to efforts to capture the CO_2 from high-emitting stationary sources of the gas (e.g. power plants) and store it such that it is permanently sequestered. This report summarizes the status of CCS and the NWPCC's request to explore information regarding the potential of CCS in the states currently associated with the Western Climate Initiative (WCI) EcoSecurities Consulting Ltd. (ECL) focuses on these states given the geographical scope of the GHG mitigation supply curve forecasting exercise conducted as part of our larger effort to assist the NWPCC.

There are a number of technologies reported to be in development, but not covered in this report, that could significantly change the picture presented here. For example, some researchers are investigating the injection of CO_2 into magnesium-bearing rock strata, where the CO_2 would chemically react with the magnesium and be fixed. Other companies are investigating totally different sequestration approaches, like Calera's proposed technology to use seawater to produce a carbonate from flue gas, without the intermediate step of removing the CO_2 from the flue gas, and without the need to transport the CO_2. These and other technologies are not included in the current literature around CCS, and are difficult to evaluate from the standpoint of technical or practical potential. As climate change mitigation efforts evolve, however, and a price tag is attached to carbon, it is quite possible that completely new technologies like these will become key players in the CCS field.

1.1 Capturing CO_2

CCS involves the separation of CO_2 from flue gas in one of three ways:

1. *Post-combustion* - CO_2 is "scrubbed" from other flue gases after the burning of fossil fuel.

2. *Pre-combustion* - Fossil fuel is gasified rather than combusted and the CO_2 is captured from the exhaust stream.

3. *Oxy-fuel combustion* - Combusting fuel in an all-oxygen environment results in emissions of just CO_2 and water vapor, allowing for a pure, easily-transportable CO_2 stream.

Of these three options, *post-combustion* is currently the most widely used. The applied technology has been in existence for over 60 years and is commonly employed in industrial processes (IPCC 2005, 59). The *Pre-combustion* method is often seen in chemical plants and oxy-*fuel combustion*, while effective, involves processes that are extremely energy intensive and have yet to gain traction in the industrial or energy sectors.

1.2 Storing CO_2

After collecting the CO_2, it is then compressed and transported to the sequestration site via pipeline or tanker. Deep geologic sequestration can take place in a number of different types of subsurface formations. Of the possible sites for carbon storage, oil and natural gas reservoirs, coal seams, and deep saline formations exhibit the most potential for storage, although a variety of other formations are being explored.

1.2.1 Depleted Oil and Natural Gas Reservoirs

Oil and natural gas reservoirs are comprised of two layers of rock: a permeable layer where the oil or gas sits and a non-permeable layer, called a “caprock,” which prevents the oil or gas from escaping. Once the oil or natural gas in a reservoir has been extracted from a formation, CO_2 can then be injected into the permeable layer, while the caprock serves to keep the CO_2 in place.

Enhanced Oil Recovery (EOR) is the process of injecting CO_2 into an oil reservoir to improve the flow rate of the oil. CO_2, when combined with oil, decreases the viscosity of oil, which then increases the amount that may be extracted from a given reservoir. CO_2 also acts to displace the oil, pushing more of it to the production wellbore. EOR generally results in a 10 to 15 percent increase in the amount of oil recovered from a particular site (US DOE 2008, 18). Several pilot projects are currently exploring the use of CO_2 in natural gas fields and other uncommon applications, such as using the gas to repressurize depleted reservoirs.

1.2.2 Un-mineable Coal Seams

Coal contains many natural fractures, or “cleats,” which allow for the adsorption of a number of gases—including methane. Because coal has a higher affinity for CO_2 than for methane, CO_2 injected into coal systems will displace the methane and allow for its enhanced recovery. While the effectiveness of this process depends both on the type of coal and future plans for the coal bed, it still represents a promising avenue for carbon storage. Note that mining the coal from a site previously employing CO_2 injection would release all sequestered CO_2. Beds that are too deep or too thin for cost-effective mining are therefore the preferred CO_2 injection sites. Enhanced coal bed methane (ECBM) has yet to be employed commercially, and its effectiveness on a large scale has yet to be proven.

1.2.3 Deep Saline Formation Storage

Saline formations are porous layers of sedimentary rock within the earth’s surface which are saturated with formation water or brine and held in place by a caprock. Much more common than either oil and gas reservoirs or coal seams, this type of sequestration site is relatively untested. The salt content of the associated water makes the waters unfit for human use, and thus comparatively little research has been done on these formations (US DOE 2008, 20). Moreover, while existing well and mining infrastructure can assist with sequestration activities in oil and gas reservoirs and coal beds, comparable infrastructure does not exist around saline formations. On the other hand, successful pilot projects have done much to demonstrate the technical potential of this sequestration method.

2 CCS Costs

Three main components of the CCS process drive the overall cost of this GHG mitigation option. Carbon capture, transport and storage each have their own distinct cost challenges.

2.1 Capture

CO_2 capture is currently the most costly portion of the CCS process, and this cost varies widely depending on a number of factors as shown in Table 1 below.

Plant Type	Cost for Capture & Compression (per tCO_2)	Factors Driving Estimated Cost of Capture & Compression
Steam Rankine Power	25 - 60	• CO_2 content in flue gas stream • Capital cost • Energy requirements for solvent cycling
IGCC Power	25 - 40	• CO_2 content in flue gas stream • Capital cost
Refinery Flue Gas	35 - 55	• CO_2 content in flue gas stream • Capital cost • Energy requirements for solvent cycling (if applicable)
Steel	20 - 35	• CO_2 content in flue gas stream • Capital cost • Energy requirements for solvent cycling (if applicable)
Cement	35 - 55	• CO_2 content in flue gas stream • Capital cost • Energy requirements for solvent cycling (if applicable)
Ethanol (Fermentation)	6 - 12	• No capture cost for pure CO_2 stream • Compression cost only
Ethylene Oxide (Process Stream)	6 - 12	• No capture cost for pure CO_2 stream • Compression cost only
Ammonia (Reformer Gas)	6 - 12	• No capture cost for pure CO_2 stream • Compression cost only
Source: Dooley et al 2006, 33		

Table 1: The cost of CO_2 capture for various industrial processes

Capture costs depend significantly on the source from which the CO_2 is captured. Costs at coal or gas-fired power plants, for example, range from $15 to $75 per tonne CO_2, while hydrogen and ammonia production facilities face a range from $5 to $55 per tonne. Other industrial sources range from $25 to $115 per tonne of CO_2 captured (IPCC 2005, 11).

2.2 Transport

Unless a facility has been sited based on local CO_2 injection potential, captured CO_2 will need to be transported via pipeline or tanker to a disposal site. Tanker systems have not yet been employed on a scale that would serve for the large-scale transport of CO_2, whereas there are already over 3,600 miles of CO_2 pipeline in the US that serve existing EOR operations

(Fernando et al. 2008, 12). The cost of building and maintaining a new pipeline, however, is highly dependent on terrain. Costs may increase up to 100%, for example, if the pipeline intersects with urban or mountainous regions (IPCC 2005, 190). For a 250km pipeline, the IPCC predicts costs of transport ranging from \$1 to \$8 per tonne CO_2, with higher costs associated with a lower flow rate, and lower costs for a higher flow rate.

2.3 Storage

As with capture and transport, the likely cost of storing CO_2 in the US is highly variable. Studies project that injecting carbon into oil and gas reservoirs without enhanced recovery would cost from \$0.50 to \$4 per tonne stored for oil reservoirs and \$0.50 to \$12 for gas reservoirs. Variables that affect this cost include: a) the depth of the field, and b) whether existing equipment can be used to assist the storage process (IPCC 2005, 261). Storage costs may be offset with revenues experienced as a result of enhanced oil or gas recovery—as much as \$25 per tonne—but the benefit received is highly dependent on oil and natural gas prices as well as individual site characteristics (McKinsey & Company 2007, 61). It is also the case that even modest levels of CCS in the US would simply overwhelm the market for CO_2 in EOR applications, and eliminate any such revenue benefit.

The costs of storage within saline formations are comparable to oil and gas reservoirs with projections ranging from \$0.4 to \$4.5 per tonne CO_2 stored. This number depends on: a) the depth and thickness of the formation, b) its permeability, c) the injection rate, and d) the number of wells at a site (IPCC 2005, 261).

Enhanced coal bed methane, as mentioned above, has yet to be proven commercially; the costs associated with this process are thus relatively unknown. Well-run sites could have negative costs if considering the sale of methane, but this result depends on storage costs and gas prices.

3 CCS in the WCI Region

This section of the report reviews the publicly available literature regarding the technical and practical potential of CCS in the states currently associated with the Western Climate Initiative (WCI). Those states and provinces include Arizona, British Columbia, California, Manitoba, Montana, New Mexico, Ontario, Oregon, Quebec, Utah, and Washington.

3.1 Technical Potential

The technical potential for storing CO_2 in the Northwest and the rest of the WCI states is significant, as presented in Table 2. These technical potential numbers, however, do not take into account any economic or regulatory considerations.

Resource Estimates (million tonnes CO_2)							
	Enhanced Oil and Gas Recovery	Enhanced Coal Bed Methane		Deep Saline Formation Storage		Total	
		Low	high	Low	High	low	High
Arizona	70	0	0	184	740	254	810
British Columbia	/	/	/	749	749	749	749
California	7,692	/	/	75,875	303,502	83,567	311,194
Manitoba	618	0	0	/	/	618	618
Montana	1,262	293	293	265,407	988,831	266,962	990,386
New Mexico	8,246	78	310	32,186	128,744	40,510	137,300
Ontario	/	0	0	1	3	1	3
Oregon	/	/	/	16,727	66,909	16,727	66,909
Utah	1,410	30	120	32,565	128,990	34,005	130,520
Washington	0	2,800	2,800	90,245	360,979	93,045	363,779
Source: US DOE 2008, 139							

Table 2: Resource estimates for the Northwest

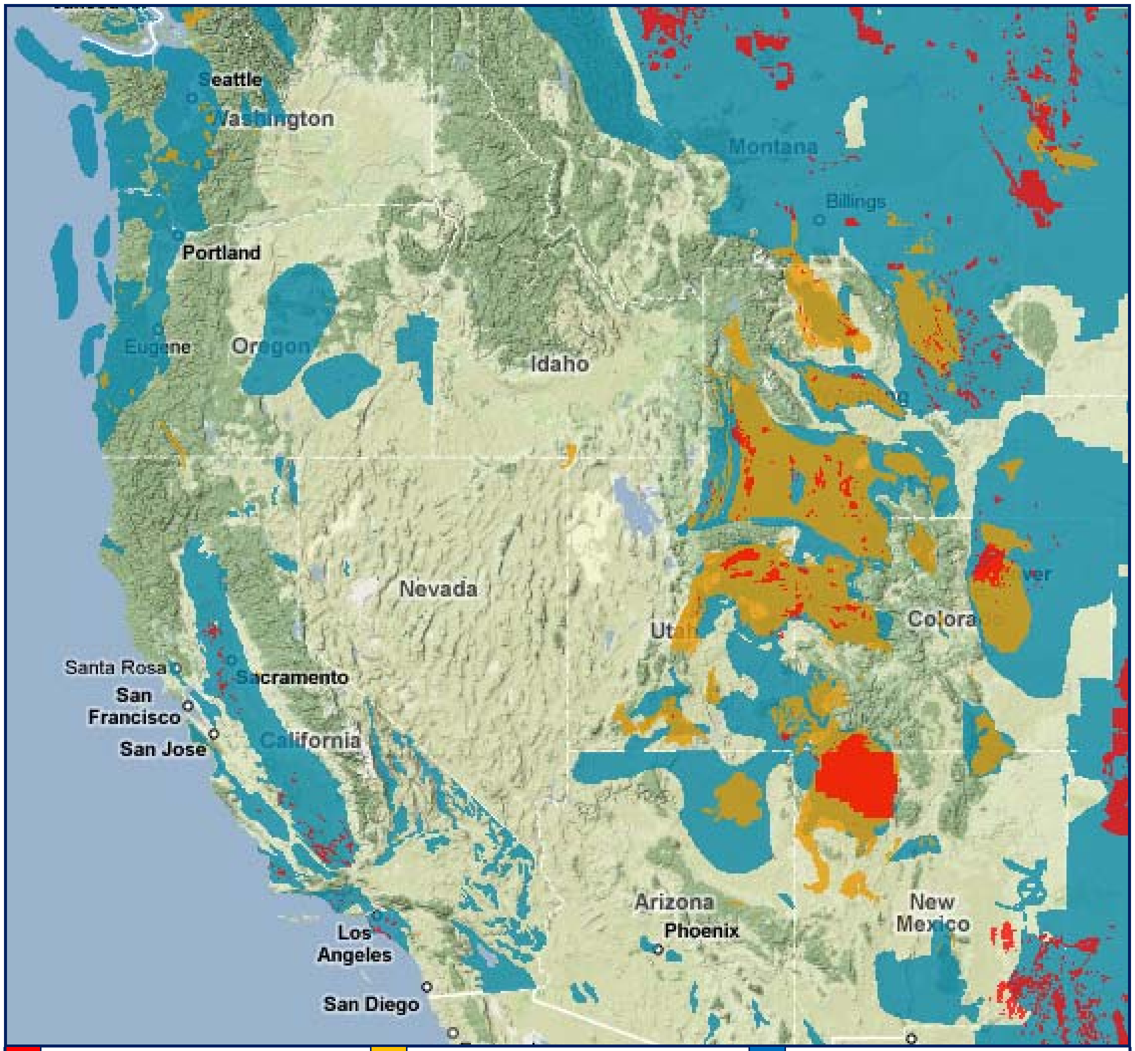
As shown in Table 2, the ability of the WCI states to store CO_2 in oil and gas reservoirs is modest, ranging from an estimated 0 tons in Washington to more than 7 billion tons in California and 8 billion tones in New Mexico. In the Pacific Northwest, Montana and Utah have at least a reasonable amount of potential.

The West Coast Regional Carbon Sequestration Partnership (WESTCARB) estimates that California's oil reservoirs, mostly found in the San Joaquin Basin, the Los Angeles Basin and the southern coastal basins, have a CO_2 EOR storage potential of approximately 3.4 billion metric tons. The gas reservoirs in the Sacramento River Delta are estimated to have a CO2 storage capacity of 1.7 billion metric tons.

The ability of the WCI states to store CO_2 in un-mineable coal seams ranges from 0 tons to almost 3 billion tones. WESTCARB also investigated the ability to store CO_2 in the coal basins of the West Coast. The group found three promising storage sites in the Pacific Northwest. These locations include the Bellingham Basin in Washington, the Upper Puget Sound region and the small, deep coal deposits of southwestern Oregon. The coal beds in Puget Sound, for example, are estimated to provide approximately 2.8 billion metric tons of CO_2 storage capacity. Washington's coal bed deposits in the Puget Sound are currently hosting pilot projects to assess their injectivity and storage potential (DOE 2008, 92-96).

The estimated ability of the WCI states to store CO_2 in saline aquifers is much larger than in the region's oil and gas reservoirs and un-mineable coal seams, ranges to almost one trillion tones in Montana. California has 10 sedimentary basins containing saline formations which promise to offer an estimated 75 to 300 billion metric tons of CO_2 storage capacity. Oregon and Washington contain a combined 7 sedimentary basins with a total estimated CO_2 storage capacity of 20 to 85 billion metric tons (WESTCARB, http://www.westcarb.org/about_overview.htm).

Figure 1 illustrates the geographical distribution of CCS potential in the Northwest.



🟥	Oil and Gas Reservoirs	🟨	Unmineable Coal Seams	🟦	Deep Saline Formations

Source: NatCarb 2008

Figure 1: Geographic Distribution of Potential CCS in the Western US

3.2 Practical Potential

While the technical potential for CCS in the WCI states, and in the Pacific Northwest specifically, is significant, the amount of this potential that will actually be developed and become available for power plant use hinges on a number of variables. Among the most significant variables that will affect the deployment of CCS technology are:

- *Environmental Policy*. Due to the high cost of capture and storage, the CCS technologies described here will not be deployed on a significant scale without significant emissions reduction mandates. Moreover, the sectors touched by policy will also have a significant effect on probable deployment. Apart from power plants, large emitters in the Northwest include iron and steel plants, cement plants, refineries, gas processing facilities, and chemical plants (Dooley et al 2006, 29). The prevalence of CCS will depend on which of these emission sources are included in GHG emissions reduction mandates. Note: the most current iteration of the WCI cap-and-trade program includes all electricity generation and any industrial sources that emit more than 25,000 metric tons CO_2e.

The use of flexible mechanisms also has a bearing on the implementation of CCS technology. All things being equal, the greater the use of carbon trading, the lower the price of carbon is likely to be, and the more challenging it will be to justify the multi-billion dollar financial commitments associated with a major CCS project.

- *Advances in Technology*. The various technologies included under the umbrella of CCS are at various stages of maturity, as evidenced in Table 3 below. As market experience with CCS systems grows and energy demands are addressed by focused R&D (current capture technologies include a very significant energy penalty), the costs of CCS could decline. One study goes so far as to predict that the economic potential of CCS will increase by 150 percent if CCS technological learning follows the pace of sulphur removal technologies (IPCC 2005, 351).

Technical Components of CCS				
CCS Component	CCS Technology	Demonstration Phase	Economically Feasible Under Specific Conditions	Market Mature
Capture	Post-combustion		**X**	
	Pre-combustion		**X**	
	Oxy-fuel combustion	**X**		
Transport	Pipelines			**X**
	Shipping		**X**	
Storage	Enhanced oil recovery			**X***
	Oil and gas reservoirs		**X**	
	Saline formation		**X**	
	Enhanced coal bed methane recovery	**X**		

* CO_2 injection for EOR is a mature market technology, but when used for CO_2 storage, it is only economically feasible under specific conditions

Source: IPCC 2005, 8

Table 3: Current maturity of CCS system components

- *Siting and Liability Issues.* Serious questions regarding the effectiveness and safety of CCS systems have been raised among the general population, leading to major challenges to the technology in terms of siting and liability issues. Whether these challenges can be overcome, and how much any solution to these challenges would add to the cost of the technology itself, is still speculative. Liability and siting issues have the potential to derail any meaningful adoption of CCS systems.

- *The Price and Quantity of Coal and Natural Gas in a Given Region*. Because the carbon capture process itself is quite energy intensive, regions where coal is relatively abundant and cheap will be more likely to employ CCS than those where a less carbon-intensive fuel is more commonly employed.

At the end of the day, even global projections of how CCS will be deployed vary widely. Many researchers predict that large-scale implementation of capture and storage technology will not occur before 2015, while others believe that 2030 is the earliest plausible date. Some models suggest that sustained CO_2 prices of $30/metric ton would be sufficient to make CCS economically viable for power plants (WRI 2008, 17), while others predict that prices of $50 to $100 would be necessary (IPCC 2007, 300).

In its Fourth Assessment Report, the Intergovernmental Panel on Climate Change places total world capture potential from 2015 to 2030 at 23 billion tonnes of CO_2 (note that this figure only includes CCS systems within coal- or gas-fired power plants and not any other industrial processes). The scenarios being used by the International Energy Agency, however, range widely in the assumed deployment of CCS. One scenario estimates that CCS will be part of 9 percent of power generation by 2030 and 16 percent by 2050, while projections from another scenario have CCS systems employed in 12 percent of power generation in 2030 and 30 percent by 2050 (IEA 2008, 29).

Energy and Environmental Economics, Inc. (E3) recently led a project for the California Public Utilities Commission that analyzed the various costs associated with potential CCS systems in the western U.S. The data as summarized in Table 4 provides a useful reference for estimating regional costs.

	2008 Value	**Range of 2008 Values in Model**
Base overnight capital cost ($/kW)	3,418	3,144 - 4,101
Variable O&M ($/MWh)	4.50	4.50
Fixed O&M ($/kW-yr)	46.11	42.42 - 55.33
Nominal Heat Rate (BTU/kWh)	9,713	9,713
Capacity factor (%)	85	85

Table 4: Coal IGCC with CCS Cost, Resources, & Performance

A CCS equipped IGCC plant with the characteristics specified in Table 4 would generate energy at a levelized cost of approximately $142 per MWh. Relative to a natural gas CCGT plant with a levelized cost of $52 per MWh, the implied cost of carbon for this plant is almost $400. We should be careful not to read too much into such estimates and the uncertainties that are built into them, but the analysis does provide insight into the challenges of deploying CCS in the region.

4 Conclusions

Translating the various uncertainties and projections shown above into an assessment of CCS practical potentials in the Pacific Northwest in the near- to mid-term is almost impossible. While there is significant technical potential to store CO_2 in the Pacific Northwest, the region is unlikely to significantly influence either the pace of public policy around emissions mandates, or the pace of technology development around CCS itself. Given the very large upfront costs associated with CCS facilities, as well as the siting and liability issues involved, it is unlikely that policy initiatives in the Pacific Northwest alone could plausibly incentivize the commercial deployment of any of the CCS technologies described in this report.

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A Report for NWPCC

GHG Market Forecasting Services

Assigning Carbon Price Estimates to Alternative Policy Scenarios

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1 Introduction

This is the last of four summary reports prepared by EcoSecurities Consulting Ltd. (ECL) for NWPCC. The first three of ECL's reports provided NWPCC with:

- A literature review of carbon price forecasts based on alternative modeling approaches, targets, and timeframes.
- A compilation of mitigation supply curves reflecting estimated sectoral mitigation potentials and mitigation costs for the Western U.S., the U.S. as a whole, and globally.
- A review of carbon capture and storage information specific to the WCI region.

This final summary report addresses NWPCC's request for ECL's insight into the cost of carbon under three general policy scenarios:

- A "Pessimistic" scenario, in which the Western Climate Initiative and other regional initiatives operate in the absence of material national and international policy.
- A "Base Case" scenario, in which national and international policy measures target a return to 1990 emissions levels by 2030.
- An "Optimistic" scenario, in which aggressive national and international policy interventions are used to dramatically reduce global GHG emissions with the goal of stabilizing CO_2e concentrations at 550 ppm by 2100.

As documented in ECL's other reports, the impacts of numerous policy and market variables make it impossible to truly predict the future value (or cost) of carbon in a carbon constrained world. Even how to think about the question of future carbon costs varies based on the question being asked, since the impact of different market variables will vary across short-, mid-, and long-term time horizons, and also based on the specific policy mechanisms being used. The availability of "low-hanging fruit," for example, is key to near-term carbon market analysis, while assumptions about economic growth are not. Over the longer term, however, current estimates of "low-hanging fruit" become much less important to anticipating the cost of carbon, while assumptions about population and economic growth become pivotal. As a result tools like static supply and demand analysis can generate useful near-term insight, while over the longer term macroeconomic modeling becomes key to any projection of how the economy will respond to alternative carbon constraints.

Any GHG market forecasting exercise must recognize that carbon markets are fundamentally different from other commodity markets. It is clear that the *demand* for GHG emission reductions is determined largely by policy decisions; what makes the GHG market so unusual is that the near- to mid-term market *supply* of emissions reductions will also be largely determined by policy decisions. Relevant supply curve policy variables range from specification of which mitigation sectors can participate in carbon trading, to determination of how project-based "additionality" is defined and implemented. These and other supply variables can fundamentally affect the market supply curve for emissions reductions, and hence GHG credit prices. In addition, the economics of reducing GHG emissions in many sectors can be materially affected by future prices for fossil fuel feedstocks. Table 1, for example, illustrates that a technology like wind energy, assuming set capital and operating costs, can go from being an expensive carbon mitigation option at low natural gas prices, to a cost-effective technology in its own right at higher natural gas prices.

Typical Project	Natural Gas Price		
	$2.00/MMBtu	$4.00/MMBtu	$8.00/MMBtu
Coal Mine Methane Capture	$5.77	$0.79	Negative
Large-Scale Wind Energy	$47.08	$8.50	Negative
Coal-to-Gas Fuel-Switching*	$15.12	$72.44	$187.07
Pulverized Coal CO_2 Capture**	$279.99	$220.86	$102.59

*Assumes coal prices stay constant.

**Lost electricity sales are assumed due to the energy penalty associated with CO_2 capture.

Table 1: Mitigation Project Costs per ton of CO_2 (2007$) Given Different Values for Natural Gas Prices

The bottom line is that there can be no such thing as a “correct” forecast of future carbon market prices. That said, market forecasting under conditions of uncertainty is nothing new. Energy companies, for example, routinely forecast oil and gas prices even while knowing that these forecasts will not be “correct.” In the carbon arena, ECL can work with policymakers and companies to generate a Best Available Forecast that reflects their judgments regarding a wide range of policy and market variables. By incorporating their own “world view,” into the policy and market scenario building process, as well as their own perceptions of and sensitivity to carbon risk, the results can provide decision makers with an informed foundation for strategic planning and capital investments in anticipation of a carbon-constrained world. Note that different companies and policy makers, with different views of the future, and different sensitivities to carbon risk, can appropriately arrive at very different Best Available Forecasts.

This report does not seek to provide NWPCC with a Best Available Forecast of carbon prices. To do so would require the in-depth exploration and specification of one or more policy and market scenarios around which a Best Available Forecast would be built. This process has not taken place. Instead, NWPCC has asked ECL to provide a high-level view of potential carbon prices under the three generally specified scenarios identified above.

Although the results presented in this report are not based on detailed market scenarios, they do reflect ECL’s approach to and experience with carbon market forecasting. This approach is briefly documented in the following sections of this report, to provide context for the scenario results presented at the end of the report.

2 The Context for Near-Term Carbon Price Forecasting

EcoSecurities Consulting Ltd. has actively tracked the GHG market for more than a decade, extensively researched mitigation options and costs, and closely tracked ongoing policy development at the national and international levels. Based on ECL's experience, a number of variables need to be considered in any effort to forecast future carbon prices.

- *Context Variables:* Those variables that drive the priority and shape of public policy on climate change. They include the developing science of climate change, public opinion, and the international political context related to multilateral cooperation.

- *Mitigation Demand Variables:* Those variables that determine the demand for GHG credits in a future mitigation market. They include economic and emissions growth, the impact of voluntary emission reduction programs, the severity of regulatory emission reduction mandates, the timing of mandates, the role of developing countries in global mitigation efforts, the treatment of sinks, and compliance and penalty regimes.

- *Mitigation Supply Variables:* Those variables that influence the supply of emission reductions available to meet compliance mandates. These include the fungibility of reductions from different sectors and crediting systems, the technical potential of sectors to deliver emission reductions, additionality and quality standards that limit market participation to "real" reductions, whether credit banking is permitted, treatment of sinks and potentially impermanent reduction options, and expectations regarding the future market. Almost any of these variables could dramatically affect the supply of credits under many market scenarios.

- *Project-Level Transaction Variables:* Those variables that determine the transaction costs involved with creating credits in the GHG market. They include baseline and other documentation requirements, approval and certification processes, adaptation or other tax levies, guarantee requirements, and costs associated with project monitoring and verification.

- *Technology Variables:* Those variables that change the shape of the supply curve over time, and comprise the many factors that influence the evolving cost-effectiveness of different technologies. These factors include changes in related commodity prices (e.g. natural gas and electricity) and the emergence of new emissions reduction technologies (e.g., long-term geological sequestration).

In principle these variables could factor into creating different carbon prices in different emissions trading systems that operate simultaneously. In theory there could be operational carbon trading systems functioning in the Pacific Northwest, nationally, and internationally. Each of these programs could, in principle, have different market clearing prices owing to different operating rules and differing access to cost-effective emissions reduction opportunities. From the standpoint of projecting carbon prices in a carbon-constrained world, however, trying to anticipate a range of geographically or sectorally specific trading markets simply adds too much complexity to an analysis of future carbon prices, and the uncertainty bands around such projections would render the projections themselves of questionable value.

For these reasons ECL believes that a broad-based look at GHG markets is likely to generate the most useful policy insight into the economic implications of future carbon constraints. An international carbon market-clearing price, for example, reflecting a market that is able to take advantage of the broadest array of emission reduction options, should reflect a reasonably conservative estimate of the economic impacts associated with any given level of carbon emissions constraint. While local decision makers could choose to constrain access to the international market to drive carbon prices higher, we suspect that with enough time political pressures will shrink any major differential between the market-clearing prices in parallel domestic and international GHG trading systems.

For purposes of this report, carbon markets over the next 20+ years can also be broken into three distinct phases.

- *Phase 1*: 2008-2012 reflects the timing of the first commitment period of the Kyoto Protocol. Countries will sort out their compliance strategies during this phase, and the GHG market will endeavor to develop a solid foundation for future phases. The near-term market will be enormously affected by additionality standards, implementation barriers, and market psychology in terms of both demand and supply. Although economic modeling can cover this timeframe, macroeconomic modeling is unable to account for most of the variables that will be important to how the market actually behaves. As a result, we rely primarily upon supply and demand analysis for this phase.

- *Phase 2*: 2013-2020 reflects a transition phase, when targets will initially govern the GHG market for the Kyoto Protocol’s second commitment period (or other agreed-upon international agreement). Supply variables like market establishment rates and ramp-up potentials should not be as critical as in the short-term, while factors including economic growth and associated GHG emissions will become more important. Yet realistic supply and demand scenarios can still be structured and, as a result, it makes sense to continue use of the supply and demand approach while at the same time integrating macroeconomic modeling results.

- *Phase 3*: 2021-2030 is a period where climate change policy objectives could extend well beyond existing regulatory targets, and be integrated into a wide variety of other aspects of our energy economy. The implications of economic growth for GHG emission reduction objectives and the potential changes in technology costs (particularly in terms of renewable energy sources and mitigation technologies like geological carbon sequestration) will be large. As a result, the uncertainty bands around supply and demand forecasts in this phase become much larger. This situation makes it more appropriate to rely increasingly on macroeconomic market modeling while at the same time recognizing the limitations of such models in terms of predicting the appropriate prices to use in carbon risk-management efforts.

3 Building Blocks of Market Demand and Supply

To forecast near-term carbon markets, a number of important supply and demand "building blocks" can be identified. Each of these building blocks has the ability to materially affect carbon market clearing prices through its impact on the demand for or supply of emissions reductions.

3.1 The Building Blocks of Credit Demand

Credit demand in future carbon markets will depend on a number of factors and the relative importance of different demand variables will likely vary over time. Beyond the quantitative targets themselves, and the timing of their implementation, key building blocks of demand include:

- *State, Regional, or Country Participation in the Trading Regime.* Of the industrialized countries, the United States constituted by far the largest expected demand under the Kyoto Protocol, yet it is currently not a part of the system, with huge implications for the demand for emissions reductions. Even countries not party to the Protocol, however, could potentially affect international credit demand and prices through domestic initiatives that proceed separately from the Protocol, whether voluntary or mandatory.

- *The Political Issuance of "Free Credits."* This includes Russian and Former Soviet Union (FSU) Hot Air in the first Kyoto Protocol commitment period, which could have a tremendous impact on the need for incremental project-based credits. To the extent this Hot Air is held for future commitment periods, or additional "free credits" are issued as a result of the political negotiations around the future of the Kyoto Protocol, this variable will continue to be very significant.

- *The Demand for Extra-Territorial Offset Credits.* The higher the proportion of an overall target that is required to be met through "local" policies and measures within capped regions and sectors, the smaller the demand for project-based reductions outside those regions and sectors. This would tend to raise the price of a localized trading system, while lowering the international market-clearing price for offsets.

- *Economic Growth as a Contributor to GHG Market Demand.* This includes primarily industrialized countries in the near-term, but potentially includes developing countries in the future. Rapid economic growth significantly increases the difficulty of meeting any given target.

- *How National Forest Sinks are Accounted For.* Forest and soil sinks can have a significant effect on national targets, and affect remaining project-based demand.

- *The Likelihood of Government Compliance with Targets.* Although not commonly discussed, this variable should be taken into account, and will certainly be considered in the market psychology on the supply side of the market. If countries ultimately decide it is too difficult or costly to comply with targets such as those in the Kyoto Protocol, they might well fall short, or agree later on the ability to "borrow" from future commitment periods. This could have a significant impact on project-based credit demand, even in the near term.

It is relatively easy to define these building blocks of demand. What is more complicated is to assess how these building blocks will combine to form credit demand in the context of any given policy and market scenario, and how demand is likely to vary over time.

3.2 The Building Blocks of Supply

As in the case of demand, it is relatively easy to define the building blocks of GHG market supply. What is more complicated is to assess how these blocks will combine to form the supply curve available to the GHG market under a given policy scenario, at a given point in time. The key building blocks are summarized here:

- *Market Psychology.* This is a crucial supply variable as long as market demand itself is relatively uncertain, and susceptible to a variety of decision-making processes. A report published in December of 2008 by the U.K.-based Carbon Trust, entitled *Global Carbon Mechanisms: Emerging Lessons and Implications*, calculates that the GHG mitigation supply jump-started through the Kyoto Protocol will exceed likely post-2012 demand. This could significantly influence decision-making around the development of new projects and emissions reduction technologies.

- *Rules Governing Trading Systems' Market Mechanisms.* For the Clean Development Mechanism (CDM) of the Kyoto Protocol, additionality standards, crediting periods, and the specification of what mitigation sectors are included or excluded from consideration has been key to determining project-based credit supplies, and the same is likely to apply to other markets.

- *Baseline "Creep."* Under the current rules of the CDM, projects either have a 7-year (renewable up to three times) or a 10-year (non-renewable) window to generate CO_2 reductions. Many projects will therefore come to an end during the second market phase. Others will seek to be renewed for another 7 years. The protocols for how this is done, and the potential for "baseline creep" in which most project activities are assumed to become business as usual in the future, could have a significant effect on market supply of qualifying reductions.

- *Technical and Implementation Barriers.* A number of barriers—development lead times, for example, or project review requirements—will have a major effect on credit supply.

- *Project Economics.* Project economics are a function of capital and operating costs, risk-adjusted hurdle rates, and project lifetimes over which a project can earn GHG credits. Project economics can also change over time as technologies evolve or achieve economies of scale.

- *The Cost of Electricity and Fossil Fuels.* These costs are important to the supply curve facing many mitigation sectors. Different relative energy prices can significantly affect the cost-effectiveness of certain technologies for reducing emissions. Table 1 above, for example, showed how natural gas prices can affect the cost per ton of CO_2 for several GHG emissions reduction options.

- *The Availability of GHG Project Financing.* The availability of financing for GHG emission reduction projects will be crucial to the development of a robust supply of such projects. Such financing, however, can be constrained in the face of significant uncertainties regarding future credit demand and supply.

3.3 Implications of Credit "Quality" for GHG Markets and Prices

The market variable that has received the most attention in press coverage of carbon markets to date is the "quality standard" being used in defining what counts as an emissions reduction for GHG credit generation purposes. In addition, the wide range in market prices associated with GHG reductions over the last several years, ranging from pennies to more than $50/ton, largely reflects the lack of clear standards for what constitutes a "creditable" reduction, and the fact that carbon commodities of very different quality are currently available to buyers in carbon markets.

Ultimately, a clear set of credit quality standards will hopefully be established under any trading system that allows emission reductions from unregulated sectors to "opt in" to the trading system. Such standards would not be required if CO_2 emissions were regulated only at power plants, and if only CO_2 emissions reductions at power plants were eligible for crediting (because everything remains under the cap). But as soon as reductions can be introduced from other sectors, other gases, and other countries, where those reductions are not under the same emissions "cap", "credit quality" becomes of paramount concern in terms of preserving the environmental integrity of the original emission reduction targets. Some attributes of emission reductions commonly characterized as elements of credit quality include:

- *Additionality*. Probably the single most important offset project quality criterion in today's market, "additionality" refers to the extent to which a project activity diverges from (or is "additional" to) business as usual. The conceptual goal is to credit only projects producing reductions that would not have happened in the absence of carbon markets, since those are obviously the reductions that we want to incentivize through carbon markets. But while easy to understand in principle, additionality is very difficult to apply in practice.

  Because there is no single "right" way to measure additionality, a wide variety of additionality tests have been proposed, ranging from simple "project in/project out" tests that largely ignore the question of what was BAU, to financial additionality tests that ask for proof that a reduction is not the financially-preferred project alternative. None of the proposed tests are perfect, and the challenge for policymakers in setting an additionality hurdle is to strike a balance between the goal of minimizing the number of BAU credits that slip over the hurdle and are credited, with the goal of minimizing the number of “real” reductions that are excluded from being credited (since this will tend to restrict supply and drive up prices). The policy challenge for designing future GHG trading systems is to identify the standards and the methodologies by which these competing objectives can be balanced.

- *Quantifiability*. The degree to which the GHG reductions from a project can be reliably quantified, including the ease with which a project baseline can be identified and quantified. Many otherwise attractive offset projects generate emission reductions that are difficult to measure and quantify.

- *Permanence*. Whether or not emission reductions will last over time. This criterion is most often applied to forestry and land-use projects where sequestered carbon may be re-released into the atmosphere through human or natural disruptions, and the reductions potentially lost. Creating fungibility between non-permanent and permanent reductions is proving difficult.

- *Leakage*. The degree to which GHG reductions may be counteracted by compensating actions or feedbacks external to a project’s immediate boundaries. The emission reductions associated with shutting down a factory, for example, would be subject to “leakage” if the factory’s production simply shifted to another factory.

- *Direct or Indirect Reductions*. Whether the reductions generated by a project occur at the emission source (direct), or away from the emission source (indirect). Many project sectors, including end-use energy efficiency improvements and renewable energy, produce indirect reductions that actually occur at power plants far removed from the project. Such a situation creates credit ownership and double-counting problems that become very important in a regulated carbon market.

How policymakers choose to define emission reductions credits will have a significant impact on the available supply of emission reductions and ultimately the cost of achieving emissions targets. Denying credit to projects that reduce emissions indirectly, for example, or whose reductions are difficult to measure precisely, could sharply restrict the supply of emissions reductions available to carbon markets. Most importantly, the manner in which policymakers guide the development of additionality testing will be critical to future GHG markets and market-clearing prices in those markets.

4 Carbon Prices Under Three Policy Scenarios

NWPCC asked ECL to consider carbon values under three potential policy scenarios:

- A “Pessimistic” scenario, in which the Western Climate Initiative and other regional initiatives operate largely in the absence of material national and international policy.

- A “Base Case” scenario, in which national and international policy measures target a return to 1990 emissions levels by 2030.

- An “Optimistic” scenario, in which aggressive national and international policy interventions are used to dramatically reduce global GHG emissions with the goal of stabilizing CO2e concentrations at 550 ppm (2x pre-industrial levels) by 2100.

As previously noted, ECL has not worked with NWPCC to specify these scenarios in the detail required to generate Best Available Forecasts. Instead, ECL has drawn upon a range of data sets and prior modeling to provide NWPCC with the scenario profiles provided below. The dollar figures expressed in this report are in 2007 dollars.

4.1 “Regional Initiatives Dominate” (Pessimistic) Scenario

This scenario assumes that very little headway is made regarding national and international climate management policy, leaving U.S. emissions reduction efforts regionally focused and enforced through localized mechanisms such as the Western Climate Initiative (WCI). This scenario also assumes that “proxy” measures aimed at providing an economic stimulus, e.g. clean energy measures, may dominate the policy agenda rather than GHG emissions reductions per se.

- *Implied Magnitude of Reductions:* The Western Climate Initiative is seeking to reduce emissions to 15% below 2005 levels by 2020. For the WCI region, this amounts to approximately 125 million tons of reductions from a business as usual baseline in 2020[1]. Emissions reductions are also being pushed under this scenario through other regional initiatives, but this demand is not clearly quantified.

- *Key Variables in Projecting Carbon Prices:* Political acceptability of carbon prices is likely to be pivotal to this scenario. Almost regardless of what the supply and demand profiles look like, it simply wouldn’t be politically acceptable for WCI ratepayers and residents to be paying a high price for carbon in the absence of coordinated national and international policy.

- *Price Forecast:* We project a carbon price of $10-20/ton in the 2020-2030 time frame, that might well be primarily expressed as a subsidy for “green” projects like renewable energy, and that would drive access to whatever sources and types of offsets would allow this price to be achieved. There is not likely to be a real link between the implementation of regional policy and the achievement of a firm emissions reduction target. Any specific target is simply too easy to modify over time to assume that it will drive carbon prices to be much more robust than those projected here. The scenario also does not assume any changes in the nature of the policy measures being implemented that would lead to significant changes in the price forecast between 2020 and 2030.

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[1] Based on 2020 greenhouse projections by the EIA.

4.2 "1990 Emissions by 2030" (Base Case) Scenario

This scenario assumes that climate policy is primarily national in scope, with emissions reduction targets and market mechanisms being geographically defined. Emissions targets are assumed to be either: 15% below 1) 2005 emission levels or 2) 1990 levels by 2030. The targets and the structure of market mechanisms are assumed to be relatively rigorous.

- *Implied Magnitude of Reductions:* In 1990 U.S. emissions totaled 6.2 billion tons. A national "business as usual" baseline suggests 2030 emissions of 8.5 billion tons. A target of a 15% reduction from 2005 emissions, or a return to 1990 emissions by 2030, each requires approximately 2.3 billion tons of reductions.

- *Key Variables in Projecting Carbon Prices:* Given the definition of the scenario, we assume that supply and demand are the key variables in establishing a market clearing price for GHG emissions reductions, and that offsets would deliver up to half of the necessary reductions.

- *Price Forecast:* Based on the demand for reductions as indicated above, and by the mitigation cost curves developed separately by ECL, we would project a carbon price of $20-50 for this scenario in the 2020 to 2030 timeframe. Depending on how the mandates are implemented the price could rise early and level out, or climb over time.

4.3 "Atmospheric Stabilization" (Optimistic) Scenario

This scenario assumes that climate change mitigation becomes a higher global political priority than it is today, and that political rhetoric around the climate change issue is matched by political action. Stabilizing atmospheric concentrations of GHGs by 2100 will require that global emissions ultimately be reduced by some 70% *from today's levels*.[2] The world's energy economy would have to be fundamentally transformed. . This would reasonably start with adoption of post-Kyoto targets that go significantly beyond the targets adopted for the first commitment period, and that quickly encompass all major emitters including developing countries.

- *Implied Magnitude of Reductions:* Global emissions today total almost 40 billion tons of CO2e. A global "business as usual" baseline suggests emissions in 2100 of as much as 100 billion tons. Stabilizing atmospheric concentrations of GHGs in the atmosphere might require limiting emissions in 2100 to approximately 10 billion tons of CO_2e, suggesting a 90% reduction from the business as usual baseline.

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[2] The Intergovernmental Panel on Climate Change has carried out extensive modeling of what would be required to stabilize atmospheric concentrations of GHGs at different levels by different dates, using alternative baseline and other assumptions. The figures presented here reflect a very simplified view of this larger body of work.

- *Key Variables in Projecting Carbon Prices:* The reductions being sought in this scenario are so large that they suggest a large-scale transformation in the world's use of energy. This in turn will require the imposition of a material carbon price signal that incentivizes this transformation, and the development and implementation of a wide range of new "reduced carbon" technologies, from carbon capture and storage to transportation systems that are fully electrified. The magnitude of the needed price signal is most appropriately derived from macro-economic analysis, an overview of which has been separately provided to NWPCC. Beyond the level of any given price signal, however, the timing of the price signal is a key predictive variable. The earlier a price signal is imposed, the easier it should be to achieve the ultimate targets (by giving the system more time to react). But there will always be political pressure to start with a low price signal under the assumption that 1) a much higher signal can be phased in later for political reasons, or 2) that the needed price signal is actually lower than a lot of economic modeling suggests.

- *Price Forecast:* We assume for purposes of this price forecast that climate change quickly becomes the policy priority required under this scenario, and that a material price signal is imposed on the economy almost immediately, whether through a carbon tax or a cap-and-trade market clearing price. Based on the assumption that ultimate achievement of the stabilization goal is the true priority, we would see a carbon price of $30/ton in 2020 as a reasonable step towards stabilization, with that price ratcheting up to $50/ton in 2030.

5 Conclusions

The results presented here should only be seen as indicative, and reflecting a complicated set of underlying assumptions. A lot simply isn't yet known about how the economy and technology development efforts will respond to a carbon-constrained world. There is at least some possibility that, given the appropriate incentive structures, low-carbon technologies will appear more quickly and more cheaply than is generally assumed. The Catch-22 of the situation is that such technologies are much less likely to appear if there is not a clear signal that carbon reductions will in fact have a significant value in the future.

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A Report for the Northwest Power and Conservation Council

Selected GHG Mitigation Supply Curves

January 30, 2009

Table of Contents

1 Introduction

For organizations assessing the implications of a CO_2-constrained world, the future cost of emissions (or the value of reductions) is critical to developing appropriate strategies.

Mitigation supply curves are one component of estimating the future cost of emissions (or the value of reductions) in a carbon-constrained world. This report looks at regional, national, and international mitigation supply curves in order to provide NWPCC with insight into how these mitigation supply curves could influence future market-clearing prices in carbon markets.

How policymakers determine the eligibility of emission reductions from non-capped sectors (offset sectors) will have a significant impact on the available supply of reductions, and ultimately on the cost of achieving emission targets. Denying credit to projects that reduce emissions indirectly, for example, or reductions that may be more difficult to measure, could materially restrict the supply of reductions to the GHG market. A key feature of any offset supply curve is how emission reductions are credited from the standpoint of “additionality,” i.e., the extent to which reductions can be shown to result from the existence of a carbon market (see Annex 1 for how additionality is addressed in ECL’s modeling). While easy to understand in principle, testing for additionality is difficult to apply in practice.

2 Supply Curves for NWPCC

This report highlights emission reduction measures believed to be available in the following sectors based on a variety of studies and data sources, and new sources are added as information becomes available. Technologies like carbon capture and storage, ocean fertilization, and others still in development, could dramatically expand these curves as their practical potential is better understood. The supply curves shown in this report are intended to reflect “practical potential,” namely achievable emissions reductions, as opposed to a more theoretical potential based purely on engineering or other considerations. Most supply curve analysis has focused on mitigation measures that cost less than $100/ton, which is why many of the curves experience a sharp increase at about that cost level. It does not mean that there literally are no reductions for more than $100/ton, but that the reductions are often simply not included in this kind of analysis. Supply curves can vary year to year due to a number of factors, and are often dependent on other variables such as fossil fuel prices. The curves presented in this report represent a snapshot as of 2012, using 2007 dollars, and using EIA’s 20-year projection of fossil fuel prices

These supply curves are constantly evolving as information improves. The sectors included in the supply curve modeling conducted for the purposes of this project (described further in Annex 2) include:

- Industrial reductions from cement and chemical production, and industrial efficiency
- Methane
- Forestry and agriculture
- High global warming potential gases
- Transport
- Electricity production

The sectors are aggregated and their respective supply curves are expressed in different ways for the purposes of this report. Different supply scenarios are show graphically according to the following specifications:

- Geography (Moderate Additionality)
    - WCI
    - US
    - Global

- Additionality Sensitivity Cases (Additionality 1 and 5)
    - WCI
    - US
    - Global

- Cap and Trade Supply Cases
    - WCI[1] Capped Sectors and Eligible Offsets
    - US Capped Sectors and Eligible Offsets

- Individual Mitigation Sector Supply Curves
    - Methane
    - Forestry and Agriculture
    - Global Electric Sector
    - High GWP Gases

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[1] The Western Climate Initiative (WCI) is a collaboration of seven US states and four Canadian Provinces to reduce GHG emissions through a cap-and-trade program. In this report, WCI mitigation information has been assembled for the participating US states, including Arizona, California, Montana, New Mexico, Oregon, Utah, and Washington

2.1 Mitigation Supply Curves By Geography (Moderate Additionality)

WCI Region: The supply curve shown in Figure 1 encompasses all sectors within the US states of the WCI, as identified for the purposes of this report, and suggests availability of approximately 150 million tons of reductions before costs escalate rapidly.

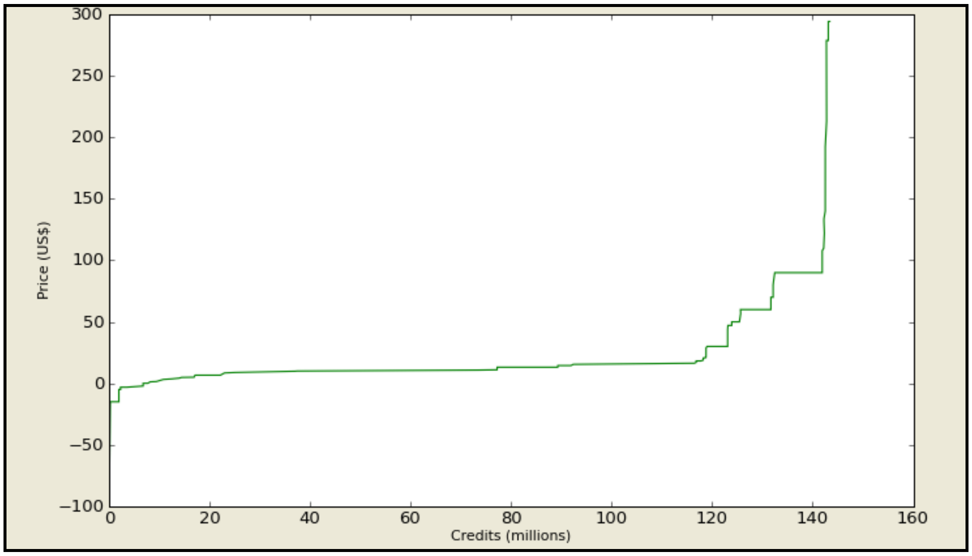

Figure 1: Reference Case, WCI Region

U.S. Region: The graph in Figure 2 covers the same sectors as Figure 1, and likewise has an applied additionality level of 3. This supply curve, however, comprises all the United States (including those in the WCI region). Within this scenario, almost 500 million tons are available before costs escalate very rapidly.

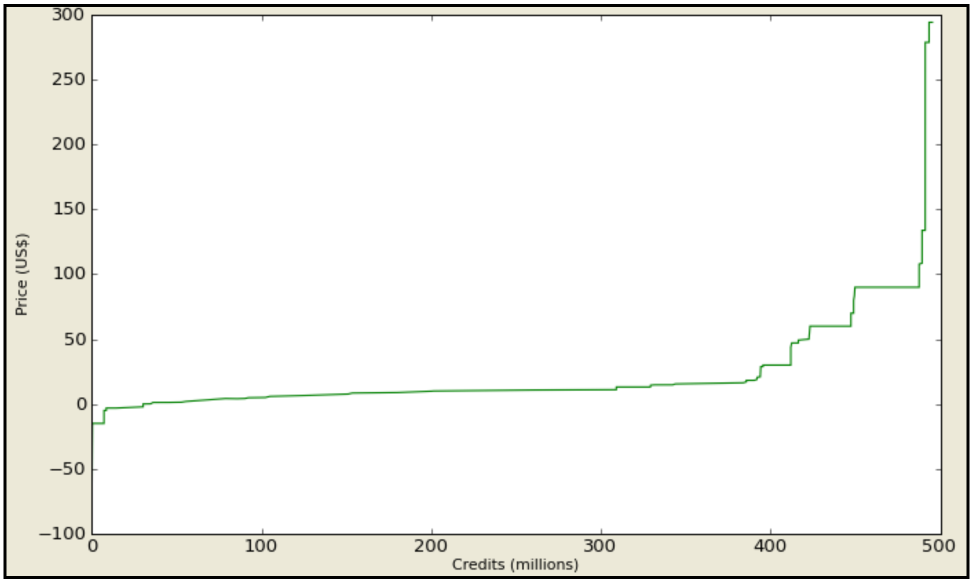

Figure 2: Reference Case, US Region

Global Region: The supply curve in Figure 3 encompasses all sectors on a global level, including the US and those states in the WCI region. As can be seen in the graph, almost 3 billion tons are available before costs go out of range.

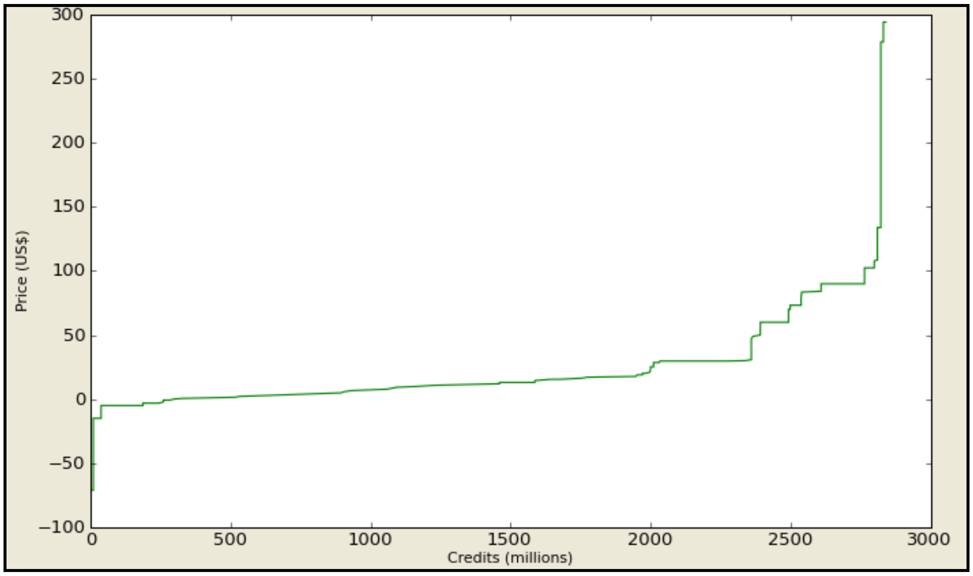

Figure 3: Reference Case, Global Region

2.2 Additionality Sensitivity Cases

Because the manner in which additionality is applied in offset markets is an important consideration, the following graphics show alternative additionality screens applied to the offset supply curves shown above. The offset supply curves shown above assume a moderate level of additionality stringency – treated as Level 3 stringency on a scale of 1 to 5 in the model. A Level 1 additionality screen indicates a relatively moderate level of additionality stringency and could likely lead to many "false positive" reductions being counted as offsets; relatively few truly "additional" reductions would be accidentally excluded as "false negatives." A Level 5 additionality screen indicates a very rigorous level of additionality stringency, allowing very few "false positive" reductions to be captured by the modeled offset pool (except as a byproduct) also excluding many truly "additional" reductions as "false negatives." It is the combination of these two factors that dramatically shrinks supply curves displaying a Level 5 additionality screen.

2.2.1 Low Additionality Stringency (Level 1) Supply Curves

WCI Region: Based on a minimally stringent additionality screen, the supply curve in Figure 4 results in approximately 250 million tons, an almost 100 million ton increase from the estimates shown in Figure 1.

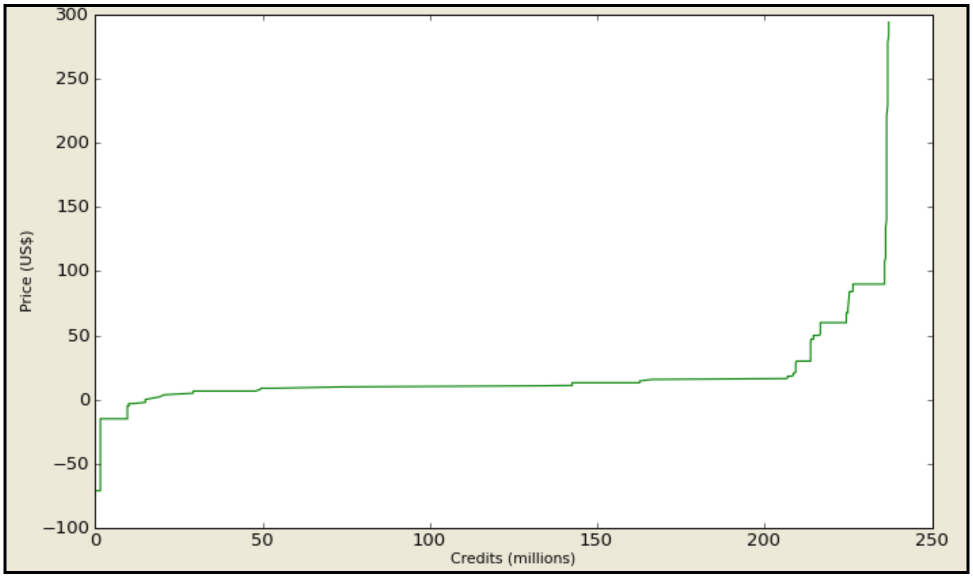

Figure 4: Low Additionality Stringency, WCI Region

U.S. Region: With a minimally stringent additionality screen, the U.S. supply curve shown in Figure 5 increases by almost 350 million tons from Figure 2, to almost 850 million tons.

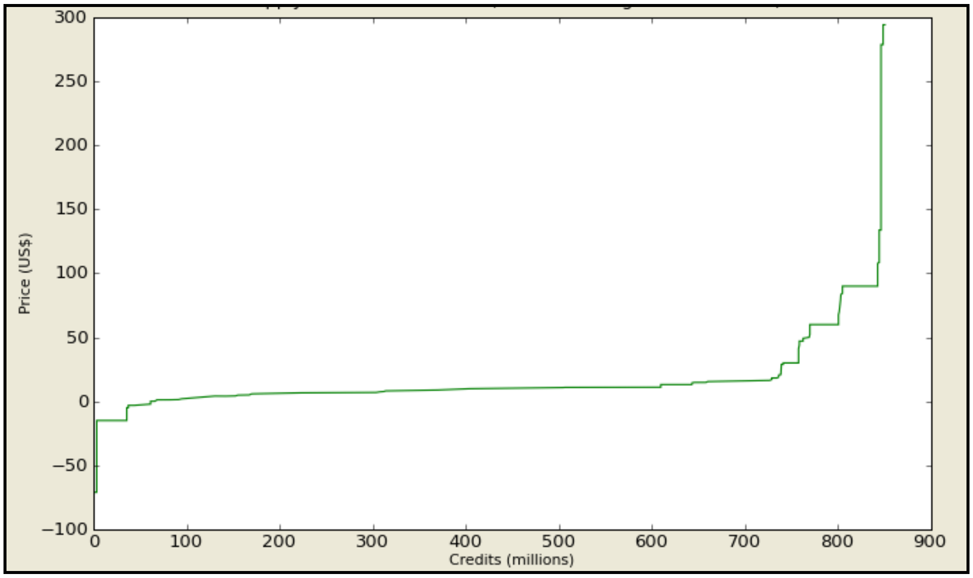

Figure 5: Low Additionality Stringency, US Region

Global Region: With a minimally stringent additionality screen, almost 5.5 billion tons of reductions are included in the curve shown in Figure 6, an increase of 2.5 billion tons from Figure 3. More than $3 billion of these tons cost less than $20/ton.

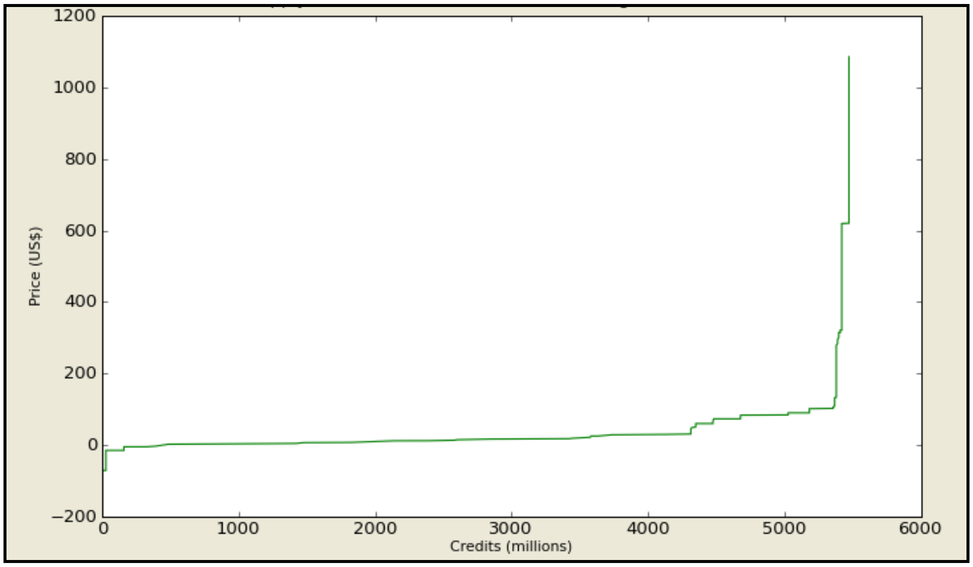

Figure 6: Low Additionality Stringency, Global Region

2.2.2 High Additionality Stringency (Level 5)

WCI Region: Under a particularly strict application of additionality rules, the supply curve shown in Figure 7 reflects only 50 million tons of reductions, a reduction in supply of almost 100 million tons from Figure 1. In Figure 7, forty million tons are available at less than $20/ton.

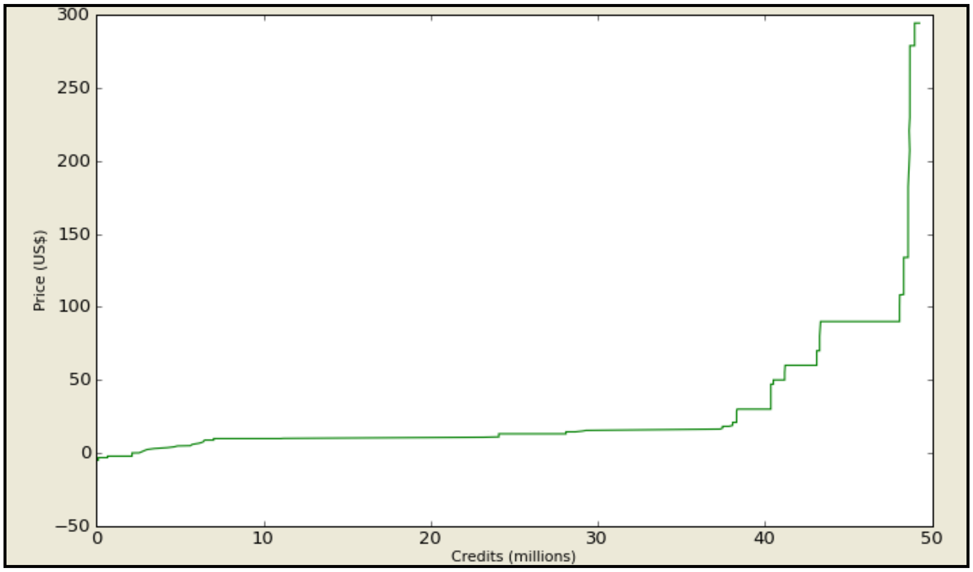

Figure 7: High Additionality Stringency, WCI Region

U.S. Region: Under a particularly strict application of additionality, the U.S. supply curve in Figure 8 includes approximately 160 million tons of reduction, a 300 million ton reduction from Figure 2. In Figure 8, 115 million of these tons are available at a cost of less than $20 per ton.

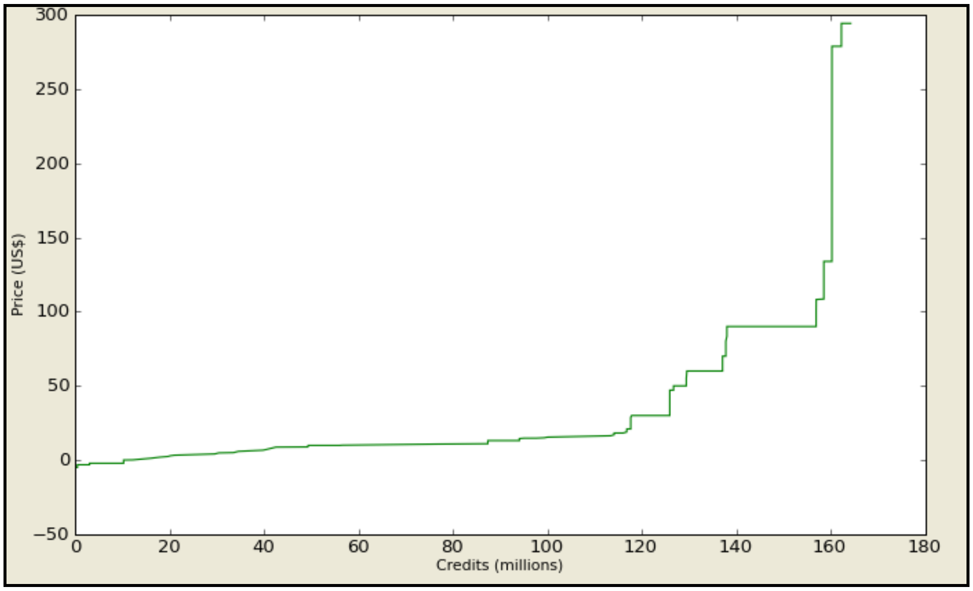

Figure 8: High Additionality Stringency, US Region

Global Region: Under a particularly strict application of additionality, the global supply curve shown in Figure 9 includes almost 1 billion tons, almost 2 billion tons less than shown in Figure 3. In Figure 9, approximately 600 million tons are available at less than $20.

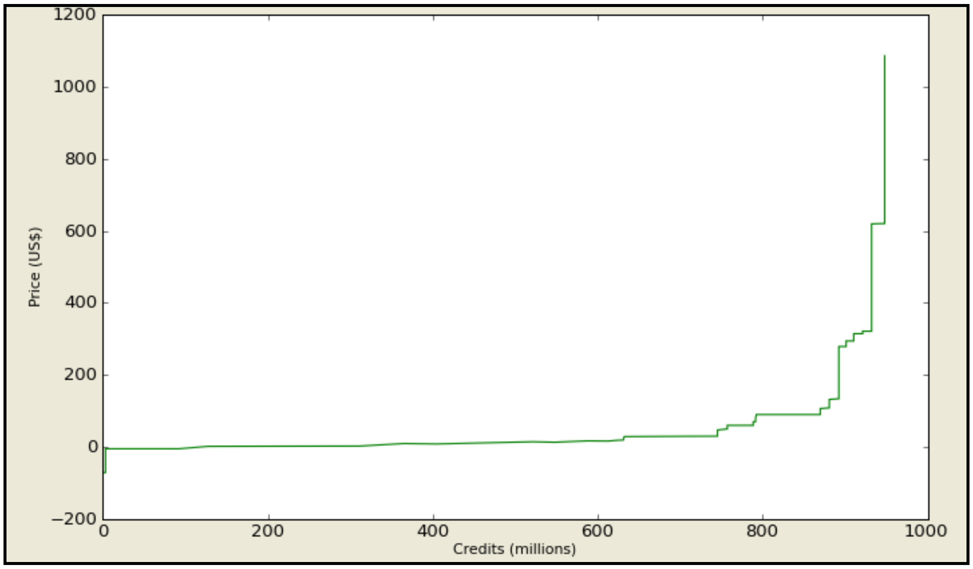

Figure 9: High Additionality Stringency, Global

2.3 The Implications of a Cap and Trade Program for Offset Supply

In a cap-and–trade system, an emission cap is assigned to certain economic sectors while other sectors are permitted to generate offsets. Our supply curve modeling assumes that the electric sector, transport sector, and industrial sectors are incorporated under the cap in a cap and trade system. As a result, reductions from these sectors are not longer available as offsets, although the available reductions can still be shown as a supply curve. These reductions are also not subject to additionality rules (the “why” of emissions reductions doesn’t really matter in capped sectors at the level of the emission reduction, although it’s a variable policy makers need to account for in setting the cap). Under the cap and trade system, other sectors can supply offsets into the system and are still subject to additionality screening.

The following graphics distinguish between the reductions estimated to be available within the capped sectors, and the reductions estimated to be available as offsets from sectors outside the cap. To that end the following supply curves are presented for a WCI cap and trade scenario:

- Estimated reductions available from within capped sectors in the WCI
- Estimated offsets available from non-capped sectors within the WCI region
- Estimated offsets available from non-capped sectors within the U.S. region
- Estimated offsets available from non-capped sectors within the global region (excluding industrialized countries)

In addition, the following curves are presented for a U.S. cap and trade scenario:

- Estimated reductions available nationally from within capped sectors
- Estimated offsets available from non-capped sectors within the U.S. region
- Estimated offsets available from non-capped sectors within the global region (excluding industrialized countries)

2.3.1 WCI Cap and Trade Scenario

WCI Region (Reductions from Capped Sectors): As shown in Figure 10, approximately 50 million tons of reductions within the capped sectors are estimated to be available within the WCI states.

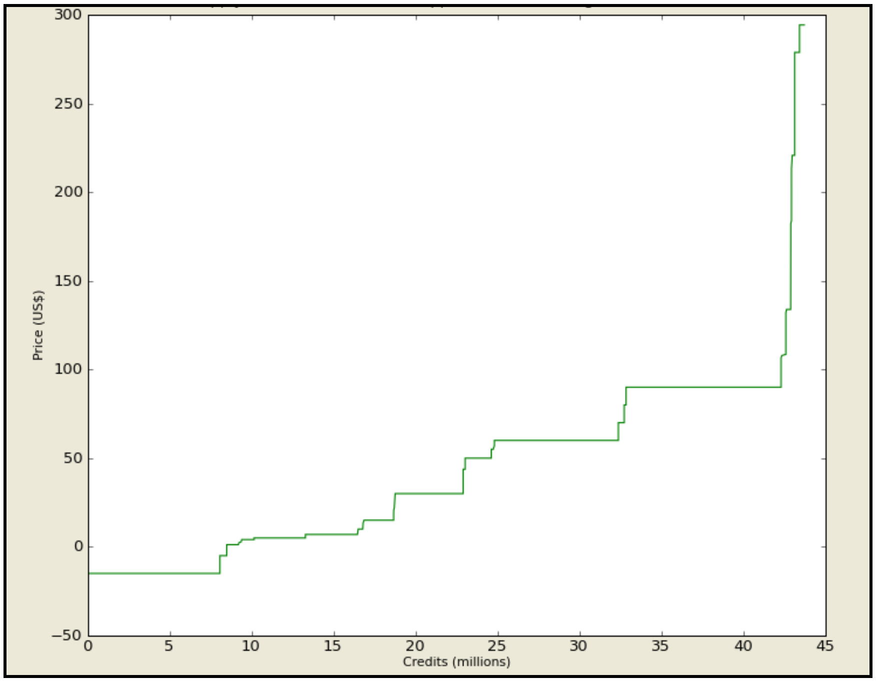

Figure 10: WCI Cap and Trade Supply Curve

WCI Region (Offsets from non-capped Sectors): As shown in Figure 11, offsets from non-capped sectors in the WCI region are estimated to total almost 75 million tons. Almost all of these tons would cost less than $20/ton to generate. This compares to the approximately 60 million tons of offsets that could potentially be used for WCI compliance based on the rules as currently drafted (under which up to 49 percent of total reductions can be met through offsets).

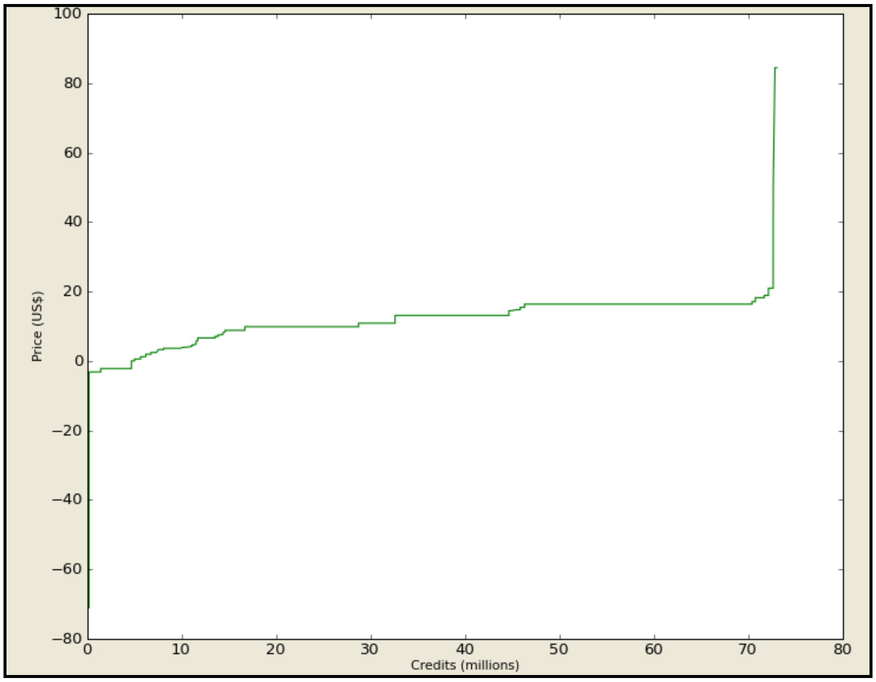

Figure 11: WCI Cap and Trade Scenario, WCI Region Offsets (Moderate Additionality Stringency)

U.S. Region (Offsets from non-Capped Sectors): As shown in Figure 12, potential offsets from non-capped sectors across the U.S. total almost 300 million tons, most of which are estimated to cost less than $20/ton.

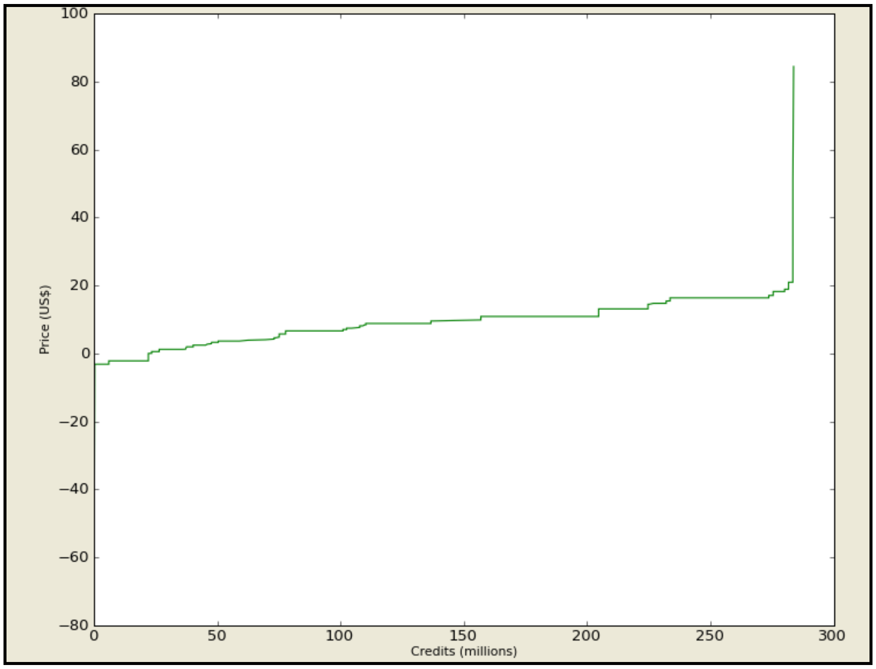

Figure 12: WCI Cap and Trade Scenario, US Region Offsets (Moderate Additionality Stringency)

Global Region (Offsets from non-capped sectors): As shown in Figure 13, potential global offsets (excluding reductions from other industrialized countries that are assumed to be implementing targets of their own) total approximately 1.9 billion tons.

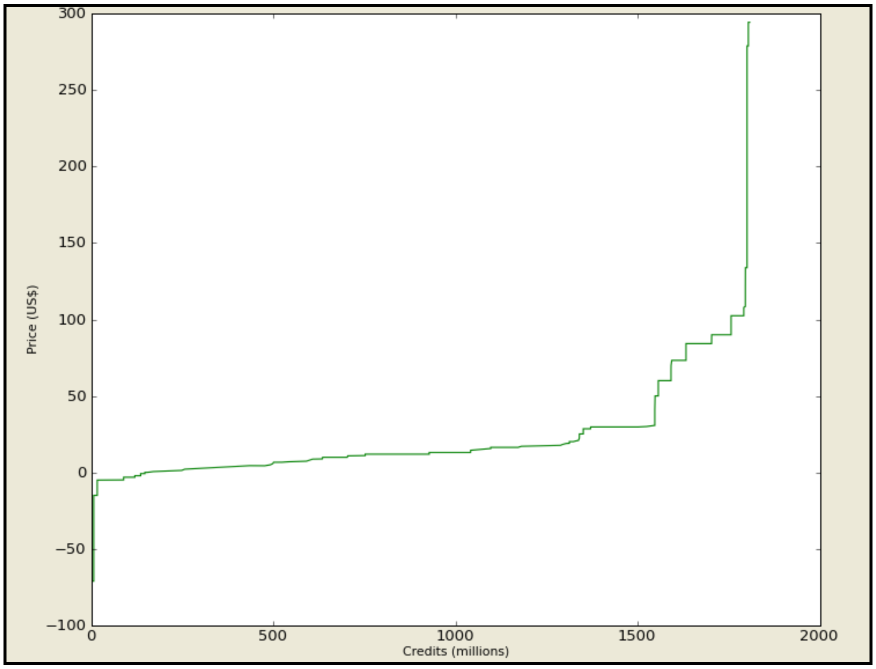

Figure 13: WCI Cap and Trade Scenario, Global Offsets (Moderate Additionality Stringency)

2.3.2 US Cap and Trade Scenario

U.S. Region (Reductions from Capped Sectors): As shown in Figure 14, reductions available within the capped sectors in the U.S. total almost 300 million tons, of which almost 190 million tons would be available at a cost of less than $20/ton.

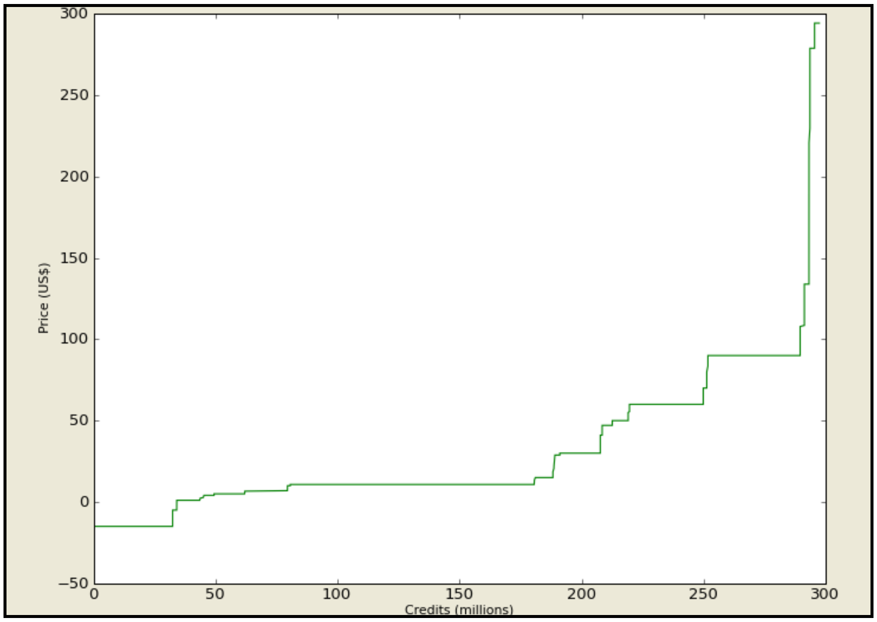

Figure 14: US Cap and Trade Supply Curve

U.S. Region (Offsets from non-Capped Sectors): As shown in Figure 15, potential offsets from non-capped sectors in the U.S. are estimated at almost 300 million tons.

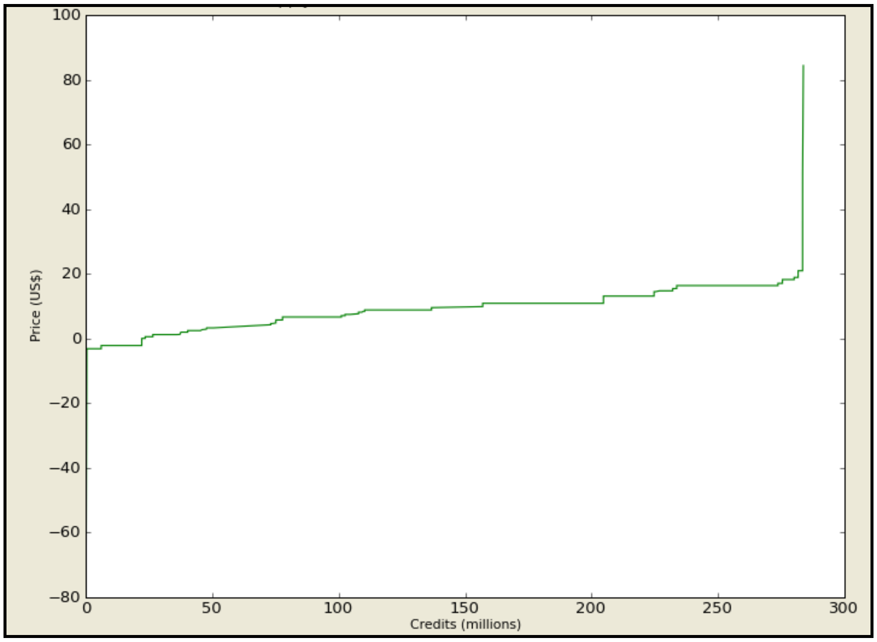

Figure 15: US Cap and Trade Scenario, US Region Offsets (Moderate Additionality Stringency)

Global Region (Offsets from non-capped Sectors): As shown in Figure 16, international offsets supply (excluding other industrialized countries) is estimated at almost 1.8 billion tons, of which 1.3 billion tons are available for less than $20/ton.

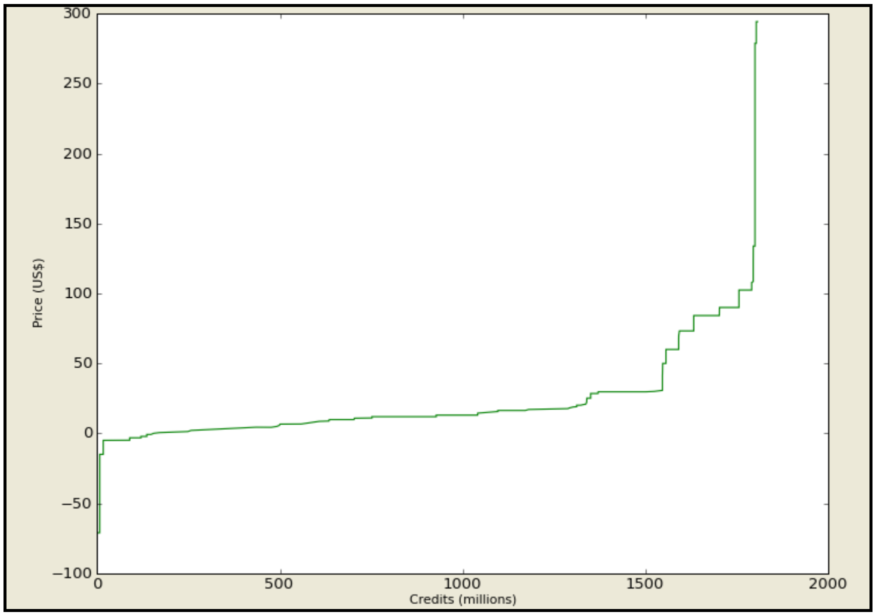

Figure 16: US Cap and Trade Supply Curve, Global Offsets (Moderate Additionality Stringency)

2.4 Key Mitigation Sector Supply Curves

This sub-section of the report presents supply curves for several individual offset sectors, to illustrate some of the specific underlying data sets.

2.4.1 Methane

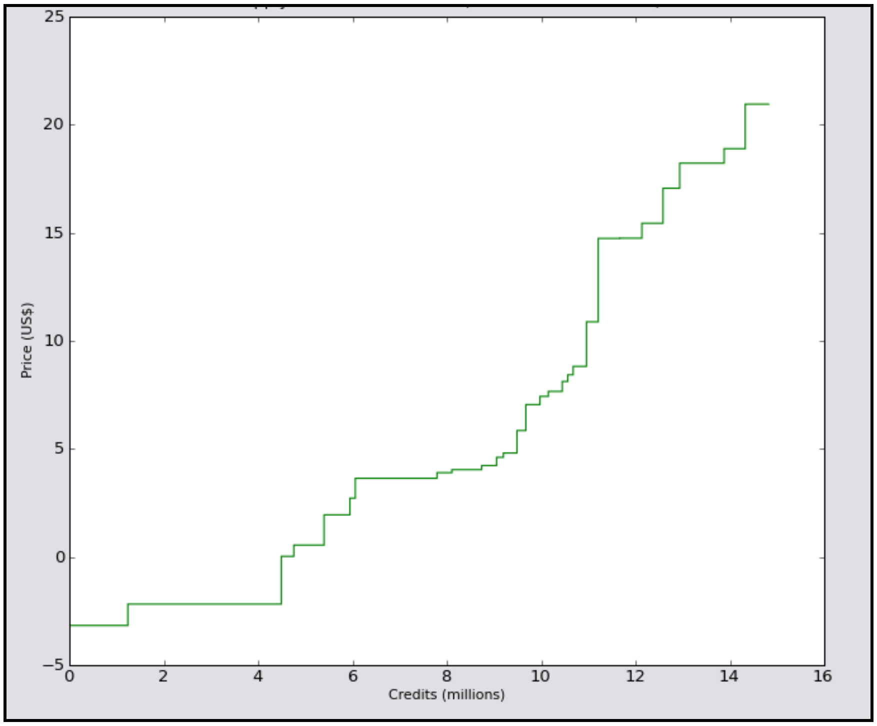

Figure 17: WCI Methane Sector (Moderate Additionality)

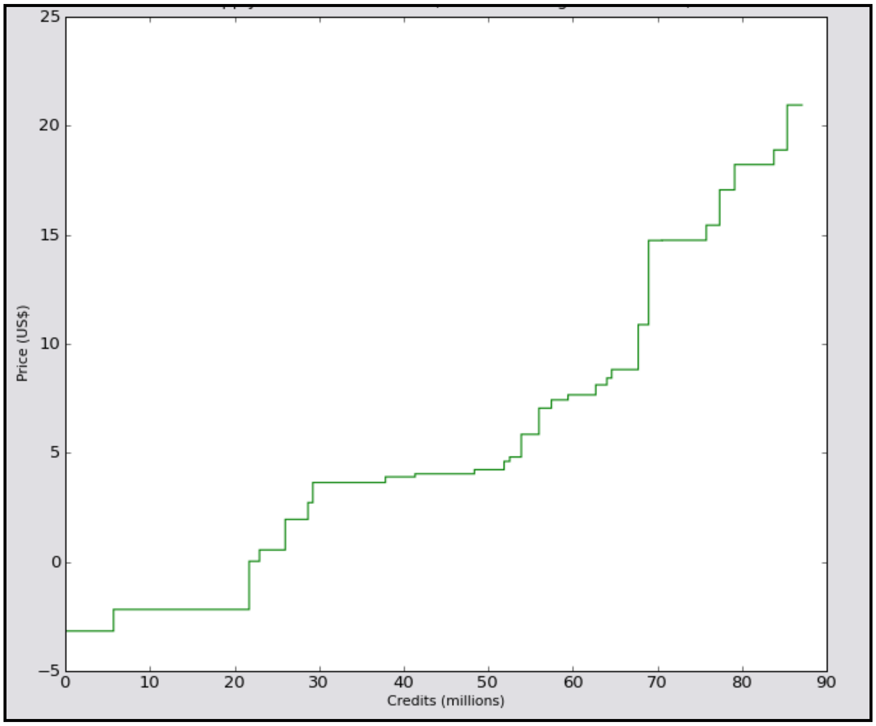

Figure 18: US Methane Sector (Moderate Additionality)

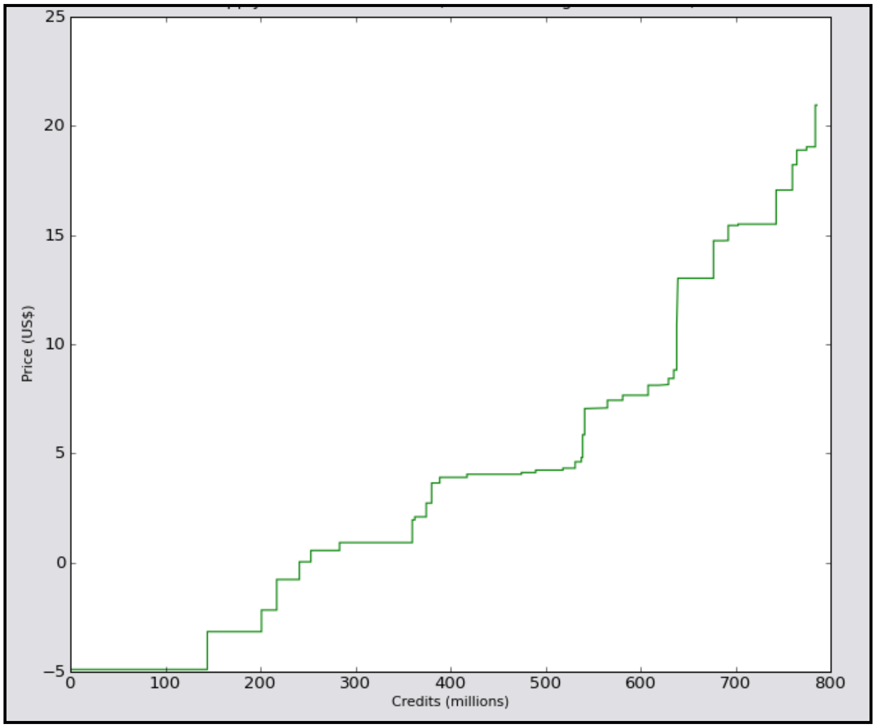

Figure 19: Global Methane Sector (Moderate Additionality)

2.4.2 Forestry

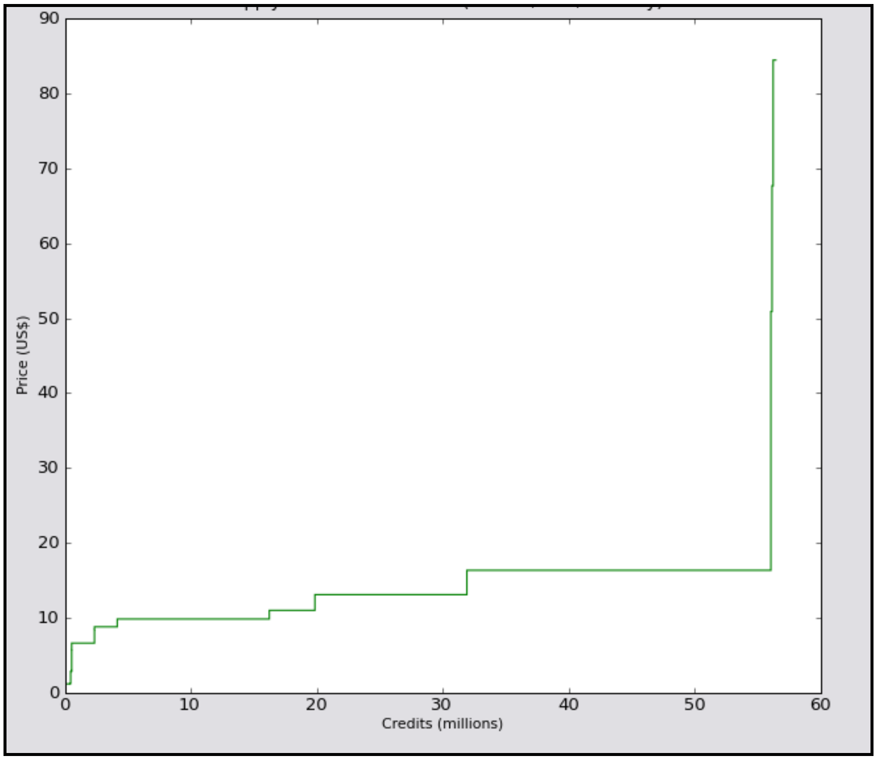

Figure 20: WCI Forestry Sector (Moderate Additionality)

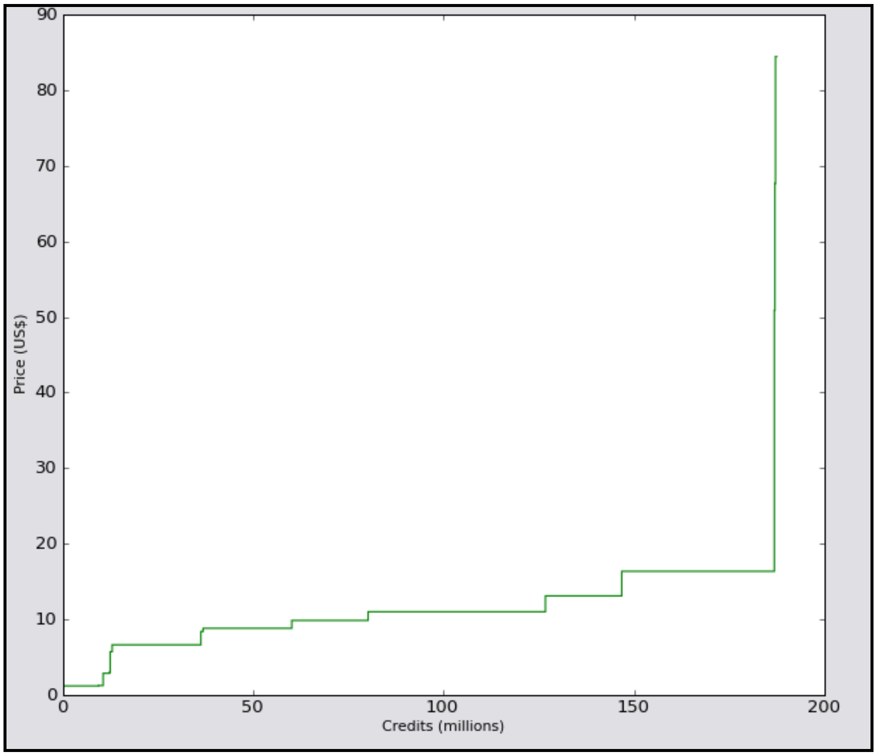

Figure 21: US Forestry Sector (Moderate Additionality)

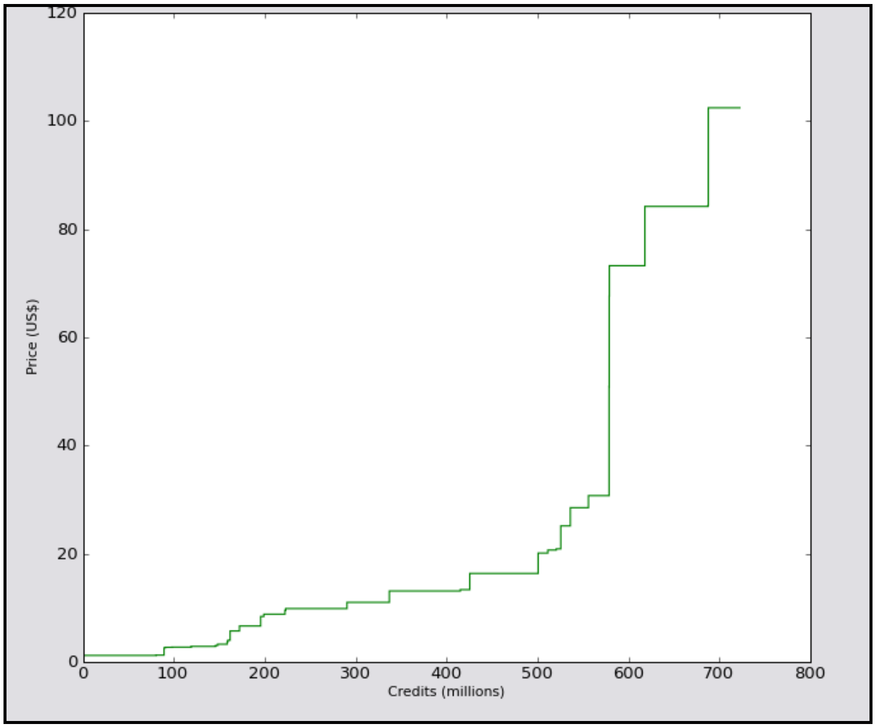

Figure 22: Global Forestry Sector (Moderate Additionality)

2.4.3 Electric Sector

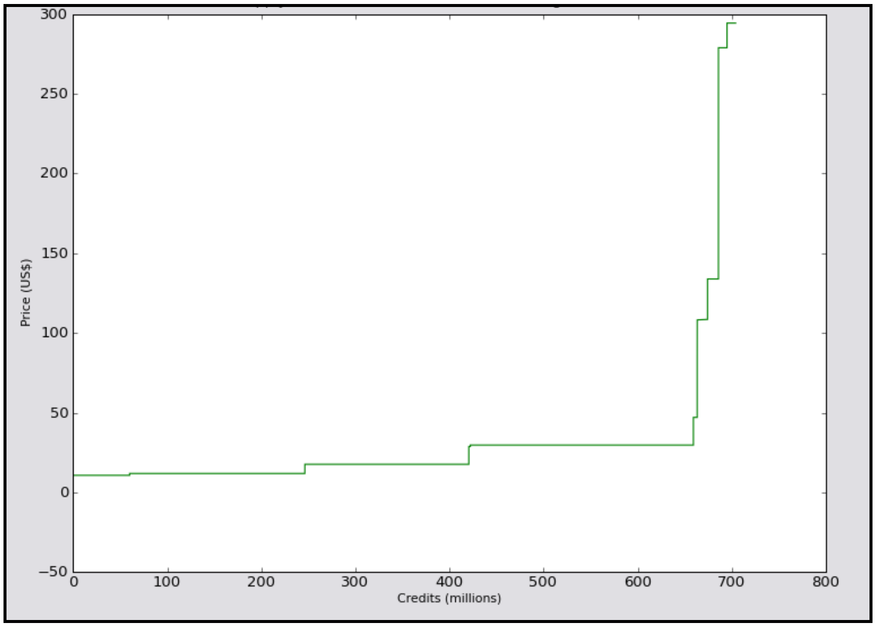

Figure 23: Global Electric Sector (Moderate Additionality)

2.4.4 High GWP

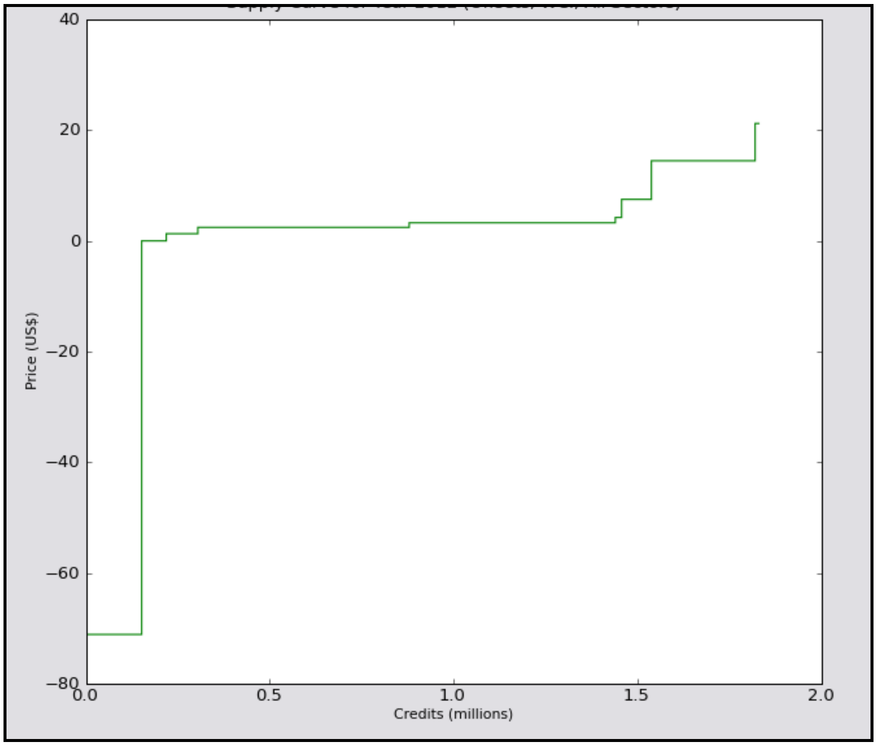

Figure 24: WCI High GWP Sector (Moderate Additionality)

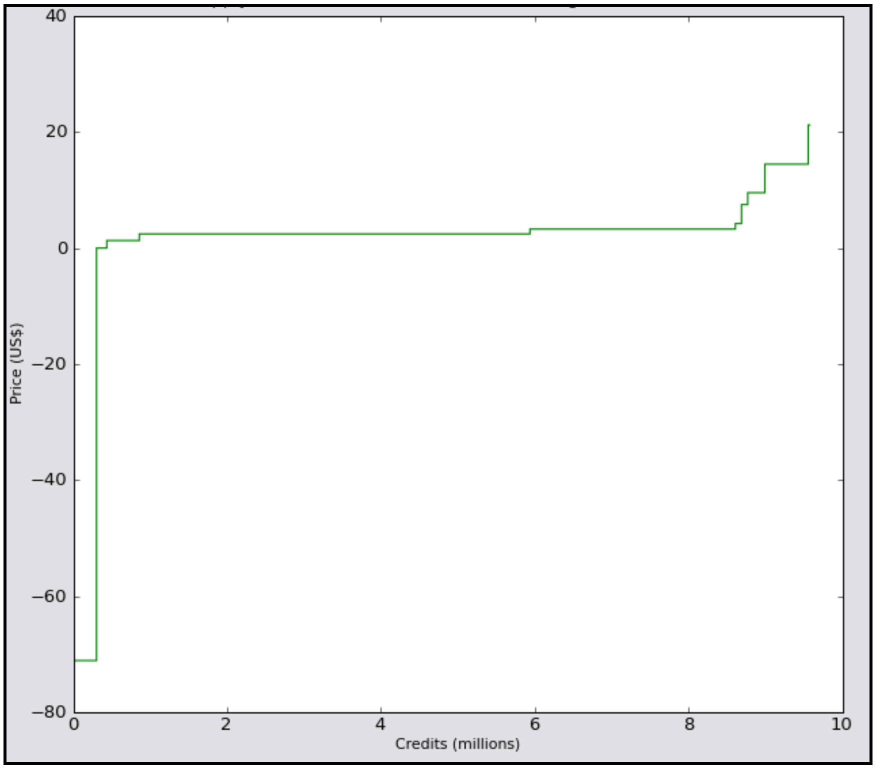

Figure 25: US High GWP Sector (Moderate Additionality)

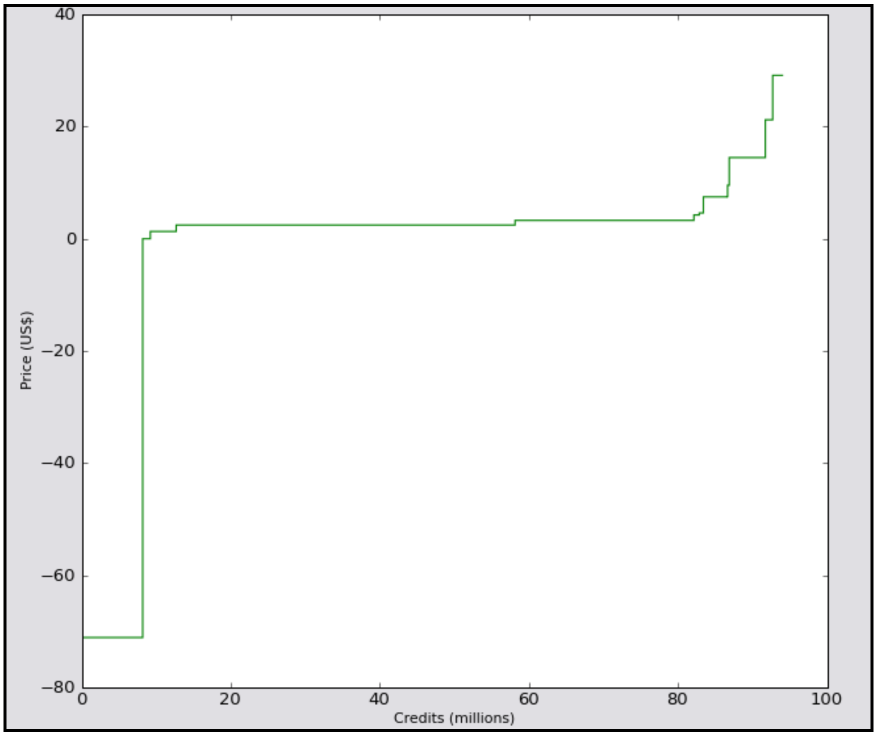

Figure 26: Global High GWP Sector (Moderate Additionality)

Annex 1 Background to the ECL Supply Curve Model

ECL’s supply curve model is based on publicly available data from bottom-up studies of the regional and global technical potential for emissions reductions, and is combined with ECL’s own analysis of costs and additionality. The model generates supply curves for *project-based reductions*.[2]

The ECL supply curve model includes data on potential emission reductions for approximately 60 separate technology options. It allows the examination of multiple scenarios involving the inclusion or exclusion of technology sectors or individual technology options. For each technology option, a cost per ton is calculated based on project level characteristics (such as capital costs, operating costs, and typical project size), as well as assumptions of the discount rate, fuel costs, and electricity prices. For most technologies, a range of cost estimates are available; consequently total potential can be distributed among the range of costs. The technological characteristics for each option are derived from estimates made by the IPCC, EPA. or other publically available sources.

The supply model offers a powerful way to examine the potential availability of project-based emission reductions under a range of policy and technology scenarios. A critical insight offered by this approach is how available supply may change based on differing levels of stringency applied to the evaluation of project additionality. Depending on total demand and the realization of technological potentials, project additionality rules may have a significant impact on the ultimate price of GHG reductions. The supply model also facilitates understanding of which technology sectors have the greatest potential for reducing emissions, the cost characteristics of these sectors, and how these sectors will fare under different interpretations of additionality.

Every ton of potential supply in the model is assigned an additionality “rank,” ranging from 1 to 5. These ranks do not correspond to specific baseline policies or additionality criteria, but rather are qualitative assessments about the degree to which the emission reductions arise from activities that go beyond “business as usual.” A rank of one implies “poor” additionality, meaning that the reduction in question probably would have happened anyway. A rank of five implies “unquestioned” additionality, meaning that the reduction would receive credit under almost any possible baseline or screening standard. The supply curve can be configured to reflect only those tons of a certain additionality rank or higher, indicating what effect different policy standards may have on the market. Note that the tighter the additionality restrictions, the more “additional” reductions that accidentally get excluded along with the non-additional reductions.

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[2] Many of the technical potential studies used as the basis for ECL’s supply curve estimate reductions achievable through government policies and measures in addition to project-based activities. The supply model is focused exclusively on project-based reductions. Thus, while there may be quite a large potential for emission reductions in the transportation sector, e.g. through CAFÉ standards, the *achievable* level of reductions in the supply curve will be much smaller, reflecting the difficulty involved in pursuing such reductions through project-based activities.

Annex 2 The ECL Supply Curve Model Data Sets

2.4.5 Cement Sector

The cement manufacturing industry is a major source of carbon dioxide (CO_2) emissions from three sources: 1) emissions from fuel combustion, 2) emissions from limestone calcinations, and 3) emissions from electricity use including direct and indirect sources. Reducing CO_2 emissions from the cement sector requires manufacturing facilities to improve energy efficiency practices and technologies in cement production and altering the composition of cements that are less energy intensive to produce per ton.

2.4.6 Chemical: N20 Emissions from Nitric and Adipic Acid Production

Global industrial N_2O emissions account for over 154 million metric tons of CO_2 equivalent ($MTCO_2eq$) (USEPA, 2006). Nitric and adipic acid production in the chemical industry accounts for around five percent of the global total for N_2O emissions, of which nitric acid production accounts for two thirds of the N_2O emissions (USEPA, 2003). The United States accounts for 40 percent of the total adipic acid production worldwide (USEPA, 2001). Abatement options decompose N_2O into nitrogen and oxygen using various catalysts. The average reduction efficiency is approximately 90 percent.

2.4.7 High-GWP Gases from Industrial Processes (High GWP)

The three major groups of high GWP gasses include: hydroflurocarbons(HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). These compounds have the highest global warming potential (GWP), up to 20,000 times the GWP of carbon dioxide on a per unit of weight basis. Various abatement options for the largest sources of industrial high-GWP emissions include:

- *Electric Transmission and Distribution*: Sulfur hexafluoride(SF_6) is a colorless, odorless, nontoxic, and nonflammable gas with a global warming potential that is 23,900 times more potent than CO_2. Approximately 20 percent of total global SF_6 sales go into electric power systems. SF_6 emissions from transmission and distribution systems occur through leakages from gasket seals, flanges, and threaded fittings and handling losses during servicing.

- *HFC-23 Emissions from HCFC-22 Production*: Trifluoromethane (HFC-23) is generated and emitted as a by-product during the production of chlorodifluoromethane (HCFC-22). HCFC-22 is used in air-conditioning and refrigeration and as a feedstock for production of synthetic polymers. HCFC-22 production from non- feedstock uses is scheduled to discontinue under the Montreal Protocol. However, feedstock production is permitted to continue indefinitely. HFC-23 emissions can be reduced through thermal destruction measures that are relatively inexpensive. Because HFC-23 has a GWP of 11,700 and an atmospheric lifetime of 264 years, HFC-23 reduction options present a low cost abatement option.

- *SF6 Emissions from Magnesium (Mg) Production*: The production of Magnesium uses SF_6 as a cover gas to prevent the spontaneous combustion of molten magnesium. Fugitive SF_6 emissions occur at various stages of magnesium manufacturing and casting. Abatement options include replacing the use of SF_6 gas with either SO_2 or fluorinated gases.

- *PFC and SF6 Emissions from Semiconductor Manufacturing*: The manufacturing of semiconductors emits a fraction of several fluorinated compounds (CF_4, C_2F_6, C_3F_8, HFC-$_{23}$, NF_3, and SF_6) during the plasma etching of thin films and the cleaning of chemical-vapor-deposition chambers. Abatement options include thermal destruction, catalytic decomposition, and capture/recovery of SF_6.

2.4.8 Methane

Methane has a global warming potential 21 times that of CO_2, and as such is a prime avenue for emission reductions. This sector comprises several different mitigation measures:

- *Coalmine Methane:* Where CH_4 that would otherwise be released during or after mining operations is captured, flared, or converted into heat or electricity.

- *Landfill Gas*: Where CH_4 from the degradation of waste is captured and either flared or converted into heat or electricity.

- *Manure Management*: Where CH_4 from animal waste is reduced via anaerobic digestion (which captures the gas and either disposes of it or converts it to energy).

2.4.9 Transport

Globally, the transportation sector accounts for a growing fraction of global GHG emissions. Of the various abatement options that exist, vehicle electrification and the use of alternative fuels were incorporated into the supply curves.

- *Electrification*: Electrification of vehicles includes the adoption of Plug-in Hybrid Electric Vehicles (PHEVs) that reduce the consumption of fossil fuels through the displacement of fossil fuel with an electric motor for a portion of the vehicle’s travel.

- *Alternative Fuels*: The model focuses on the reduction of carbon dioxide emissions by switching the use of fossil fuels in vehicles to ethanol or biodiesel. Both ethanol and biodiesel can operate in internal combustion engines with little to no modifications and therefore provides a viable short term option to reduce carbon dioxide emissions from the transportation sector.

2.4.10 Forestry

Between 2000 and 2005, gross deforestation occurred at a rate of 12.9 million ha/yr (IPCC, 2007) with the largest losses in South America, Southeast Asia, and Africa. Within this sector there are four main abatement options:

- *Afforestation*: Afforestation is the direct conversion of non-forest land to forest land through planting and other human-induced reforestation efforts. Historically, carbon sequestration has not been the largest driver of afforestation efforts, but increases in the value of carbon can greatly affect afforestation rates.

- *Reduced Deforestation*: Deforestation – the anthropogenic conversion of forest to non-forest land - accounts for nearly a fifth of global greenhouse gas emissions (IPCC, 2007). Deforestation can either be reduced or delayed through protection measures, sustainable forest management policies, or by providing economic returns on non-timber forest products. Reduced deforestation accounts for the largest and most immediate carbon stock impact per hectare globally and offers a cost effective option to significantly reduce global emissions in the short term.

- *Forest Management*: Although nearly 90 percent of forests in industrialized countries are managed “according to a formal or informal management plan” (FAO, 2001), only around six percent of forest land in developing countries are covered under a forest management plan (IPCC, 2007). Proper forest management is a vital prerequisite to any of the above abatement options. Carbon markets can provide a financial incentive to foster national level forest management programs within developing countries.

- *Agriculture*: Conventional tillage practices increase the amount of carbon dioxide that is released into the atmosphere. Abatement options for this sector include conservation tillage practices, changing land and crop management, modifying the intensity of crops, or retiring land from production.

2.4.11 Electric Sector

The model incorporates a natural gas plant as its baseline project in order to develop a supply curve for the abatement options below.

- *Geothermal*: The thermal energy from geothermal reservoirs can be used to produce electricity. For this model, geothermal energy focuses on Enhanced Geothermal Systems which include all geothermal resources that are currently not in commercial production and is based on a report published by MIT, “The Future of Geothermal Energy” (2007) that assesses the practical potential of geothermal EGS in 2050 at 100,000 MW.

- *Wind*: In 2007, cumulative wind power capacity increased more than 26 percent worldwide (IEA, 2007 Annual Report). The United States has a total installed capacity of 16,904 MW, of which 5,329 MW was installed in 2007 (IEA, 2007 Annual Report). The model takes regional wind potential based on NREL's WinDS model and applies a practical adoption rate year over year for onshore and offshore wind turbines.

- *Solar*: Solar power has a tremendous technical potential but is severely limited by land, energy-storage and investment constraints. The model focuses on two prevailing solar technologies.

    - *Solar Photovoltaic (PV):* Accounts for most rooftop and commercial solar installations. Solar PV technologies are based on crystalline silicon cells with efficiencies of around 18 percent. Solar PV accounts for 33 percent of the solar market (IPCC, 2007)

    - *Concentrating Solar Power (CSP):* CSP plants are categorized by concentrating solar flux by parabolic trough-shaped mirrors which increase the sun's concentration up to 100 times. Installed capacity in 2007 was 354 MWe with capacities ranging from 14-80 MWe (IPCC, 2007).

- *Carbon Capture and Storage*: Carbon Capture and Storage (CCS) captures emissions from a large stationary source (usually a power plant) and sequesters it in geologic formations such that it is permanently stored underground. Common areas for sequestration include depleted oil and natural gas reservoirs, coal seams, and deep saline formations. This is a relatively controversial technology, as concerns over permanence and environmental risks have led to questions regarding its efficacy. The long-term potential for CCS will rely heavily on future legislation as well as general public acceptance of the technology.