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A Report for the Northwest Power and Conservation Council

Selected GHG Mitigation Supply Curves

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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

[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.

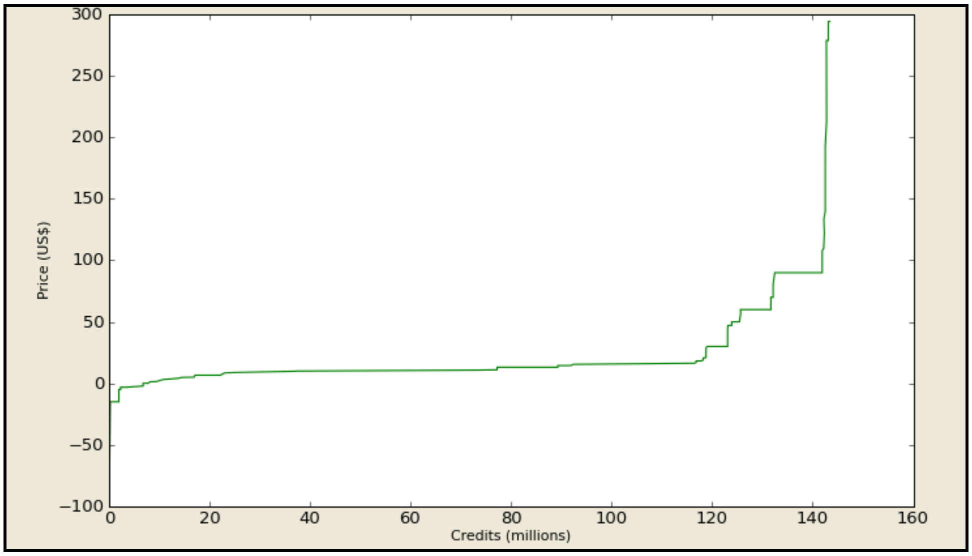

Figure 1: Reference Case, WCI Region

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.

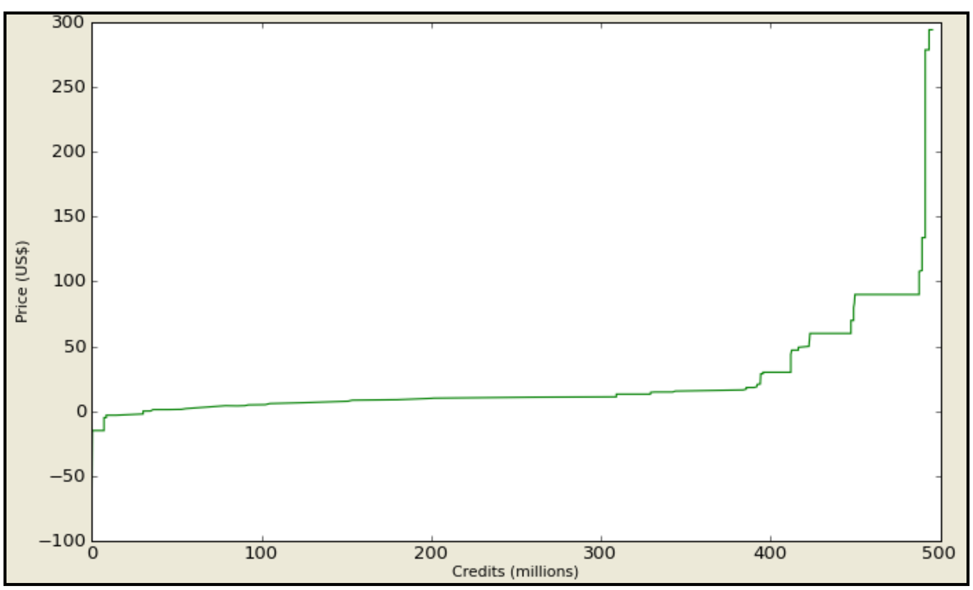

Figure 2: Reference Case, US Region

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.

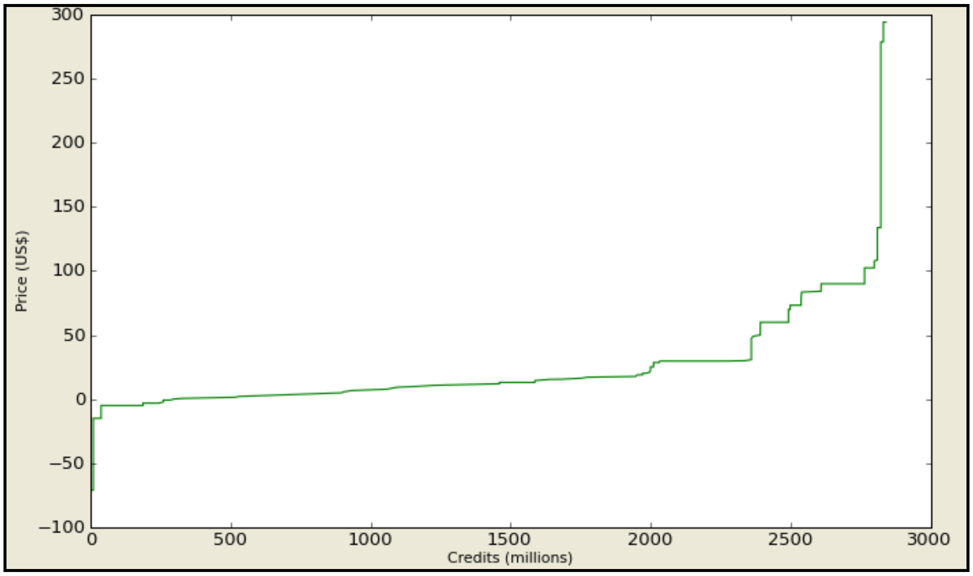

Figure 3: Reference Case, Global Region

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.

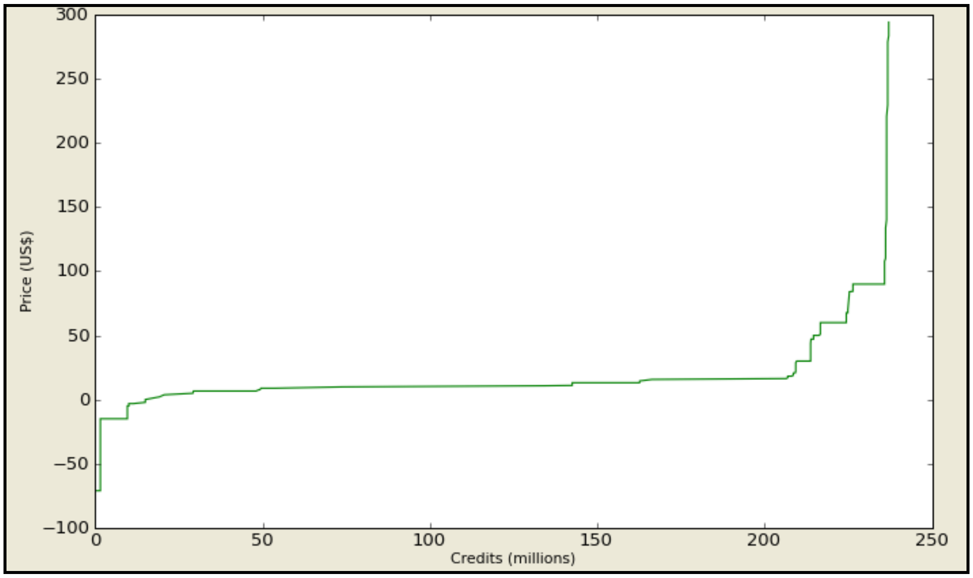

Figure 4: Low Additionality Stringency, WCI Region

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.

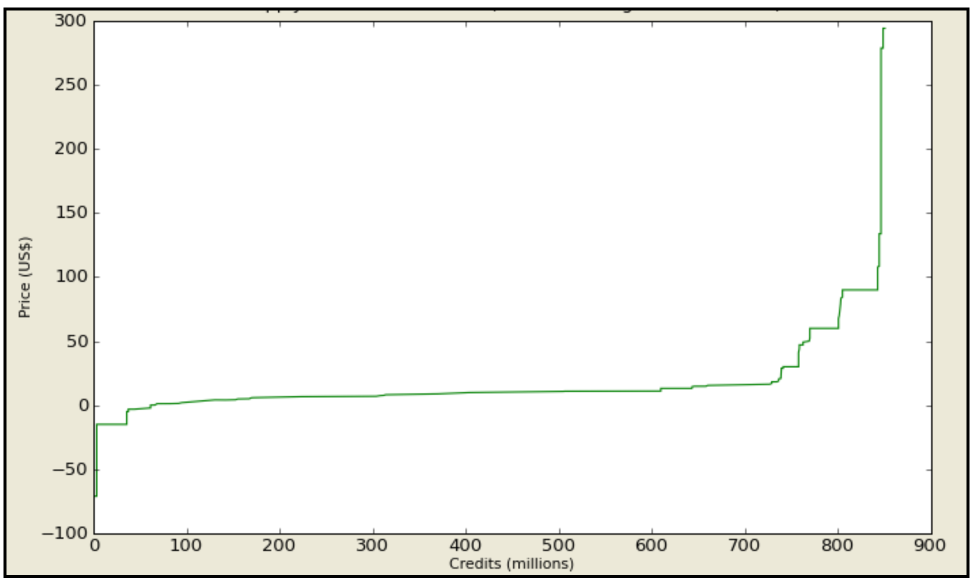

Figure 5: Low Additionality Stringency, US Region

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.

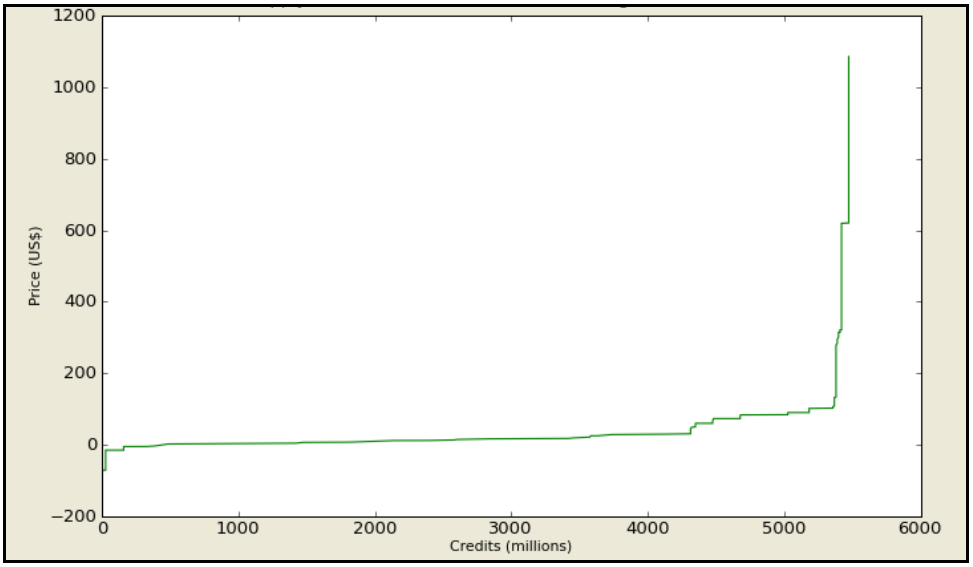

Figure 6: Low Additionality Stringency, Global Region

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.

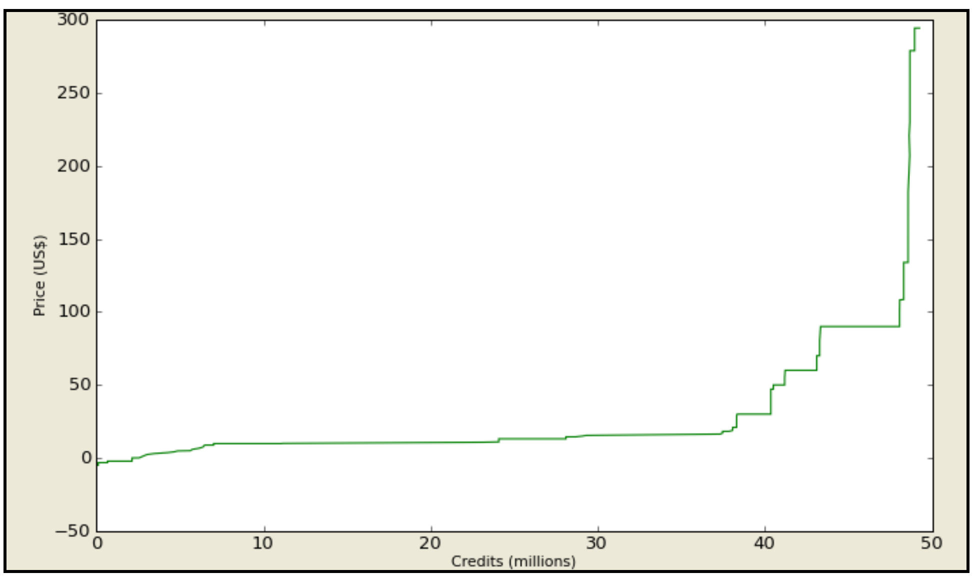

Figure 7: High Additionality Stringency, WCI Region

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.

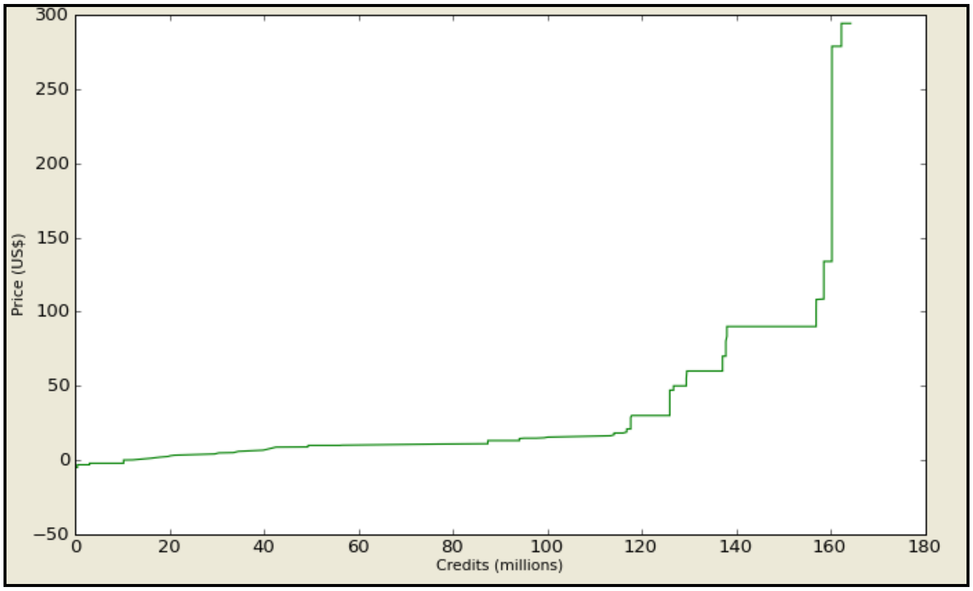

Figure 8: High Additionality Stringency, US Region

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.

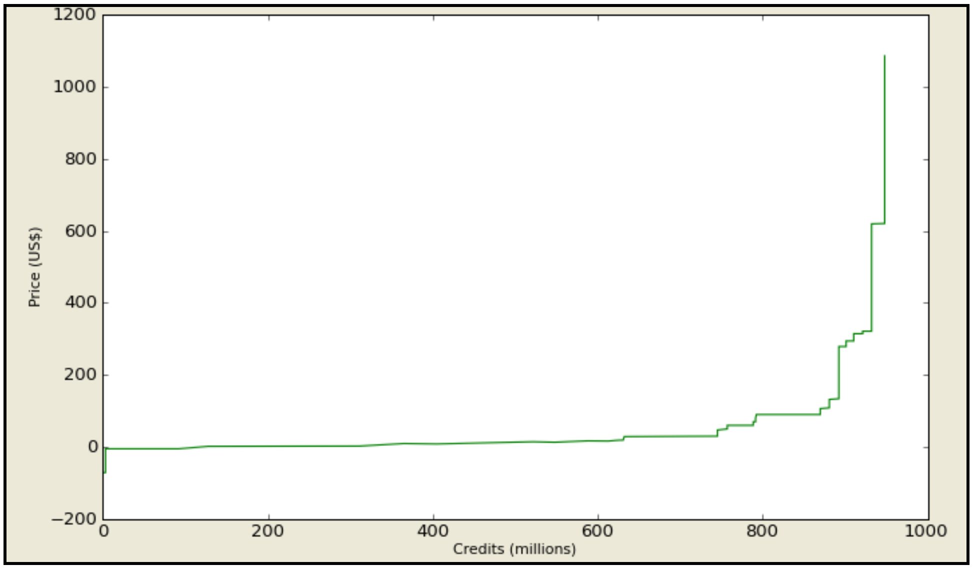

Figure 9: High Additionality Stringency, Global

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.

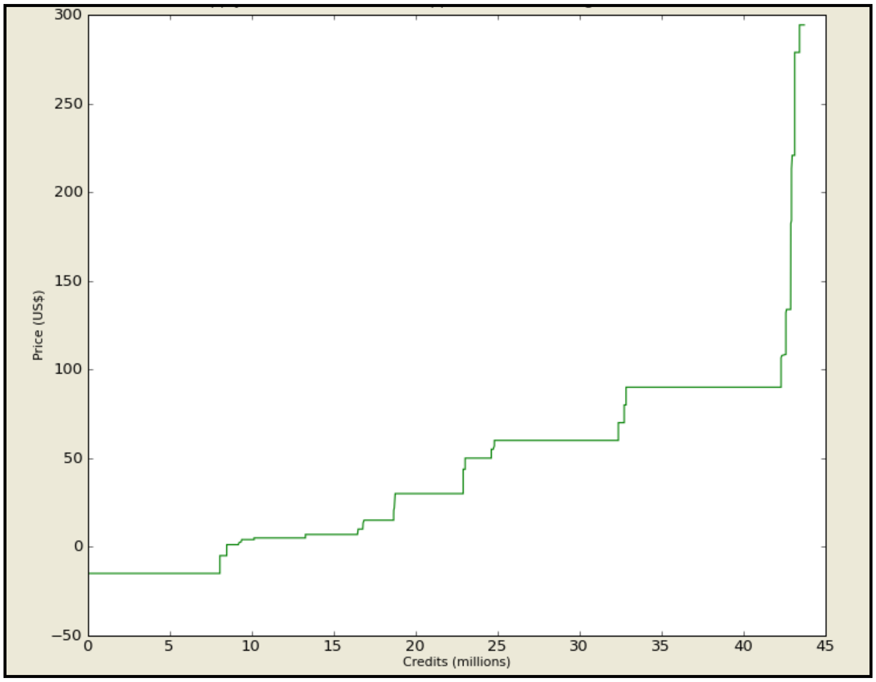

Figure 10: WCI Cap and Trade Supply Curve

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).

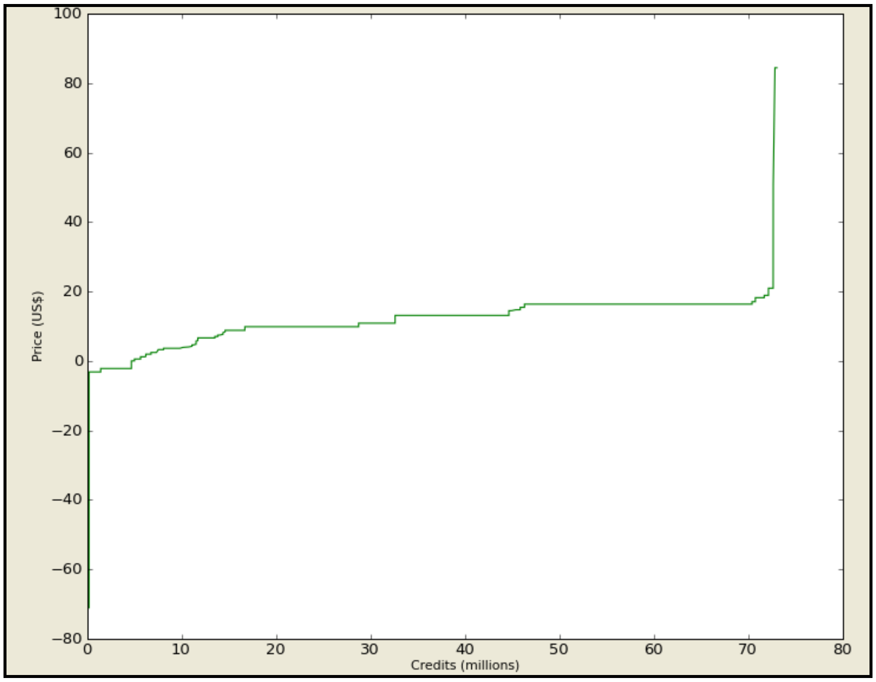

Figure 11: WCI Cap and Trade Scenario, WCI Region Offsets (Moderate Additionality Stringency)

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.

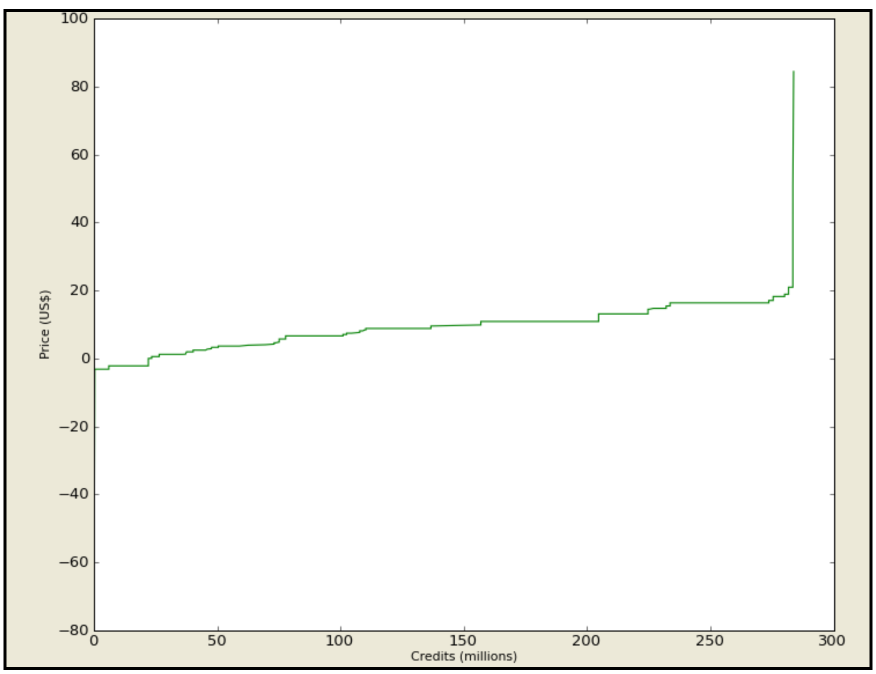

Figure 12: WCI Cap and Trade Scenario, US Region Offsets (Moderate Additionality Stringency)

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.

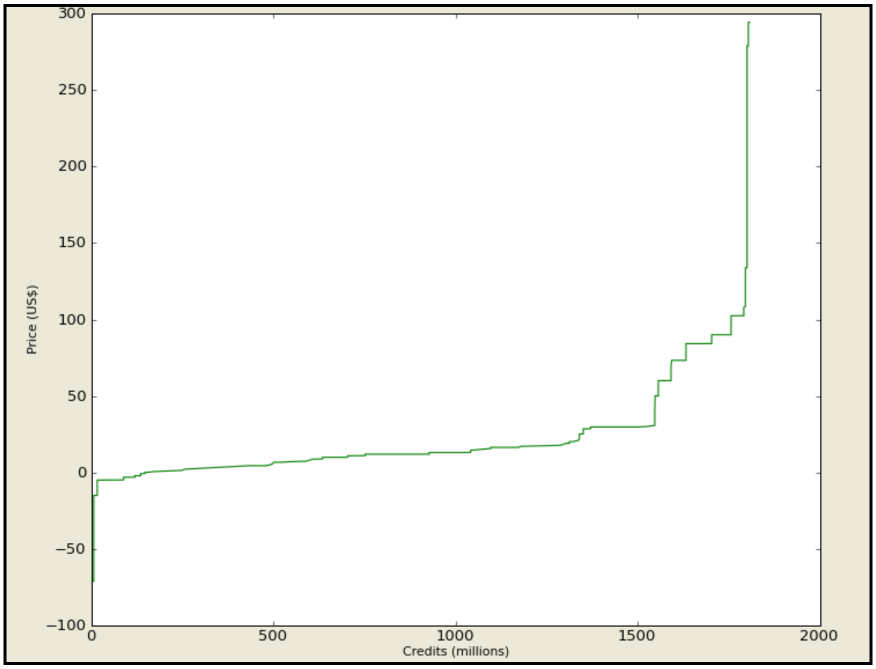

Figure 13: WCI Cap and Trade Scenario, Global Offsets (Moderate Additionality Stringency)

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.

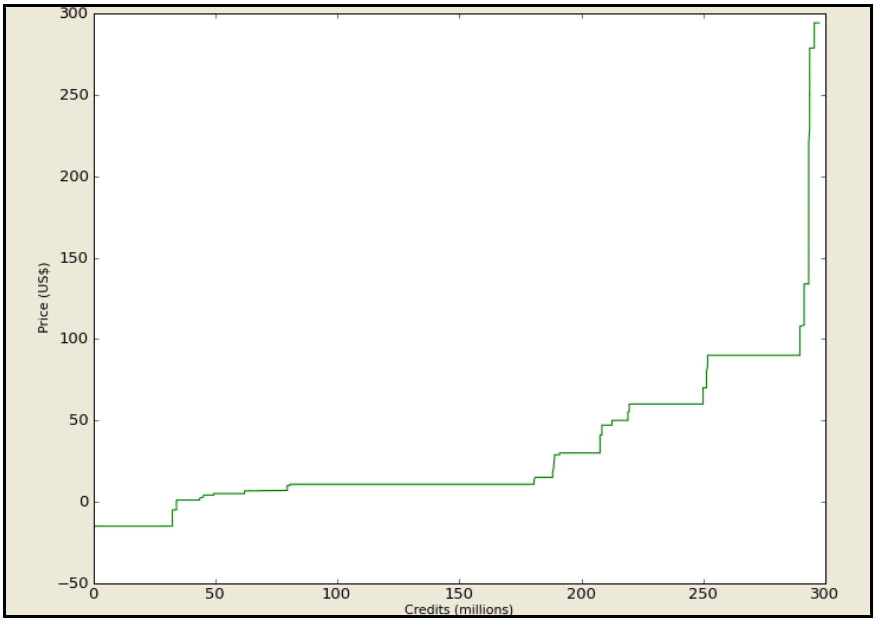

Figure 14: US Cap and Trade Supply Curve

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.

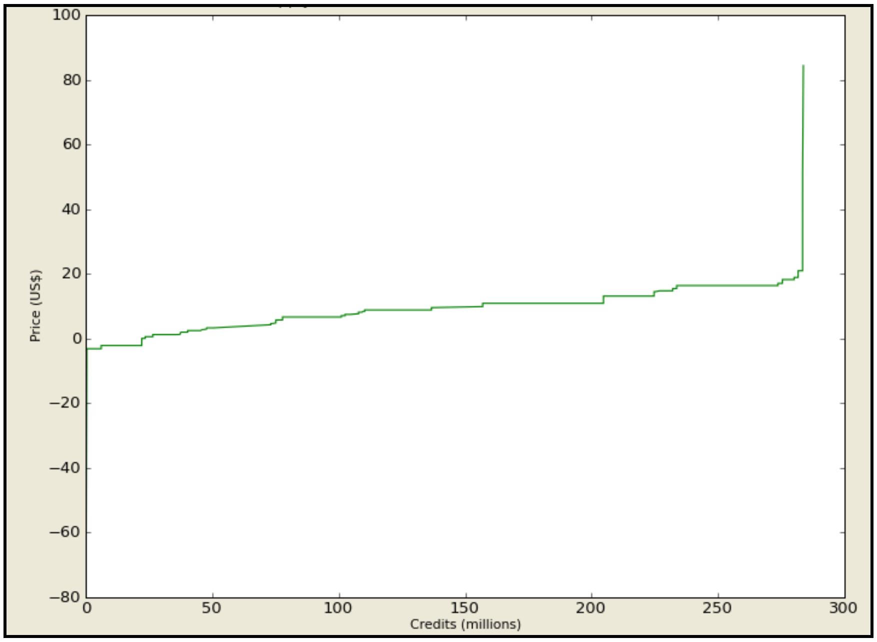

Figure 15: US Cap and Trade Scenario, US Region Offsets (Moderate Additionality Stringency)

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.

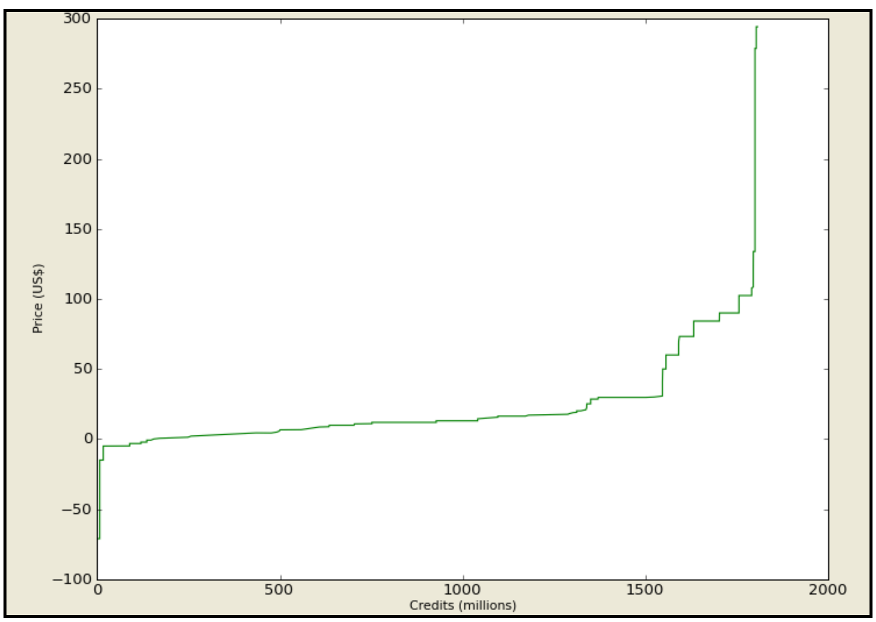

Figure 16: US Cap and Trade Supply Curve, Global Offsets (Moderate Additionality Stringency)

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

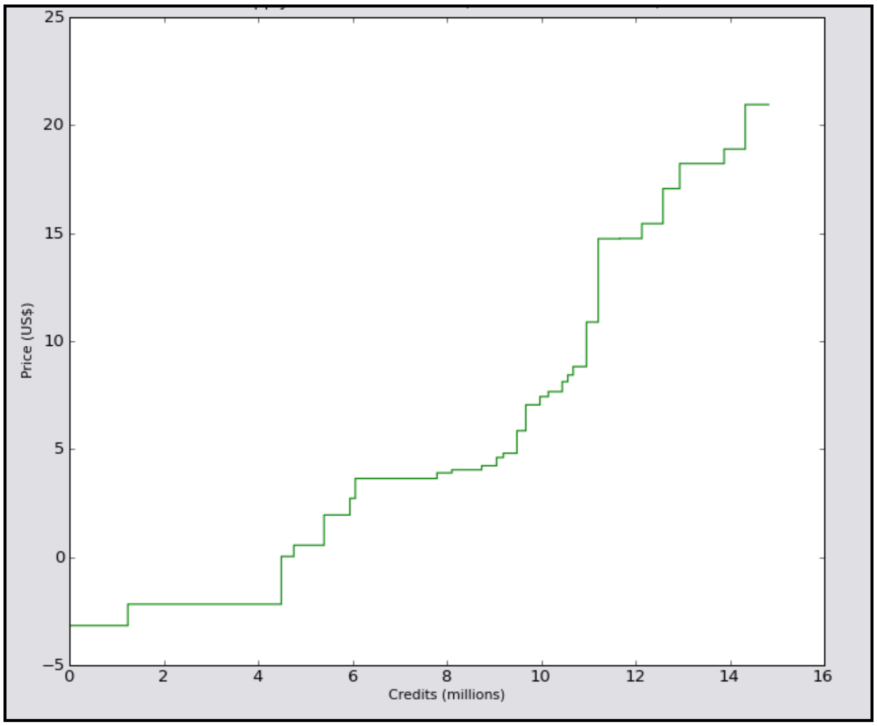

Figure 17: WCI Methane Sector (Moderate Additionality)

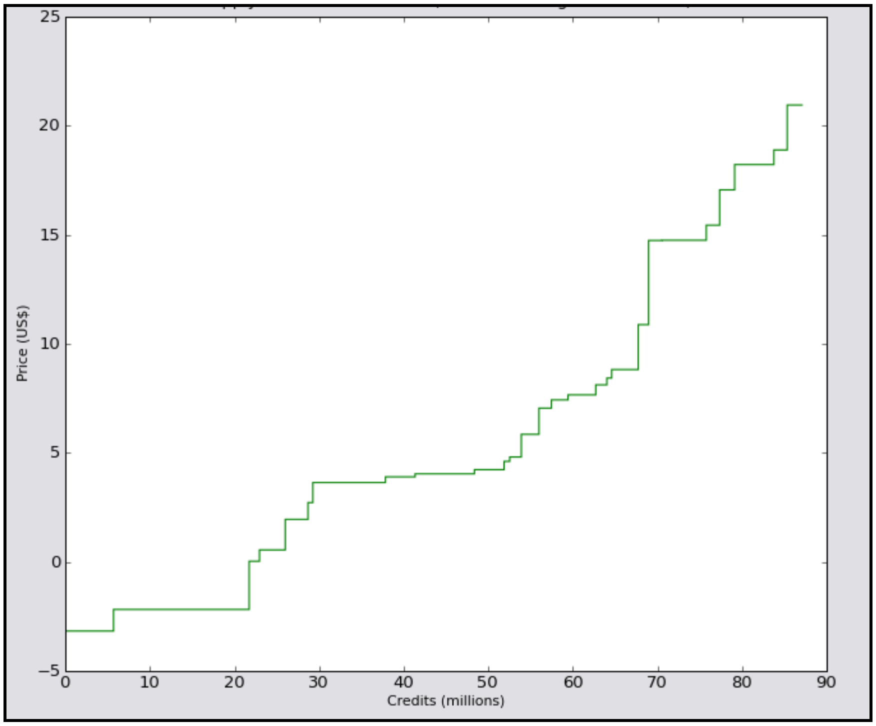

Figure 18: US Methane Sector (Moderate Additionality)

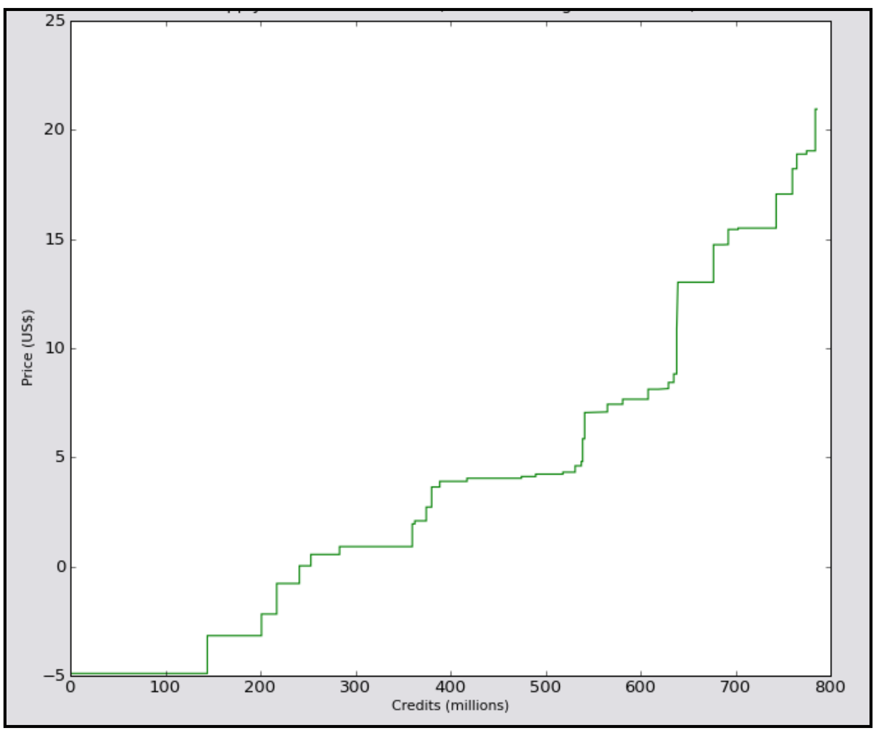

Figure 19: Global Methane Sector (Moderate Additionality)

2.4.2 Forestry

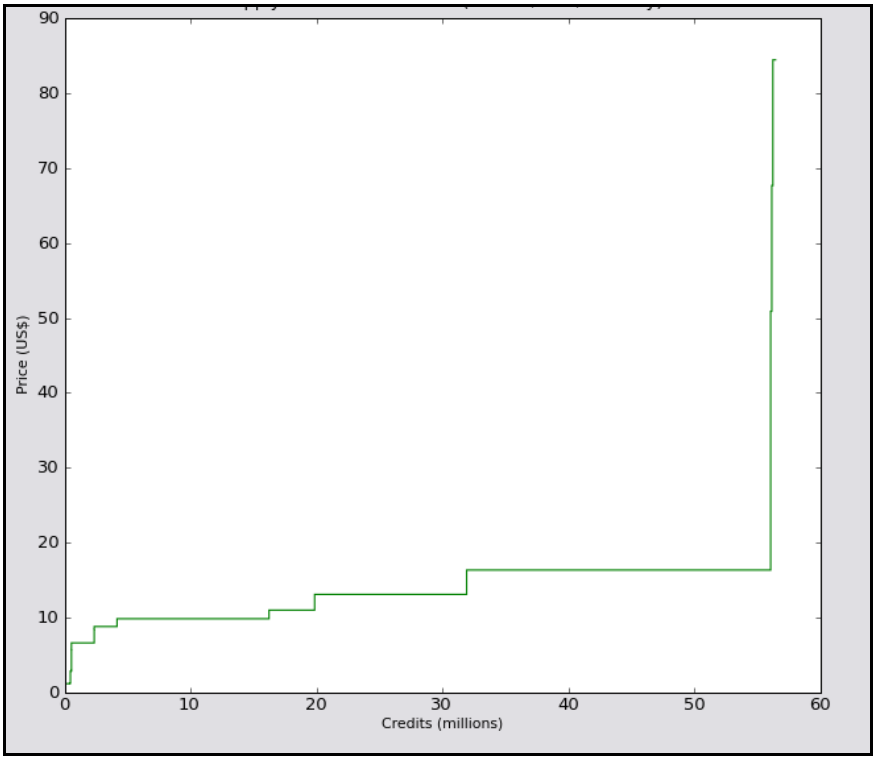

Figure 20: WCI Forestry Sector (Moderate Additionality)

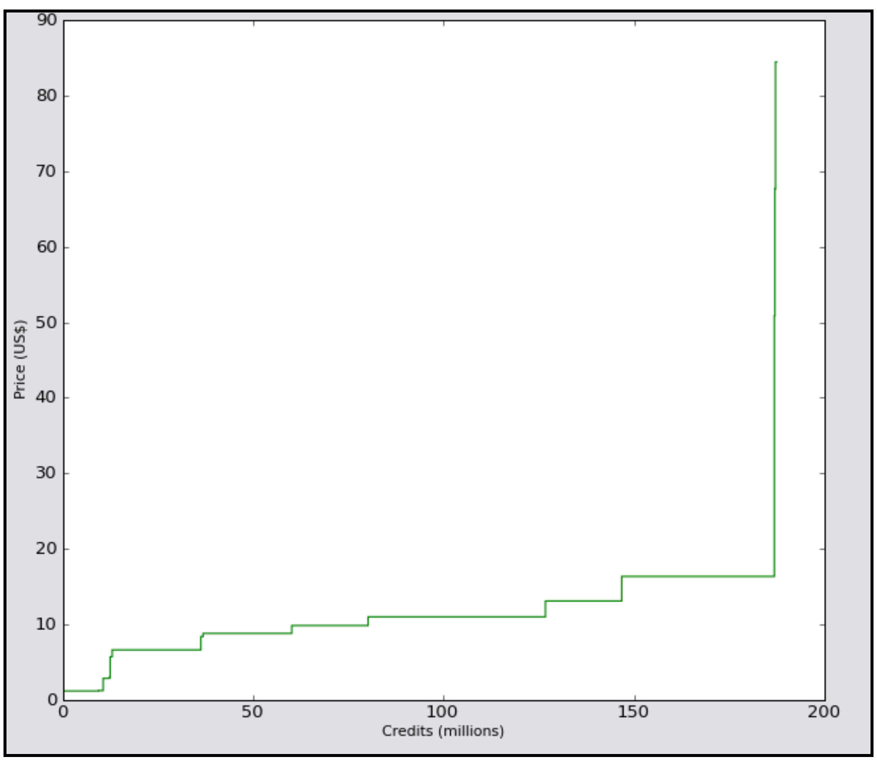

Figure 21: US Forestry Sector (Moderate Additionality)

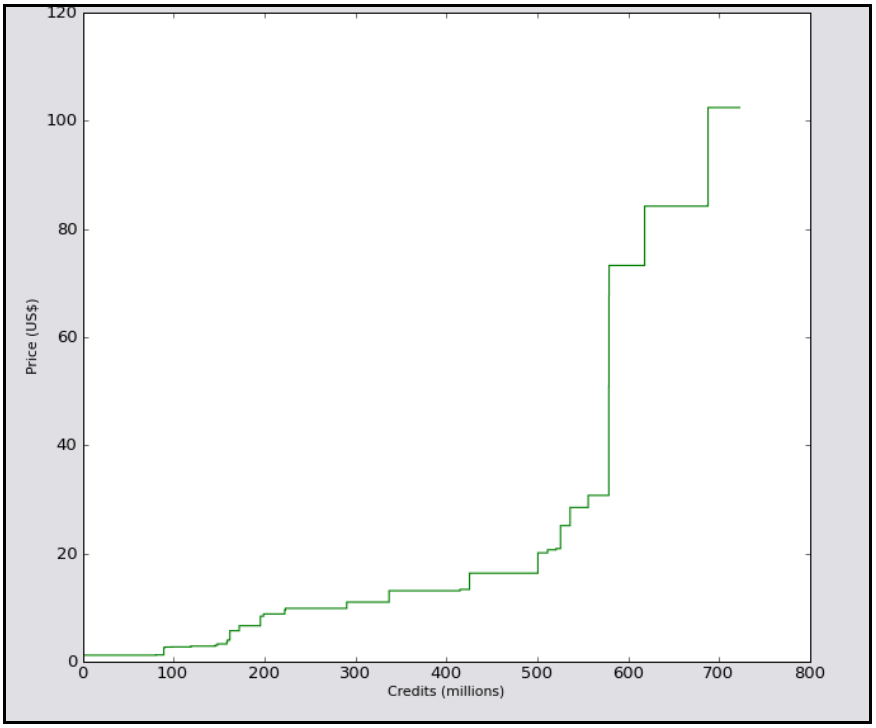

Figure 22: Global Forestry Sector (Moderate Additionality)

2.4.3 Electric Sector

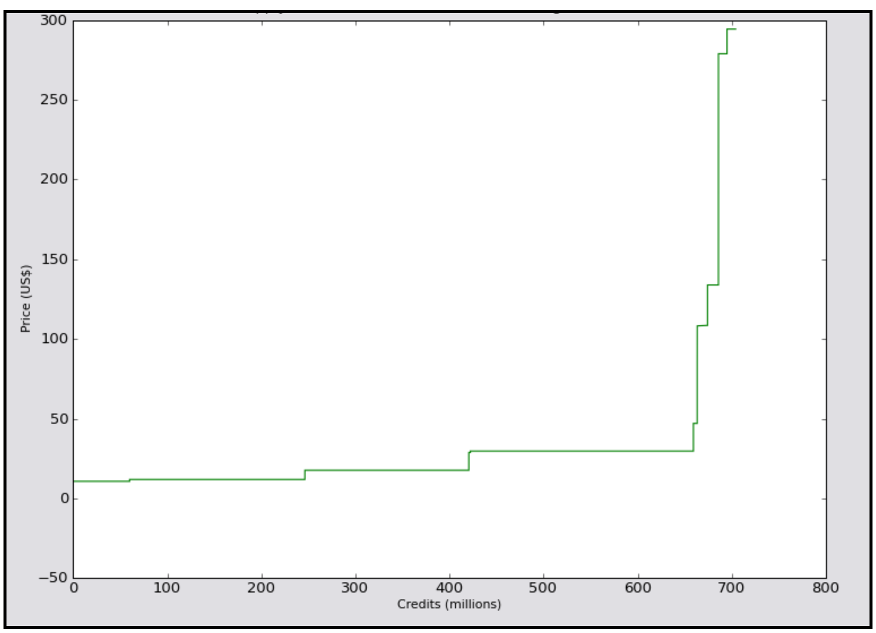

Figure 23: Global Electric Sector (Moderate Additionality)

2.4.4 High GWP

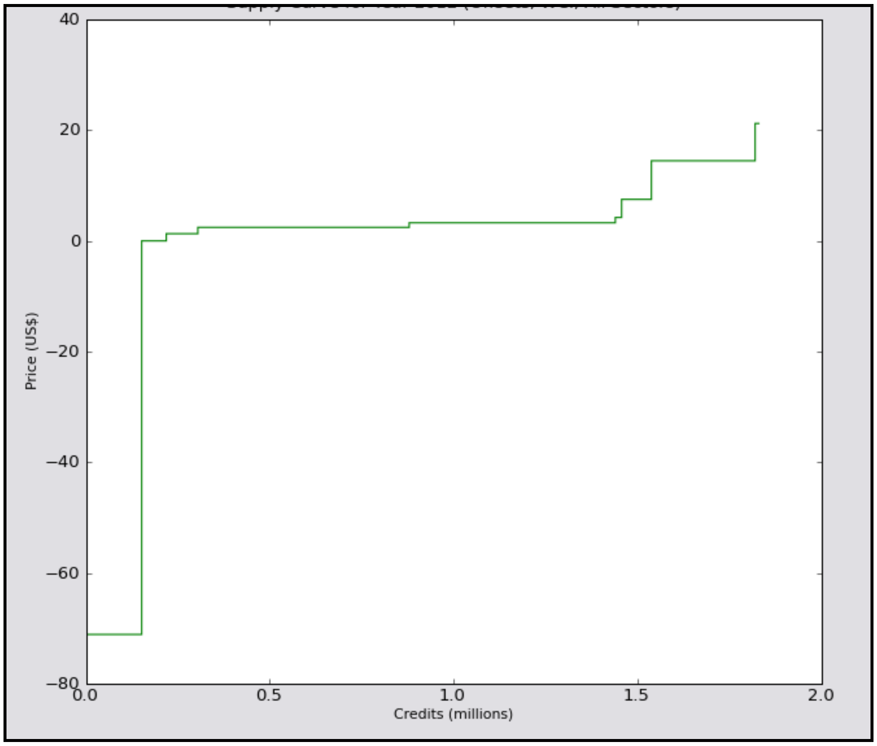

Figure 24: WCI High GWP Sector (Moderate Additionality)

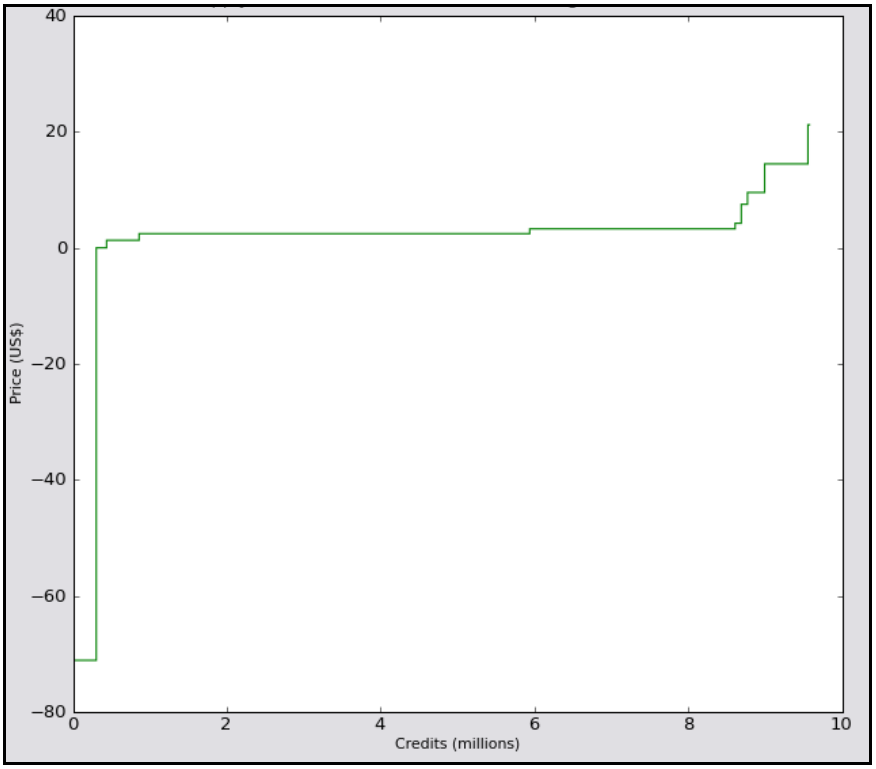

Figure 25: US High GWP Sector (Moderate Additionality)

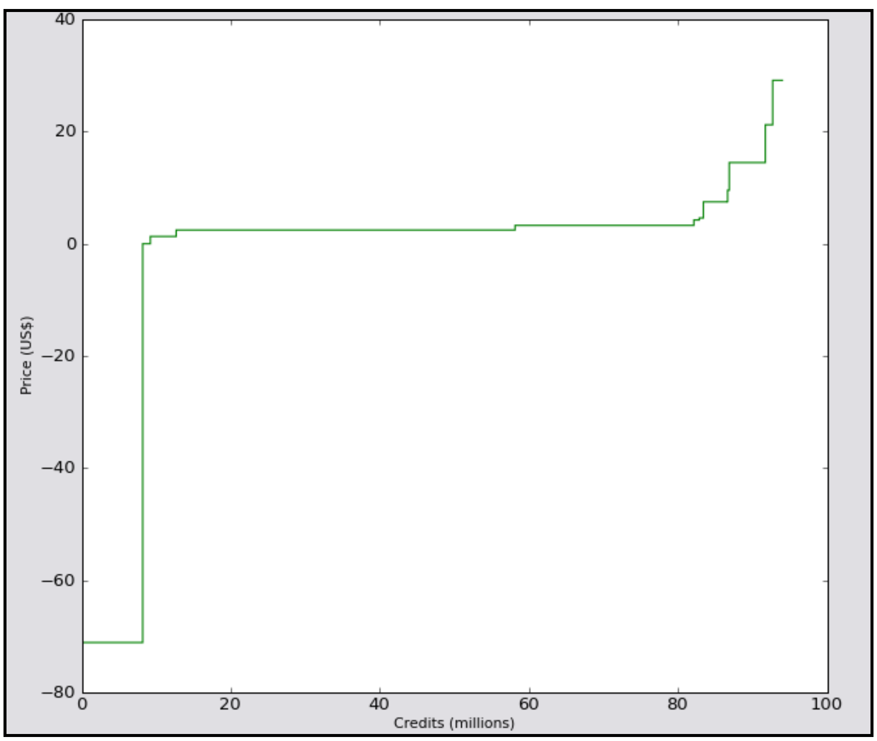

Figure 26: Global High GWP Sector (Moderate Additionality)

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.