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# Final Arizona Greenhouse Gas Inventory and Reference Case Projections 1990-2020

The Center for Climate Strategies

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## Acronyms and Key Terms

ACC – Arizona Corporation Commission  
ADEQ – Arizona Division of Environmental Quality  
AEO2005 – US DOE Energy Information Administration’s Annual Energy Outlook 2005  
AZ DOT – Arizona Department of Transportation  
BC – Black Carbon\*  
CH<sub>4</sub> – Methane\*  
CO<sub>2</sub> – Carbon Dioxide\*  
CO<sub>2</sub>e – Carbon Dioxide equivalent\*  
EIA – US DOE Energy Information Administration  
GHG – Greenhouse Gases\*  
GWP - Global Warming Potential\*  
HFCs – Hydrofluorocarbons\*  
IPCC – Intergovernmental Panel on Climate Change\*  
Mt - Metric ton (equivalent to 1.102 short tons)  
MMt – Million Metric tons  
MOVEAZ – Arizona DOT’s Long Range Transportation Plan  
MTBE – Methyl Tertiary Butyl Ether  
N<sub>2</sub>O – Nitrous Oxide\*  
OC – Organic Carbon\*  
ODS – Ozone-Depleting Substances  
OM – Organic Material\*  
PFCs – Perfluorocarbons\*  
RCI – Residential, Commercial, and Industrial  
SF<sub>6</sub> – Sulfur Hexafluoride\*  
Sinks – Removals of carbon from the atmosphere, with the carbon stored in forests, soils, landfills, wood structures, or other biomass-related products.  
US EPA – US Environmental Protection Agency  
US DOE – US Department of Energy  
VMT – Vehicle-miles Traveled  
WRAP – Western Regional Air Partnership  
\* - See Appendix H for more information.

# 1. Summary of Preliminary Findings

## *Introduction*

This report presents initial estimates of historical and projected Arizona anthropogenic greenhouse gas (GHG) emissions and sinks for the period from 1990 to 2020. These estimates are intended to assist the State, stakeholders and technical work groups with an initial comprehensive understanding of current and possible future Arizona's greenhouse gas (GHG) emissions, and thereby inform the upcoming analysis and design of GHG mitigation strategies.

Historical GHG emissions estimates (1990 through 2003)<sup>1</sup> were developed using a set of generally-accepted principles and guidelines for State greenhouse gas emissions, as described in Section 2, relying to the extent possible on Arizona-specific data and inputs.<sup>2</sup> The initial reference case projections out to 2020 are based on a compilation of various existing Arizona and regional projections of electricity generation, fuel use, and other GHG emitting activities, along with a set of simple, transparent assumptions described later in this report. These estimates should be viewed as a preliminary input to the stakeholder process; many data sources and experts have not yet been tapped and some sectors are still undergoing initial assessment. Therefore, further input and suggestions are welcomed.

This report covers the six types of gases included in the US Greenhouse Gas Inventory: carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>). Emissions of these greenhouse gases are presented using a common metric, CO<sub>2</sub> equivalence (CO<sub>2</sub>e), which indicates the relative contribution of each gas to global average radiative forcing on a Global Warming Potential (GWP) weighted basis. Appendix H to this report provides a fuller discussion of greenhouse gases and GWPs. Appendix I contains a White Paper on a 2002 base year and reference case emissions inventory of black carbon (BC) and organic carbon (OC) aerosols. Black carbon and organic carbon aerosols could have a significant climate impact, with black carbon having a particularly powerful warming impact. However, because the science is less certain on the relative magnitude of this impact, and because there are as yet no widely-accepted GWPs to enable comparison with greenhouse gases, these black and organic carbon emissions are not integrated in the CO<sub>2</sub> equivalent emissions estimates provided in the main GHG inventory and projection figures presented here.

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<sup>1</sup> For some sectors and sources, historical data is only available through 2000, 2001 or 2002.

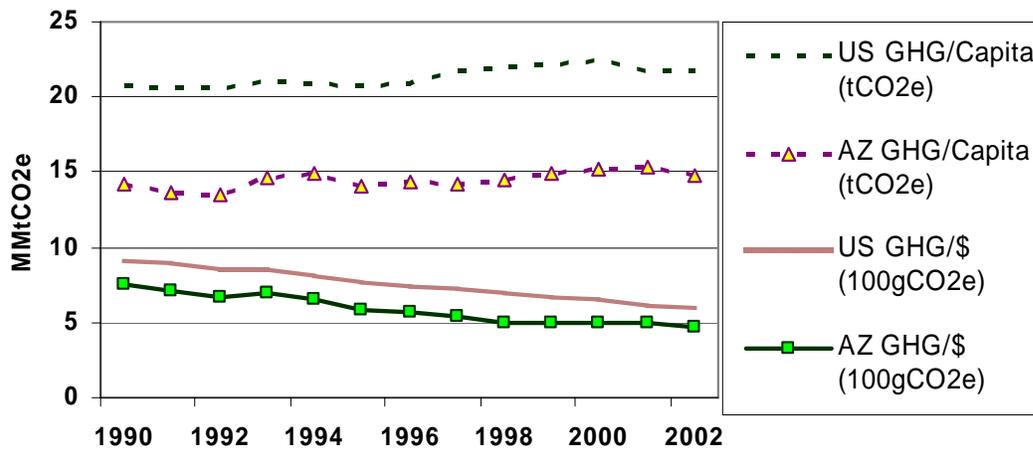
<sup>2</sup> In September 2004, the Arizona Department of Environmental Quality (ADEQ) prepared a preliminary GHG inventory assessment, which provided a starting point for this analysis. This final report was formally approved by the Arizona CCAG in March 2006.

## Arizona Greenhouse Gas Emissions: Sources and Trends

Preliminary analysis suggests that in 2000, Arizona accounted for approximately 80 million metric tons<sup>3</sup> (MMt) of *net* carbon dioxide equivalent (CO<sub>2</sub>e) emissions, an amount equal to 1.2% of total US GHG emissions.<sup>4</sup> Arizona GHG emissions are rising rapidly compared with the nation as a whole, driven by the rapid pace of Arizona's population and economic growth. Arizona GHG emissions were up 51% from 1990 to 2000, while national emissions rose by 23% during this period.<sup>5</sup>

On a per capita basis, Arizonans emit about 14 tCO<sub>2</sub>e, 36% less than the national average of 22 tCO<sub>2</sub>e per capita. Lower per capita emissions are due in part to Arizona's mild climate, and also to the State's less emissions-intensive economic base.<sup>6</sup> Figure 1 illustrates the State's lower emissions per capita and per unit of economic output. It also shows that like the nation as a whole, per capita emissions have remained fairly flat, while economic growth outpaced emissions growth throughout the 1990-2002 period. During the 1990s, emissions per unit of gross product dropped by 29% nationally, and by 33% in Arizona.

**Figure 1. Arizona and US GHG Emissions, Per Capita and Per Unit Gross Product (2000\$)**



Electricity use and transportation are the State's principal GHG emissions sources. Together, the combustion of fossil fuels in these two sectors accounts for nearly 80% of Arizona's *gross* GHG

<sup>3</sup> All GHG emissions are reported here in metric tons.

<sup>4</sup> United States emissions estimates are drawn from Climate Analysis Indicators Tool (CAIT) version 1.5. (Washington, DC: World Resources Institute, 2003). Available at: <http://cait.wri.org>.

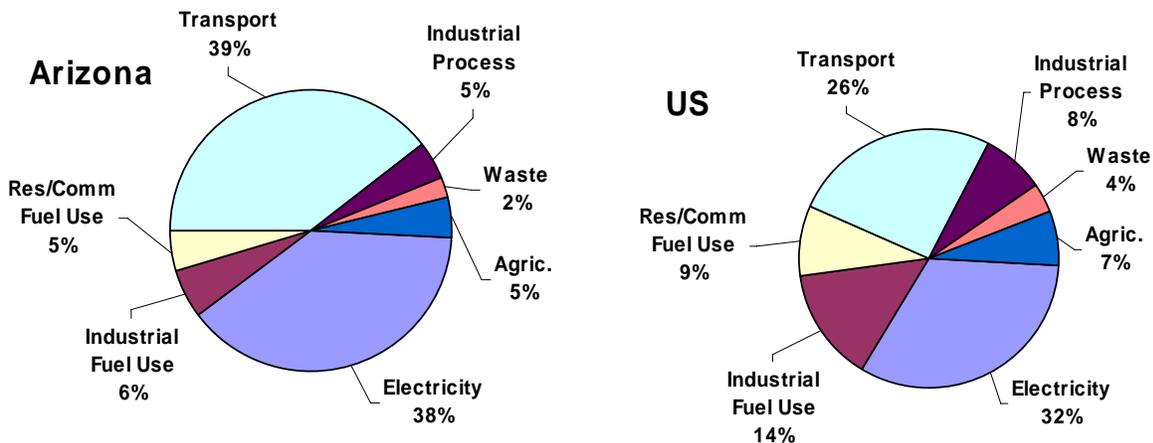
<sup>5</sup> During the 1990s, population grew by 39% in Arizona compared with 13% nationally. Furthermore, Arizona's economy grew faster on a per capita basis (up 63% vs. 52% nationally).

<sup>6</sup> Arizona's economy has a lower share of emissions-intensive industrial and agricultural activities, such as steel production, petroleum refining, or dairy farming. Furthermore, while cooling demands are significant, the emissions associated with air conditioning are lower on average than those for space heating in the rest of the country.

emissions, as shown in Figure 3.<sup>7</sup> The remaining use of fossil fuels – natural gas, oil products, and coal -- in the residential, commercial, and industrial (RCI) sectors constitutes another 11% of State emissions.

Agricultural activities such as manure management, fertilizer use, and livestock (enteric fermentation) result in methane and nitrous oxide emissions that account for another 5% of State GHG emissions. Industrial process emissions also comprise about 5% of State GHG emissions today, and these emissions are rising rapidly due to the increasing use of hydrofluorocarbons (HFC) as substitutes for ozone-depleting chlorofluorocarbons.<sup>8</sup> Other industrial processes emissions result from perfluorocarbon (PFC) use in semiconductor manufacture, carbon dioxide released during cement and lime production, and methane released by natural gas systems, and coal mines. Landfills and wastewater management facilities produce methane and nitrous oxide emissions accounting for the remaining 2% of current State emissions; these emissions have declined slightly in recent years as landfill gas is increasingly captured and flared or used for energy purposes.

**Figure 2. Gross GHG Emissions by Sector, 2000, Arizona and US**



*Gross* emissions estimates do not include the effects of carbon sinks, i.e. the net carbon sequestered in, or released from, soils and vegetation. Recent US Forest Service estimates suggest that Arizona forests and the use of forest products sequestered on average about 7 MMtCO<sub>2</sub>e per year from 1985 to 2002. Much of this increase appears to have occurred during a period when the formal definition of forestland under FIA surveys was liberalized from a minimum ten percent forest cover to five percent cover requirements. As a result, refined

<sup>7</sup> *Gross* emissions estimates only include those sources with positive emissions. Carbon sequestration in soils and vegetation is included in *net* emissions estimates..

<sup>8</sup> Chlorofluorocarbons (CFCs) are also potent greenhouse gases; however they are not included in GHG estimates because of concerns related to implementation of the Montreal Protocol. See final Appendix.

estimates regarding total statewide biomass sequestration, may result in significant changes to current estimates, but additional reviews of the data suggest the effects are more likely very small. This issue is discussed below and should be the focus of further analysis. (See *Key Uncertainties and Next Steps*). We report *net* GHG emissions – which include the above sequestration estimates -- separately from the *gross* GHG emissions.

### ***A Closer Look at the Two Major Sources: Electricity and Transportation***

As shown in Figure 3, electricity use accounts for nearly 40% of Arizona's gross GHG emissions, or about 35 MMtCO<sub>2</sub>e, slightly higher than national share of emissions from electricity production (32%).<sup>9</sup> On a per capita basis, in contrast, Arizona emits slightly less in terms of greenhouse gases (7 MMtCO<sub>2</sub>e/capita vs. 8 MMtCO<sub>2</sub>e/capita nationally). The average Arizonan uses about the same amount of electricity as the average US resident (12,000 kWh per person per year), but Arizona electricity has lower emissions than the national average.<sup>10</sup> Arizona gets slightly less electricity from coal (46% vs. 52% nationally in 2000) and more from low-emitting sources, such as nuclear, hydro, and other renewables (44% vs. 29% nationally in 2000).

During the 1990s, Arizona electricity demand grew at a rate of 4.0% per year, while electricity emissions grew 3.3% annually, reflecting a decline in emissions per kWh. This decline was due largely to the rapid growth on new natural gas generation, and to a lesser extent increases in nuclear generation.

It is important to note that these preliminary electricity emissions estimates reflect the *GHG emissions associated with the electricity sources used to meet Arizona demands*, corresponding to a consumption-based approach to emissions accounting (see Section 2). Another way to look at electricity emissions is to consider the *GHG emissions produced by electricity generation facilities in the State*. For many years, Arizona power plants have tended to produce considerably more electricity than is consumed in the State – in the year 2000, for example, Arizona produced 23% more electricity than it used, exporting on a net basis to consumers in nearby states. As a result, in 2000, emissions associated with electricity production (44.5 MMtCO<sub>2</sub>e) were considerably higher than those associated with electricity use (34.5 MMtCO<sub>2</sub>e).<sup>11</sup>

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<sup>9</sup> Unlike for Arizona, for the US as a whole, there is relatively little difference between the emissions from electricity use and emissions from electricity production, as the US imports only about 1% of its electricity, and exports far less.

<sup>10</sup> In 2000, electricity generation in Arizona emitted 1107 lbCO<sub>2</sub>e (0.50tCO<sub>2</sub>e) per MWh; as a placeholder we are presently assuming the same emission rate for electricity delivered to Arizona consumers. In 2000, electricity generation in the US averaged 1321 lbCO<sub>2</sub>e (0.60tCO<sub>2</sub>e) per MWh.

<sup>11</sup> Estimating the emissions associated with electricity use requires an understanding of the electricity sources (both in-state and out-of-state) used by utilities to meet consumer loads. The current estimate reflects some very simple assumptions described in the electricity appendix. We are currently collecting data from the state's larger electricity utilities that will help in refining these estimates.

While we estimate both the emissions from electricity production and use, unless otherwise indicated, tables, figures, and totals in this report reflect electricity use emissions. The consumption-based approach can better reflect the emissions (and emissions reductions) associated with activities occurring in the State, particularly with respect to electricity use (and efficiency improvements), and is thus particularly useful in a policy-making context. Under this approach, emissions associated with electricity exported to other states would need to be covered in those states' accounts in order to avoid double counting or exclusions. (Indeed, California, Oregon, and Washington are currently considering such an approach.)

Like electricity emissions, GHG emissions from transportation fuel use have risen steadily since 1990 at an average rate of slightly over 3% annually. Gasoline-powered vehicles account for about 65% of transportation GHG emissions. Diesel vehicles account for another 20%, air travel for roughly 10%, and the remainder of transportation emissions come from and natural gas and LPG vehicles. As the result of Arizona's rapid expansion and an increase in miles traveled during 1990s (from 35 billion VMT in 1990 to 50 billion VMT in 2000), gasoline use has grown at rate of 3.2% annually.<sup>12</sup> Meanwhile, diesel use has risen 6.5% annually, suggesting an even more rapid growth in freight movement within the State.

With respect to black carbon emissions, which are shown in the figures or tables, the transportation sector is the largest contributor. Transportation sources such as onroad diesel vehicles contributed 59% of Arizona's black carbon emissions in 2002 (see Appendix I). Other important BC emissions sectors include nonroad diesel engines (18%; e.g., generators, construction equipment) and railroad engines (about 11%). Coal-fired electricity generating units contributed another 6%.

### ***Reference Case Projections***

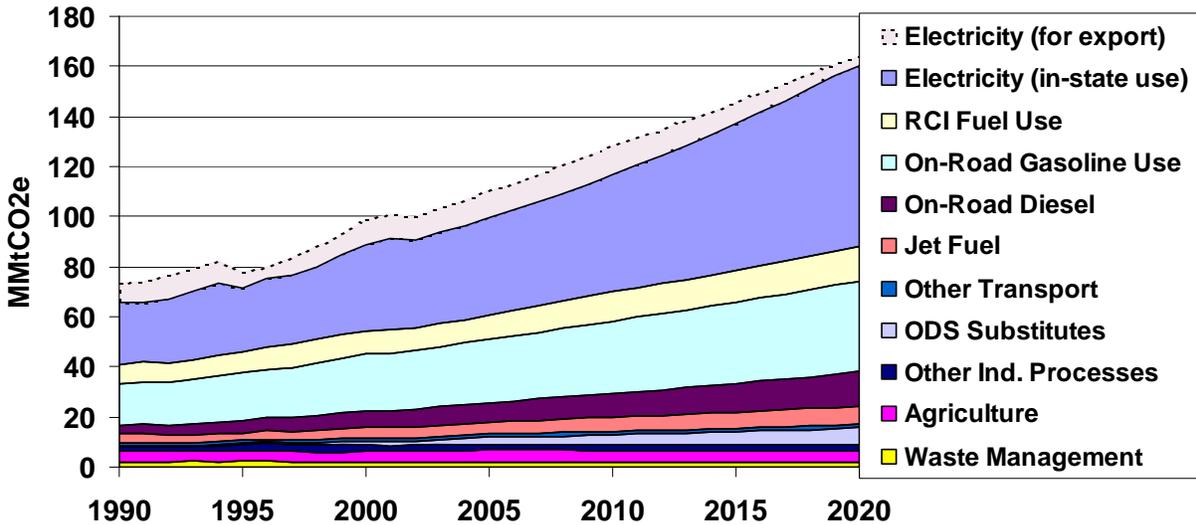
Relying on USDOE and Arizona agency projections of electricity and fuel use, and other assumptions noted below, we developed a simple reference case projection of GHG emissions through 2020.<sup>13</sup> The reference case assumes a continuation of current trends and reflects, to the extent possible, announced plans (e.g. power plant construction and retirement) and the implementation of recently enacted policies. One such policy is the Environmental Portfolio Standard, which currently requires investor-owned utilities to provide 1.1% of the electricity sales from renewable sources by 2012, and could result in emissions savings of slightly over 0.2 MMtCO<sub>2</sub>e by 2012. As base case projections are finalized through collaboration with stakeholders and technical work groups, it will be important to include other existing and planned actions.

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<sup>12</sup> Based on US Energy Information Agency data for the year 2000, Arizona gasoline use is also slightly below the national average (1.1 vs. 1.3 gallons per person per day). [www.eia.doe.gov](http://www.eia.doe.gov)

<sup>13</sup> Historical data runs through 2001 to 2003 depending on the emissions source.

**Figure 3. Gross GHG Emissions by Sector, 1990-2020: Historical and Projected**



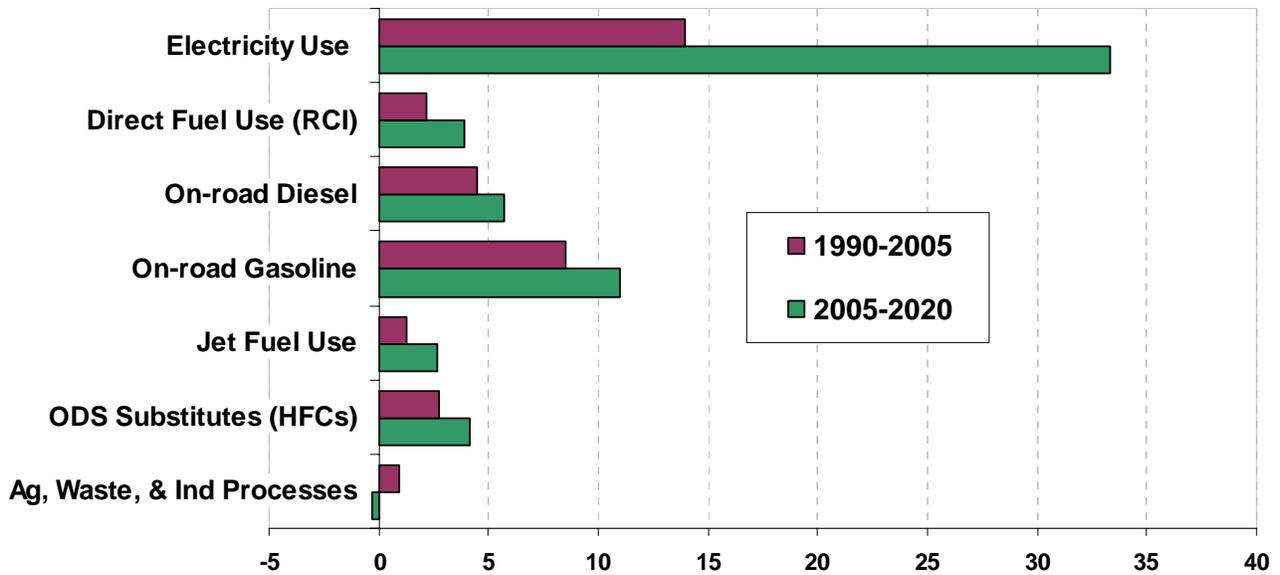
\*This chart does not show net carbon sinks (forestry and land use) which average slightly over 10 MMtCO<sub>2</sub>e/year.

Figure 5 illustrates the results of the reference case projection in terms of gross GHG emissions; corresponding numerical results are shown at the bottom of Table 1, under the four different emissions accounting approaches considered here: consumption basis, production basis, gross, and net. Under the gross, consumption-basis approach – i.e. excluding emissions associated with net electricity exports – Arizona GHG emissions would climb to 160 MMtCO<sub>2</sub>e by 2020, 80% above 2000 levels and 143% above 1990 levels. Assuming current estimates for forest sequestration (6.7 MMtCO<sub>2</sub>) continue through 2020, net emissions are lower than gross emissions, but the relative increase is greater.

The percentage increases in emissions relative to historical levels are slightly lower under a production-based approach, i.e. one that includes all emissions associated with in-state electricity production. Under the gross emissions case, 2020 production-based emissions are 75% above 2000 levels and 123% above 1990 levels. This difference results from the assumption – based on estimates from the Arizona Corporation Commission and US DOE – that Arizona electricity sales will grow slightly faster than electricity generation from 2010 onwards.

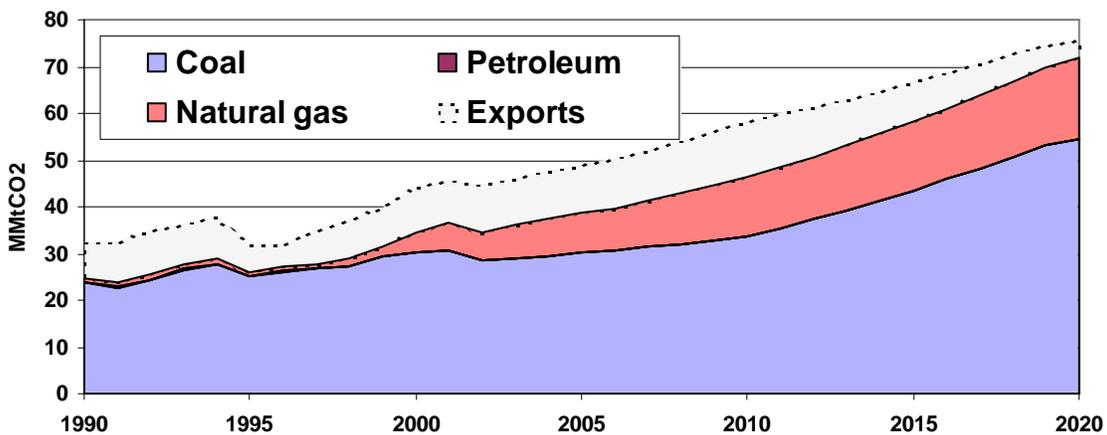
Electricity and gasoline use are projected to be the largest contributors to future emissions growth, as shown in Figure 6. Other major sources of emissions growth include freight transport (diesel), fuel use in buildings and industry (RCI), hydrofluorocarbons (HFCs) used in place of ozone-depleting substances (ODS), and air travel.

**Figure 4. Contributions to Emissions Growth, 1990-2020: Reference Case Projections (MMTCO<sub>2</sub>e)**



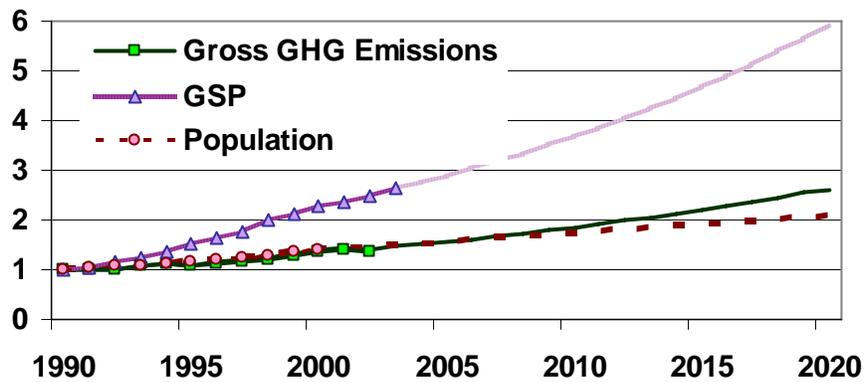
The particularly steep increase in electricity use emissions is due not only to the assumption that electricity use will continue to grow rapidly, but that natural gas prices will continue to rise, and the mix of new generation will shift heavily towards coal after 2010, as depicted in Figure 8.

**Figure 5. CO<sub>2</sub> Emissions from Electricity Production in Arizona, by Fuel Source (Includes All In-State Emissions)**



Overall, the projected rate of emissions growth is 3.0% per year from the year 2000 onward, well below anticipated levels of economic growth (4.9% per year), but nonetheless significant. As illustrated in Figure 10, emissions track population growth fairly closely until the latter half of this decade, after which they begin to rise more rapidly. The increase in per capita emissions after 2010 appears largely as the result of four factors: 1) electricity growth at a rate faster than population growth, 2) increasing reliance on coal-based generation, 3) freight traffic growing faster than population, and 4) increasing hydrofluorocarbon emissions in refrigeration, air conditioning, and other applications. For nearly all other sources, with the exception of natural gas use in residential, commercial, and industrial sectors, emissions are projected to grow at a pace slower than State population.

**Figure 6. Historical and Projected GHG Emissions, GSP, and Population (Indexed to 1990 Value)**



**Table 1. Historical and Reference Case GHG Emissions, 1990-2020, by Source**

(Million Metric Tons CO <sub>2</sub> e)	1990	2000 <sup>a</sup>	2010	2020	Explanatory Notes for Projections
<b>Energy Use (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O)</b>	<b>57.9</b>	<b>78.8</b>	<b>103.6</b>	<b>144.6</b>	
<b>Electricity Use</b>	<b>24.9</b>	<b>34.5</b>	<b>46.6</b>	<b>72.2</b>	
Electricity Production (in-state)	32.3	44.5	58.4	75.8	Total emissions for in-state power plants
<i>Coal</i>	30.9	39.2	42.4	57.5	See electric sector assumptions
<i>Natural Gas</i>	1.3	5.1	15.9	18.3	in appendix
<i>Oil</i>	0.1	0.2	0.0	0.0	
Net Electricity Exports	-7.4	-10.0	-11.8	-3.6	
<b>Res/Comm/Ind (RCI)</b>	<b>7.7</b>	<b>9.3</b>	<b>11.6</b>	<b>13.8</b>	
Coal	1.2	1.5	1.8	1.9	Based on USDOE regional projections
Natural Gas	4.2	4.7	5.7	7.2	Based on USDOE regional projections
Oil	2.2	3.0	4.1	4.6	Based on USDOE regional projections
Wood (CH <sub>4</sub> and N <sub>2</sub> O)	0.1	0.1	0.1	0.1	Assumes no change after 2003
<b>Transportation</b>	<b>25.3</b>	<b>35.0</b>	<b>45.4</b>	<b>58.6</b>	
On-road Gasoline	16.8	22.8	28.9	36.3	VMT from MoveAZ, constant energy/VMT
On-road Diesel	3.5	6.5	9.5	13.6	VMT from MoveAZ, constant energy/VMT
Jet Fuel and Aviation Gasoline	3.5	4.3	5.7	7.4	Based on USDOE regional projections
Natural Gas (pipeline use)	1.4	1.1	1.2	1.2	constant at 2002 levels
Other	0.2	0.2	0.1	0.1	Based on USDOE regional projections
<b>Industrial Processes</b>	<b>1.9</b>	<b>4.1</b>	<b>6.3</b>	<b>9.1</b>	
ODS Substitutes	0.0	1.4	4.0	6.9	Based on national projections (USEPA)
PFCs in Semi-conductor Ind.	0.4	1.0	0.5	0.3	Based on national projections (USEPA)
SF <sub>6</sub> from Electric Utilities	0.5	0.3	0.2	0.1	Based on national projections (USEPA)
Cement & Other Industry	0.6	1.0	0.9	1.0	Increases with state population
Methane from Oil & Gas Systems	0.4	0.4	0.6	0.8	Increases with natural gas use
Methane from Coal Mining	0.1	0.1	0.1	0.1	Assumes no change after 2003
<b>Agriculture, Land Use, Forestry</b>	<b>-2.6</b>	<b>-2.5</b>	<b>-2.1</b>	<b>-2.1</b>	
Agriculture (CH <sub>4</sub> & N <sub>2</sub> O)	4.1	4.2	4.7	4.7	Assumes (for now) no change after 2002
Soils and Forest Sinks	-6.7	-6.7	-6.7	-6.7	Subject to considerable uncertainty
<b>Waste Management</b>	<b>2.1</b>	<b>1.9</b>	<b>2.0</b>	<b>1.9</b>	
Solid Waste Management	1.7	1.3	1.4	1.1	Based on national projections (USEPA)
Wastewater Management	0.4	0.5	0.7	0.8	Increases with state population
<b>Total Emissions - Consumption-Basis (Excluding Emissions from Net Electricity Exports)</b>					
<b>Gross (excluding sinks)</b>	<b>66.0</b>	<b>89.0</b>	<b>116.6</b>	<b>160.3</b>	
<i>increase relative to 1990</i>		35%	77%	143%	
<i>increase relative to 2000</i>			31%	80%	
<b>Net (including sinks)</b>	<b>59.3</b>	<b>82.3</b>	<b>109.9</b>	<b>153.5</b>	
<i>increase relative to 1990</i>		39%	85%	159%	
<i>increase relative to 2000</i>			34%	87%	
<b>Total Emissions - Production-Basis (Including All In-State Electricity Generation)</b>					
<b>Gross (excluding sinks)</b>	<b>73.5</b>	<b>99.0</b>	<b>128.4</b>	<b>163.9</b>	
<i>increase relative to 1990</i>		35%	75%	123%	
<i>increase relative to 2000</i>			30%	66%	

<b>Net (including sinks)</b>	<b>66.7</b>	<b>92.3</b>	<b>121.6</b>	<b>157.2</b>
<i>increase relative to 1990</i>		38%	82%	135%
<i>increase relative to 2000</i>			32%	70%

<sup>a</sup> These emissions estimates do not include black carbon and organic carbon contributions. These emissions are difficult to convert into CO<sub>2</sub> equivalents, given the lack of commonly accepted GWPs. Nonetheless, available research provides the basis for some initial GWP estimates, as discussed in Appendix I. Application of these indicative GWPs suggests that Arizona black and organic carbon emissions may have accounted for 3 to 6 million metric tons CO<sub>2</sub> equivalent emissions in 2002.

## ***Key Uncertainties and Next Steps***

Efforts are ongoing to resolve key data gaps and uncertainties in the inventory and projections. Key tasks, among others, include the incorporation of anticipated actions and policies (efficiency programs, voluntary actions, new cement plants and refineries, etc.), a better understanding of the electricity generation sources currently used to meet Arizona loads (in collaboration with State utilities), and review and revision of key drivers such as the electricity and gasoline use growth rates that will be major determinants of Arizona's future GHG emissions (See Table 3).

These growth rates are driven by economic, demographic, and land use trends (including growth patterns and transportation system impacts), all of which are subject to uncertainty and deserve closer examination. Population estimates are based on official projections from the Arizona Department of Economic Security. These projections, however, are widely recognized as outdated (based on assumptions circa 1997). Population growth has been more rapid than these projections would indicate. The DES projections are currently under revision, and it is likely that revised projections will be available during the stakeholder process. Emissions projections can then be revised accordingly.<sup>14</sup>

As described in Appendix I, the need to develop black and organic carbon emissions projections will be based on feedback from the AZ CCAG. CCS recommends incorporating projections from the Western Regional Air Partnership (WRAP) when they are made available. Specifically, the 2008 and 2018 WRAP projections are best aligned with the GHG forecasts provided in this report. CCS has submitted a request to the WRAP for projections from the most important BC sectors (onroad and nonroad engines).

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<sup>14</sup> If the projected growth rates are higher than currently projected (2.0%), then some emissions projections could rise. However, it is important to note that several of the key drivers for this analysis, such as electricity demand growth and passenger VMT, are already higher than projected population, and may implicitly reflect population projections higher than the official forecast.

**Table 2. Key Annual Growth Rates, Historical and Projected**

Parameter	Historical		Projected	Sources/Uses
	1980-1990	1990-2000	2000-2020	
<b>Population*</b>	3.1%	3.4%	2.0%	US Census Bureau for historic, AZ Department of Economic Security for projection
<b>GSP</b>	4.1%	6.3%	4.9%	(not used for projections)
<b>Employment*</b>	3.9%	2.9%	2.5%	AZ DOT's MoveAZ report for historic, AZ Department of Economic Security for projection
<b>Electricity sales</b>	4.5%	4.0%	3.6%	EIA SEDS for historic, RCI TWG for projections
<b>Personal Vehicle Miles Traveled*</b>	n/a	n/a	2.4%	Bureau of Transport Statistics for historic, AZ DOT's MoveAZ for projections
<b>Freight Vehicle Miles Traveled*</b>	n/a	n/a	3.7%	Bureau of Transport Statistics for historic, AZ DOT's MoveAZ for projections

\* Population, employment and VMT projections for Arizona were used together with US DOE's Annual Energy Outlook 2005 projections of changes in fuel use on a per capita, per employee, and per VMT, as relevant for each sector. For instance, growth in Arizona residential natural gas use is calculated as the Arizona population growth times the change in per capita Arizona natural gas use for the Mountain region. Arizona population growth is also used as the driver of growth in cement production, soda ash consumption, solid waste generation, and wastewater generation.

Furthermore, the current reference case does not include an analysis of future agriculture emissions, which might change significantly if water scarcity, commodity programs, and trade agreements, among other factors, induce major shifts among crops and livestock grown in the State.

In addition, the following two areas are subject to considerable uncertainty, not simply because the future is hard to predict, but because of data availability and scientific understanding:

- Terrestrial carbon emissions and sinks:** The net forest and land use sequestration estimates noted above are based on recent improvements to US Forest Service carbon stock inventory data but do not fully address all issues that ultimately will be needed to develop final estimates. As a result, initial estimates may change as additional data is developed. For instance, US Forest Service assessments only cover the parts of the state that the US Forest Service defines as forest, representing 16% of the total State land area in 2002 (4.85 of 30.3 million hectares). During the FIA survey periods used for FORCARB2 estimates, the definition of forestland changed from a minimum forest cover requirement of ten percent, to a minimum of five percent. As a result rangelands may or may not be included in these estimates, depending on their level of tree stocking. To the extent that they may sequester or emit carbon, while small on a per acre basis, rangelands

may be quite significant at the State level.<sup>15</sup>

Second, what the USFS defines as forest area in Arizona has increased by 14% since 1985, when it totaled 4.25 million hectares. This addition appears to account for much of the net gain in carbon stock in the USFS estimates (offsetting a decrease in carbon stock per hectare from 1996 to 2002) and may or may not be attributable to the change in the definition of forestland and the addition of lands at between five and ten percent forest cover. As a consequence of the change in forest definition, the USFS methods may overestimate carbon gains associated with the lands not formally defined as forest under the previous definition. Any carbon added from this definition change was not covered in the previous cycles and potentially distorts the effects of carbon change in total.

- **Black carbon and other aerosol emissions.** Emissions of aerosols, particularly black carbon from fossil fuel and biomass combustion, could have potentially significant impacts in terms radiative forcing (i.e., climate impacts). Methodologies for conversion of black carbon mass estimates and projections to global warming potential involve significant uncertainty at present. Our methods for estimating black carbon emissions and their carbon dioxide equivalent are provided in Appendix I. Results are also summarized in this appendix and are incorporated into the sector-level results below. CCS is currently awaiting data from the WRAP that will be used for assessing future year emissions.

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<sup>15</sup> However, the carbon cycle for rangelands is not well understood, and has not been included in current surveys.

## 2. Approach

The principal goal of the inventory and reference case projections is to provide the State, stakeholders and technical work groups with a general understanding of Arizona's historical, current and projected (expected) greenhouse gas emissions. Over the coming months, we will work with stakeholders and working groups to augment, refine and disaggregate these estimates.

### 2.1 General Principles and Guidelines

A key part of this effort involves the establishment and use of a set of generally accepted accounting principles for evaluation of historical and projected GHG emissions, as follows:

- **Transparency:** We report data sources, methods, and key assumptions to provide open review and opportunities for additional revisions later based on stakeholder and technical work group input.
- **Consistency:** To the extent possible, the inventory and projections are designed to be externally consistent with current or likely future systems for state and national GHG emission reporting. We have used USEPA tools for state inventories and projections as a starting point. These initial estimates were then augmented to conform to local data and conditions, as informed by Arizona-specific sources and experts.
- **Comprehensive Coverage of Gases, Sectors, State Activities, and Time Periods.** This analysis aims to comprehensively cover GHG emissions associated with activities in Arizona. It covers all six greenhouse gases covered by US and other national inventories: carbon dioxide, (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), sulfur hexafluoride (SF<sub>6</sub>), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). Black carbon and organic carbon emissions have been quantified for a 2002 base year (see Appendix I). Other potential GHG emission sources that have not already been covered will be considered as data and methods allow.
- **Priority of Significant Emissions Sources:** In general, activities with relatively small emissions levels may not be reported in the same level of detail as other activities.
- **Priority of Existing State and Local Data Sources:** In gathering data and in cases where data sources may conflict, we will place highest priority on local and state data and analyses, followed by regional sources, with national data used as defaults where necessary.
- **Use of Consumption-Based Emissions Estimates:** To the extent possible, we will estimate emissions that are caused by activities that occur in Arizona. For example, we

will report emissions associated with the electricity consumed in Arizona. The rationale for this method of reporting is that it can more accurately reflect the impact of state-based policy strategies such as energy efficiency on overall GHG emissions, and it resolves double counting and exclusion problems with multi emissions issues. This approach can differ from how inventories are compiled, i.e. on an in-state production basis, in particular for electricity. For electricity, we estimate, in addition to the emissions due to fuels combusted at electricity plants in the State, the emissions related to electricity *consumed* in Arizona. This entails accounting for the electricity sources used by Arizona utilities to meet consumer demands. As we refine this analysis, we may also attempt to estimate other sectoral emissions on a consumption basis, such as fuel used for transportation purchased out-of-state. In some cases this can require venturing into the relatively complex terrain of life cycle analysis. In general, we recommend considering a consumption-based approach where it will significantly improve the estimation of the emissions impact of potential mitigation strategies. (For example re-use, recycling, and source reduction can lead to emission reductions resulting from lower energy requirements for material production (such as paper, cardboard, and aluminum), even though these activities and their emissions may not occur within the State.)

## 2.2 General methodology

We prepared this analysis in close consultation with Arizona agencies, in particular, the Department of Environmental Quality (ADEQ) staff. The overall goal of this effort is to provide simple and straightforward estimates, with an emphasis on robustness and transparency. As a result, we rely on straightforward spreadsheet analysis rather than detailed modeling.

In most cases, we follow the same approach to emissions accounting used by the US EPA in its national GHG emissions inventory<sup>16</sup> and its guidelines for states.<sup>17</sup> These inventory guidelines were developed based on the guidelines from the Intergovernmental Panel on Climate Change, the international organization responsible for developing coordinated methods for national greenhouse gas inventories.<sup>18</sup> The inventory methods provide flexibility to account for local conditions.

The electricity sector is one area in which we expand the US EPA inventory approach, by looking at consumption-based in addition to production-based emissions, as described above. We encourage Arizona stakeholders to closely consider the question of whether and how to count GHG emissions from exported electricity in setting and tracking emissions. Stakeholders may also want to consider strategies that work together with neighboring states to reduce overall

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<sup>16</sup> US EPA, Feb 2005. *Draft Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2003*.  
<http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterPublicationsGHGEmissionsUSEmissionsInventory2005.html>.

<sup>17</sup> <http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsStateInventoryGuidance.html>

<sup>18</sup> <http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.htm>

GHG emissions. A number of other accounting questions also need to be resolved, such as the treatment of transportation fuels used out of state and for international travel.

**Table 3. Key Sources for Data, Inventory Methods And Projection Growth Rates**

<b>Source</b>	<b>Information provided</b>	<b>Use of Information in this Analysis</b>
<b>US EPA State Greenhouse Gas Inventory Tool (SGIT)</b>	EPA SGIT is a collection of linked spreadsheets designed to help users develop state GHG inventories. EPA SGIT contains default data for each state for most of the information required for an inventory.	Where not indicated otherwise, SGIT is used to calculate emissions from industrial processes, agriculture and forestry, and waste. We use SGIT emission factors (CO <sub>2</sub> , CH <sub>4</sub> and N <sub>2</sub> O per BTU consumed) to calculate energy use emissions. <sup>19</sup>
<b>US DOE Energy Information Administration (EIA) State Energy Data System (SEDS)</b>	EIA SEDS source provides energy use data in each state, annually to 2002.	EIA SEDS is the source for all energy use data except on-road gasoline and diesel consumption. Emission factors from EPA SGIT are used to calculate energy-related emissions.
<b>US DOE Energy Information Administration Annual Energy Outlook 2005 (AEO2005)</b>	EIA AEO2005 projects energy supply and demand for the US from 2005 to 2025. Energy consumption is estimated on a regional basis. Arizona is included in the Mountain Census region (AZ, CO, ID, MT, NM, NV, UT, and WY)	EIA AEO2005 is used to project changes in per capita (residential), per employee (commercial/industrial), and per VMT (transportation) fossil fuel use. (See Table 3)
<b>Arizona Department of Transportation (AZDOT)</b>	AZDOT reports on-road gasoline and diesel consumption based on calculations from tax revenue. <sup>20</sup>	AZDOT provides data for gasoline and diesel consumption.
<b>from Arizona DOT's Long Range Transportation Plan (MOVEAZ)</b>	The MOVEAZ analysis projects population, employment, and transportation demand. <sup>21</sup>	The MOVEAZ report is the the source vehicle mileage growth rates in the transportation sector.

<sup>19</sup> We did not use the EPA SGIT tool directly to calculate emissions from energy use because the data in the tool has not been updated to the most recent energy consumption data. By calculating GHG emissions directly from energy use multiplied by the emissions factors from SGIT, we are able to use locally sourced energy data, such as AZDOT gasoline and diesel sales data.

<sup>20</sup> [www.azdot.gov/Inside\\_ADOT/fms](http://www.azdot.gov/Inside_ADOT/fms)

<sup>21</sup> [www.moveaz.org](http://www.moveaz.org)

## Appendix A. Electricity Use and Supply<sup>22</sup>

For reasons described above – largely to better assess the impacts of potential GHG mitigation options – we estimate electricity emissions on both a consumption basis, i.e. accounting for the GHG emissions associated with electricity used in the State. We also calculate electricity emissions on a production basis, based on the fuel used by in-state generators, since this is a simpler calculation, and one more commonly used for historical inventories.

Estimating the sources of electricity associated with electricity consumed in the state, and their emissions, poses some challenges. Precisely tracking the sources of electricity used to meet Arizona loads is impossible; doing so would require a system to trace each kWh as it flowed from the generator throughout the regional transmission and distribution system to the ultimate user. A more technically feasible approach would be to follow the “contract path” of electricity purchases and sales by generators and load-serving entities (e.g. utilities); however, such a system does not currently exist. As a result, we must turn to simpler approximations, such as the fuel mix reporting methods used by several Western states.<sup>23</sup> In essence, this method relies on utilities to report the sources of electricity they use to meet their loads, based on their plants, contracts, and net market purchases.<sup>24</sup> In collaboration with state utilities, we are currently exploring the feasibility of such a method.

Meanwhile, we have adopted a simple and transparent approach to estimate consumption-based emissions. We begin by examining the fuel consumed, and emissions generated, by power plants in the state. We then assume, for now, that this in-state generation fuel mix is representative of the fuel mix used to meet in-state loads. As a result, if the state is a net electricity exporter, we deduct the emissions associated with exports to other states, using the same average fuel mix.

Projecting generation sources, sales, and emissions for the electric sector out to 2020 requires a number of key assumptions, such as including economic and demographic activity, changes in electricity-using technologies, regional markets for electricity (and competitiveness of various technologies and locations), access to transmission and distribution, the retirement of existing generation plants, the response to changing fuel prices, and the fuel/technology mix of new generation plants. Key simplifying assumptions used here are summarized in Table 6.

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<sup>22</sup> The Energy Supply Technical Working Group reviewed the draft GHG inventory and forecast, and the corresponding assumptions, for this sector. They recommended that the inventory and forecast be accepted with a change to reflect growth in peak demand as distinct from growth in total demand; figures cited in this report reflect growth in peak demand.

<sup>23</sup> See, for example, the California and Washington fuel mix and emissions reports at [http://www.cted.wa.gov/CTED/documents/ID\\_1338\\_Publications.pdf](http://www.cted.wa.gov/CTED/documents/ID_1338_Publications.pdf) and [http://www.energy.ca.gov/consumer/power\\_content\\_label.html](http://www.energy.ca.gov/consumer/power_content_label.html)

<sup>24</sup> The fuel mix of net market purchases – i.e. short-term and other purchases that are not associated with a specific electricity source – can be estimated in consistent manner using the regional average electricity mix (as Washington and Oregon do) or using other techniques.

**Table 4. Key Assumptions and Methods for Electricity Projections**

<b>Electricity sales</b>	3.75% annual growth rate to 2010, and 3.50% growth after 2010, based on input from the RCI Technical Working Group
<b>Electricity generation</b>	3% annual growth from 2004-2010, based on regional growth in Western Electricity Coordinating Council report, <sup>25</sup> 2% annual growth from 2011-2020, based on regional growth in EIA AEO2005 (region includes AZ, NM and southern NV)
<b>Transmission and Distribution losses</b>	10%, based on average statewide losses, 1994-2000, (data from EPA Emission & Generation Resource Integrated Database <sup>26</sup> )
<b>New Renewable Generation Sources</b>	For Arizona Public Service and Tucson Electric Power, we assume no renewables beyond compliance with the current Environmental Portfolio Standard (1.1% of generation from 2012 onward, 60% solar). For all other utilities, we assume no additional new renewables.
<b>New Non-Renewable Generation Sources (2004-2010)</b>	From 2006-2010, we assume 17% coal, 78% natural gas, 5% nuclear (based on mix of planned additions from the Western Electricity Coordinating Council, <sup>27</sup> including nuclear uprates of Palo Verde).
<b>New Non-Renewable Generation Sources (2011-2020)</b>	For 2011 to 2020, we assume 80% coal and 20% natural gas, based on a review of studies including EIA AEO2005, ICF/WRAP 2002, and others. <sup>28</sup> To meet peak demands with an increasing shift to coal baseload plants, new natural gas plants are assumed to be predominantly combustion turbines during this period.
<b>Heat Rates</b>	The assumed heat rates for new gas and coal generation are 7000 Btu/kWh and 9000 Btu/kWh, respectively.
<b>Operation of Existing Facilities</b>	We assume that the current sources of coal-based electricity generation will increase output according to analysis completed for the WRAP. <sup>29</sup> However, future changes in fuel prices may have an important impact; these dynamics will be considered in more depth later.

<sup>25</sup> Western Electric Coordinating Council, 2004. 10-Year Coordinated Plan Summary. <http://www.wecc.biz/documents/library/publications/10year/tenyr04.pdf>

<sup>26</sup> <http://www.epa.gov/cleanenergy/egrid/index.htm>

<sup>27</sup> Western Electric Coordinating Council, 2004. 10-Year Coordinated Plan Summary. <http://www.wecc.biz/documents/library/publications/10year/tenyr04.pdf>

<sup>28</sup> Western Resource Advocates, 2004. *A Balanced Energy Plan for the Interior West*. <http://www.westernresourceadvocates.org/energy/bep.html> and ICF 2002. *Economic Assessment of Implementing the 10/20 Goals and Energy Efficiency Recommendations* (prepared for Western Regional Air Partnership).

<sup>29</sup> See emissions reconciliation documentation for 2000/2001 at [http://www.wrapair.org/forums/mtf/documents/group\\_reports/TechSupp/SO2Tech.htm](http://www.wrapair.org/forums/mtf/documents/group_reports/TechSupp/SO2Tech.htm). The results of this analysis are referenced in subsequent WRAP analyses, including *An Assessment of Critical Mass for the Regional SO<sub>2</sub> Trading Program* (ICF 2002)

Figure 12 shows historical sources of electricity generation in the state by fuel source, along with projections to the year 2020 based on the assumptions described above. Natural gas generation has grown considerably during the past decade, while coal, nuclear, and hydro generation have stayed relatively constant. Based on the above assumptions for new generation, natural gas continues to dominate new generation through 2010, at which point coal assumes an increasing market share, reflecting assumptions that natural gas prices will continue to rise.

**Figure 7. Electricity Generated By Arizona Power Plants, 1990-2020**

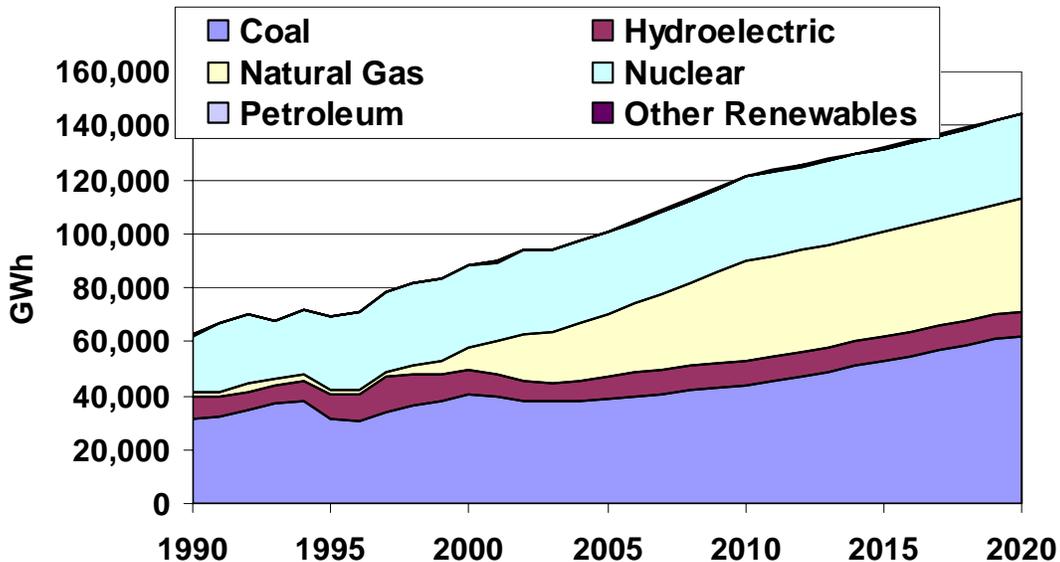
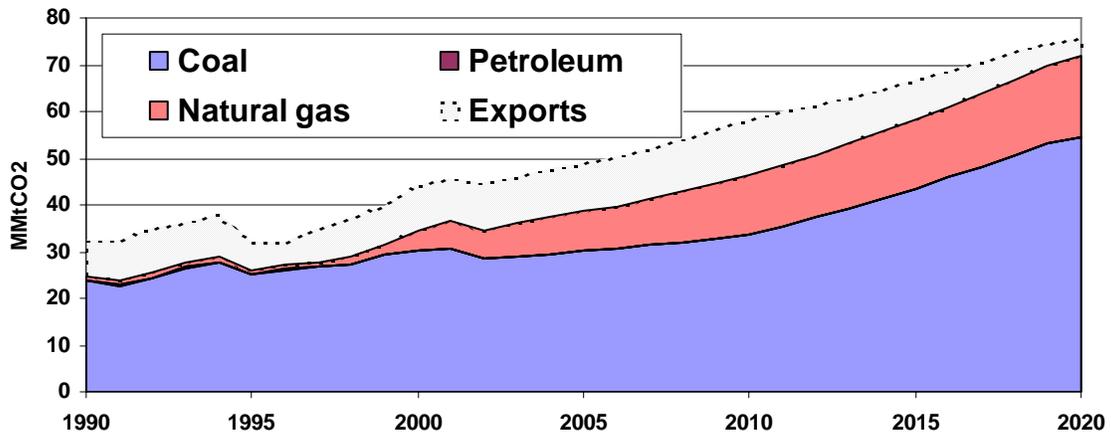


Figure 14 shows the GHG emissions associated with electricity use, based on the assumptions described above. From 1990 to 2000, electricity sales in the state grew by about 4% per year annually, with CO<sub>2</sub> emissions growing at roughly 3% year in this period. Emissions grew more slowly than electricity sales, as the share of natural gas generation increased while the coal share decreased. The decreasing share of coal led to a slight decreasing CO<sub>2</sub> emissions per MWh generated (1,142 lb CO<sub>2</sub>/MWh in 1990 to 1,107 lb CO<sub>2</sub>/MWh in 2000). From 2000 to 2020, emissions associated with electricity use are projected to grow at 3.8% per year, as the fraction of coal generation increases, especially after 2010.

Appendix I suggests that current GHG emissions associated black and organic carbon emissions from electricity generating units in Arizona could be between 0.2 and 0.4 MMtCO<sub>2</sub>e. Nearly all of these emissions are from coal-fired power plants.

**Figure 8. CO2 Emissions Associated with Electricity Use (Consumption-Basis) and Exports**



*Key uncertainties*

Each of the key assumptions reported in Table 6 represents a key uncertainty in this analysis. At this point, we have relied on public information to inform these assumptions, but we are discussing the key assumptions with staff from Arizona utilities to further refine these assumptions and the resulting emission projections.

## Appendix B. Residential, Commercial, and Industrial Energy Use<sup>30</sup>

Residential, commercial and industrial<sup>31</sup> (RCI) sectors produce carbon dioxide, methane, and nitrous oxide emissions as fuels are combusted for space heating, process heating, and other applications. Carbon dioxide accounts for over 99% of these emissions on a tCO<sub>2</sub>e basis. In addition, since these sectors consume electricity, one can also attribute electricity use emissions to these sectors.<sup>32</sup> This is particularly important to consider as stakeholders begin to explore options to improve energy efficiency; as can be seen below, the emissions associated with electricity use exceed those from direct fuel use in each sector, especially in residential and commercial buildings.

Direct use of coal, oil, natural gas, and wood<sup>33</sup> in RCI accounted for about 11% of gross GHG emissions in 2000. However, if emissions associated with RCI electricity use are included, RCI energy use then accounts for nearly half of gross GHG emissions.

Reference case emissions GHG estimates depend upon estimates of future energy use by sector and source. For electricity use, the assumption is 3.75% per year growth to 2010 and 3.50% per year thereafter, as described above. Assumed electricity sales growth in individual sectors is shown in Table 8, and is based on historical differences (1990-2002) in growth among sectors. For the direct use of fuels, we rely on regional projections from the EIA Annual Energy Outlook 2005, which we adjust for Arizona's growth rates of population and employment (see Table 3), resulting in the growth rates shown in Table 10.

**Table 5. Electricity Sales Projections, 2002-2020**

Sector	Growth Rate	
	2002-2010	2010-2020
Residential	5.0%	4.6%
Commercial	4.1%	3.8%
Industrial	0.8%	0.8%
<b>Total</b>	<b>3.75%</b>	<b>3.50%</b>

<sup>30</sup> The Residential, Commercial, and Industrial Technical Working Group reviewed the draft GHG inventory and forecast, and the corresponding assumptions, for this sector. They recommended that the inventory and forecast be accepted with a change in projected growth rate for electricity sales, as noted in Table 4. .

<sup>31</sup> The industrial sector includes agricultural energy use as well.

<sup>32</sup> One could similarly allocate GHG emissions due to natural gas transmission and distribution and other sources, but we have not done so here due to the relatively small level of emissions.

<sup>33</sup> Emissions from wood combustion include only N<sub>2</sub>O and CH<sub>4</sub>. Carbon dioxide emissions from biomass are assumed to be "net zero" consistent with USEPA and IPCC methodologies, and any net loss of carbon stocks due to biomass fuel use should be picked up in the land use and forestry analysis.



**Table 6. Projected Annual Growth in Energy Use, by Sector and Fuel, 2002-2020**

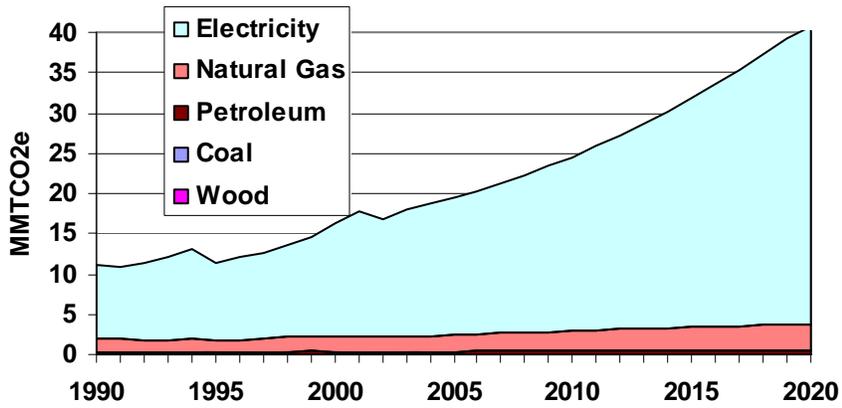
	2002-2010	2010-2015	2015-2020
<b>Residential</b>			
natural gas	4.2%	2.8%	2.4%
petroleum	2.5%	2.2%	1.6%
coal	-0.7%	-0.7%	-0.7%
wood	0.4%	0.4%	0.4%
<b>Commercial</b>			
natural gas	3.8%	3.0%	2.9%
petroleum	3.0%	1.6%	1.0%
coal	0.9%	0.8%	0.5%
wood	0.8%	0.8%	0.6%
<b>Industrial</b>			
natural gas	2.9%	0.9%	0.8%
petroleum	3.5%	1.1%	0.8%
petroleum feedstocks	0.0%	0.0%	0.0%
coal	0.9%	-0.8%	-1.0%
wood	0.0%	0.0%	0.0%

Figure 16, Figure 18, and Figure 20 illustrate historical and projected emissions for the residential, commercial, and industrial sectors from 1990 to 2020. Electricity consumption accounts for the largest component of each sector’s emissions. The residential sector shows the highest emissions growth, due to assumed strong growth in both electricity and natural gas consumption, for which per capita use actually increases. Commercial sector emissions also show strong growth with electricity use growing at about the same rate as commercial sector employment, with natural gas consumption growing slightly faster. The assumed growth rate for industrial sector electricity consumption is lower than the employment growth with the growth rate of natural gas consumption at a similar level. For both the commercial and industrial sectors energy consumption and resulting GHG emissions grow at a slower pace than gross state product, indicating an overall decrease in GHG intensity.<sup>34</sup>

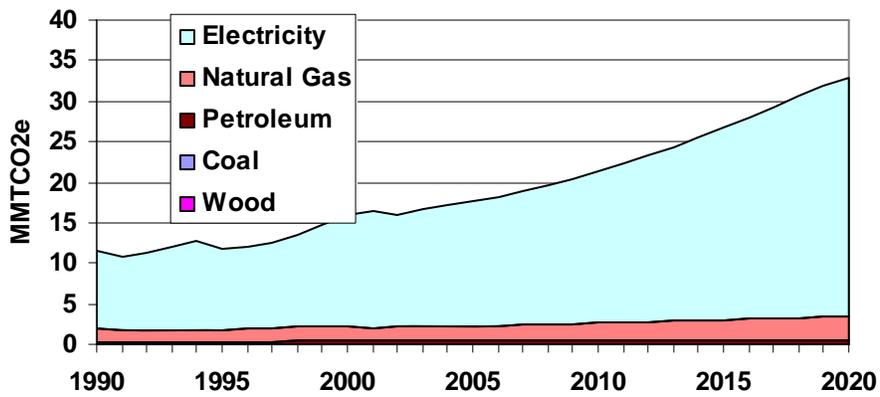
Appendix I suggests current GHG emissions associated black and organic carbon emissions from RCI activities in Arizona could be between 0.5 and 1.1 MMtCO<sub>2e</sub>, largely from nonroad diesel engines used in construction, industry, agriculture, and other areas.

<sup>34</sup> These estimates of growth relative to population and employment reflect expected responses – as modeled by the EIA NEMS model -- to changing fuel and electricity prices and technologies, as well as structural changes within each sector (subsectoral shares, energy use patterns, etc.).

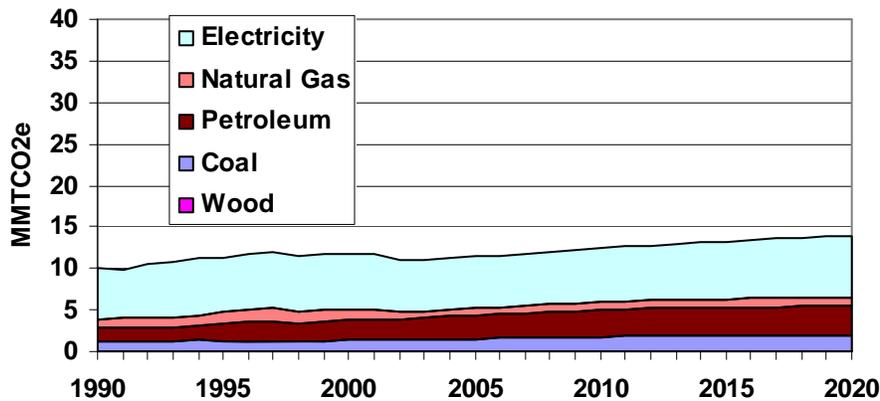
**Figure 9. Residential Sector GHG Emissions from Energy Use**



**Figure 10. Commercial Sector GHG Emissions from Energy Use**



**Figure 11. Industrial Sector GHG Emissions from Energy Use**



*Key Uncertainties*

Key sources of uncertainty underlying the projections are as follows:

- Natural gas consumption is the major source of on-site GHG emissions in the RCI sectors. We based assumptions of projected natural gas consumption on the regional results of the EIA AEO2005, adjusting for Arizona's expected population and employment. These growth rates should be reviewed by natural gas distributors.
- We also based industrial sector growth on regional results of the EIA AEO2005. We have not directly accounted for proposed new facilities in Arizona, including the clean fuels refinery and new or expanded cement plants. We will work with technical working groups to develop consensus on whether and how such facilities should be included in the reference case.
- The uncertainties related to overall electricity emissions are described in the electricity appendix. With respect the RCI analysis, further analysis and disaggregation of electricity use (historical and projected) by sector and end-use would be helpful.

## Appendix C. Transportation Energy Use<sup>35</sup>

The transportation sector is a major source of GHG emissions in Arizona – currently accounting for about 40% of Arizona’s gross GHG emissions. Carbon dioxide accounts for about 97% of transportation GHG emissions from fuel use; much of the remaining 3% is due to nitrous oxide emissions from gasoline engines.

As shown in Figure 22, on-road gasoline consumption accounts for the majority of transportation GHG emissions in 1990 and in 2000 – increasing by over a third during this period.<sup>36</sup> In 1990, on-road diesel<sup>37</sup> and air travel energy consumption<sup>38</sup> had similar GHG emissions, but diesel consumption nearly doubled from 1990 to 2000 while jet fuel and aviation gasoline increased by only 24%. Consumption of natural gas (largely for pipeline use) and propane plus emissions from petroleum lubricants accounted for about 7% of transportation emissions in 1990 and the total emissions from these sources declined slightly from 1990 to 2000.

Both Phoenix and Tucson have oxygenate requirements for their winter gasoline that are currently met by mixing ethanol with gasoline. In the 1990s, these requirements were met with a mix of methyl tertiary butyl ether (MTBE) and ethanol.<sup>39</sup> State agencies only collect data on total fuel sales (based on tax receipts), and thus data reported by AZDOT on total gasoline consumption includes a fraction that is actually ethanol (and historically MTBE as well). We estimated ethanol consumption based on information from the Maricopa and Pima Associations of Government and deducted this ethanol consumption from gasoline sales in order to calculate GHG emissions.<sup>40</sup> (Since ethanol is a biomass-derived fuel, its CO<sub>2</sub> emissions are not typically counted in inventory assessments.<sup>41</sup>) We also estimated MTBE consumption and emissions, and these are included in the historical emissions estimates.

Appendix I suggests that current GHG emissions associated black and organic carbon emissions from RCI activities in Arizona could be between 2.1 to 4.4 MMtCO<sub>2</sub>e. Over 70% of these emissions are contributed by onroad diesel vehicles. This sector takes on added significance given the projected growth in onroad diesel use mentioned below.

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<sup>35</sup> The Transportation and Land Use Technical Working Group reviewed the GHG inventory and forecast, and the corresponding assumptions, for the transportation sector. In particular, this group discussed and reviewed the assumptions regarding constant energy consumption per VMT through 2020. After this review, the group recommended that the inventory and forecast be accepted with no changes.

<sup>36</sup> Data sources are from AZ DOT for 1990 to 2003, [http://www.azdot.gov/Inside\\_ADOT/fms/gasgals.asp](http://www.azdot.gov/Inside_ADOT/fms/gasgals.asp)

<sup>37</sup> Data are from AZ DOT for 1990 to 2003, [http://www.azdot.gov/Inside\\_ADOT/fms/diesgals.asp](http://www.azdot.gov/Inside_ADOT/fms/diesgals.asp)

<sup>38</sup> Data sources are EIA SEDS for 1990 to 2002.

<sup>39</sup> Personal communication with Cathy Arthur, Maricopa Association of Governments, and Lee Comrie, Pima Association of Governments, March 30, 2005.

<sup>40</sup> Based on information regarding the months ethanol is blended (5-6), and oxygenate requirements (1.8-3.5%), we estimate ethanol consumption of 12 million gallons in 1990 and 73 million gallons in 2003.

<sup>41</sup> Nonetheless, ethanol, like gasoline, can require significant upstream GHG emissions in production and refining.

GHG emissions from transportation are expected to grow considerably over the next 15 years due to population growth and increased demand on transportation services. Arizona studies suggest on-road vehicle miles traveled (VMT) will continue to grow faster than population.<sup>42</sup> As a simplifying assumption, we projected that energy consumption per VMT will remain constant from 2002 to 2020. The MoveAZ report suggests that energy consumption per VMT will grow, while EIA AEO2005 shows this rate declining. Other assumptions are listed in Table 12.

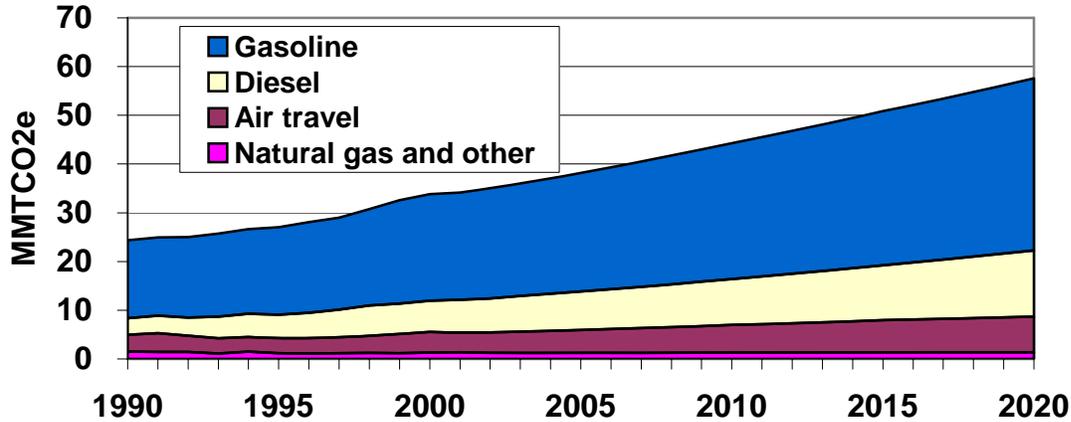
These assumptions combine to produce more than a doubling of GHG emissions from on-road gasoline from 1990 to 2020. On-road diesel consumption is expected to increase even more rapidly, while jet fuel consumption increases at slightly less than population growth. The high overall growth in transportation sector emissions – more than doubling from 1990 to 2020 – suggests many opportunities and challenges for reducing Arizona’s GHG emissions.

**Table 7. Key Assumptions and Methods for Transportation Projections**

<b>Passenger VMT growth</b>	The average annual growth rate for VMT is assumed to be 2.4% per year from 2002 to 2020, based on MOVEAZ report.
<b>On-road gasoline consumption</b>	Gasoline use is assumed to grow with passenger VMT; no change in gasoline use per VMT is assumed.
<b>Ethanol consumption</b>	Average annual ethanol consumption is assumed to remain at 2.8% of total gasoline consumption (representing Phoenix and Tucson winter fuel requirements).
<b>Freight VMT growth</b>	The average annual growth rate for VMT is assumed to be 3.7% per year from 2002 to 2020, based on MOVEAZ report.
<b>On-Road diesel consumption</b>	Diesel use is assumed to grow with freight VMT; no change in diesel use per VMT is assumed.
<b>Aviation fuel, jet fuel, natural gas and propane</b>	The average annual growth rates for these fuels are based on EIA AEO2005 growth rates for region (2.5% for aviation gasoline and jet fuel, 0% for natural gas and 5% for propane). Ethanol consumption is projected to grow by 7.8% per year (EIA AEO2005).

<sup>42</sup> We used MoveAZ ([www.moveaz.org](http://www.moveaz.org)) as the primary data source for VMT growth (appendix E), but also compared VMT growth projections from Maricopa Association of Governments *Conformity Analysis* (<http://www.mag.maricopa.gov/detail.cms?item=3092>), which showed similar VMT growth assumptions.

**Figure 12. Transportation GHG Emissions, 1990-2020**



*Key uncertainties*

A major uncertainty in this analysis is the projected increase in on-road gasoline consumption from 2003 to 2020. We found two sources for these projections, the MOVEAZ report from Arizona Department of Transportation (AZDOT 2004) and EIA AEO2005. As mentioned earlier, the EIA AEO2005 projections are regional (including the entire Mountain census region), while the MOVEAZ report is a recent state-specific source. For this reason we chose to base the projection on MOVEAZ. However the growth in gasoline use in MOVEAZ far exceeds VMT growth, with gasoline use per VMT growing 4.5% per year (owing presumably to increased congestion). EIA AEO2005, in contrast, projects gasoline use per VMT to a decline slightly as the result of expected improvements in fuel economy. For this analysis, we assumed no change in gasoline use per VMT, an assumption that should be more closely examined.

## Appendix D. Industrial Process and Related Emissions<sup>43</sup>

Emissions in this category span a wide range of activities, and reflect GHG emissions from CO<sub>2</sub> produced through industrial manufacturing (cement, lime, and soda ash) to the release of high GWP gases from cooling and refrigeration equipment (HFCs), semiconductor manufacture (PFCs), and electricity transformers (SF<sub>6</sub>).<sup>44,45</sup>

Though small overall today, emissions from this category are expected to continue to grow rapidly, as shown in Figure 24, almost entirely due to the increasing use of HFCs in refrigeration and air conditioning equipment. HFCs are being used to substitute for ozone-depleting substances (ODS)<sup>46</sup>, most notably chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) in compliance with the *Montreal Protocol*.<sup>47</sup> Even low amounts of HFC emissions, from leaks and other releases under normal use of the products, can lead to high GHG emissions. Emissions from the ODS substitutes in Arizona have increased from 0.005 MMTCO<sub>2</sub>e in 1990 to 1.4 MMTCO<sub>2</sub>e in 2000, with further increases of 8.4% per year expected from 2000 to 2020.<sup>48</sup>

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<sup>43</sup> The Residential, Commercial, and Industrial Technical Working Group reviewed the GHG inventory and forecast, and recommended that the inventory and forecast for industrial processes and related emissions be accepted with no changes.

<sup>44</sup> For example, cement production results in CO<sub>2</sub> emissions as calcium carbonate, CaCO<sub>3</sub> is converted to lime CaO.

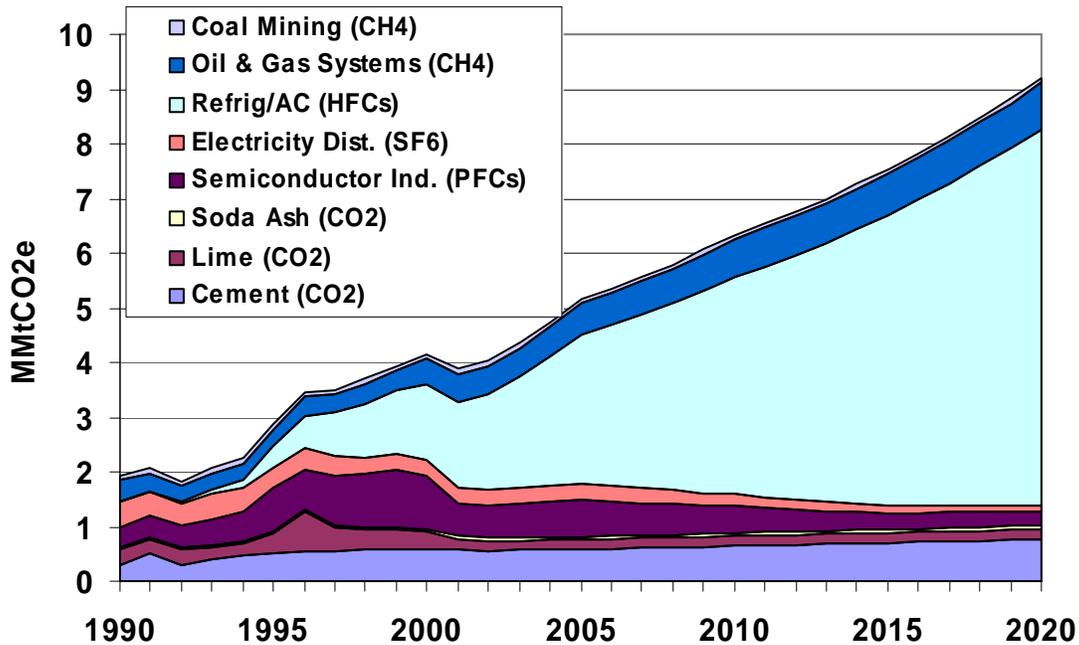
<sup>45</sup> As noted in Appendix I, this sector is an insignificant contributor to black and organic carbon emissions.

<sup>46</sup> ODS substitutes are primarily associated with refrigeration and air conditioning, but also many other uses such as fire extinguishers, solvent cleaning, aerosols, foam production and sterilization.

<sup>47</sup> ODS substitutes are primarily associated with refrigeration and air conditioning, but also many other uses such as fire extinguishers, solvent cleaning, aerosols, foam production and sterilization. Although CFCs and HCFCs include potent global warming gases, they are not included in national and international GHG estimates because of concerns related to implementation of the Montreal Protocol. Their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which is itself an important greenhouse gas in addition to shielding the Earth from harmful levels of ultraviolet radiation.

<sup>48</sup> Growth rates are based on growth in projected national emissions from recent EPA report, US EPA 2004, *Analysis of Costs to Abate International ODS Substitute Emissions*, EPA 430-R-04-006. [http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR62AS98/\\$File/IMAC%20Appendices%2006-24.pdf](http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/RAMR62AS98/$File/IMAC%20Appendices%2006-24.pdf)

**Figure 13. GHG Emissions from Industrial Processes**



Emissions of PFCs in the semi-conductor industry and of SF6 from electrical equipment have experienced declines since the mid-nineties (see Figure 24), mostly due to voluntary action by industry. Future emissions could increase due to expected increases in semi-conductor manufacturing and electricity supply, or decrease due to process changes and continued industry efforts. Projections from the US Climate Action Report<sup>49</sup> shows expected decreases in these emissions at the national level due to a variety of industry actions to reduce emissions, and we have assumed the same rate of decline for emissions in Arizona.

Emissions from cement production, lime manufacture, limestone and dolomite use and soda ash consumption accounted for almost 1/3 of industrial process emissions in 1990 but have not grown significantly since. By 2000, these emissions were less than 25% of total industrial process emissions. Emissions declined by a further 0.2 MMtCO<sub>2</sub>e from 2000 to 2002, due to decreased lime manufacture.

For 2003 to 2020, we applied the following assumptions for projected changes:

<sup>49</sup> U.S. Department of State, *U.S. Climate Action Report 2002*, Washington, D.C., May 2002.  
[http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BNQ76/\\$File/ch5.pdf](http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BNQ76/$File/ch5.pdf)

- Emissions from cement production and soda ash consumption increase at the same rate as population growth (1.8% per year).
- Emissions from lime manufacture, limestone and dolomite show no change from 2002 levels.

The emissions from cement production need further review and analysis. Clinker and masonry cement production information for Arizona was obtained from the United States Geological Survey (USGS) *Cement Annual*. This report lists production by state where possible, but the data for Arizona and New Mexico are combined together, for confidentiality reasons. As a first approximation, we relied on the approach used by the EPA SGIT tool and divided the production data evenly between the two states. We are currently working with ADEQ to use information on permits for the Arizona plants to determine if better estimates are available for clinker production. ADEQ is also helping to estimate production from newly approved plants in the state. We will update the inventory and reference case values as this information becomes available.

We estimated methane emissions from oil and gas systems based on the length and type of pipeline in the state and number of services, combined with emission factors provided by EPA. From 1990 to 2000, emissions remained constant as length of pipeline increased but leakier pipelines were replaced with better quality ones. For emissions projections, we assume that emissions increase with natural gas demand. Several key uncertainties exist with these estimates:

- We collected information from the US Office of Pipeline Safety for the length of pipeline in Arizona; this dataset appears to have some missing or inconsistent data. We have asked ADEQ to review these input values and provide any improvements to them.
- Increasing emissions with natural gas demand accounts mostly for increases in the distribution network, but may not accurately estimate emissions from increased transmission network (especially for pipelines that do not serve the Arizona demand). This assumption needs to be reviewed and updated if better information is available.

Methane emissions from coal mining accounts are the final emission source in this category. These emissions are less than 0.1 MMTCO<sub>2</sub> and have remained relatively constant from 1990 to 2002, varying with coal production in the state. Most coal production in the state is from one mine, Kayenta. In the past, this mine has provided coal to the Mohave coal plant in Nevada, which may close down in 2006. It is unknown whether the mine would also shut down or whether the coal will be supplied to other power plants in the region. As a first approximation, we have assumed that coal production and resulting methane emissions remain at 2002 levels through 2020.

## Appendix E. Agriculture, Forestry and Other Land Use<sup>50</sup>

The emissions discussed in this appendix refer to non-energy emissions from agriculture, forestry and other land uses. These emissions include emissions from livestock, agriculture soil management and field burning, CO<sub>2</sub> emitted and removed (sinks) due to forestry activities, and emissions linked to rangeland and forest fires.<sup>51</sup>

Agriculture emissions include CH<sub>4</sub> and N<sub>2</sub>O emissions from enteric fermentation, manure management, agriculture soils and agriculture residue burning. Data on crops and animals in the state from 1990 to 2004 were provided by the USDA National Agriculture Statistical Service.<sup>52</sup> As shown in Figure 26, emissions from these sources remained stable from 1990 to 2000, then increased in 2001 and 2004. GHG emissions in 2004 are about 11% above 1990 levels. Emissions from agriculture soils account the largest portion (about 50%) of agricultural emissions; this category includes N<sub>2</sub>O emissions resulting from activities that increase nitrogen in the soil, including fertilizer (synthetic, organic and livestock) application and production of nitrogen fixing crops. These activities have generally increased slightly from 1990 to 2004 and subsequently emissions have increased by about 0.1% per year. Enteric fermentation and manure management accounted for about 32% and 17% of agriculture emissions in 1990, respectively. Enteric fermentation emissions remained relatively constant to 2002 but manure management emissions rose by 3.6% per year (similar to increase in number of dairy cattle). Emissions from agriculture residue burning are very small and also remained relatively constant from 1990 to 2004.

As a first approximation for projecting emissions from this source, we have assumed no change from 2004 levels. Emissions from enteric fermentation and manure management depend on the number of livestock and management of these stocks and land. Agricultural soils emissions depend on land-use conversions out of croplands, management of soils and types of crops. While we search for existing reports and analyses, we are applying the simple assumption of no growth to these emissions from 2002 to 2020.

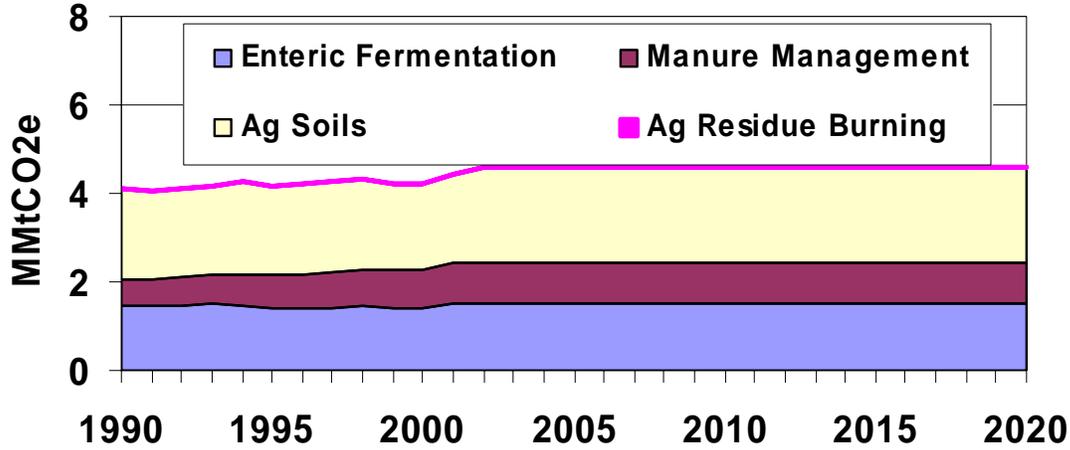
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<sup>50</sup>The Agriculture and Forestry Technical Work Group reviewed the reference case and forecasts for agriculture and forestry. No changes to the agriculture reference case or forecasts were recommended. For forestry, the work group recommended that the forecasted forestry sinks should remain static from the reference case. Therefore, the total GHG estimates for forestry in 2010 and 2020 remain at -6.7 MMT

<sup>51</sup> This sector was not found to contribute any CO<sub>2</sub>e impact associated with BC+OM emissions (see Appendix I). Black carbon emissions associated with diesel combustion in agricultural or forestry equipment are included as part of the fossil fuel combustion emissions in the RCI sector.

<sup>52</sup> Personal communication, Steve Manheimer, AZ National Agriculture Statistical Service, March 2005.

**Figure 14. GHG Emissions from Agriculture**



*Forestlands*

Forestland emissions refer to the net CO<sub>2</sub> flux<sup>53</sup> from forested lands in Arizona, which account for about 16% of the state’s land area. Recent US Forest Service estimates suggest that Arizona forests and the use of forest products sequestered on average 6.7 MMtCO<sub>2</sub>e per year from 1987 to 2002, as shown in Table 14. During the FIA survey periods used for FORCARB2 estimates, the definition of forestland changed from a minimum forest cover requirement of ten percent, to a minimum of five percent. As a result rangelands may or may not be included in these estimates, depending on their level of tree stocking, although the largest class of forested rangeland, pinyon juniper, is included in the US Forest Service forest stock assessments. As a result, much of the carbon on rangeland is likely to be covered in the US Forest Serviced FORCARB assessment.

The net forest and land use sequestration estimates noted above are based on recent improvements to US Forest Service carbon stock inventory data.. It is important to note that US Forest Service assessments only cover the parts of the state that the US Forest Service defines as forest, representing 16% of the total state land area (4.85 of 30.3 million hectares in 2002). Asd noted, during the FIA survey periods used for FORCARB2 estimates, the definition of forestland changed from a minimum forest cover requirement of ten percent, to a minimum of five percent. The, US Forest Service is not able to make corrections associated with these changes in forest definition, but review of the data conducted by CCS and the US Forest Service suggests that

<sup>53</sup> “Flux” refers to both emissions of CO<sub>2</sub> to the atmosphere and removal (sinks) of CO<sub>2</sub> from the atmosphere.

effects are likely to be small.

As with the agricultural sector, emissions of BC+OM from forestry equipment fired on fossil fuels are included as part of the RCI sector.

**Table 8. Average Annual Changes in Carbon Stocks from Forest Lands and Related Activities, 1985-2002 (Million MtCO<sub>2</sub>)**

Live and dead-standing trees and understory	2.5
Forest floor and coarse woody debris	-3.8
Soils	-5.5
Wood products and landfills <sup>54</sup>	0.0
<b>Total</b>	<b>-6.7</b>

*Other Lands and Land Uses*

The carbon cycle for rangelands is not well understood; existing studies have focused on forest lands. Rangelands and pasture account for almost 56% of the state’s land area, and therefore the extent to which they sequester or emit carbon, even a net source or net sink, while small on a per acre basis, may be significant at the state level. Time and resource constraints did not allow for the development of a rangeland carbon inventory at this time. However, detailed review of data and conferrals with the US Forest Service indicate that the carbon stock change effects of rangeland are likely to be small. One key reason is that the pinyon juniper forest system is included in US Forest Service estimates under the definition of forest, while this is often referred to as rangeland in other surveys, such as those conducted by USDA. CCS recommends that additional work be performed in the future to characterize the GHG source or sink potential of rangelands.

*Key Uncertainties and Further Analysis*

As noted above, there may be significant changes in total statewide biomass-related carbon stocks as estimates are refined, and further analysis in this area should be a high priority, particularly for rangelands.

One of the uncertainties for the historic (1990-2004) emissions is the contribution of cotton crops to emissions. The EPA SGIT does not include emissions from cotton crops in its estimate of

<sup>54</sup> Wood products and landfills, according to USFS data, showed no net change in the two most recent estimates (1992 and 1997). <http://www.fs.fed.us/ne/global/pubs/books/epa/states/AZ.htm>

N<sub>2</sub>O emissions, but these are thought to be minimal from the perspective of crop-residue management and the fertilizer use on cotton is captured in the total amount of N-fertilizer used in the state each year.

## Appendix F. Waste Management

GHG emissions from waste management accounted for are summarized in Table 16. Emissions in this category include:

- Solid waste management – methane emissions from landfills, accounting for any methane that is flared or captured for energy production, and
- Wastewater management – methane and nitrous oxide from municipal wastewater treatment facilities.

Any emissions associated with energy consumed to transport of solid waste and wastewater is included in the RCI accounting above.

**Table 9. Emissions from Waste Management**

Reference Case GHG Emissions for Arizona					
(Million Metric Tons CO <sub>2</sub> e)	1990	2000	2010	2020	Explanatory Notes for Projections
<b>Waste Management</b>	<b>2.1</b>	<b>1.9</b>	<b>2.0</b>	<b>1.9</b>	
Solid Waste Management	1.7	1.3	1.4	1.1	Based on national projections (USEPA)
Wastewater Management	0.4	0.5	0.7	0.8	Increases with state population

We used the EPA SGIT tool to estimate emissions.<sup>55</sup> However, since emissions from these types of facilities are site-specific, we are also working with ADEQ to determine if better estimates exist. Of particular concern are emissions from solid waste management where the EPA SGIT tool estimates negative emissions – this tool uses different sources for (1) methane emission generation from landfills,<sup>56</sup> (2) methane emissions avoided by flaring at landfills,<sup>57</sup> and (3) methane emissions avoided by waste-to-energy plants.<sup>58</sup> We are working with the US EPA to check the emissions avoided by flaring and with ADEQ to determine if better data are available for methane generation from landfills. For now, we have included the EPA SGIT results with simple projections – methane emissions from generation increase with population - on the assumption that municipal solid waste increases with population, while emissions avoided by flaring and waste to energy plants remain at 2002 levels – these avoided emissions depend on adding equipment to landfills and are not directly tied to other drivers in this analysis.

<sup>55</sup> As noted in Appendix I, this sector is an insignificant contributor to black and organic carbon emissions.

<sup>56</sup> Estimates are based on 30 year data on municipal solid waste generation from *Biocycle* magazine, combined with national emission factors.

<sup>57</sup> Based on information supplied directly to contractors for EPA from flare vendors

<sup>58</sup> EPA (2002) Landfill Gas-to-Energy Project Database 2001, Landfill Methane and Outreach Program.

Emissions from wastewater were also estimated using the EPA SGIT tool. These emissions increased by 4.4% per year from 1990 to 2000<sup>59</sup>. Projected emissions are assumed to increase with population growth, 2.1% per year from 2003 to 2020.

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<sup>59</sup> Emissions are calculated in EPA SGIT based on state population, assumed biochemical oxygen demand and protein consumption per capita, and emission factors for N<sub>2</sub>O and CH<sub>4</sub>.

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## **Appendix G. List of Contacts Made**

### **ENERGY**

Mark Catchpole, AZCommerce  
Jim Westberg, AZCommerce  
Mark Ellery, AZCommerce  
Mark Hope, AZCommerce  
Mark Catchpole, AZCommerce  
Jeff Schlegel, Southwest Energy Efficiency Project  
Matthew Rowell, ACC  
Ray Williamson, ACC  
Prem Bahl, ACC

### **TRANSPORTATION**

Dave Cousineau, AZDOT  
Philip Chang, AZDOT  
John Pein, AZDOT  
Cathy Arthur, Maricopa Association of Governments  
Lee Comrie, Pima Association of Governments

### **INDUSTRIAL PROCESSES and WASTE**

Eric Massey, AZDEQ  
Dick Jefferies, AZDEQ

### **AGRICULTURE**

Jim Nowlin – AZ Department of Agriculture (AZDA)  
Jack Peterson – AZDA  
Gary Christian- AZDA  
Gilbert Carranza – Arizona Farm Services, USDA  
Stephanie Helgeson – NRCS, USDA  
Balaji Vaidyanathan – AZDEQ  
Ron Sherron – AZDEQ  
Steve Manheimer – Arizona Statistical Office, NASS, USDA  
Larry Antilla - AZ Cotton Growers Association  
Diana Reed – Biosolids, Water Quality Division, AZDEQ  
George Frisvold – Agricultural & Resource Economics, University of Arizona

### **RANGELANDS**

Steven Archer – School of Natural Resources, University of Arizona  
Dean Martens, - ARS, Tucson Experiment Station, USDA

## Appendix H. Greenhouse Gases and Global Warming Potential Values: Excerpts from the *Inventory of U.S. Greenhouse Emissions and Sinks: 1990-2000*

**Original Reference:** All material taken from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 - 2000*, U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-003, April 2002. [www.epa.gov/globalwarming/publications/emissions](http://www.epa.gov/globalwarming/publications/emissions)  
The preparation of this document was directed by Michael Gillenwater.

### **Introduction**

The *Inventory of U.S. Greenhouse Gas Emissions and Sinks* presents estimates by the United States government of U.S. anthropogenic greenhouse gas emissions and removals for the years 1990 through 2000. The estimates are presented on both a full molecular mass basis and on a Global Warming Potential (GWP) weighted basis in order to show the relative contribution of each gas to global average radiative forcing.

The Intergovernmental Panel on Climate Change (IPCC) has recently updated the specific global warming potentials for most greenhouse gases in their Third Assessment Report (TAR, IPCC 2001). Although the GWPs have been updated, estimates of emissions presented in the U.S. *Inventory* continue to use the GWPs from the Second Assessment Report (SAR). The guidelines under which the *Inventory* is developed, the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) and the United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines for national inventories<sup>60</sup> were developed prior to the publication of the TAR. Therefore, to comply with international reporting standards under the UNFCCC, official emission estimates are reported by the United States using SAR GWP values. This excerpt of the U.S. *Inventory* addresses in detail the differences between emission estimates using these two sets of GWPs.

Overall, these revisions to GWP values do not have a significant effect on U.S. emission trends.

Additional discussion on emission trends for the United States can be found in the complete *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*.

### **What is Climate Change?**

Climate change refers to long-term fluctuations in temperature, precipitation, wind, and other elements of the Earth's climate system. Natural processes such as solar-irradiance variations, variations in the Earth's orbital parameters, and volcanic activity can produce variations in climate. The climate system can also be influenced by changes in the concentration of various gases in the atmosphere, which affect the Earth's absorption of radiation.

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial (thermal) radiation back into space. On average, the absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space. A portion of this terrestrial radiation, though, is itself absorbed by gases in the atmosphere. The energy from this absorbed terrestrial radiation warms the Earth's surface and atmosphere, creating what is known as the "natural greenhouse effect." Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 33°C lower (IPCC 2001).

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<sup>60</sup> See FCCC/CP/1999/7 at <[www.unfccc.de](http://www.unfccc.de)>.

Under the UNFCCC, the definition of climate change is “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.” Given that definition, in its Second Assessment Report of the science of climate change, the IPCC concluded that:

*Human activities are changing the atmospheric concentrations and distributions of greenhouse gases and aerosols. These changes can produce a radiative forcing by changing either the reflection or absorption of solar radiation, or the emission and absorption of terrestrial radiation (IPCC 1996).*

Building on that conclusion, the more recent IPCC Third Assessment Report asserts that “[c]oncentrations of atmospheric greenhouse gases and their radiative forcing have continued to increase as a result of human activities” (IPCC 2001).

The IPCC went on to report that the global average surface temperature of the Earth has increased by between  $0.6 \pm 0.2^{\circ}\text{C}$  over the 20th century (IPCC 2001). This value is about  $0.15^{\circ}\text{C}$  larger than that estimated by the Second Assessment Report, which reported for the period up to 1994, “owing to the relatively high temperatures of the additional years (1995 to 2000) and improved methods of processing the data” (IPCC 2001).

While the Second Assessment Report concluded, “the balance of evidence suggests that there is a discernible human influence on global climate,” the Third Assessment Report states the influence of human activities on climate in even starker terms. It concludes that, “[I]n light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations” (IPCC 2001).

## **Greenhouse Gases**

Although the Earth’s atmosphere consists mainly of oxygen and nitrogen, neither plays a significant role in enhancing the greenhouse effect because both are essentially transparent to terrestrial radiation. The greenhouse effect is primarily a function of the concentration of water vapor, carbon dioxide, and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC 1996). Changes in the atmospheric concentrations of these greenhouse gases can alter the balance of energy transfers between the atmosphere, space, land, and the oceans. A gauge of these changes is called radiative forcing, which is a simple measure of changes in the energy available to the Earth-atmosphere system (IPCC 1996). Holding everything else constant, increases in greenhouse gas concentrations in the atmosphere will produce positive radiative forcing (i.e., a net increase in the absorption of energy by the Earth).

Climate change can be driven by changes in the atmospheric concentrations of a number of radiatively active gases and aerosols. We have clear evidence that human activities have affected concentrations, distributions and life cycles of these gases (IPCC 1996).

Naturally occurring greenhouse gases include water vapor, carbon dioxide ( $\text{CO}_2$ ), methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ), and ozone ( $\text{O}_3$ ). Several classes of halogenated substances that contain fluorine, chlorine, or bromine are also greenhouse gases, but they are, for the most part, solely a product of industrial activities. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are halocarbons that contain chlorine, while halocarbons that contain bromine are referred to as bromofluorocarbons (i.e., halons). Because CFCs, HCFCs, and halons are stratospheric ozone depleting substances, they are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer. The UNFCCC defers to this earlier international treaty; consequently these gases are not included in national

greenhouse gas inventories. Some other fluorine containing halogenated substances—hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>)—do not deplete stratospheric ozone but are potent greenhouse gases. These latter substances are addressed by the UNFCCC and accounted for in national greenhouse gas inventories.

There are also several gases that, although they do not have a commonly agreed upon direct radiative forcing effect, do influence the global radiation budget. These tropospheric gases—referred to as ambient air pollutants—include carbon monoxide (CO), nitrogen dioxide (NO<sub>2</sub>), sulfur dioxide (SO<sub>2</sub>), and tropospheric (ground level) ozone (O<sub>3</sub>). Tropospheric ozone is formed by two precursor pollutants, volatile organic compounds (VOCs) and nitrogen oxides (NO<sub>x</sub>) in the presence of ultraviolet light (sunlight). Aerosols—extremely small particles or liquid droplets—often composed of sulfur compounds, carbonaceous combustion products, crustal materials and other human induced pollutants—can affect the absorptive characteristics of the atmosphere. However, the level of scientific

understanding of aerosols is still very low (IPCC 2001).

Carbon dioxide, methane, and nitrous oxide are continuously emitted to and removed from the atmosphere by natural processes on Earth. Anthropogenic activities, however, can cause additional quantities of these and other greenhouse gases to be emitted or sequestered, thereby changing their global average atmospheric concentrations. Natural activities such as respiration by plants or animals and seasonal cycles of plant growth and decay are examples of processes that only cycle carbon or nitrogen between the atmosphere and organic biomass. Such processes—except when directly or indirectly perturbed out of equilibrium by anthropogenic activities—generally do not alter average atmospheric greenhouse gas concentrations over decadal timeframes. Climatic changes resulting from anthropogenic activities, however, could have positive or negative feedback effects on these natural systems. Atmospheric concentrations of these gases, along with their rates of growth and atmospheric lifetimes, are presented in Table 1.

**Table 1: Global atmospheric concentration (ppm unless otherwise specified), rate of concentration change (ppb/year) and atmospheric lifetime (years) of selected greenhouse gases**

Atmospheric Variable	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	SF <sub>6</sub> <sup>a</sup>	CF <sub>4</sub> <sup>a</sup>
Pre-industrial atmospheric concentration	278	0.700	0.270	0	40
Atmospheric concentration (1998)	365	1.745	0.314	4.2	80
Rate of concentration change <sup>b</sup>	1.5 <sup>c</sup>	0.007 <sup>c</sup>	0.0008	0.24	1.0
Atmospheric Lifetime	50-200 <sup>d</sup>	12 <sup>e</sup>	114 <sup>e</sup>	3,200	>50,000

Source: IPCC (2001)

<sup>a</sup> Concentrations in parts per trillion (ppt) and rate of concentration change in ppt/year.

<sup>b</sup> Rate is calculated over the period 1990 to 1999.

<sup>c</sup> Rate has fluctuated between 0.9 and 2.8 ppm per year for CO<sub>2</sub> and between 0 and 0.013 ppm per year for CH<sub>4</sub> over the period 1990 to 1999.

<sup>d</sup> No single lifetime can be defined for CO<sub>2</sub> because of the different rates of uptake by different removal processes.

<sup>e</sup> This lifetime has been defined as an “adjustment time” that takes into account the indirect effect of the gas on its own residence time.

A brief description of each greenhouse gas, its sources, and its role in the atmosphere is given below. The following section then explains the

concept of Global Warming Potentials (GWPs), which are assigned to individual gases as a

measure of their relative average global radiative forcing effect.

**Water Vapor (H<sub>2</sub>O).** Overall, the most abundant and dominant greenhouse gas in the atmosphere is water vapor. Water vapor is neither long-lived nor well mixed in the atmosphere, varying spatially from 0 to 2 percent (IPCC 1996). In addition, atmospheric water can exist in several physical states including gaseous, liquid, and solid. Human activities are not believed to directly affect the average global concentration of water vapor; however, the radiative forcing produced by the increased concentrations of other greenhouse gases may indirectly affect the hydrologic cycle. A warmer atmosphere has an increased water holding capacity; yet, increased concentrations of water vapor affects the formation of clouds, which can both absorb and reflect solar and terrestrial radiation. Aircraft contrails, which consist of water vapor and other aircraft emittants, are similar to clouds in their radiative forcing effects (IPCC 1999).

**Carbon Dioxide (CO<sub>2</sub>).** In nature, carbon is cycled between various atmospheric, oceanic, land biotic, marine biotic, and mineral reservoirs. The largest fluxes occur between the atmosphere and terrestrial biota, and between the atmosphere and surface water of the oceans. In the atmosphere, carbon predominantly exists in its oxidized form as CO<sub>2</sub>. Atmospheric carbon dioxide is part of this global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Carbon dioxide concentrations in the atmosphere increased from approximately 280 parts per million by volume (ppmv) in pre-industrial times to 367 ppmv in 1999, a 31 percent increase (IPCC 2001). The IPCC notes that “[t]his concentration has not been exceeded during the past 420,000 years, and likely not during the past 20 million years. The rate of increase over the past century is unprecedented, at least during the past 20,000 years.” The IPCC definitively states that “the present atmospheric CO<sub>2</sub> increase is caused by anthropogenic

emissions of CO<sub>2</sub>” (IPCC 2001). Forest clearing, other biomass burning, and some non-energy production processes (e.g., cement production) also emit notable quantities of carbon dioxide.

In its second assessment, the IPCC also stated that “[t]he increased amount of carbon dioxide [in the atmosphere] is leading to climate change and will produce, on average, a global warming of the Earth’s surface because of its enhanced greenhouse effect—although the magnitude and significance of the effects are not fully resolved” (IPCC 1996).

**Methane (CH<sub>4</sub>).** Methane is primarily produced through anaerobic decomposition of organic matter in biological systems. Agricultural processes such as wetland rice cultivation, enteric fermentation in animals, and the decomposition of animal wastes emit CH<sub>4</sub>, as does the decomposition of municipal solid wastes. Methane is also emitted during the production and distribution of natural gas and petroleum, and is released as a by-product of coal mining and incomplete fossil fuel combustion. Atmospheric concentrations of methane have increased by about 150 percent since pre-industrial times, although the rate of increase has been declining. The IPCC has estimated that slightly more than half of the current CH<sub>4</sub> flux to the atmosphere is anthropogenic, from human activities such as agriculture, fossil fuel use and waste disposal (IPCC 2001).

Methane is removed from the atmosphere by reacting with the hydroxyl radical (OH) and is ultimately converted to CO<sub>2</sub>. Minor removal processes also include reaction with Cl in the marine boundary layer, a soil sink, and stratospheric reactions. Increasing emissions of methane reduce the concentration of OH, a feedback which may increase methane’s atmospheric lifetime (IPCC 2001).

**Nitrous Oxide (N<sub>2</sub>O).** Anthropogenic sources of N<sub>2</sub>O emissions include agricultural soils, especially the use of synthetic and manure

fertilizers; fossil fuel combustion, especially from mobile combustion; adipic (nylon) and nitric acid production; wastewater treatment and waste combustion; and biomass burning. The atmospheric concentration of nitrous oxide (N<sub>2</sub>O) has increased by 16 percent since 1750, from a pre industrial value of about 270 ppb to 314 ppb in 1998, a concentration that has not been exceeded during the last thousand years. Nitrous oxide is primarily removed from the atmosphere by the photolytic action of sunlight in the stratosphere.

**Ozone (O<sub>3</sub>).** Ozone is present in both the upper stratosphere, where it shields the Earth from harmful levels of ultraviolet radiation, and at lower concentrations in the troposphere, where it is the main component of anthropogenic photochemical “smog.” During the last two decades, emissions of anthropogenic chlorine and bromine-containing halocarbons, such as chlorofluorocarbons (CFCs), have depleted stratospheric ozone concentrations. This loss of ozone in the stratosphere has resulted in negative radiative forcing, representing an indirect effect of anthropogenic emissions of chlorine and bromine compounds (IPCC 1996). The depletion of stratospheric ozone and its radiative forcing was expected to reach a maximum in about 2000 before starting to recover, with detection of such recovery not expected to occur much before 2010 (IPCC 2001).

The past increase in tropospheric ozone, which is also a greenhouse gas, is estimated to provide the third largest increase in direct radiative forcing since the pre-industrial era, behind CO<sub>2</sub> and CH<sub>4</sub>. Tropospheric ozone is produced from complex chemical reactions of volatile organic compounds mixing with nitrogen oxides (NO<sub>x</sub>) in the presence of sunlight. Ozone, carbon monoxide (CO), sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>) and particulate matter are included in the category referred to as “criteria pollutants” in the United States under the Clean Air Act and its subsequent amendments. The tropospheric concentrations of ozone and these

other pollutants are short-lived and, therefore, spatially variable.

**Halocarbons, Perfluorocarbons, and Sulfur Hexafluoride (SF<sub>6</sub>).**

Halocarbons are, for the most part, man-made chemicals that have both direct and indirect radiative forcing effects. Halocarbons that contain chlorine—chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl chloroform, and carbon tetrachloride—and bromine—halons, methyl bromide, and hydrobromofluorocarbons (HBFCs)—result in stratospheric ozone depletion and are therefore controlled under the Montreal Protocol on Substances that Deplete the Ozone Layer. Although CFCs and HCFCs include potent global warming gases, their net radiative forcing effect on the atmosphere is reduced because they cause stratospheric ozone depletion, which is itself an important greenhouse gas in addition to shielding the Earth from harmful levels of ultraviolet radiation. Under the Montreal Protocol, the United States phased out the production and importation of halons by 1994 and of CFCs by 1996. Under the Copenhagen Amendments to the Protocol, a cap was placed on the production and importation of HCFCs by non-Article 5 countries beginning in 1996, and then followed by a complete phase-out by the year 2030. The ozone depleting gases covered under the Montreal Protocol and its Amendments are not covered by the UNFCCC.

Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>) are not ozone depleting substances, and therefore are not covered under the Montreal Protocol. They are, however, powerful greenhouse gases. HFCs—primarily used as replacements for ozone depleting substances but also emitted as a by-product of the HCFC-22 manufacturing process—currently have a small aggregate radiative forcing impact; however, it is anticipated that their contribution to overall radiative forcing will increase (IPCC 2001). PFCs and SF<sub>6</sub> are predominantly emitted from various industrial processes including aluminum

smelting, semiconductor manufacturing, electric power transmission and distribution, and magnesium casting. Currently, the radiative forcing impact of PFCs and SF<sub>6</sub> is also small; however, they have a significant growth rate, extremely long atmospheric lifetimes, and are strong absorbers of infrared radiation, and therefore have the potential to influence climate far into the future (IPCC 2001).

**Carbon Monoxide (CO).** Carbon monoxide has an indirect radiative forcing effect by elevating concentrations of CH<sub>4</sub> and tropospheric ozone through chemical reactions with other atmospheric constituents (e.g., the hydroxyl radical, OH) that would otherwise assist in destroying CH<sub>4</sub> and tropospheric ozone. Carbon monoxide is created when carbon-containing fuels are burned incompletely. Through natural processes in the atmosphere, it is eventually oxidized to CO<sub>2</sub>. Carbon monoxide concentrations are both short-lived in the atmosphere and spatially variable.

**Nitrogen Oxides (NO<sub>x</sub>).** The primary climate change effects of nitrogen oxides (i.e., NO and NO<sub>2</sub>) are indirect and result from their role in promoting the formation of ozone in the troposphere and, to a lesser degree, lower stratosphere, where it has positive radiative forcing effects. Additionally, NO<sub>x</sub> emissions from aircraft are also likely to decrease methane concentrations, thus having a negative radiative forcing effect (IPCC 1999). Nitrogen oxides are created from lightning, soil microbial activity, biomass burning – both natural and anthropogenic fires – fuel combustion, and, in the stratosphere, from the photo-degradation of nitrous oxide (N<sub>2</sub>O). Concentrations of NO<sub>x</sub> are both relatively short-lived in the atmosphere and spatially variable.

**Nonmethane Volatile Organic Compounds (NMVOCs).** Nonmethane volatile organic compounds include compounds such as propane, butane, and ethane. These compounds participate, along with NO<sub>x</sub>, in the formation of tropospheric ozone and other photochemical

oxidants. NMVOCs are emitted primarily from transportation and industrial processes, as well as biomass burning and non-industrial consumption of organic solvents.

Concentrations of NMVOCs tend to be both short-lived in the atmosphere and spatially variable.

**Aerosols.** Aerosols are extremely small particles or liquid droplets found in the atmosphere. They can be produced by natural events such as dust storms and volcanic activity, or by anthropogenic processes such as fuel combustion and biomass burning. They affect radiative forcing in both direct and indirect ways: directly by scattering and absorbing solar and thermal infrared radiation; and indirectly by increasing droplet counts that modify the formation, precipitation efficiency, and radiative properties of clouds. Aerosols are removed from the atmosphere relatively rapidly by precipitation. Because aerosols generally have short atmospheric lifetimes, and have concentrations and compositions that vary regionally, spatially, and temporally, their contributions to radiative forcing are difficult to quantify (IPCC 2001).

The indirect radiative forcing from aerosols are typically divided into two effects. The first effect involves decreased droplet size and increased droplet concentration resulting from an increase in airborne aerosols. The second effect involves an increase in the water content and lifetime of clouds due to the effect of reduced droplet size on precipitation efficiency (IPCC 2001). Recent research has placed a greater focus on the second indirect radiative forcing effect of aerosols.

Various categories of aerosols exist, including naturally produced aerosols such as soil dust, sea salt, biogenic aerosols, sulphates, and volcanic aerosols, and anthropogenically manufactured aerosols such as industrial dust and carbonaceous aerosols (e.g., black carbon, organic carbon) from transportation, coal

combustion, cement manufacturing, waste incineration, and biomass burning.

The net effect of aerosols is believed to produce a negative radiative forcing effect (i.e., net cooling effect on the climate), although because they are short-lived in the atmosphere—lasting days to weeks—their concentrations respond rapidly to changes in emissions. Locally, the negative radiative forcing effects of aerosols can offset the positive forcing of greenhouse gases (IPCC 1996). “However, the aerosol effects do not cancel the global-scale effects of the much longer-lived greenhouse gases, and significant climate changes can still result” (IPCC 1996).

The IPCC’s Third Assessment Report notes that “the indirect radiative effect of aerosols is now understood to also encompass effects on ice and mixed-phase clouds, but the magnitude of any such indirect effect is not known, although it is likely to be positive” (IPCC 2001).

Additionally, current research suggests that another constituent of aerosols, elemental carbon, may have a positive radiative forcing (Jacobson 2001). The primary anthropogenic emission sources of elemental carbon include diesel exhaust, coal combustion, and biomass burning.

### **Global Warming Potentials**

Global Warming Potentials (GWPs) are intended as a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas. It is defined as the cumulative radiative forcing—both direct and indirect effects—integrated over a period of time from the emission of a unit mass of gas relative to some reference gas (IPCC 1996). Carbon dioxide (CO<sub>2</sub>) was chosen as this reference gas. Direct effects occur when the gas itself is a greenhouse gas. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases. The

relationship between gigagrams (Gg) of a gas and Tg CO<sub>2</sub> Eq. can be expressed as follows:

$$\text{Tg CO}_2 \text{ Eq} = (\text{Gg of gas}) \times (\text{GWP}) \times \left( \frac{\text{Tg}}{1,000 \text{ Gg}} \right)$$

where,

Tg CO<sub>2</sub> Eq. = Teragrams of Carbon Dioxide Equivalents  
Gg = Gigagrams (equivalent to a thousand metric tons)  
GWP = Global Warming Potential  
Tg = Teragrams

GWP values allow policy makers to compare the impacts of emissions and reductions of different gases. According to the IPCC, GWPs typically have an uncertainty of roughly ±35 percent, though some GWPs have larger uncertainty than others, especially those in which lifetimes have not yet been ascertained. In the following decision, the parties to the UNFCCC have agreed to use consistent GWPs from the IPCC Second Assessment Report (SAR), based upon a 100 year time horizon, although other time horizon values are available (see Table 2).

*In addition to communicating emissions in units of mass, Parties may choose also to use global warming potentials (GWPs) to reflect their inventories and projections in carbon dioxide-equivalent terms, using information provided by the Intergovernmental Panel on Climate Change (IPCC) in its Second Assessment Report. Any use of GWPs should be based on the effects of the greenhouse gases over a 100-year time horizon. In addition, Parties may also use other time horizons. (FCCC/CP/1996/15/Add.1)*

Greenhouse gases with relatively long atmospheric lifetimes (e.g., CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, HFCs, PFCs, and SF<sub>6</sub>) tend to be evenly distributed throughout the atmosphere, and consequently global average concentrations can be determined. The short-lived gases such as water vapor, carbon monoxide, tropospheric ozone, other ambient air pollutants (e.g., NO<sub>x</sub>, and NMVOCs), and tropospheric aerosols (e.g., SO<sub>2</sub> products and black carbon), however, vary

spatially, and consequently it is difficult to quantify their global radiative forcing impacts. GWP values are generally not attributed to these

gases that are short-lived and spatially inhomogeneous in the atmosphere.

**Table 2: Global Warming Potentials (GWP) and Atmospheric Lifetimes (Years) Used in the Inventory**

Gas	Atmospheric Lifetime	100-year GWP <sup>a</sup>	20-year GWP	500-year GWP
Carbon dioxide (CO <sub>2</sub> )	50-200	1	1	1
Methane (CH <sub>4</sub> ) <sup>b</sup>	12±3	21	56	6.5
Nitrous oxide (N <sub>2</sub> O)	120	310	280	170
HFC-23	264	11,700	9,100	9,800
HFC-125	32.6	2,800	4,600	920
HFC-134a	14.6	1,300	3,400	420
HFC-143a	48.3	3,800	5,000	1,400
HFC-152a	1.5	140	460	42
HFC-227ea	36.5	2,900	4,300	950
HFC-236fa	209	6,300	5,100	4,700
HFC-4310mee	17.1	1,300	3,000	400
CF <sub>4</sub>	50,000	6,500	4,400	10,000
C <sub>2</sub> F <sub>6</sub>	10,000	9,200	6,200	14,000
C <sub>4</sub> F <sub>10</sub>	2,600	7,000	4,800	10,100
C <sub>6</sub> F <sub>14</sub>	3,200	7,400	5,000	10,700
SF <sub>6</sub>	3,200	23,900	16,300	34,900

Source: IPCC (1996)

<sup>a</sup> GWPs used here are calculated over 100 year time horizon

<sup>b</sup> The methane GWP includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO<sub>2</sub> is not included.

Table 3 presents direct and net (i.e., direct and indirect) GWPs for ozone-depleting substances (ODSs). Ozone-depleting substances directly absorb infrared radiation and contribute to positive radiative forcing; however, their effect as ozone-depleters also leads to a negative

radiative forcing because ozone itself is a potent greenhouse gas. There is considerable uncertainty regarding this indirect effect; therefore, a range of net GWPs is provided for ozone depleting substances.

**Table 3: Net 100-year Global Warming Potentials for Select Ozone Depleting Substances\***

Gas	Direct	Net <sub>min</sub>	Net <sub>max</sub>
CFC-11	4,600	(600)	3,600
CFC-12	10,600	7,300	9,900
CFC-113	6,000	2,200	5,200
HCFC-22	1,700	1,400	1,700
HCFC-123	120	20	100
HCFC-124	620	480	590
HCFC-141b	700	(5)	570
HCFC-142b	2,400	1,900	2,300

CHCl <sub>3</sub>	140	(560)	0
CCl <sub>4</sub>	1,800	(3,900)	660
CH <sub>3</sub> Br	5	(2,600)	(500)
Halon-1211	1,300	(24,000)	(3,600)
Halon-1301	6,900	(76,000)	(9,300)

Source: IPCC (2001)

\* Because these compounds have been shown to deplete stratospheric ozone, they are typically referred to as ozone depleting substances (ODSs). However, they are also potent greenhouse gases. Recognizing the harmful effects of these compounds on the ozone layer, in 1987 many governments signed the *Montreal Protocol on Substances that Deplete the Ozone Layer* to limit the production and importation of a number of CFCs and other halogenated compounds. The United States furthered its commitment to phase-out ODSs by signing and ratifying the Copenhagen Amendments to the *Montreal Protocol* in 1992. Under these amendments, the United States committed to ending the production and importation of halons by 1994, and CFCs by 1996. The IPCC Guidelines and the UNFCCC do not include reporting instructions for estimating emissions of ODSs because their use is being phased-out under the *Montreal Protocol*. The effects of these compounds on radiative forcing are not addressed here.

The IPCC recently published its Third Assessment Report (TAR), providing the most current and comprehensive scientific assessment of climate change (IPCC 2001). Within that report, the GWPs of several gases were revised relative to the IPCC's Second Assessment Report (SAR) (IPCC 1996), and new GWPs have been calculated for an expanded set of gases. Since the SAR, the IPCC has applied an improved calculation of CO<sub>2</sub> radiative forcing and an improved CO<sub>2</sub> response function (presented in WMO 1999). The GWPs are drawn from WMO (1999) and the SAR, with updates for those cases where new laboratory or radiative transfer results have been published. Additionally, the atmospheric lifetimes of some gases have been recalculated. Because the revised radiative forcing of CO<sub>2</sub> is about 12 percent lower than that in the SAR, the GWPs of the other gases relative to CO<sub>2</sub> tend to be larger, taking into account revisions in lifetimes. However, there were some instances in which other variables, such as the radiative efficiency or the chemical lifetime, were altered that resulted in further increases or decreases in particular GWP values. In addition, the values for radiative forcing and lifetimes have been calculated for a variety of halocarbons, which were not presented in the SAR. The changes are described in the TAR as follows:

*that are proposed as halocarbon substitutes. Some of the GWPs have larger uncertainties than that of others, particularly for those gases where detailed laboratory data on lifetimes are not yet available. The direct GWPs have been calculated relative to CO<sub>2</sub> using an improved calculation of the CO<sub>2</sub> radiative forcing, the SAR response function for a CO<sub>2</sub> pulse, and new values for the radiative forcing and lifetimes for a number of halocarbons.*

Table 4 compares the lifetimes and GWPs for the SAR and TAR. As can be seen in Table 4, GWPs changed anywhere from a decrease of 15 percent to an increase of 49 percent.

*New categories of gases include fluorinated organic molecules, many of which are ethers*

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## Appendix I. White Paper: 2002 Arizona Reference Case Emissions Inventory for Black Carbon and Organic Material



### White Paper: 2002 Arizona Reference Case Emissions Inventory for Black Carbon and Organic Material

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**WHITE PAPER:****2002 Reference Case Arizona Emissions Inventory for Black Carbon and Organic Material**

This White Paper summarizes the methods, data sources, and results of an estimate of 2002 emissions for black carbon (BC) and organic material (OM) in Arizona. To develop this inventory, we relied on several different data sources. Where possible and within the time-frame available, we used emissions data from the Western Regional Air Partnership (WRAP) to achieve consistency with the regional haze inventory developed for the western States. Data were taken from the following sources:

- Particulate matter (PM) speciation data from EPA's SPECIATE database: these data include aerosol fractions of elemental carbon (aka black carbon) and primary organic aerosols (POA; aka organic material or OM). Our starting point was the speciation data currently being used for regional haze modeling by the Carolina Environmental Program (Vukovich, 2004). Most of these data come from EPA's current SPECIATE3.2 database. We augmented these data with new profiles developed under our ongoing EPA project to update SPECIATE. Note that these new profiles have not yet been released by EPA.
- WRAP's Emissions Data Management System (EDMS): we obtained emissions data for Arizona directly from EDMS for all sources, except wildfires and prescribed burns. We used the particulate matter (PM) emission estimates for AZ from EDMS as one of the primary starting points in this analysis. According to ADEQ, these data represent the best available emissions data compiled for the State. Note that although EDMS was designed to house BC and organic carbon<sup>61</sup> (OC) emission estimates and that WRAP has developed BC and OC estimates for some source sectors, no BC/OC estimates are currently available for AZ in EDMS.

For the mobile source sector, WRAP developed BC and OC estimates (Environ et al, 2004); however, EDMS indicates that the AZ mobile source data are from EPA's 2002 National Emissions Inventory (NEI). This means that nonroad and onroad Maricopa County data are included, as well as onroad Pima County data (for criteria pollutants). For the rest of the State, EPA populated the data using the National Mobile Inventory Model (NMIM). NMIM uses top-down methods and data sources and the EPA models MOBILE6 and NONROAD 2004 to estimate emissions.

We reviewed the documentation on how the WRAP mobile source inventory was speciated to derive BC and OC. In most cases, the speciation profiles we used are comparable to those used in the WRAP work as shown below. There are fairly significant differences shown for brake and tire wear. The WRAP fractions for tire wear are based on the original SPECIATE PM profile (circa 1988). Our profile is based on recent data from CARB that will be contained in the latest SPECIATE version. This profile is supported by a study of car tires

<sup>61</sup> Note that OC is a measurement of carbon mass only for the organic material. Other functional groups associated with OM contain atoms of oxygen, nitrogen, hydrogen, and other compounds. Jacobson (2002) used a factor of 1.3 to convert between OC and OM. This compares to a factor of 1.2 used by EPA for its POA estimates (PES, 2003). For this analysis, we assumed POA is equivalent to OM as defined by Jacobson.

showing that carbon black makes up 25-35% of tire rubber (Wik and Dave, 2005). The brake wear profile is also based on new CARB profile data. Instead of using the same BC/OC data for nonroad gasoline exhaust and onroad gasoline exhaust (as was done in the WRAP work), we used an existing SPECIATE profile, which is similar to pre-1991 onroad vehicles. We believe that this profile better represents nonroad gasoline engine emissions (e.g. primarily non-catalyzed and less combustion efficient than newer onroad engines). Secondly, although we do not have speciation data for 2-stroke engines, we expect the OC fractions to be much higher than in onroad gasoline vehicles (thus, the selected profile is a better fit).

Sector	Subsector	WRAP		This Study	
		Weight Fraction <sup>a</sup>			
		BC	OC	BC	OC
Onroad Gasoline	Exhaust	0.239	0.518	0.169	0.597
	Tire Wear	0.609	0.2175	0.22	0.472
	Brake Wear	0.028	0.972	0.0261	0.107
Onroad Diesel	Light Duty Exhaust	0.613	0.303	0.613	0.303
	Heavy Duty Exhaust	0.75	0.189	0.75	0.189
	Tire Wear	0.609	0.2175	0.22	0.472
	Brake Wear	0.028	0.972	0.0261	0.107
Nonroad Gasoline		0.239	0.518	0.0801	0.655
Nonroad Diesel		0.75	0.189	0.7411	0.187

<sup>a</sup> Note that the weight fractions do not add to one, since other aerosol species (not shown) also make up the PM profile – e.g. sulfates, nitrates, metals, etc.

Except for wildfires/prescribed burns, we are not aware of any BC/OC emission estimates from the WRAP (or elsewhere) covering the rest of the stationary source sector (e.g. Pechan developed much of the WRAP's point source inventory data; however we did not provide BC/OC estimates as part of that work).

- For wildfires and prescribed burns: we used State-level particulate matter less than 2.5 microns (PM<sub>2.5</sub>) emissions from the WRAP's draft 2002 inventory (Air Sciences, 2004). We then speciated the BC and POA from the PM<sub>2.5</sub>, using new speciation data from our ongoing SPECIATE update project for EPA. As shown below, these aerosol fractions are nearly identical to those used to develop the WRAP inventory. Note that we could not develop BC/OC estimates directly from the WRAP documentation, since the prescribed burn and wildfire emissions were not broken out separately. For the same reason, we could not use the WRAP BC/OC fractions in this study; however as shown below, the values we used are very similar.

WRAP Draft 2002 Inventory				This Study	
Prescribed Fire – Piled Fuels		Prescribed/Wildfires – Non-Piled Fuels		Prescribed Fires and Wildfires	
Weight Fraction					
BC	OC	BC	OC	BC	OC
0.072	0.54	0.062	0.48	0.075	0.532

### *Development of BC and OM Mass Emission Estimates*

In order to convert the BC/POA estimates into CO<sub>2</sub> equivalents, we first assumed that the POA estimate is a reasonable estimate for OM. The BC and POA (OM) mass emission estimates were derived by multiplying the PM<sub>10</sub> emission estimates by the appropriate aerosol fraction. After some additional consideration of this approach, we decided that, for certain sources, particulate matter less than 2.5 microns (PM<sub>2.5</sub>) emission estimates would be a better starting point for BC and OM emissions. The source categories where PM<sub>2.5</sub> estimates were favored over PM<sub>10</sub> estimates are those associated with fugitive dust emissions. These categories include agricultural tilling, paved and unpaved road dust, and construction activities. These categories tend to have a large amount of coarse mass (particles with mass between PM<sub>10</sub> and PM<sub>2.5</sub>). Much of this coarse mass is not transported far from the source.

After estimating both BC and OM emissions for each source category, we summed these two aerosol species into a BC+OM estimate. We then collapsed the inventory down to the sector level to be consistent with the gaseous portion of AZ's greenhouse gas (GHG) inventory. The mass emission results are shown in Table 1 below.

### *Development of CO<sub>2e</sub> for BC+OM Emissions*

We used similar methods to those applied in the northeast for converting BC mass emissions to CO<sub>2</sub> equivalents (ENE, 2004). These methods are based on the modeling of Jacobson (2002) and his updates to this work (Jacobson, 2005a). Jacobson (2005) estimated a range of 90:1 to 190:1 for the climate response effects of BC+OM emissions as compared to CO<sub>2</sub> carbon emissions (depending on either a 30-year or 95-year atmospheric lifetime for CO<sub>2</sub>). It is important to note that the BC+OM emissions used by Jacobson were based on a 2:1 ratio of OM:BC (his work in these papers focused on fossil fuel BC+OM).

For Maine and Connecticut, ENE (2004) applied climate response factors from the earlier Jacobson work (220 and 500) to the estimated BC mass to estimate the range of CO<sub>2e</sub> associated with BC emissions. Note that the analysis in the northeast was limited to BC emissions from onroad diesel exhaust. An important oversight from this work is that the climate response factors developed by Jacobson (2002, 2005a) are on the basis of CO<sub>2</sub> carbon (not CO<sub>2</sub>). Therefore, in order to express the BC emissions as CO<sub>2e</sub>, the climate response factors should have been adjusted upward by a factor of 3.67 to account for the molecular weight of CO<sub>2</sub> to carbon (44/12).

For this inventory, we started with the 90 and 190 climate response factors adjusted to 330 and 697 to obtain a low and high estimate of CO<sub>2e</sub> for each sector. An example calculation of the CO<sub>2e</sub> emissions for 10 tons of PM<sub>10</sub> from onroad diesel exhaust follows:

$$\text{BC mass} = (10 \text{ tons PM}_{10}) \times (0.613 \text{ ton EC/ton PM}_{10}) = 6.13 \text{ short tons BC}$$

$$\text{Low estimate CO}_{2e} = (6.13 \text{ tons BC}) (330 \text{ tons CO}_{2e}/\text{ton BC+OM}) (3 \text{ tons BC+OM/ton BC}) (0.907 \text{ metric ton/ton}) = 5,504 \text{ metric tons CO}_{2e}$$

$$\text{High estimate CO}_{2e} = (6.13 \text{ tons BC}) (697 \text{ tons CO}_{2e}/\text{ton BC+OM}) (3 \text{ tons BC+OM/ton BC}) (0.907 \text{ metric ton/ton}) = 11,626 \text{ metric tons CO}_{2e}$$

The factor 3 tons BC+OM/ton BC comes directly from the modeling assumptions used by Jacobson (2002, 2005a; i.e. 2 tons of OM/ton of BC).

For source categories that had an OM:BC mass emission ratio >4.0, we zeroed out these emission estimates from the CO<sub>2e</sub> estimates. The reason for this is that the net heating effects of OM are not currently well understood. Therefore, for source categories where the PM is dominated by OM (e.g. biomass burning), the net climate response associated with these emissions is highly uncertain. Further, OM:BC ratios of 4 or more are well beyond the 2:1 ratio used by Jacobson in his work.

### *Results, Conclusions and Next Steps*

We estimate that BC mass emissions in AZ total 12,370 tons in 2002 (see Table 1). The CO<sub>2e</sub> emissions range from about 2.8 to 6.0 million metric tons. These estimates are approximately 3 to 6 percent of the entire CO<sub>2e</sub> estimated for the gaseous GHG inventory. Wildfires and prescribed burns contributed nearly 68% of the BC mass emissions; however they were removed from the CO<sub>2e</sub> estimates due to the high OM to BC ratio (about 7:1). Emissions for residential wood combustion and open burning, two more important biomass combustion sectors, were also left out of the CO<sub>2e</sub> estimates for the same reason.

By far, the highest contributions to CO<sub>2e</sub> are from the onroad diesel sector at 59% (this includes exhaust, plus brake and tired wear). Nonroad diesel engines contribute 18% of the CO<sub>2e</sub> emissions. Construction diesel engines contributed nearly 60% of the CO<sub>2e</sub> for the nonroad diesel engines sector. The “nonroad other” sector contributes about another 11% of the CO<sub>2e</sub>. This sector is dominated by railroad engines. Onroad gasoline vehicles contribute another 3%, however these emissions are strictly related to tire wear (the OM:BC ratios for exhaust and brake wear are both >4). Coal-fired electricity generating units (EGUs) contribute 6% of the CO<sub>2e</sub>.

If directed to do so by the AZ Climate Change Advisory Group, our next steps will be to develop projection year estimates. We suggest focusing on just the primary CO<sub>2e</sub> contributors (e.g. onroad diesel and the nonroad diesel sectors). Forecast inventories from the Western Regional Air Partnership (WRAP) process could be used and are recommended in order to maintain consistency with the regional haze program. To represent 2010 conditions, the WRAP 2008 forecast year would provide the best estimates. For 2020, the WRAP 2018 forecast is the best surrogate.

While the state of science in aerosol climate forcing is still developing, there is a good body of evidence supporting the net warming impacts of black carbon. Aerosols have a *direct* radiative forcing because they scatter and absorb solar and infrared radiation in the atmosphere. Aerosols also alter the formation and precipitation efficiency of liquid water, ice and mixed-phase clouds, thereby causing an *indirect* radiative forcing associated with these changes in cloud properties (IPCC, 2001). There are also a number of other indirect radiative effects that have been modeled (e.g. Jacobson, 2002).

The quantification of aerosol radiative forcing is more complex than the quantification of radiative forcing by greenhouse gases because the direct and indirect radiative forcing, and the fact that aerosol mass and particle number concentrations are highly variable in space and time. This variability is largely due to the much shorter atmospheric lifetime of aerosols compared with the important greenhouse gases. Spatially and temporally resolved information on the atmospheric burden and radiative properties of aerosols is needed to estimate radiative forcing.

The quantification of indirect radiative forcing by aerosols is especially difficult. In addition to the variability in aerosol concentrations, some quite complicated aerosol influences on cloud processes must be accurately modeled. For example, the warm (liquid water) cloud indirect forcing may be divided into two components. The first indirect forcing is associated with the change in droplet concentration caused by increases in aerosol cloud condensation nuclei. The second indirect forcing is associated with the change in precipitation efficiency that results from a change in droplet number concentration. Quantification of the latter forcing necessitates understanding of a change in cloud liquid-water content and cloud amount. In addition to warm clouds, ice clouds may also be affected by aerosols.

To put the radiative forcing potential of BC in context with CO<sub>2</sub>, the Intergovernmental Panel on Climate Change estimated the radiative forcing for a doubling of the earth's CO<sub>2</sub> concentration to be 3.7 watts per square meter (W/m<sup>2</sup>). For BC, various estimates of current radiative forcing have ranged from 0.16 to 0.42 W/m<sup>2</sup> (IPCC, 2001). These BC estimates are for direct radiative effects only. There is a higher level of uncertainty associated with the direct radiative forcing estimates of BC compared to those of CO<sub>2</sub> and other GHGs. There are even higher uncertainties associated with the assessment of the indirect radiative forcing of aerosols.

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**Table 1. BC+OM Emissions Summary**

Sector	Subsector	Mass Emissions				CO <sub>2e</sub>		
		BC Short Tons	POA Metric Tons	BC Metric Tons	POA Metric Tons	BC + OM	Low Metric Tons	High Metric Tons
Electric Generating Units (EGUs)	Coal	193	275	175	250	425	173,028	365,456
	Oil	1.1	0.4	1.0	0.33	1.3	994	2,100
	Gas <sup>a</sup>	0	94	0	86	86	0	0
Non-EGU Fuel Combustion (Residential, Commercial, and Industrial)	Coal	5.7	8.2	5.2	7.5	13	5,161	10,900
	Oil	22	11	20	9.5	29	19,691	41,589
	Gas	0.03	241	0.03	218	218	0	0
	Other <sup>b</sup>	237	1,161	215	1,054	1,269	1,985	4,193
Onroad Gasoline (Exhaust, Brake Wear, & Tire Wear)		192	737	174	669	843	82,966 <sup>c</sup>	175,235 <sup>c</sup>
Onroad Diesel (Exhaust, Brake Wear, & Tire Wear)		1,864	728	1,692	661	2,353	1,671,922	3,531,302
Aircraft <sup>d</sup>		50	28	45	25	70	44,589	94,177
Other Energy Use	Nonroad Gasoline	52	560	47	508	555	0	0
	Nonroad Diesel	579	193	526	175	701	520,169	1,098,660
	Nonroad Other <sup>e</sup>	338	106	307	96	403	303,511	641,160
	Other Combustion <sup>f</sup>	8.7	72	7.9	65	73	237	500
Industrial Processes <sup>g</sup>		42	606	38	550	588	326	690
Agriculture <sup>h</sup>		27	1,362	25	1,236	1,261	0	0
Waste Management	Landfills	0.12	7.3	0.11	6.6	7	0	0
	Incineration <sup>i</sup>	5.3	9.8	4.8	8.9	14	4,741	10,015
	Open Burning <sup>j</sup>	260	3,039	236.28	2,758.88	2,995	0	0
Wildfires/Prescribed Burns <sup>k</sup>		8,400	71,501	7,626	64,909	72,534	0	0
Miscellaneous <sup>l</sup>		94	1,446	85	1,312	1,398	86	182
<b>Totals</b>		<b>12,370</b>	<b>82,183</b>	<b>11,230</b>	<b>74,606</b>	<b>85,835</b>	<b>2,829,406</b>	<b>5,976,157</b>

NOTE: CO<sub>2e</sub> is zeroed out for sources with OM:BC ratio >4.0 (see text).

<sup>a</sup> The SPECIATE3.2 PM profile showed zero for PEC (BC). A review of other in-house data showed that BC is present in PM emissions from natural gas combustion at a OM:BC ratio of around 1:1. This ratio was used to calculate BC+OM and the associated CO<sub>2e</sub> emissions.

<sup>b</sup> Most of these emissions are from residential wood combustion.

<sup>c</sup> The CO<sub>2e</sub> estimates are associated with tire wear only, since the exhaust and brake wear components have OM:BC ratios >4:1.

<sup>d</sup> Note for aircraft, criteria pollutant emissions are only estimated for the boundary (mixing) layer (i.e., mainly landing and take-off cycle emissions). Therefore, these estimates do not include emissions occurring above the mixing layer but within AZ airspace.

<sup>e</sup> Nearly all emissions are from the railroad source categories.

<sup>f</sup> About 60% of emissions are from vehicle fires. Other contributors include structure fires and aircraft/rocket engine firing and testing.

<sup>g</sup> In this summary, construction is included in the Industrial Processes sector. Construction source categories (industrial/commercial/institutional, residential, road, and other) are the major contributors (96%) of the Industrial Processes emissions.

<sup>h</sup> The Agriculture sector includes food industries. 80% of the BC emissions come from agricultural tilling. Agricultural tilling and commercial cooking each contribute about 43% of the POA emissions.

<sup>i</sup> About 97% of BC and POA emissions come from commercial/institutional incineration.

<sup>j</sup> Open burning of land clearing debris contributes about 68% of BC/POA emissions. Other contributors include open burning of yard waste and household waste.

<sup>k</sup> Wildfire/Prescribed burn emissions were excluded from the CO<sub>2e</sub> estimates due to the much higher OM to BC ratio (about 7:1).

<sup>l</sup> Paved and unpaved road dust are significant contributors to the EC and OC emissions.