PROJECTING ANTHROPOGENIC METHANE EMISSIONS AND POTENTIAL REDUCTION STRATEGIES OF SIX SOURCES IN SIX NATIONS

by

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Abstract

Methane concentrations in our atmosphere have more than doubled since pre-industrial times. Although the rate of change of global concentrations has recently slowed, studies predict that this stabilization will be short-lived. There is a growing need to better understand the emissions sources for this potent greenhouse gas and to assess possible reduction strategies. Global methane emissions pathways have been proposed by the IPCC but the relative contributions from different source types and individual countries is not well determined. I analyze six main anthropogenic sources including emissions from enteric fermentation, rice production, landfills, wastewater treatment, coal mining, and natural gas and oil production. Future changes in the main drivers of population, economic, and technological parameters can impact methane emissions from these six sources in Brazil, China, India, Mexico, Russia, and the United States through 2050. I develop a simple framework to characterize and project methane emissions enabling the building of a business as usual and multiple alternative scenarios. The methane concentration implications of these projections are analyzed using a simple climate model. Finally, a technological potential reduction scenario is proposed by maintaining baseline assumptions while improving methane capture technologies and options. Under business as usual assumptions, global anthropogenic methane emissions are projected to double by 2030 but there is potential to cause a global decrease by 40 % per year of projected baseline levels which would reduce global temperature changes by 0.5 degrees Celsius by 2100.

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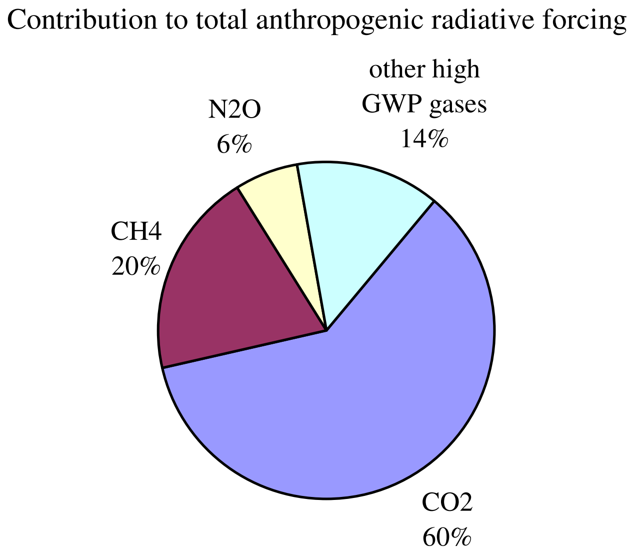
Introduction

It has been documented that global concentrations of methane have doubled since pre-Industrial times (Dlugokencky, 1994). In 2005, the globally averaged concentration of methane was recorded to be 1774 ppbv (IPCC, FAR 2007).

According to the Intergovernmental Panel on Climate Change (IPCC), the significance of global methane concentrations in terms of its radiative forcing potential is 3rd after CO_2 and water vapor (IPCC, 2006). This is largely due to the fact that methane is more effective at absorbing outgoing longwave radiation on a per molecule basis than CO_2 (Wuebbles, 2002). Therefore, even though the overall concentration of CH_4 is much lower than that of CO_2, it is very effective at aiding the greenhouse effect associated with global warming. However, the atmospheric lifetime or residence time of methane is substantially shorter than CO_2 at only 8-12 years but has a Global Warming Potential (GWP) of 21 meaning that one methane molecule released into the atmosphere will effectively absorb an amount of the outgoing longwave energy equal to that of 21 CO_2 molecules (IPCC, 2001).

Radiative forcing is defined as the change in net solar irradiance (solar plus long-wave) measured in W/m^2 produced due to the presence of certain gases in the atmosphere. The IPCC estimates that between 1750 and 2005, increases in methane concentration, largely caused by human activities, have caused roughly 20 % of the increased change in radiative forcing. In other words, 20 % of the extra-trapped outgoing radiation is due to the presence of increased methane concentration which has led to overall global warming. Although this accounts for the direct effects of methane, some indirect effects include the impact that methane has on ozone (also a GHG) and CO_2 which effectively could increase this forcing estimate by 10-35 %. Even though the overall concentration of methane is orders of magnitude lower than that of CO_2, measured in parts per billion as opposed to parts per million, the effect on the climate on a per molecule basis makes methane a "potent" greenhouse gas (Figure 1).

Figure 1 – Methane contribution to total radiative forcing



The importance of methane as a global greenhouse gas (GHG) and the need for a better understanding of the sources and potential emissions reduction options cannot be overstated. In light of the present policy of GHG reduction in Europe as well as the inevitable policies in the United States warrants study on the sources and future emissions scenarios of CH_4 in a county-specific and global context.

There are few existing projections of methane emissions on an individual country-specific and source-specific basis. The IPCC documents projections per country out to 2100 in its Special Report on Emissions Scenarios (SRES) but the assumptions inherent in their analysis are fixed and key drivers are imbedded. Also, these analyses are highly detailed and involve complicated models to forecast emissions and cover a wide range of pathways to highlight the uncertainty in emissions projections through time. The IPCC further declares that future work on emissions scenarios should include (1) "capacity building, particularly in developing countries, in the area of modeling tools and emissions scenarios" (2) "multiple storyline, multi-model approaches in future scenario analyses" (3) new research activities to assess future developments in key GHG driving forces in greater regional, sub-regional, and sectoral detail which allow for a clearer link between emissions scenarios and mitigation options" (SRES, IPCC, 2001).

In order to better understand some of the key drivers of anthropogenic methane emissions I use a simple framework that characterizes emissions as a function of population, economic status, and methane intensity. In this way, alterations to any one of these parameters can be made allowing for scenario building. The building of this model allows for sensitivity analysis, which will shed insight into how emissions profiles will change based on varying each of the variables independently. With this tool, one can develop multiple storylines for methane emissions pathways while observing key driving forces.

I used a basic identity known as IPAT, which decomposes the impact, methane emissions, into the product of four factors. These are population size, affluence (GDP/capita) and a technology term, which is an "intensity" measure. In other words, the relative economic importance of the producing source per dollar GDP times the methane intensity of that producing source.

Here, the assumption is that emissions will scale linearly with increases in population and GDP/capita. Historically, total anthropogenic methane emissions have correlated linearly with increases in GDP and human population (Kaufman, 1994; Khalil, 1987; EPA, 2006). This framework is simple because it provides a macro scale view to the key drivers of methane emissions. It is transparent because my projections are based on the product of population, affluence, and technology parameters. Finally, it is interactive because one can create alternate scenarios based on technology alterations.

After characterizing methane emissions per country through 2050, I use the framework tool to generate emissions scenarios. These are fed into a simple climate model called MAGICC that describes the resulting climate implications in terms of concentrations, temperature and sea-level rise associated with the emissions pathway. Therefore, this analysis has a "cradle-to-grave" scope in that one can obtain emissions pathways by altering the main drivers and observe the resulting impacts on climate from these changes alone or in concert with other emissions reductions.

This paper addresses the following questions:

- What are the main sources of anthropogenic methane emissions in terms of nations and processes?
- How are these emissions sources projected to change in the future in the context of population, economic and technological drivers?
- What are the climate impacts of the projected methane emissions in a global context in terms of future methane concentration levels and temperature changes?
- What policy and technological recommendations can be obtained by this analysis?

Materials and Methods

Building upon the foundation laid by Paul Ehrlich and Holdren in the 1970's, the IPAT identity has been used to assess and project carbon dioxide emissions for six countries from 1995 through 2100 (Brundage, 2006). This equation is representative of the demographic and technological variables whose interaction results in environmental impact, namely CO_2 emissions (Chertow, 2001). The variables that comprise the equation include population, affluence, and technology.

$$\mathbf{I = P * A * T}$$
$$\textbf{Impact = Population * Affluence * Technology}$$
$$\mathbf{CO_2\ Emissions = \{Population\} * \{\$GDP/capita\} * [\{Service/\$GDP\} * \{CO_2/Service\}]}$$

Implicit in this framework the basic drivers for future emissions include population growth, economic growth, and the technological aspects of a particular emissions source reflected in the amount of emissions per GDP. According to the Department of Energy, the "common drivers of future emissions include human population growth, GDP per capita, and energy production and consumption" (Annual Energy Outlook, DOE, 2001).

The six countries that are analyzed and characterized in depth include Brazil, China, India, Mexico, Russia, and the United States. The main motivation for the selection of these six countries is the fact that since the beginning of the Industrial Revolution, these countries were responsible for about half of global CO_2 emissions (Marland, 2006). Also, these nations include a mixture of developing nations (China and India), emerging economies (Mexico and Brazil) and developed nations (United States and Russia). Furthermore, these six countries are projected to continue their collective CO_2 emissions majority through at least 2050 (EIA 2006).

Having built a spreadsheet model for CO_2, the model provides a framework to assess and project methane (CH_4) emissions from the same six countries. I can redefine this IPAT framework as follows:

I = P * A * T

Impact = Population * Affluence * Technology

CH_4 Emissions = {Population} * {$GDP/capita} * [{Source/$GDP} * {CH_4/Source}]

Here, “service” is replaced with “source” since the analyzed anthropogenic sources of methane will be modeled based on their respective process. These parameters will change over time and thus I obtain evolving profiles for each parameter and ultimately for anthropogenic CH_4 emissions. Assumptions concerning population and economic growth, as well as technological changes provide projections for methane emissions.

Historically, methane emissions from anthropogenic sources have correlated with increases in population and economic wealth as measured by Gross Domestic Product (GDP) (Wuebbles, 2002). There is generally agreement between the increase in global population and the increase in agricultural emissions in the past (Khalil, 1994).

Inherent in this analysis is the lack of integration and feedback between the four variables. In other words, an integrated assessment is not performed or analyzed here. There is no internal dynamics in this model. Rather, using this framework the relative importance of each of these factors can be assessed by independently varying assumptions about their trajectory. I use this framework to project methane emissions from initial values and rates of change of each our four parameters and thus demonstrate the sensitivity of CH_4 emissions per source and country to assumptions about changes in population, economic growth, and specifically, methane intensity of a producing anthropogenic source.

I develop source-specific and country-specific assessments and projections for methane emissions as well as use the model assessment to create recommendations for reductions. I therefore create scenarios for emissions pathways from the six sources labeled “business as usual” (BAU) and “technological potential” (TP) methane reduction scenarios. After I have created these emissions scenarios I observe and calculate the resulting global concentration using a simple climate model. This analysis would be driven purely by technological and/or policy capabilities. There is no quantitative consideration of costs although some technological recommendations are cost-effective simply because they act to increase productivity and efficiency.

I will analyze the six sources described above which comprise the three main sectors of the economy (Table 1):

Table 1 – Analyzed Methane Sources

MAIN SECTOR	AGRICULTURE	ENERGY	WASTE
Sources	***Rice Production***	***Coal production***	***Landfills***
	Enteric Fermentation	***Natural Gas and Oil production***	***Wastewater systems***

For emissions benchmarking and comparisons, I will rely on two emissions databases that have broken down methane emissions based on country and source since 1990. These are the Emissions Database for Global Atmospheric Research (EDGAR) jointly developed by the National Institute for Public Health (RIVM) and the Netherlands Organization for Applied Scientific Research (TNO) and stores global emission inventories of direct and indirect greenhouse gases from anthropogenic sources. Also, the Environmental Protection Agency (EPA) created a database that projects emissions per country and source through 2020 in its document “Global Anthropogenic Non-CO_2

Greenhouse Gas Emissions: 1990-2020" (EPA, 2006). Both of these datasets use the IPCC Guidelines for National Greenhouse Gas Inventories as their bottom-up methodology to characterize methane emissions from all known anthropogenic sources (IPCC, 2006).

Methodologies to determine emissions

Each parameter of the IPAT identity is outlined below. The Technology parameter based on the source is further divided into its dependent components. For this analysis, I assume that the baseline projections for population and affluence are not changed. Thus, the different emissions pathways reflect changes to the technology parameter for each source, which is described in detail below.

Population

Data regarding historical population for the six countries was obtained from the World Bank for the years 1960 through 2004 inclusive (World Bank 2006). After 2004, population per country and year is projected using the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (UN 2003). The projections have three modes labeled "high", "medium", and "low". These modes reflect the different scenarios that the UN envisions as possible population growth levels in the future and are given in five-year increments starting in 2005. To fill in the missing years, I use a linear series fill function so that the population projections are yearly values. The base case for the calculation of total CH_4 emissions per country and year utilizes the "medium" population projection.

Affluence

The affluence parameter is measured by the GDP per capita on a country specific level per year. Since I am comparing six countries with very different economies and consumption levels I use the respective GDP measured in purchasing power parity (PPP) terms. The World Bank describes PPP, GDP as the "gross domestic product converted to international dollars using purchasing power parity rates. An international dollar has the same purchasing power over GDP as the U.S. dollar has in the United States. GDP at purchaser's prices is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products" (WDI 2006). According to the CIA World Factbook, "the data derived from the PPP method probably provides the best available starting point for comparisons of economic strength and well-being between countries" (CIA, 2006). Thus, to accurately reflect societal consumption based on GDP, it is important to utilize PPP as a more comparable measure between countries. The historical GDP, PPP per capita is obtained through the World Bank between the years 1975-2004 inclusive. All values are quoted in International 2000$.

The projections into the future are obtained from a Goldman Sachs report (Wilson and Purushothaman 2003) that models GDP/capita though 2050 for all of the six countries except for Mexico. Also, for the short-term GDP/capita projections, a USDA report that projects per capita GDP for all six countries to 2016 was used (USDA, 2007). The Goldman Sachs projections are recorded in five-year increments and thus I used a linear fill function to extrapolate these values and fill in missing years. The GDP/capita projections are originally in US $ 2003 which was converted to US $ 2000 using the GDP deflator, which describes the deflation rate of -5.5%. Finally, these projections were converted into International 2000$ by calculating the historical average exchange rate GDP to GDP, PPP values and projecting the conversion rates into the future (WDI 2006). History shows that PPP exchange rates and market exchange rates converge as economies develop (Wilson and Purushothaman 2003); I assumed that all countries in our model would linearly converge in the year 2100.

Mexico was not included in the Goldman Sachs paper and thus I obtained the GDP/capita value from the CIA World Factbook for the year 2005 and converted this into International 2000$ using the same conversion method (WDI 2006). The projected values were obtained by increasing the 2005 GDP/capita value by 3.3 % per year. This growth rate is quoted by the EIA: Country Overview - Mexico (EIA 2006).

The baseline for this framework assumes the GDP/capita projections in International 2000$ that are converted as described above. I have calculated GDP/capita growth rates per country and year through 2050 by taking the percentage change from the previous year and recording this value. Mexico is the exception in that the GDP/capita growth rate is assumed to be 3.3 % per year through 2050. All other countries have various GDP/capita growth rates that fluctuate slightly per year but are pretty stable throughout the projection period.

ENERGY SECTOR

Here I use the IPAT framework which comprises the main drivers namely population and economic growth along with a methane intensity parameter affecting the use of coal, oil and natural gas production. The two Energy Sector sources include coal mining and natural gas and oil production which have fugitive methane emissions associated with these processes. Again, in this analysis, the emissions scenarios maintain the medium growth rate for population and GDP/capita and only the technology parameter is altered.

Coal Mining

Methane is released to the atmosphere during the mining and production of coal since this gas is trapped between coal layers during its formation. Coal mining activities comprise three levels: underground mining, surface mining, and post-mining or coal-crushing. In terms of methane emissions, the majority comes from the mining of coal from deep underground mines. Although there has been a shift to surface mining recently in the United States, the prospects of deeper underground mining, especially in China, would lead to increased fugitive methane emissions (EPA, 2006). It is important to note that abandoned mines also continually contribute a small amount of methane to the atmosphere. However, using this framework, they are not accounted for since I am concerned with emissions stemming from current and future coal production.

The basic method for characterizing methane emissions from coal production is to obtain coal production data per country and multiply by a default or country specific emission factor. The coal production data contains country-specific historical data from 1995-2004. The coal production values are taken from the EIA and converted to million metric tons.

This takes into account the amount of methane released per volume of coal produced in a coal mine. To account for the different amount of methane released dependent on the coal mine depth, a default fraction of the overall production is included in the calculation indicating surface mine coal production or underground mine coal production. Finally, since a small portion of methane emissions comes from post-mining operations including the crushing and handling of coal, another emission factor fraction accounts for post-mining activities (IPCC, 1996). The Emission Factor that I use is derived from the EPA and EDGAR reports by dividing the total CH_4 from historical coal production processes by total coal production statistics from EIA. Within the IPAT model I therefore have:

Population x (GDP/capita) x (coal production/GDP) x (CH_4/coal production)

→ CH_4 from coal mining

Projections for Business As Usual Scenario

The availability of coal production data on a national basis is very scarce if not non-existent (IEA, 2003). Therefore, as a proxy to project coal production per country, I can use projections of coal demand or consumption and apply the projected growth rates to productive capacity. I rely on the EIA’s International Energy Outlook and use regional or country-specific growth rates of projected coal consumption and apply this to production.

In North America, the consumption of coal grows about 20 % from 2003 values in 2015 and 60 % of 2003 values by 2030. This is essentially a linear growth that is expected to continue out through 2050 as the United States and Mexico are largely dependent on coal as a feedstock for electricity generation and thus will grow to meet future demand (EIA, 2006).

The majority (~70%) of the global increased coal consumption comes from China and India (EIA, 2006). For China, the relationship of coal production over time as of the early 2000's is looking more exponential. This is due to the extreme growth in energy use in China and thus a linear projection in the short term may actually underestimate actual production values. Therefore, I can utilize projections from the DOE that state that by 2015, Chinese coal production will top 4000 Mtce (DOE, 1996). This is consistent with the projection that the demand for coal consumption will triple that of current consumption by 2030 (EIA, 2006). Post 2030 and out to 2050, we can continue the projected exponential trend via extrapolation of the curve.

For India, the projected coal production is also expected to increase drastically in the short-term with reports stating that the production will double by 2010 (IndiaSTAT, 2006). According to the EIA's International Energy Outlook 2006, a more realistic figure for coal production in India states that its consumption will likely double the 2003 value by 2030. In keeping with this projection, we extrapolate this exponential trend out to 2050. This projection indicates that by 2020, India will surpass the United States in coal production. The IEO 2006 projects that Russia's coal consumption will grow by about 50 % of 2003 levels by 2030 and therefore we can project the productive capacity to grow at this rate. The projections out to 2050 are simple extrapolations of this trend. Although coal consumption in Brazil is expected to grow substantially in the next 30 years, by as much as 20 million metric tons, it relies mostly on imported coal to meet its demand. Therefore, as a small player compared to the other nations, I linearly extrapolate historic trends to dictate the coal production from Brazil out to 2050.

The business as usual (BAU) projections for coal production is divided by the country-specific GDP values per year to obtain the coal production/GDP term within the IPAT equation. This term indicates what contribution coal production plays within the context of the economy. Nations such as India and China that are rapidly producing coal to meet rising demand have an increasing coal/GDP term whereas nations such as Mexico, Brazil and Russia whose dependence on coal is stable or decreasing will see a decline in the coal/GDP term over time.

To project the technology efficiency factor of the amount of methane released per ton of coal produced, we note that there is a very large discrepancy between the EPA and EDGAR estimates of methane emissions coming from the coal production sector. Both data sets incorporate coalbed methane capture and recovery as well as the inclusion of both underground and surface mines. However, EPA does not include emissions from abandoned coal mines. For the United States, a separate document was prepared in which estimates for the US from abandoned coal mines was estimated. These values are typically small compared to the overall surface plus underground coal emissions and for the year 2000 was estimated at ~300 Gg, which was 10 % of the overall CH_4 emissions from coal mining. For EDGAR, the year 2000 documents estimates of ~ 10,000 Gg from coal mining operations in the United States. A much higher emission factor is documented to have been used for the EDGAR estimates. This is probably due to the fact that the EDGAR database lists total methane emissions from coal operations which include the methane recovery rates. However, EPA subtracts the methane recovery from their estimates of coal production emissions giving only the estimated amount released to the atmosphere.

To be consistent and conservative, I take the EPA 1995 and 2000 estimates of methane released per unit coal produced. This parameter remains constant at this averaged level throughout the projection period for the business as usual projections (Table 2). However, this technological parameter has the potential to be altered in future scenario planning to reflect methane capture from coal production.

Table 2 – Average methane (Gg) release per unit coal produced (mmt)

	BRAZIL	CHINA	INDIA	MEXICO	RUSSIA	UNITED STATES
EPA Average Years 1995 - 2000 Methane (Gg) per coal production (mmt)	9.7	4.9	2.2	9.0	6.4	3.0

Recommendations for Technological Potential Scenario

The methane emissions projected to come from the coal mining sector are largely determined by the increase in global coal production which is in turn dictated by the demand for energy. In the business as usual scenario assumptions, the demand for coal globally increases linearly based on historical rates with the lion's share of coal production coming from China. Thus, not surprisingly, China has the greatest projected emissions of methane from the coal mining sector through 2050. Aside from the options of decreasing coal production, which would stem from an unlikely decrease in energy demand and fuel-switching, which would require policy changes to allow for decreased reliance on coal-fired electricity generation, another technological option would be to increase methane capture while producing coal. In fact, it will be beneficial for nations to adopt methane capture systems not only since the recovered gas could be used as a valuable fuel source but also because of decreased potential of mining hazards and an increase in actual mine productivity (Methane to Markets, 2006). Within IPAT, this can be modeled and observed via a decrease in the methane intensity technological parameter of methane/unit of coal produced.

There are many options for reducing the amount of methane released into the atmosphere while producing from coal mines, as well as during the handling of coal post-mining. Although abandoned coal mines are responsible for continued emissions release, since the majority (~90%) of methane emissions from coal production occurs during the mining stage itself, I can focus on describing some of the options available for the actual mining production itself. Also, as part of mining operations, a major component to methane release occurs whether the mine is underground or a surface mine. The majority of methane emissions come from underground mines since the amount of stored methane is a function of coal depth and type (Wuebbles, 2002). Generally, the deeper mines contain higher methane content which enables more methane to escape to the atmosphere (EPA, 2006). The production of coal from underground mines is expected to increase in the future to meet the surging demand of coal and the majority of the increase in coal production, and thus fugitive methane emissions, comes from China, India, and the United States (EPA, 1999). As coal is mined at increasing depths, the amount of stored methane that potentially can be released will also increase.

For safety reasons, the United States and other countries have adopted some methods for capturing methane that occurs during underground mining. This was done mainly to prevent explosions within the mine since at concentrations greater than 5%, methane is extremely explosive (EPA, 1999). Typically, the methane is simply vented to the atmosphere so that concentrations with the mine remain below 1%. Here I can describe specific options that coal mines could employ to utilize the previously ventilated methane. The use of the recovered methane could be either for use within the natural gas system via pipeline injection or for nearsite power generation. Regardless of the eventual use, all methane recovery methods require a degasification system that essentially taps into the locked methane before or during the mining operation. For example, vertical or horizontal wells could be drilled either from the surface or within the mine towards the coal seam (Table 3). The estimated recovery values for these options are up to 60 % of the otherwise ventilated methane using these basic degasification techniques (EPA, 1999).

Table 3 – Methane emissions reduction technologies for coal mining (EPA, 1999)

RECOVERY METHOD	EFFICIENCY	COMMENTS
Vertical Wells	60 %	Preemptive methane capture wells
Gob Wells	50 %	Short wells to capture methane prior to mining
Longhole Boreholes	40 %	Preemptive inside-mine holes
Shorthole Boreholes	15 %	Short holes inside-mine holes

Of course, not all the released methane is in useable form as the purity of the released gas depends on the location and coal type of the mine. Also, the ability to utilize the otherwise ventilated gas depends on local infrastructure (i.e. proximity to natural gas pipelines or gas-fired electricity power plant). Many of the coal mines in China are located in rural and remote areas of the country and thus are not in good locations to allow for direct pipeline injection (CMM Global Overview, China, 2006). However, there is potential for China to update its natural gas pipeline infrastructure to allow for the use of fugitive methane emissions from its vast amount of coal mines. This would require careful planning and analysis that realistically would be greatly aided through specific policies directed towards mandating the capture and use of a certain percentage of fugitive methane emissions from coal mines. Although the economic incentives are apparent, there is a disconnect in the necessary infrastructure, both politically and technically, to tap into this valuable resource. The barriers to improved implementation of coal mine methane capture include:

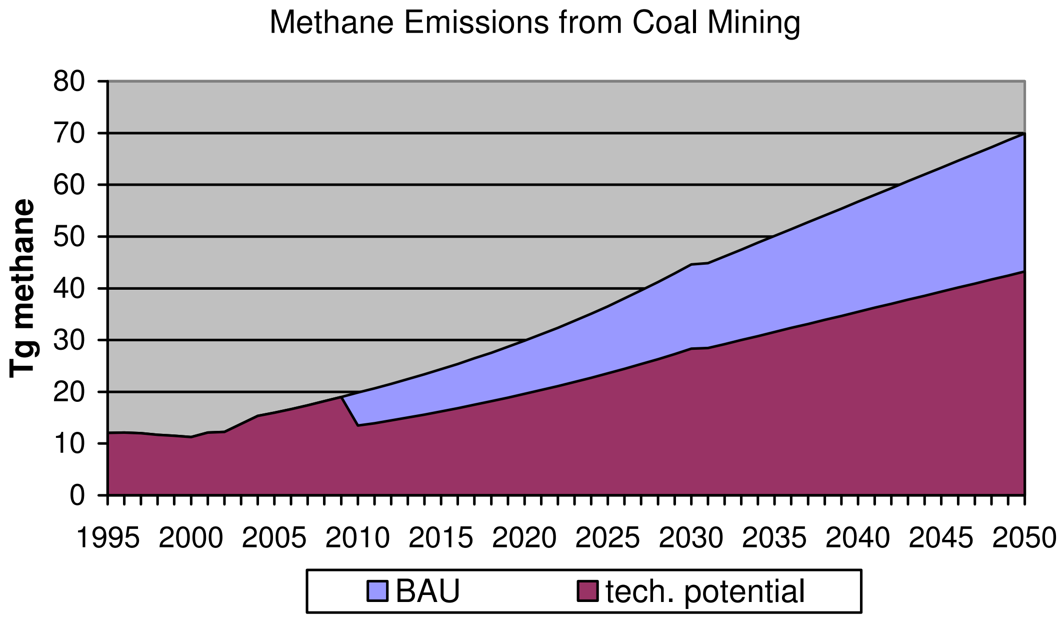
- Education on the use of coalbed methane as a commodity fuel source.
- Dissemination of technological capacities to tap into coalbed methane.
- Addressing limitations while making laws and regulations for use clearer.
- More access to markets; namely cooperation with the natural gas pipeline infrastructure.

I can highlight the potential for methane capture from underground coal mines by citing an example in Shanxi Province, China. There, a large mining group, Jincheng Anthracite Mining Group, Inc., is able to tap into the large amount of methane stored in its mines by having built 3 gas-fired power plants that together generate electricity on the order of about 100 MW and essentially allow for the avoided emissions release of about 0.5 Tg methane per year (CCM, 2006). This is equivalent to avoided emissions of about 500,000 metric tons CO_2 equivalent. This includes the emissions generated by using the captured methane to create electricity in the on-site plant.

I incorporate these possible recovery systems into the IPAT technology term and observe the resulting decrease in methane emissions from this sector. I will not alter the projected coal production estimates per country but can alter the percentage capture per country assuming an adoption of the aforementioned degasification capture technologies as well as an upgraded infrastructure for the use of coalbed methane as a feedstock for natural gas-fired electricity generation and injection into the natural-gas pipeline system.

For the Technological Potential (TP) scenario the percentage of methane captured from active coalmines increases by 50% for China. Since China is responsible for the majority of the increase in coal productive capacity throughout the projection period it will certainly have the greatest impact. A 50 % reduction in methane emitted per coal produced will match the year 2000 rate in the United States. This seems feasible given the existence of technologies for methane capture highlighted above. With so much new capacity coming online, China especially has the opportunity to recover much of the underground methane before production. I present the reduction from coal mining methane capture for the six countries below (Figure 2).

Figure 2 – Estimated methane emissions from coal mining through 2050



Overall, for the 50% reduction for China from coal, there is potential for about a 45 % reduction in methane emissions from this sector starting in 2010 from the baseline scenario. The message here is that through increasing technologies for coal mining methane capture in only the largest coal-producing nation, there is potential to mitigate fugitive methane emissions by 45 % throughout the projection period assuming baseline population, economic, and coal production/GDP growth parameters.

Natural Gas and Oil Production Systems

Within the Energy Sector, emissions stemming from the production of natural gas and oil account for the largest source of anthropogenic emissions. Since methane is a large component of natural gas (95%), during the extraction of natural gas, methane is released through field production, processing, transmission, and storing (EPA, 2006). In the production of oil, natural gas deposits are usually found and thus significant quantities of methane can be released through this process. In other words fugitive methane emissions from oil production result because natural gas is normally a by product of the drilling process and therefore some methane escapes to the atmosphere. I can sum the contribution of emissions from natural gas and oil production processes together to assess the total methane emissions stemming from the oil and gas infrastructure per country. Most of the resulting fugitive emissions come from the natural gas infrastructure. The productive capacity of each country and associated fugitive emissions can be framed within IPAT:

$$\textbf{Population x (GDP/capita) x (Natural Gas and Oil Production/GDP) x (CH}_4\textbf{/ Natural Gas and Oil Production)}$$

$$\rightarrow \textbf{CH}_4 \textbf{ from Natural Gas and Oil Production}$$

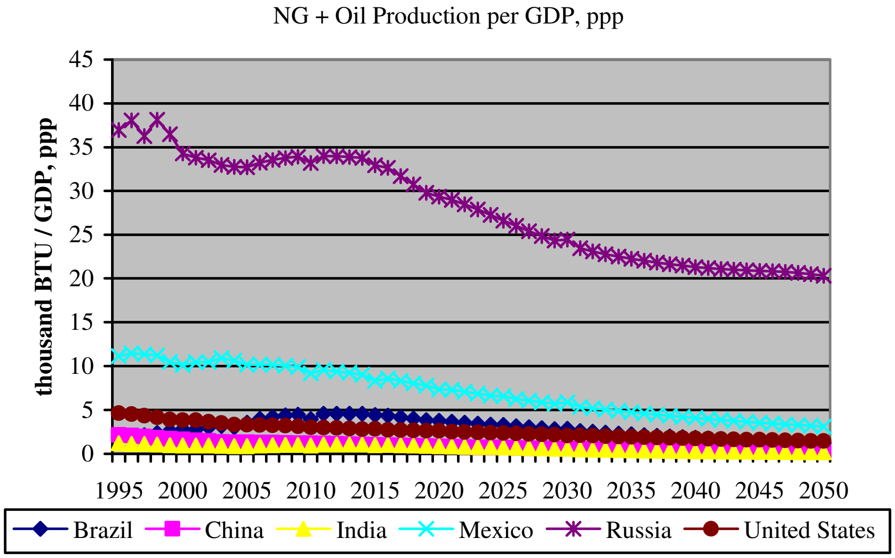
The production amount of natural gas (typically expressed in trillion cubic feet) and oil (typically expressed in barrels) must be expressed in a common unit. Therefore, after obtaining data on natural gas production per country and year from the EIA and obtaining historical crude oil and liquid fuel additives data per country and year from the IEA, I can convert both sets of data to common energy units (i.e. BTU). The heat content of each fuel type is country and year specific (Table 4). However, the value is historically the same every year and therefore I will use the year 2004 value. Therefore, the natural gas and oil production per country and year is multiplied by the respective heat content per country and expressed in primary energy units.

Table 4 – Average Heat Content (BTU) of Natural Gas and Oil (EIA, 2006).

BRAZIL	CHINA	INDIA	MEXICO	RUSSIA	UNITED STATES
Gross Heat Content of Crude Oil (Thousand BTU/Barrel) - Year 2004					
5,910	5,879	5,729	6,010	5,880	5,800
Gross Heat Content of Dry Natural Gas (BTU/cubic foot) - Year 2004					
1,040	1,162	1,034	1,069	1,026	1,027

The economic efficiency factor is obtained by dividing this total heat content by the GDP, PPP per country. This term gives us insight into how much energy each country produces from natural gas and oil production only. It is interesting to note that Russia is about 20 times higher than other analyzed nations in terms of the production of natural gas and oil as a function of its GDP (Figure 3). This indicates that Russia's economy is more heavily influenced by its natural gas and oil production industry that other nations.

Figure 3 – Economic importance of natural gas and oil production



The fugitive methane emissions estimates differ for both the EPA and EDGAR datasets. This may be due to various issues including leakage reporting, inherent assumptions of capture equipment technologies, and underlying assumptions of oil and natural gas production values. Therefore, we can take the average methane emission rate per BTU of energy produced via natural gas and oil per country as follows.

The technology term for methane emitted per BTU produced is back calculated by using the EPA estimates of the amount of methane emitted from the natural gas and oil systems per country and year. In other words, I take the EPA estimates and divide by our summed natural gas and oil production gross energy content (Gg CH_4 per $BTU_{NG, OIL}$) for the years 1995 and 2000 (Table 5).

Table 5 – Average methane release (Gg) per unit natural gas and oil produced (BTU)

	BRAZIL	CHINA	INDIA	MEXICO	RUSSIA	U.S.
EPA AVERAGE YEARS 1995 - 2000 METHANE PER NATURAL GAS AND OIL PRODUCTION (BTU)	2.7E-05	2.6E-05	3.0E-04	3.0E-04	2.8E-04	1.9E-04

The country-specific values for methane released per $BTU_{NG, OIL}$ produced are on the same order of magnitude as the value calculated in another report which calculated a global average value for natural gas production and transmission at 8×10^{-4} Gg CH_4/Billion BTU (Hayoe, 2002)

Projections for Business As Usual Scenario

I use the projected country-specific production data from the EIA. This data exists for both dry natural gas production and crude oil production projections. EIA has made projections for three world scenarios based on the estimated world oil price (i.e. high, low, or reference) and I will use the reference case scenario. The projections are in five-year intervals out to 2030.

Natural Gas

Again, I use the projections provided in the IEA's International Energy Outlook for natural gas production in trillion cubic feet per country in 5 year intervals out to 2030. Here the production trend does appear to be linear as opposed to logarithmic which was used for the oil production projections. Therefore, since the better trendline fit is linear, we will assume this relationship and interpolate the missing values in the 5 year intervals through 2030 as well as project the natural gas production per country out until 2050. This linear relationship reflects the growing global demand for natural gas and here is not constrained by dwindling productive capacity and "peak production" considerations as is the case for the oil projections. I again use the year 2004 gross heat value (BTU/cubic foot) for the natural gas produced per year and calculate BTU/year coming from natural gas production per country.

Oil

I interpolate the missing year values and then use the relationship to project production data out until 2050. Depending on the country and fuel, there are different relationships that we can use to project the production. Although we use the EIA's International Energy Outlook for the years 2010 – 2030 in five year intervals, different countries' have slightly different regression trendline types. For all countries, we will use a logarithmic fit starting with the 2004 value of oil production and using the 5 year projections out to 2030 from EIA. This relationship is then used to interpolate the missing values and is continued out through 2050. To obtain the heat content for each fuel, we can use the 2004 value of the gross heat content in BTU per year.

Most likely, these interpolations will overestimate future emissions since the relationship between fugitive methane emissions from natural gas and oil production processes is likely non-linear (EPA, 2006). This is especially true with the United States since the EIA Energy Outlook projects the oil production to increase in the future when historically it can be seen that the productive capacity of US oil is on the decline and has “peaked” in the 1970s.

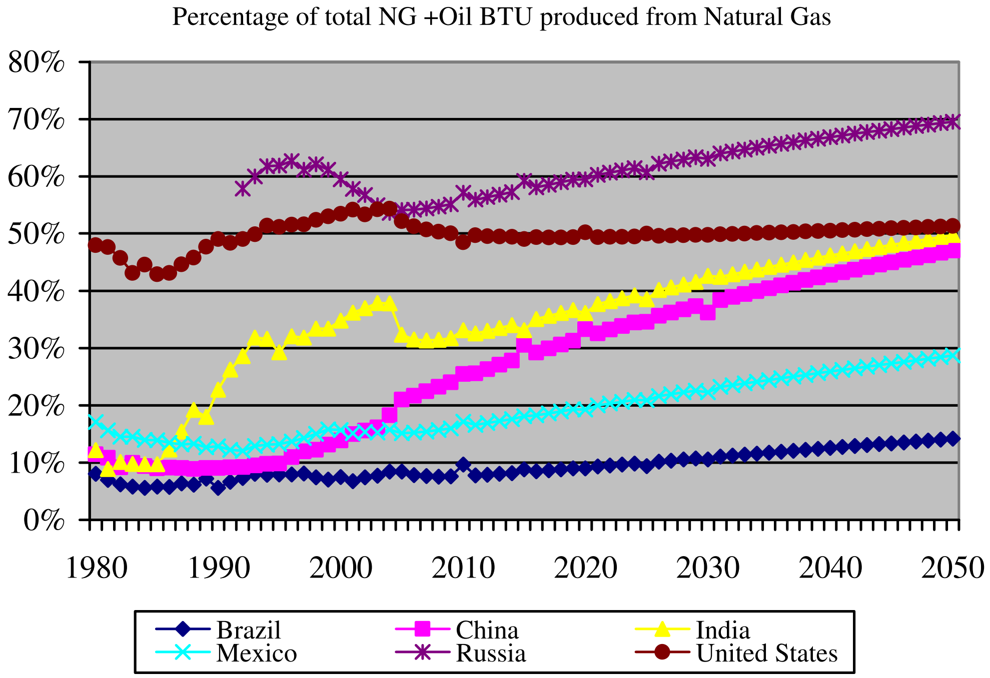
Recommendations for Technological Potential Scenario

Natural Gas

With the projected increase in natural gas and oil production, there will invariably be an increase in fugitive methane gas emissions to the atmosphere unless significant upgrades to methane capture are incorporated into the production, transmission, and distribution processes of natural gas and oil infrastructure.

Within IPAT, I can alter the parameter that describes the amount of methane released per unit of energy (BTU) produced via both natural gas and oil resources as a function of GDP. This is part of the technology methane intensity term (i.e. methane/GDP). Each nation has a different breakdown of total BTU produced from each source based on which resource is more prevalent (Figure 4). For example, of the total BTU produced from natural gas and oil resources, Russia maintains between 50-60 % from natural gas. For Brazil, this percentage is less than 10 % indicating production in Brazil mostly comes from oil processes. In the United States, the split is roughly 50 % natural gas and 50 % oil.

Figure 4 – Relative contribution of natural gas production



Therefore, it is important to recognize the importance of mitigating fugitive methane emissions will depend on the relative projected productive capacity of each resource. In other words, Russia will likely want to focus efforts on reducing fugitive emissions from its natural gas infrastructure since it will continue to produce significant amounts of natural gas whereas Brazil will want to consider options more related to its oil production capacity. In our analysis of these six key countries, the major reduction potential will come from Russia and the United States simply because of the productive capacity of each nation, which greatly overwhelms the other nations. It is apparent that the largest mitigation potential within the natural gas and oil systems infrastructure is the natural gas sector in Russia.

For natural gas, there is a direct economic incentive towards reducing the fugitive emissions associated with processing of natural gas in its entire infrastructure. The largest contributor to methane emissions from natural gas systems, and thus the greatest benefactor towards mitigating fugitive emissions is Russia. Since their natural gas reserves are the largest in the world and their productive capacity is projected to expand to more than double the current capacity by 2050, Russia stands the most to gain in terms of recovered losses via an upgrade to its ageing transmission pipeline infrastructure and processing equipment. However, all analyzed nations would benefit markedly from updating the natural gas infrastructure to minimize leakage.

Overall, we can outline the main opportunities for increased methane recovery:

- General processing technology upgrades to reduce venting of methane
- Better management of natural gas systems
- Systematic upgrade to leak detection and measurement practices

Since the IPAT model contains a specific term that relates the emissions released per BTU of natural gas and oil produced, we can talk about technology and management options to reduce fugitive emissions.

Participants in the U.S. Natural Gas STAR Program, coordinated by the EPA, have discovered that minor steps can be taken to assess and ultimately address options for increasing methane capture efficiency and minimizing leaks. An example of an enhanced assessment technique is the use of a helicopter-mounted infrared imaging camera that can effectively enable for real-time imaging of natural gas leaks from compressor stations or pipelines (Fernandez, 2005). This is an example of a directed inspection and maintenance (DI&M) technique, of which there are other more simple methods such as using ultrasound to detect leaks, and would allow for remediation of fugitive emissions. It has been documented that simply tightening existing valves and pipeline connectors can reduce methane emissions by as much as 70% (Fernandez, 2005). Other documented technology upgrades that are cost-effective and have significant natural gas savings exist (Table 6).

Table 6 – Methane emissions reduction technologies for natural gas production (Fernandez, 2005)

TECHNOLOGY	EQUIPMENT COST	O&M	COMMENTS	REDUCTION RANKING
Plunger Lift System	$8,000 per well	$1000	Maintains well pressure by removing fluid buildup	2
Sustained inspection of flowlines for existing pipelines	$250	$5000	Easy to administer with high potential savings	3
Aerial infrared imaging	n/a	$1000/hr	Can determine sizeable leakage areas	1
Replacement of high-bleed pneumatic devices	$1,350	Savings of $1,100 per device	Maintaining the necessary pressure can be done with less natural gas loss	4

The simplest and most cost-effective method of minimizing the release of fugitive methane emissions and thus maximizing economic gain from the natural gas infrastructure is the continued inspection and maintenance of all facilities. It is somewhat encouraging to see more cooperation from industry on the international level in terms of partnering with the U.S. Natural Gas STAR program. As of 2006, the following multi-national companies have joined this voluntary effort; ConocoPhillips Canada Ltd, Devon Energy Corporation, Enbridge, Inc., ExxonMobil Corporation, Marathon Oil Corporation Occidental Oil and Gas Corporation, and TransCanada (EPA Gas STAR, 2006).

Oil

In terms of the oil production projections, there is a notable increase in oil production coming from our analyzed nations, especially the United States. Historically, oil production from the US has peaked following the prediction by Hubbert in the 1970s. However, the IEO 2006 projects an increase in oil productive capacity from the US which most likely stems from increases in unconventional oil resources such as oil shale and tar sands. Not only are these processes more energy intensive in terms of producing useable motor transportation fuels but the switch to unconventional fuel production will likely lead to increased methane emissions from these processes. Producing fuels from oil shale is more similar to mining for coal than drilling for oil and thus is smitten with similar issues of methane absorption akin to coal mining. In fact, this has been documented by the Department of Interior as a safety issue (Matta 1977). As the production of these unconventional oil resources ramps up in the future to meet surging demand, measures should be taken to mitigate the release of trapped methane from oil shale. This could be accomplished using similar techniques as tapping into methane gas from coalbed methane. Again, because of the relative contribution of each source (natural gas and oil production), it makes sense for countries such as Brazil and Mexico to focus on capturing fugitive methane emissions from their oil infrastructure since most of the energy production in the natural gas and oil sector is coming from petroleum processes (Figure 4).

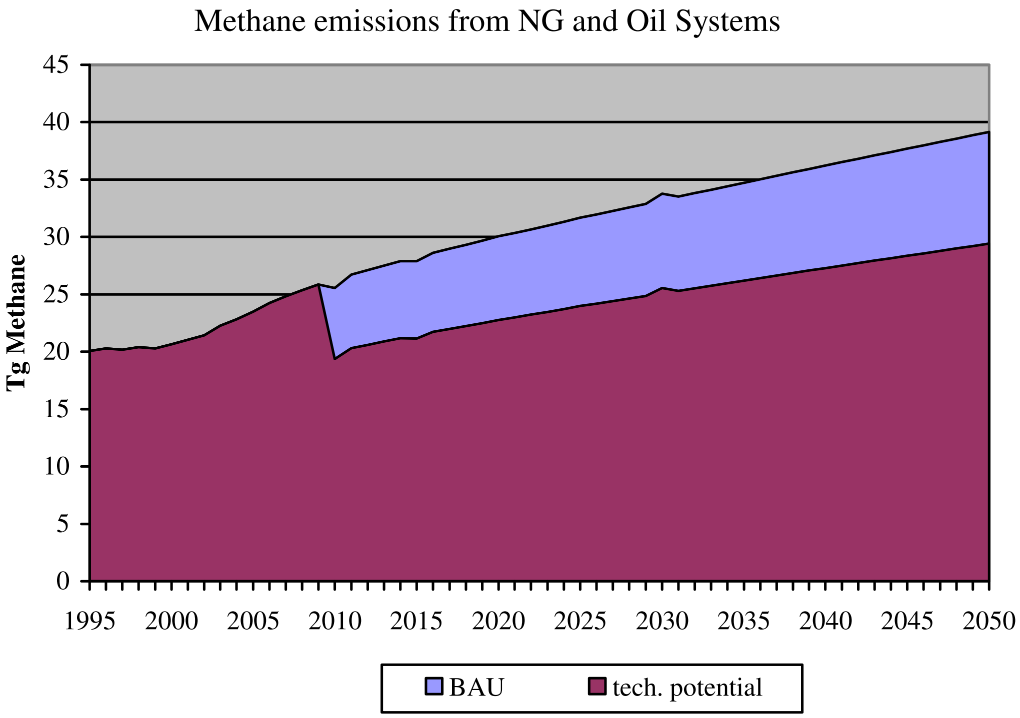
Overall, I describe the Technological Potential scenario here by focusing on Russia and the United States in terms of reducing their respective methane intensity term (methane per BTU) in IPAT. I first reduce Russia's level until it reaches that of the United States (a reduction of 35 %). Then, I further reduce the United States' term by 20% to account for increased natural gas capture during the production process (Table 7). Both reductions are assumed to take place in the year 2010.

Table 7 – Reduction of methane intensity in natural gas and oil sector per country

	Methane per production (Gg per billion BTU)					
	Brazil	**China**	**India**	**Mexico**	**Russia**	**United States**
BAU	6.10E-05	6.67E-05	2.50E-04	2.08E-04	3.62E-04	2.44E-04
reduction	0 %	0 %	0 %	0 %	35 %	20 %
TP	6.10E-05	6.67E-05	2.50E-04	2.08E-04	2.36E-04	1.95E-04

Overall, I demonstrate that a 35 % reduction in the amount of fugitive methane released per unit production of natural gas and oil (in BTUs) from Russia and a corresponding 20 % decrease from the United States beginning in 2010 and persistent throughout the projection period yields a total methane emissions reduction of about 26 % from all six nations in this sector (Figure 5).

Figure 5 – Estimated methane emissions from natural gas and oil through 2050



WASTE SECTOR

A significant amount of methane emissions comes from the waste sector and in this analysis, I project emissions from landfills and human wastewater systems for each of the six countries as well as outline a technological potential for reductions through 2050. Other waste sector emissions that have not been analyzed include manure management from livestock and industrial sources of waste.

Landfills

Due to the anaerobic digestion of waste placed in landfills, there is a significant amount of methane gas that is released, especially in the United States. In fact, this is the largest anthropogenic source of methane within the US, although due to recovery efforts, emissions have been recently decreasing (EPA, 2006).

Within the IPAT framework, I need to specify a technology term that would capture the amount of methane released per volume of waste disposed. Here, I am concerned only with municipal solid waste (MSW). That is, waste from citizens from residential use (not industry) within each country that eventually makes it to a landfill to decompose.

There are many factors that go into accounting for methane emissions coming from MSW including the type and composition of waste, percentage of waste that is disposed, and the amount of methane that is produced over a given timeframe. The most difficult to quantify is the composition of waste, especially since the data is very limited. For the United States, most of the landfilled MSW by percentage is paper, yard trimmings, and food scraps (EPA, OSW, 2006). However, the composition of waste in other countries is different and the data is sparse. To simplify matters, I will use the EPA and EDGAR estimates of the overall emissions of methane coming from landfill municipal solid waste and determine a scaling factor to be used as part of the technology factor in the IPAT equation. Both EPA and EDGAR employ a bottom-up approach following the default IPCC methodology. Therefore, inherent in their estimates are assumptions about composition and the subsequent methane emissions that are released per country. For this analysis, I will not attempt to characterize the composition of MSW placed in landfills and assume that this composition does not change through time within the IPAT framework.

$$\textbf{Population x (GDP/capita) x (MSW}_{\textbf{generated}}\textbf{/GDP) x}$$
$$\textbf{(Fraction of MSW Disposed) x (CH}_4\textbf{ /MSW}_{\textbf{disposed}}\textbf{)}$$

$$\rightarrow \textbf{CH}_4\textbf{ from landfills}$$

Determining the amount of MSW generated per country is difficult due to lack of accurate data. However, the IPCC has created default parameters that relate the average amount of waste generated per person per day. Using this scaling factor, I can project the amount of MSW generated per country and year (IPCC 1996).

Table 8 –Municipal solid waste generation per capita (years 1996 and 2000)

	Generation Rate from IPCC; country-specific					
	Brazil	**China**	**India**	**Mexico**	**Russia**	**United States**
1996 value	0.18	0.27	0.12	0.31	0.32	0.73
2000 value	0.18	0.27	0.17	0.31	0.34	1.14

Only a fraction of the total MSW generated actually makes it to a landfill. Some of the generated waste is incinerated or recycled. Again, estimated country-specific MSW disposal fraction is available through the IPCC for the year 2000.

Table 9 – MSW disposal rate (year 2000)

	Fraction of Disposal from IPCC; country-specific					
	Brazil	**China**	**India**	**Mexico**	**Russia**	**United States**
2000 value	0.8	0.97	0.7	0.49	0.71	0.55

The amount of generated waste also has an economic component within our IPAT framework. The MSWgen/GDP term is a reflection of how much waste is generated as a function of GDP.

For the actual release of methane at a particular landfill I use the methane intensity term or methane released per MSW disposed. Again, I calculate the amount of methane (in Gg) released per country per metric ton of MSW disposed using the EPA and EDGAR estimates. Note that this method does not take into account the time lag between waste disposal in a landfill and the accumulation of methane emissions. This time lag is relatively minimal however and emissions typically begin about 1 year after disposal.

Projections for Business As Usual Scenario

I project the MSW generated by using the IPCC 2000 value for MSW generated per person and multiplying by the UN population projections. I also use the IPCC disposal rate to determine the amount of MSW that is disposed in a landfill. The remaining “undisposed” fraction is considered to be incinerated or recycled and thus does not has no methane emission impact. Therefore, I obtain the amount of MSW that was actually disposed in a landfill per country and year. I obtain the methane/MSW disposed from using the EPA projections of total methane emissions from landfill waste and divid by my calculation of MSW disposed per country. The “methane intensity” term is held constant throughout the BAU projection period at this current value.

Recommendations for Technological Potential Scenario

Some efforts in developing countries have been made to capture and use the landfill methane as a source of energy, especially in the United States (Landfill Methane Outreach Program, EPA). However, although the amount captured is increasing it is still a small amount of the total methane produced. For example, in the United States, the amount of recovered landfill methane gas has increased from about 930 Gg in 1990 to 5,300 Gg in 2004 as reported by the EPA GHG Inventory Report (EPA, 2006). This is an increase from about 10 % recovery of total emitted MSW landfill methane in 1990 to about 40 % recovery in 2004. The massive increase in recovered landfill methane gas has kept emissions from landfills at a constant and even slightly declining level in the past decade in the United States. However, unless these efforts continue at this rate, the increasing amount of municipal solid waste that is generated by the voracious appetite for material consumption globally and especially in the US will cause emissions from landfills to increase in the future.

Within IPAT, there are four parameters that one can alter from the BAU path in order to gain insight into how landfill methane emissions will change over time. These options are:

1. Changing the MSW generation rate [MSW generated per capita]
2. Changing the MSW disposal rate (i.e. the amount of MSW that reaches a landfill) [Fraction of disposal term]
3. Changing the amount of methane released per MSW disposed [CH_4/MSW]
4. Changing the amount of MSW generated per dollar GDP

Firstly, the initial MSW generation rate per country can be altered to reflect a change in consumption patterns. Currently, the United States far exceeds other nations' in terms of per capita consumption rates. In fact, the MSW generated per capita (1.14 tons/person/year) is more than triple that of the next highest consuming nation in our analysis which is Russia (0.34 tons/person/year). A reduction in the consumption of material goods would result in a drastic decrease in landfilled waste. This can be seen through IPAT by changing the year 2000 IPCC default values and observing the resulting change in overall landfill methane emissions in time. Obviously, the largest impact would occur if the United States were to reduce its MSW generation rate. Therefore, for our technological potential scenario, we will reduce the US MSW generation rate from 1.14 tons/capita/year to 1 ton/capita/year, which is a 12 % decrease. This decrease in consumption would result from an aggressive packaging reduction policy for suppliers as well as increased education on behavioral patterns for the citizens of the US which presumably would decrease overall consumption.

Secondly, the amount of MSW generated that actually reaches a landfill can be altered as well. This is denoted through IPAT as the fraction of MSW generated that is disposed (the “Fraction Disposed” term). I assume that the MSW generated that does not reach the landfill is recycled or incinerated and thus, in terms of methane emissions, has a net zero impact. Certain nations stand more to gain in terms of methane reduction via this method than others. For example, China disposes 97 % of its generated MSW whereas the United States disposes only about 55 %. In other words, almost all of the MSW generated in China reaches a landfill and eventually decomposes anaerobically to release methane whereas in the US only about half of all MSW generated reaches a landfill. Therefore, China has the option of increasing recycling rates such that not all of its generated MSW reaches a landfill. Of course, simply because the fraction of disposal rate is low in the US does not necessarily mean that the country has a 45 % recycling rate. In fact, the United States incinerated 14% of the non-disposed MSW and “recycled” the remaining 31 % (IPCC, 2006). For the technological potential (TP) scenario I assume that the disposal rate for the United States remains at 0.55 but that all other nations achieve the recycling rate similar to the US (30% of MSW generated). This ensures that at least 30 % of each country’s MSW does not reach the landfill and is assumed to be recycled. Thus, each nation has a disposal rate of at least 0.7.

Finally, the amount of methane captured at a landfill is reflected in the “methane intensity” term or the CH_4/MSW disposed term. This value can be altered to reflect how a nation will decrease this value by capturing more of the landfill methane gas and use it as a fuel. The LMOP voluntary program conducted through the EPA has been moderately successful at capturing methane gas at landfills but more efforts (perhaps mandatory capture) could lower this term even more in the future. This can be simulated by inputting a percentage change to the current value of methane release per MSW disposed which will reduce the rate through the projection period. The Landfill Methane Outreach program cites about 600 out of the 2,000 landfills in the US to have the potential of methane capture (Methane to Markets, 2006). In light of this and since there has been a substantial increase in methane capture at landfills I conservatively assume that a 20 % reduction in the methane release per MSW disposed term in the United States. Other nations' percentage reduction is 10% from BAU values.

Although the "methane intensity" term also includes the MSW generated per GDP, for the technological potential scenario, I assume that this term does not change from the business as usual scenario. Therefore, I am implicitly assuming no change as to the relative economic relationship between MSW generation and GDP. Historically, poorer nations typically have a higher MSW/GDP ratio however all nations' are experiencing declining ratios.

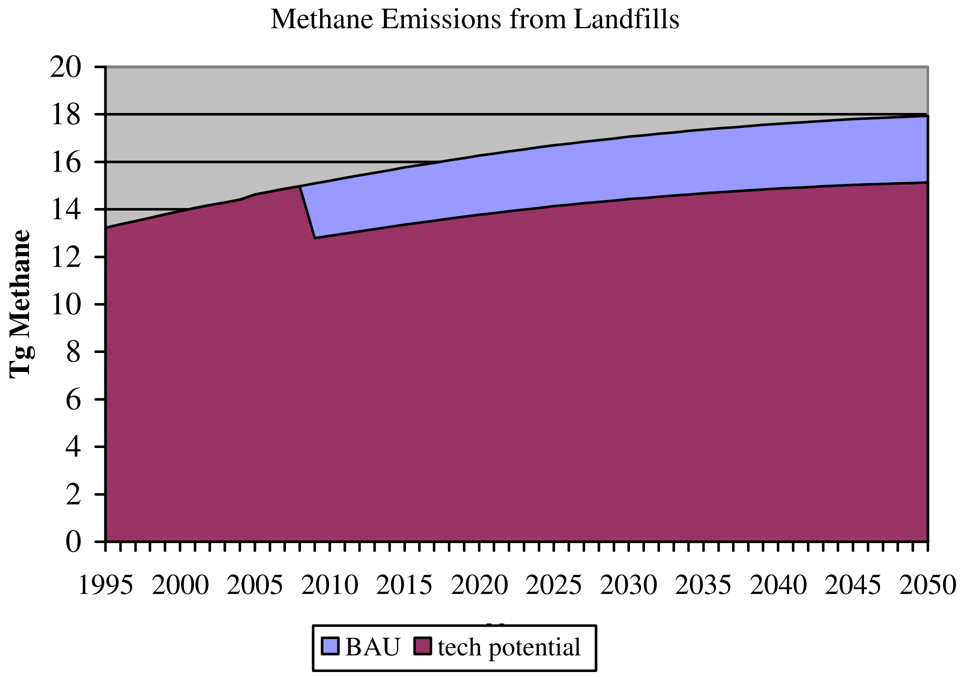
The overall change to the business as usual (BAU) scenario to create the technological potential (TP) scenario is outlined below (Table 10).

Table 10 – Reduction of methane emissions from landfills

	BRAZIL	**CHINA**	**INDIA**	**MEXICO**	**RUSSIA**	**UNITED STATES**
MSW Gen	0.18	0.27	0.17	0.31	0.34	1.14
Reduction	0	0	0	0	0	12 %
Tech Potential	0.18	0.27	0.17	0.31	0.34	1.00
Disposal Rate	0.8	0.97	0.7	0.49	0.71	0.55
Reduction	13 %	28 %	0 %	0 %	2 %	0 %
Tech potential	0.7	0.7	0.7	0.49	0.70	0.55
Emissions Rate	3.44E-05	3.84E-06	4.90E-06	8.04E-05	4.77E-05	4.39E-05
Reduction	10 %	10 %	10 %	10 %	10 %	20 %
Tech potential	3.10E-05	3.46E-06	4.41E-06	7.24E-05	4.29E-05	3.51E-05

In the TP scenario, the above reduction options which take effect in the year 2010 show that throughout the projection period, we can achieve about a 15 % mitigation of methane emissions from landfills (Figure 6).

Figure 6 – Estimated methane emissions from landfills through 2050



Wastewater

To calculate methane emissions from the wastewater sector it is important to realize that there are emissions due to the domestic sector as well as the industrial sector. Generally, the municipal sewage from humans, industrial sludge from pulp and paper plants, fruit and vegetable processing, and meat and poultry packing is treated via septic systems that allow microorganisms to consume and remove the organic matter that is present in wastewater (EPA, GHG 2005). This removal process can occur in anaerobic conditions which results in the release of methane emissions. Domestic emissions can be calculated by knowing three country-specific parameters that will ultimately determine the amount of methane released to the atmosphere through wastewater systems.

First, we need a measure of the organic content of wastewater which can be expressed as Biochemical Oxygen Demand (BOD_5) on a country-specific basis. This reflects the amount of oxygen that would be needed to aerobically digest the contained matter within the wastewater. A more crude explanation is that an increase in BOD generally describes an increase in per capita protein consumption which is driven largely by population increase as well as economic advancement. These values can be found in the IPCC Good Practice document (IPCC, 2006). The BOD varies drastically depending on the country or region (United States is over 30 kg/person/year versus India which is about 12 kg/person/year). Other countries' BOD can be are derived from regional IPCC estimates (Table 11).

Table 11 – Biological oxygen demand (BOD) per country

	BRAZIL	**CHINA**	**INDIA**	**MEXICO**	**RUSSIA**	**U.S.**
BOD_5 per year (kg/person/year)	18.25	14.6	12.41	14.6	21.9	31.025
Range	± 10 %	± 10 %	± 20 %	± 40 %	± 20 %	± 40 %

Second, a certain percentage of the organic loading of the wastewater will be anaerobically digested and thus release methane. The domestic treatment pathway, which includes treated and untreated systems according to the IPCC, impacts the amount of methane released after the anaerobic BOD loading has been determined. These treatment pathways are largely determined by the economic status of a region or country in that higher income, urbanized areas have more advanced treatment systems than lower income and rural areas (IPCC, 2006). I highlight some of the default parameters that the IPCC Good Practice describes but these will vary by country (Table 12). Developed nations such as the United States have an infrastructure where a large majority of the population has access to advanced treatment systems like aerobic plants (EPA, GHG 2005).

Table 12 – Wastewater treatment pathways and associated methane emissions release

TREATMENT PATHWAY	% OF METHANE RELEASED	RANGE	ISSUES CONCERNING PATHWAYS
TREATED SYSTEMS			
Advanced aerobic plant	0	0 – 10 %	No leaks, well managed
Anaerobic plant or lagoon	80 %	80 - 100 %	No gas recovery system
Septic system	50 %	40 – 60 %	High use in rural areas
Public latrine	10 – 70 %	1 – 100 %	Dependent on climate/size
UNTREATED SYSTEMS			
Stagnant sewer	50 %	40 – 80 %	Open to air
Sea or Ocean discharge	10 %	0 – 20 %	Dependent on local loading

Finally, of the amount of wastewater treated anaerobically, only a certain amount of methane emissions will be released and this has been determined by the IPCC Good Practice Guidelines to be on the order of 0.6 kg CH4/kg BOD (IPCC, 2000). Therefore, the general description that quantifies methane emissions from wastewater is:

$$CH_4 = \text{BOD} * \text{Emission Factor (EF)} * 0.6 \text{ kg CH4/kg BOD}$$

Where the Emission Factor takes into account the percentage of wastewater that is treated via country-specific process pathways and the associated percentage of the population with access to those processes. The underlying assumption is that the treatment pathway determines the release of methane into the atmosphere with the anaerobic treatment processes allowing for a larger emissions release.

Industrial emissions are calculated on a similar basis but instead need a measure of the volume of wastewater generated per product as well as the output of each product from industry. These values will obviously be country-specific. Again, a certain organic loading measure of the product is needed and an industry specific emission factor to determine the amount of methane released per organic loading. The EDGAR and EPA reports document the methane emissions from wastewater loading using default IPCC BOD values as well as certain assumptions about industrial wastewater output implicit in the total wastewater emissions estimate. Although the methodology is relatively straightforward, data acquisition for the six countries is very difficult. For the purposes of this analysis, a more general approach to describing emissions from wastewater systems is warranted.

Therefore, to simplify matters within the IPAT framework, I use the EPA estimates to calculate in the methane intensity in terms of CH_4 released per GDP per country and year. An explanation of the method for projecting this technology term is found below in the “Projections” section. The following function is used to characterize and project methane emissions from total wastewater loading.

Population x (GDP/capita) x (CH_4 Wastewater/GDP)

→ CH_4 from wastewater

I recognize that this parameter is a very crude measure of the technology forcing aspect of wastewater methane emissions. However, there is some general insight as to the rationale for this characterization. Countries with a low CH_4(wastewater)/GDP ratio have a better capacity and infrastructure to contain methane emissions from wastewater using advanced systems. The developing nations have aerobic treatment centers and a collection infrastructure to deal with wastewater loading. Therefore, countries like the US and Russia have lower ratios than China and India. In developing countries, there is lacking infrastructure in dealing with wastewater and thus much of it is transported via open latrines and sewers, which allows for higher methane emissions release. Although the main driver for emissions stemming from wastewater loading is population, the characterization through IPAT allows for general analysis into how economic and technological drivers may affect future emissions. This allows one to make assumptions about the future capacity for advanced aerobic treatment of wastewater as a function of a country's GDP whereby the lowering of the CH_4/GDP ratio would indicate an increase in methane capture from existing wastewater systems or simply the upgrading of the wastewater treatment infrastructure that would include more advanced aerobic septic systems.

Projections for Business As Usual Scenario

The projection of methane emissions from the wastewater loading depends mostly on the future ratio of methane emissions from wastewater per GDP per country. The bottom-up projections of methane from the EPA use the IPCC Good Practice Guidelines to assess total methane emissions from the domestic and industrial wastewater sector based on assumptions about future BOD per country and year as well as future COD stemming from the industrial sectors' composition of waste. They factor in the assumptions outlined above concerning the treatment pathway and the country-specific BOD loading. Since these assumptions are embedded in the projections through 2020 from the EPA, we can use their value and independently project the ratio of CH_4 per GDP.

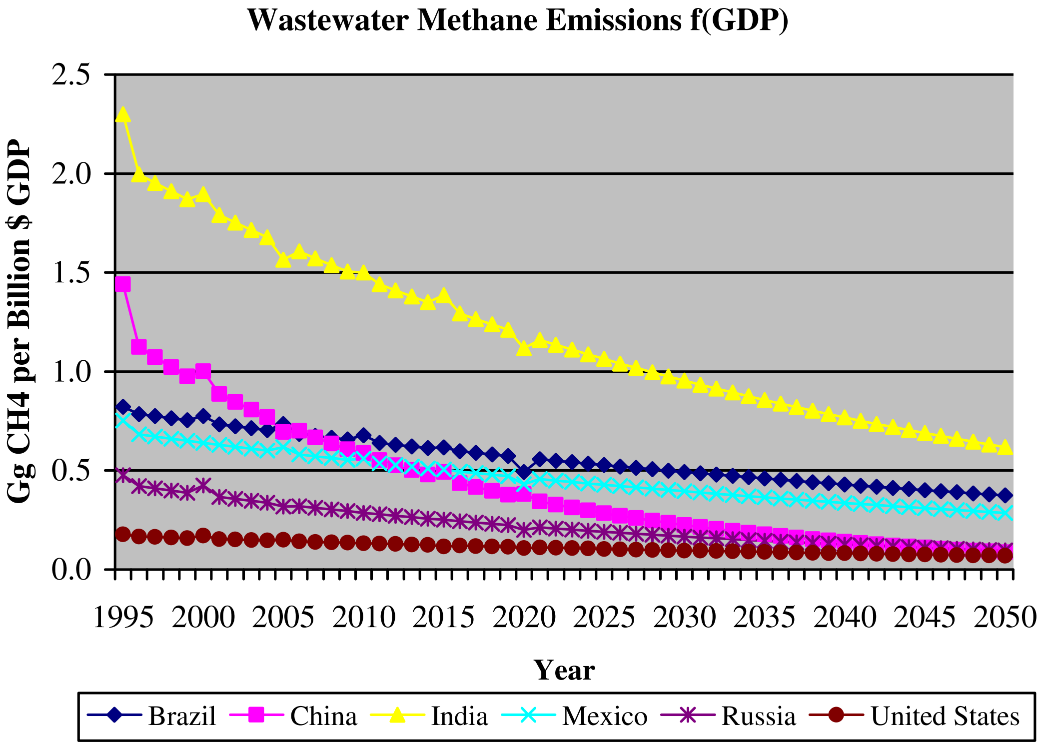
The methane released from wastewater was taken from the EPA and EDGAR estimates for the years 1995-2020 in five year intervals. Taking these values and dividing by the corresponding year GDP per country yields [CH_4 wastewater/GDP]. Starting with the year 2005, the EPA estimate will be used based on the 5 year interval projections through 2020. For example, EPA provides an estimate for methane released from wastewater for the year 2010. This value is divided by the independent projection of GDP per country for the year 2010. This process is repeated in 5 year intervals until 2020. For the intervening years and after 2020 an exponential trend is fit to the CH_4/GDP term to reflect the exponential projected growth in GDP and population, which are the main drivers of wastewater production (Figure 7). Thus, the methane released per unit wastewater is decreasing exponentially. Historically, this exponential trend has occurred, at least for the years 1995-2005. We can assume that the infrastructure of each country will continue to adapt to the increasing economic growth such that the amount of methane released per dollar GDP will decrease concurrently. This will be the technology wastewater CH_4/GDP term used within IPAT and is a crude proxy of the Emission Factor described above.

Recommendations for Technological Potential Scenario

Within the IPAT framework, I have characterized the technology term for wastewater methane emissions as simply one term: CH_4 per GDP. In the BAU scenario, this term is already decreasing exponentially based on the historical trend and also simply because countries must adjust to their increasing population and economic growth rates such that there is an adequate wastewater collection infrastructure. Therefore, as population and GDP increase exponentially, we can assume that the ratio of methane released per dollar GDP respond accordingly by decreasing exponentially.

However, I now have insight into how certain nations compare in terms of their capacity to deal with wastewater from both domestic and industrial sources. We can see below that developing nations (especially India) release more methane per dollar GDP than developed nations such as the United States (Figure 7).

Figure 7 – Wastewater methane emissions per dollar GDP



This represents an opportunity for certain developing nations to upgrade their infrastructure to incorporate more advanced aerobic treatment centers for domestic sewage rather than rely on other cruder collection systems.

For example, if developing nations were to seriously consider updating their wastewater collection and treatment infrastructure to the standards of developed nations, we could characterize this possible change by lowering the technology term (CH_4wastewater/GDP) and observe the resulting decrease in methane emissions. Here, the implication is that developing nations would reduce their respective methane emissions per dollar GDP term via an infrastructure upgrade to their existing wastewater collection system or to capture more methane from their current infrastructure. Both options would require a substantial increase in funding to build capacity. However, the option for methane capture from aging infrastructure such as the installation of a gas recovery system on an anaerobic treatment plant could create economic incentives since the captured methane could be used as a feedstock to generate electricity.

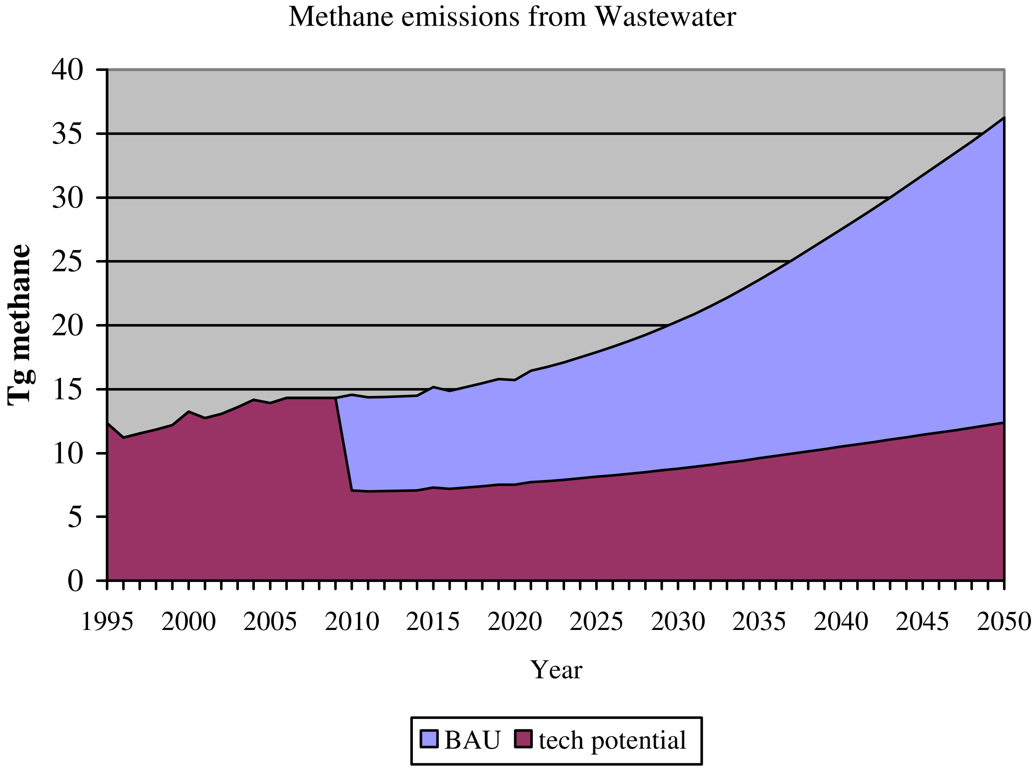
For the technological potential (TP) scenario, I reduce the CH_4/GDP term such that the emissions from wastewater for all countries drop to match the the same value of the United States in 2010. (Table 13). In other words, the wastewater infrastructure is assumed to improve such that each country releases as much methane per dollar GDP from wastewater as the United States by 2010 and remain at this level. To achieve these reductions such will require a massive infrastructure upgrade so that CH_4/GDP would decrease for the wastewater sector.

Table 13 – Reduction in "methane intensity" for wastewater systems

CHANGE TO CH_4/GDP TERM	**BRAZIL**	**CHINA**	**INDIA**	**MEXICO**	**RUSSIA**	**U.S.**
	60%	40%	80%	50%	20%	0%

Note that even though there has been a drastic decrease in the CH_4/GDP term for India, this term still remains high throughout the projection period.

Figure 8 – Estimated methane emissions from wastewater systems through 2050



We can see that the TP scenario shows a substantial reduction (50-65%) in projected methane emissions from the wastewater source. Note that there is no improvement to the US wastewater system and thus, the potential for methane reductions from this source could be even greater than what is presented above. It is also worth noting that the primary benefit and motivation to improving the wastewater infrastructure, particularly in developing nations, is for health and sanitary concerns. The ancillary benefit of reducing and capturing a greenhouse gas could perhaps accelerate the upgrading of a wastewater collection infrastructure.

AGRICULTURE SECTOR

For agriculture sector, I do not use the IPAT framework to project methane emissions because methane emissions from this sector are determined more by the operational extent of agricultural production. In other words, it is not helpful to frame emissions from agriculture as a function of GDP since the emissions are not coming directly from a produced commodity (like coal and natural gas production) or the result of increased consumption (like solid waste) but are coming from the processes of agricultural operation.

Production of agricultural products and the relation to methane emissions have been complicated by increased yield efficiency (Wood, 1998). Therefore, emissions from the agriculture sector are determined through emissions factors that rely on exogenous factors such as area harvested and animal population. In both cases, projected increases in productive capacity will require an increase in extent of operation (area increase for rice cultivation or animal stock population) and process (productive efficiency) or a combination of both. For the purpose of this simple analysis, I maintain the process values (yield efficiency for rice and methane release per animal type) with increased production to be met by increased operational extent. This way, an analysis of technological potential can be assessed by observing the impact of changing process values. Intuitively, there are biological limits to increasing productivity per unit of land or animal and although we might not have reached this limit, the baseline scenario conservatively makes this assumption.

Rice cultivation

Methane emissions from rice cultivation are variable depending on many factors including but not limited to growing season, rice type, irrigation practice, and the addition of organic fertilizer. Not surprisingly, there is much uncertainty in estimating emissions from rice paddy cultivation and the variation among nations and within nations is wide. It has been found that methane emissions from rice paddy fields in China are between 4 and 10 times higher than rice paddy fields in the United States and Europe (Khalil, 1991). The IPCC Good Practice Guidance document provides an explicit methane emission equation that incorporates emissions factors for water management schemes, ecosystem differences, and seasonal variability among other things. The bottom-up approach would simply sum the emissions stemming from the acreage of rice production per season, type, method of irrigation, and yield for each country and year. For example, methane emissions from a rain-fed and flood prone rice paddy plain are only 80% as compared to a similar rice paddy that is constantly flooded and irrigated (IPCC, 2006). These factors reflect that more methane emissions would be generated in the more anaerobic fully-flooded plain.

Population and economic growth are drivers for rice production and thus the methane emissions coming from rice cultivation. However, these drivers are linked to the actual production of rice. In other words, rice production a manifestation of the demand for rice which is driven by population and economic growth. Obviously, more populous countries will consume more rice but this is not to say that each country will produce more rice solely based on population increases. Therefore, to assess and project methane emissions stemming from rice production we simply need to know four parameters; production, acreage, yield efficiency, and amount of methane released per unit area.

I obtain rice area harvest and production projected growth rates from the International Rice Research Institute (IRRI) and the rice yield per area from Food and Agriculture Organization of the United Nations (FAOSTAT). Finally, the methane release per unit area is obtained from the average of the EPA years 1995 and 2000 values of rice emissions divided by area per country.

The area of rice production (i.e. rice acreage) is the most important determinant of emissions from rice cultivation (EPA, 2006). In this assessment, emissions from rice cultivation are simply the product of the area harvested and the amount of methane released per unit area.

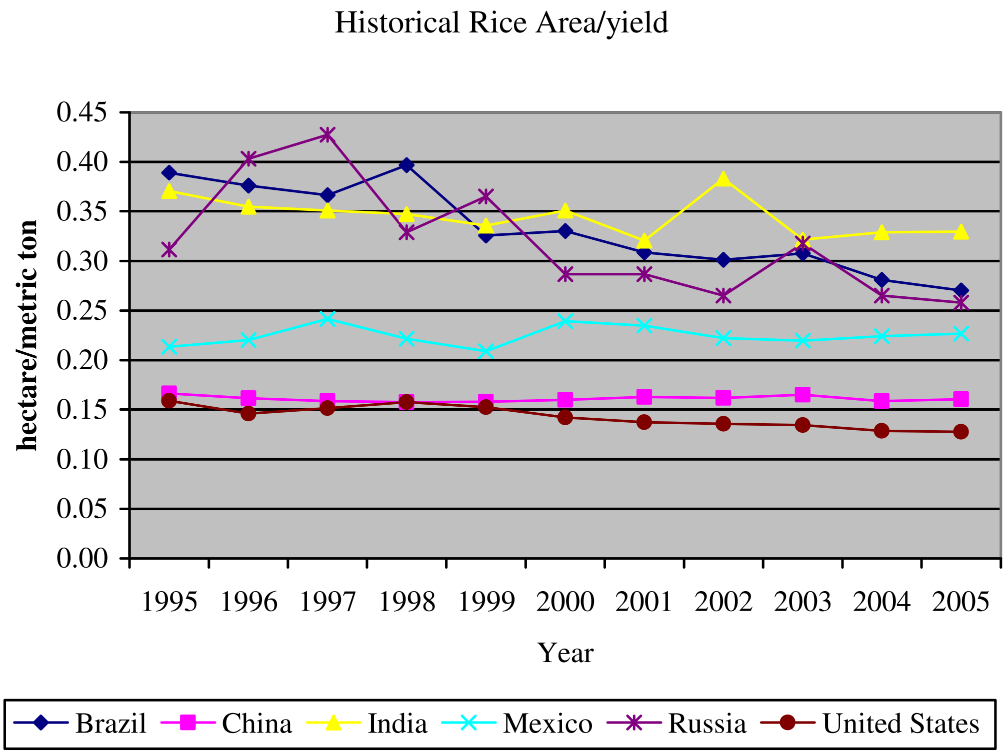
$$\textbf{[area (hectare)] x [}CH_4\textbf{ (Gg) / area (hectare)]} \rightarrow \textbf{Gg } CH_4$$

where area(hectare) = production x area/yield

Historically, the area harvested has remained relatively constant and thus the increase in production has been achieved though increases in yield efficiency. However, there are limits to increasing yield as well as limits to increasing area harvested. Here, the area harvested is directly related to the production yield and the yield efficiency. This relationship is such that in the Business As Usual (BAU) scenario, since the yield efficiency remains constant and the productivity is increasing, the only way to meet the increased productivity is through increasing the harvested area. This seems reasonable considering that the FAO has predicted an increase in area harvested at least in the year 2010, which is a departure from the historically constant levels of rice paddy harvest area.

Even though methane emissions from rice production have been partially mitigated by innovative production capacities that have increased the yield per area, in the BAU scenario, I consider that these efficiency gains have been maximized and any increase in production will come at the expense of increased harvested area and thus a corresponding increase in methane emissions. This term will be inversed (i.e. area/yield) in order to be used to dictate the area harvested. Therefore, historically the area/yield per country has generally decreased slightly indicating that less area of rice cultivated land is needed to obtain a similar sized rice yield (Figure 9).

Figure 9 – Historical rice cultivation acreage per unit produced (1995-2005)



I obtain country-specific values for the CH_4/rice area(ha) term based on the 1995 and 2000 values of CH_4 released from the EPA database. These values are averaged to obtain a single value CH_4/area per country that is used throughout the projection period. This is further explained below.

Projections for Business As Usual Scenario

The projection of methane emissions coming from rice cultivation is a difficult task since there is much uncertainty in future rice area harvest. Historically, rice production has generally followed population increases and there is growing consensus that there will be a need for an additional 50-70% of the current global rice supply through 2025 (Wassman, 2000). We can expect that global rice production will increase to meet the growing demand. According to the FAO, the growth in global production of and demand for agricultural commodities is projected to grow at less than 1 % annually through 2010. However, this is a marked slowdown since the explosion of agricultural growth in the 1990's which showed growth rates of 1.6 % globally (FAO, Medium-growth 2006). Therefore based on historical increases, I project through 2050 the production of rice per country using the FAO values.

Table 14 – Rice production growth rate (2006-2050)

RICE PRODUCTION GROWTH RATE 2006-2050	**BRAZIL**	**CHINA**	**INDIA**	**MEXICO**	**RUSSIA**	**U.S.**
	1.7 %	0.1 %	0.8 %	1.3 %	2.1 %	0.3 %

In terms of harvested area, I use the projected production values from the FAO Medium-term prospectus along with the constant year 2005 yield efficiency value to calculate the area harvested in that year. In the BAU case, I assume that all countries maintain their respective 2005 area/yield level. This is because recently the yield efficiency has remained constant since there are biological limits to productive capacity using current technologies and rice cultivars (Khush, 1995). In effect, it is the projected productive demand that is determining the future area harvest since the yield efficiency is remaining constant. This is a crucial assumption as it states that future production in the BAU will be met by increases in area harvested. It also dictates how the yield efficiency increases will allow countries to meet the projected rice production value with less area and thus reduce overall methane emissions. The most determinant factor in methane emissions from rice production is the area harvested (EPA, 2006).

Finally, for the methane emitted per rice area term, I use the averaged years 1995 and 2000 values for the amount of methane released from rice production from the EPA database and divide by the historical acreage values from FAO. This (methane/rice area) value remains constant throughout the projection period in our BAU.

In summary, rice cultivation emissions for our business as usual (BAU) case can be broken down as follows:

- independent projections of rice production per year and country using growth rates from the FAO.
- area harvested per year = production per year * constant harvested area/yield using values from FAOSTAT.
- constant methane/area = average of 1995, 2000 EPA values

Recommendations for Technological Potential Scenario

The greatest potential for mitigating emissions from rice paddy cultivation is a modification of the growing practice in terms of irrigation style. This modification would enable a much greater reduction of methane emissions as compared with the affect of different climate regimes on growing rice. For example, it has been documented that lower temperatures within temperate regions such as northern India could limit CH_4 emissions (Kahlil, 2002). However, the observed differences are negligible as compared to the altering of the growing method for irrigated rice fields. I can describe the technological potential for the mitigation of methane emissions from rice cultivation by 1.) Increasing the yield efficiency of growing rice (the area/yield term) or 2.) Direct agricultural changes (the methane/area term). Both methods would conceivably reduce overall methane emissions from rice cultivation.

1. The area/yield term so that all countries achieve the US technological max at 0.1 area/yield by 2010 and observe the change in emissions (60-80%)

For the first option, within the model, methane emissions could be reduced through an increased yield per area of rice production. Historically, the United States has achieved a high level of rice yield per area harvested. In fact, since the 1980's, rice production has increased by about 40 % through a combination of yield increases and harvest area increases with more emphasis on the former (Augenbraun, 1997). Within the IPAT framework, I represent this as the area harvested needed per unit of rice produced. Thus, smaller values of area/yield are desirable, with the United States achieving the "best" value out of the six analyzed countries at about 0.13 hectares per metric ton of rice yield (Table 15).

Table 15 – Rice harvested area per unit produced (year 2005)

Area harvested (hectare) per rice yield (metric ton)					
Brazil	**China**	**India**	**Mexico**	**Russia**	**United States**
0.28	0.16	0.33	0.23	0.26	0.13

Throughout the projection period, the area/yield term remains constant at the year 2005 value for each country. Historically, (i.e. 1995-2005) the area/yield value seems to be remaining constant, especially for major producing countries like China and India. Thus, our BAU is most likely aggressive in terms of overall methane emissions from rice because naturally the yield efficiency will likely increase in time. However, this assumption of continually increasing yield efficiency is perhaps optimistic. There are biological limits to yields and even in the best tropical conditions the maximum yield that can be reached using current rice strains and agricultural technologies is 10 tons per hectare (Khush, 1995). This translates to 0.1 hectare harvested land per metric ton of rice yield. This is the technological yield efficiency level that the United States will reach around 2010 based on historical linear extrapolation of its yield per hectare levels. Once this threshold is reached I consider this the maximum yield efficiency achievable using known rice strains and agricultural practices.

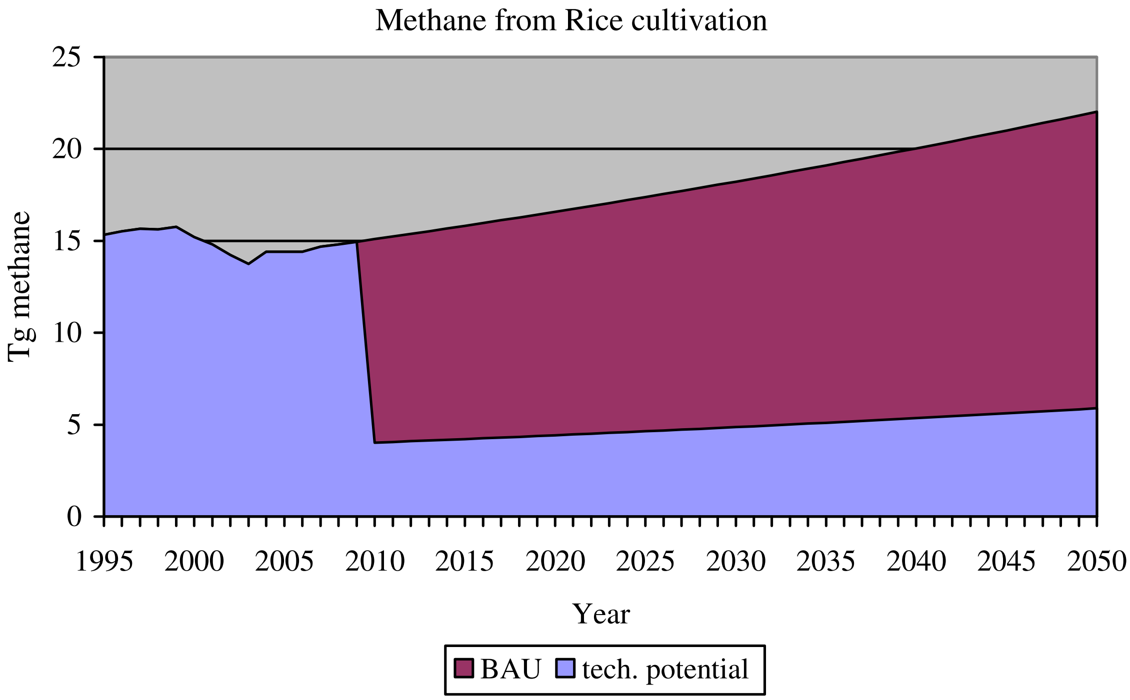
2. The CH_4/area term can be altered to reflect changing agricultural practices. In essence, the reduction of the methane released per area is a reflection of rice type, climate, irrigation practice, and addition of fertilizer used for cultivation. The overall reduction maximum is considered to be 50% reduction of CH_4/area.

For the second option, some simple agricultural management practices can be adopted to allow for a reduction in methane emissions per area. By occasionally draining the rice fields throughout the growing season, emissions reductions between 40-55% can be achieved (EPA, 1993). Also, using non-organic fertilizers or other oxidants during the growing process will potentially reduce emissions from 20-70% (Neue, 1997). Overall, the use of organic fertilizers has been found to actually *increase* methane emissions from rice paddy field by 50% (Wuebbles, 2002). With these processes in mind, as well as the potential to utilize rice strains that release less methane during its growth cycles, I reduce the CH_4/area term by 50%.

The technological potential (TP) scenario for rice cultivation emissions using these two options is described simply as:

- Each country achieves the technological yield efficiency of the United States (0.1 area/yield) by 2010
- Reduction of 50 % of the CH_4/area for each country starting in 2010.

Figure 10 – Estimated methane emissions from rice cultivation through 2050



Here we can see an overall reduction of about 75 % of projected emissions from rice cultivation in our TP scenario. This is consistent with other estimates of the potential reduction using such methods as irrigation management, nutrient management, and new rice cultivars (Cole, 1997).

Enteric Fermentation

This source of emissions results from the anaerobic digestive processes of ruminant animals and is not to be confused with animal manure management, which is typically a separate methane emissions source. Essentially, the stomachs (or rumen) of certain livestock like cattle, pigs, and sheep allow for the anaerobic digestion of grasses, plants and grain such that microbial fermentation of cellulose takes place and methane is generated (Gibbs 1997). The methane gas is produced by bacteria in the animal's rumen and exhaled through the mouth or nose. This release of energy is essentially the inefficient utilization of animal feed and can represent up to 7 % of the total energy content of animal feed (EPA, 1998). The majority (75-90%) of emissions within this sector comes from dairy and non-dairy cattle and globally contributes a substantial percentage (~15%) of the total methane budget (Augenbraun, 1997; EPA, 1999). It is therefore the largest single source of anthropogenic methane emissions.

Methane emissions from cattle and livestock are dependent on many factors but mainly come from the digestive processes of these animals. Generally, the higher feed intake leads to an increase in methane emissions coming from livestock. The various factors affecting the amount of methane emissions include the digestive process of each specific animal, the type and weight of the animals, the quality of feed and also the productive efficiency of each animal. Generally, ruminant livestock such as cattle and sheep emit more methane than pigs and horses, which are considered non-ruminant livestock (IPCC, 1996). Also, there is no information for methane emissions coming from poultry and thus these animals are not considered in this analysis.

The IPCC Good Practice guidelines use animal population statistics as the "activity data" to calculate emissions from livestock. The main driver of emissions from enteric fermentation is obviously the animal population itself which produces the methane. However, it is important to realize that the underlying drivers for the demand of meat and milk products are human population and economic increases (FAPRI, 2005). To provide an increase in the production of milk or meat from animals requires either an increase in animal population or enhanced efficiency of production per animal. In the developing world, we know that productivity of milk and meat products has been increasing through enhanced efficiency (EPA, 1998). In other words, even though the amount of methane released per head has increased substantially, the productivity has also been increasing simply because of higher feed intake for animals. Each unit of livestock is producing more meat and milk product meaning that production can be met without having to increase population. The ratio of methane emissions to milk/meat production is lower for animals with high productivity.

In this framework I assume that the future increase in productivity is met through increasing population of animals through a baseline growth rate. Therefore, I maintain the current methane emissions rate per head of animal stock in the business as usual scenario. In theory, the same result could be achieved by assuming that increased productivity will be met by increased efficiency while stabilizing or decreasing animal populations.

For our purposes, and as is calculated in the IPCC, I assess emissions from enteric fermentation to be the product of the animal population and the amount of methane released from the animal population. Again, the assumption is that future increases in production of milk/meat products, driven implicitly by increases in human population and economic growth, will be met with an increase in animal population at a constant productivity rate.

$$\textbf{(Animal population}_{\textbf{type}}\textbf{) x (CH}_4\textbf{/ Animal population}_{\textbf{type}}\textbf{)}$$

$$\rightarrow \textbf{CH}_4\textbf{ from Enteric Fermentation}$$

The Animal population$_{type}$ depends on the specific type of animal. I obtain the animal population data from the FAO. As expected, the amount of methane typically released will vary by animal and country. Even the same animal can have a vastly different emission rate depending on the country where it is raised due to feedstock issues. I use the IPCC Good Practice Guidelines to obtain regional or country-specific emission factors per type of animal.

Using the FAO database, I obtain country-specific animal stock data for various types of animals including mules, camels, buffalo, horses, pigs, sheep, and cattle. Some countries do not report stock data to the FAO, specifically buffalo data for the United States and Mexico. I assume that the buffalo data for these two countries is included in the cattle data (personal communication, FAO_statistics). Also, there is a large difference in the emission rates per head for cattle dependent on whether the cattle is used mainly to produce milk or if it is used for meat. For some countries like the United States, the emission factor for dairy cattle is twice the rate as for non-dairy cattle (IPCC, 2006). Therefore, I use the sum of the FAO cattle and buffalo statistics and subtract the sum of the FAO cattle and buffalo meat statistics per country to obtain separate stock populations for dairy and non-dairy cattle populations.

To simplify I aggregate the sheep and goat emission factors per head since they are roughly similar for developed and developing countries at 5 kg CH_4/head. Also, I aggregate the horse and mule population and then use the average emission factor of 14 kg CH_4/head. I thus have 6 animal type categories per country: 1.) Cattle/Buffalo (non-dairy), 2.) Cattle/Buffalo (dairy), 3.) Sheep/Goats, 4.) Horses/Mules, 5.) Camels, and 6.) Pigs.

I then use the default emission factors provided by the IPCC Good Practice Guidelines that describe the methane emissions per animal type, with cattle having a sub heading of Dairy or Non-Dairy. The emission factors for Sheep/Goats, Horses/Mules, Camels, and Pigs were taken from the default Tier 1 IPCC Guidelines report. The emission factors for both cattle types were taken from region-specific emission factors from the same IPCC report (Table 16). Note that this emission factors have an uncertainty level of ± 30-50 % (IPCC, 2006).

Table 16 – Methane emissions per animal type and country

Methane Emissions (kg CH_4 per head)	*Country*					
Animal Type	**Brazil**	**China**	**India**	**Mexico**	**Russia**	**United States**
Cattle/Buffalo (non-dairy)	56	47	27	53	58	53
Cattle/Buffalo (dairy)	63	61	51	121	89	121
Sheep/Goats	5	5	5	8	8	8
Camels	46	46	46	46	46	46
Horses/Mules	14	14	14	14	14	14
Pigs	1.5	1.5	1.5	1	1	1

Based on the above table, we can note differences between countries, the largest being in the diary-producing cattle in the United States. The default value for the US is almost twice that for Brazil and is directly related to the high productivity milk from dairy cattle. Since this high productivity is linked to increased feed intake for dairy cattle in the US, the amount of methane produced per head of dairy cattle is exceptionally larger in the United States. According to the IPCC Good Practice Guidelines, "feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, or pregnancy)" (IPCC, 2006).

Now that we have animal stock in population as well as the methane emission factor per animal type, we can calculate the total methane emitted per animal type in each country. Once this value is summed for all animal types, I sum the respective methane emitted per animal population. This will again give the "methane efficiency" per animal type and country.

The technology term in its entirety is therefore:

[Cattle/Buffalo (non-dairy) * CH_4/cattle/buffalo (non-dairy)] +
[Cattle/Buffalo (dairy) * CH_4/cattle/buffalo (dairy)] +
[(Sheep/Goats) * CH_4/(Sheep/Goat)] +
[(Camels) * CH_4/(Camel)] +
[(Horses/Mules) * CH_4/(Horse/Mule)] +
[(Pigs) * CH_4/(Pig)]

→ CH_4 from all animal enteric fermentation

Unlike the other characterizations, the enteric fermentation source is assessed independently of the EPA and EDGAR databases. I therefore use their estimates and projections as a comparison. Although my characterization of this source estimates methane emissions from the United States to be twice the level of the EPA estimates, the other countries' estimates seem very comparable. The discrepancy for the United States is the fact that EPA uses the IPCC default factor for emissions from cattle in "developing nations" which is 55 kg/head whereas in the my estimate, the country-specific value of 121 kg/head is used (IPCC, 2006). Therefore, since I am using the country-specific value, I maintain that this characterization more accurately describes emissions from this source. In fact, the discrepancy is valid for other countries as well, although not to the same large extent as the United States. In all instances, the our country-specific projections are larger than the EPA estimates since the IPCC country-specific emission rates (kg CH_4/cattle head) are larger than the default values (i.e. developing countries and developed countries).

Projections for Business As Usual Scenario

The FAO provides short-term projections for the production of meat and dairy products on a per country basis through 2010. However, due to the inherent difficulty of projecting animal stock populations, I use the growth rate associated with increasing production and apply directly to population. After 2010, I assume the same growth rate that corresponds to the projected 1999-2010 growth rate from the FAO report and project out to 2050 (FAO, 2003). The method is used to project the cattle/buffalo (non-dairy), cattle/buffalo (dairy), sheep/goat and pig animal populations through 2050. For the camel and horses/mules populations, we assume the 2005 value to remain constant through 2050. These particular populations are not changing historically and thus this is a valid and conservative estimate.

The individual animal type country-specific values for the emissions of methane per head remain constant throughout the projection period to 2050. As described above, the emission factor (kg methane per head) levels are highly uncertain and are subject to change based on the quality of feed, the climate, and the overall agricultural practices per country. I can reflect these differences through a percentage change to the emission factor per animal type but maintain this value at the current level throughout the BAU projection. In other words, the increased productivity of milk and meat products is reflected in an increase in animal population.

Recommendations for Technological Potential Scenario

According to the EPA Greenhouse Gas Report, population growth combined with increases in wealth in developing nations will drive the demand for livestock products including milk and meat production (EPA, June 2006). China and India alone are projected to demand a 44 % increase in milk production by 2015 (FAPRI, 2006). Not only is demand expected to increase but the agricultural production methods are becoming more centralized and commercialized which is further increasing livestock productivity and size, thereby directly increasing methane emissions.

The independent projections of each type of livestock as well as IPCC default methane release values per head of each type of livestock produces emissions estimates per country through 2050. Therefore, there are two options within the framework for achieving a reduction in methane emissions from the enteric fermentation source. We can outline the reduction potentials:

1. Reduce the projected growth rate of certain livestock to reflect a lower demand for milk and meat production.
2. Reduce the kg methane released per head of livestock from the default IPCC values

For the first option, it is highly uncertain how the growth of each animal type will increase in the future and indeed, the projections from FAO only describe population through 2010. Therefore, my values could be either an exaggeration if demand decreases or contrarily could be conservative if growth explodes in the future. Therefore, for the TP scenario, I leave the projections of animal growth as they are in the BAU.

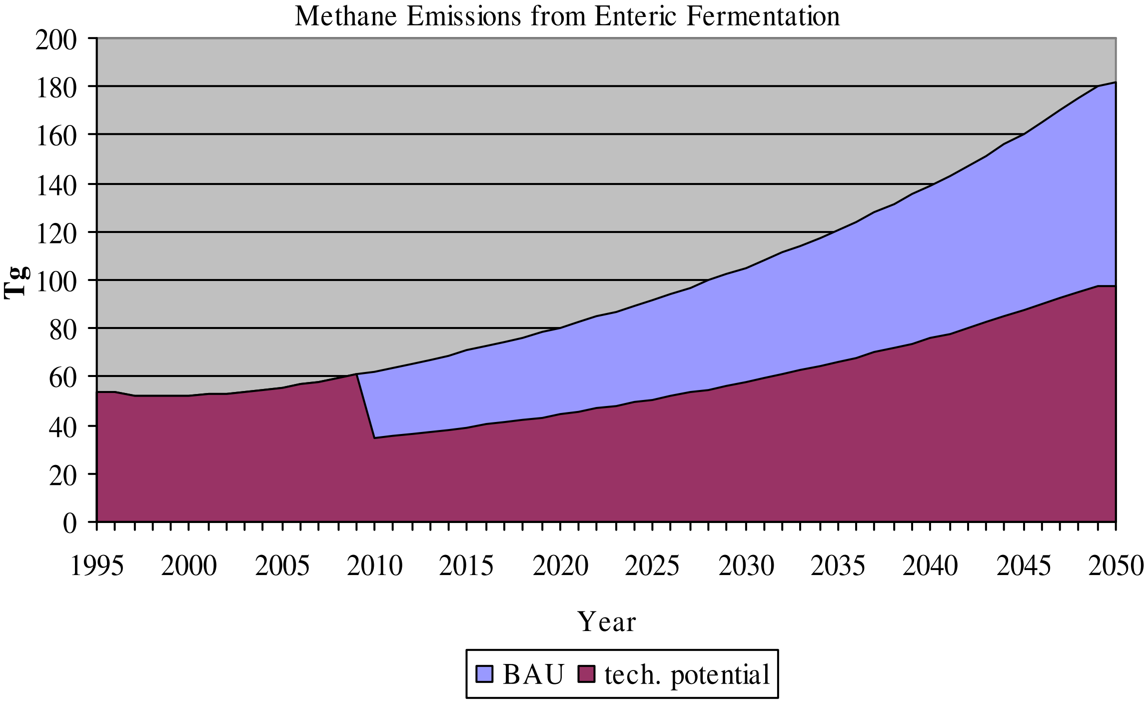
The second method deals with the agricultural and technological practices of producing milk and meat from livestock. The implication of a reduction of this term (CH_4/head) is that the productive yield is increased; the qualities of feed increases; and/or the animals have an overall healthier lifestyle. As mentioned above, historically the United States has increased the CH_4/head yet increased the productive efficiency of its animal population such that production can increase while animal populations remain constant. However, other nations have increased animal populations to meet demand and could benefit from improvement in productive efficiency. In fact, simply increasing the feed quality in developing nations for dairy cattle would allow the methane released per production of milk to decrease by as much as 75 % (Wuebbles, 2002). Other estimate potentials include supplementation of diets in Asia and Latin America that have been shown to decrease methane emissions for dairy cattle by 65 % and for meat producing cattle by up to 80 % (Cole, 1997).

On top of this, improving the grazing management practices could go a long way in reducing methane emissions. This would require a determined effort to improve the soil and grass plots on which animals graze. Also this would involve employing rotating graze management practices such that the pasture is not entirely depleted and the growth of a diverse and continuous supply of pasture is promoted (EPA, 1997).

Finally, perhaps the most controversial form of enhanced productivity which would reduce methane emissions is the use of production enhancing supplements on livestock. These include protein supplements, anabolic steroids to increase growth rate of cattle for meat production, bovine growth hormones to increase milk production from dairy cattle and other genetic improvements (EPA, 1997). All of these agents would act to increase the productive yield per head of cattle and thus would ultimately reduce methane emissions since less livestock would be needed to meet demand. However controversial this practice is, infusing protein supplements and production-enhancing vitamins could reduce ruminant methane emissions by up to 40% (EPA, 1993).

Overall, it has been documented that all currently available technologies are estimated to be able to reduce emissions from ruminant livestock per unit product by between 25-75 % (Turnbull, 2001). With all of these mitigation options in mind, I create a TP scenario for the six analyzed countries. To do this, I reduce the CH_4/head value for only dairy cattle and non-dairy cattle by 50 % starting in 2010 to reflect higher quality feed, improved grazing management practices and the usage of production-enhancing agents (Figure 11).

Figure 11 – Estimated methane emissions from enteric fermentation through 2050



Based on the technological potential (TP) assumptions, it is clear that methane emissions from the six analyzed nations from enteric fermentation can potentially be reduced by 45 % throughout the projection period. Considering that this source is the largest anthropogenic methane source, the total reduction of methane by 2050 of 100 Tg is more than the reduction of methane from all other analyzed sources combined.

Results and Observations

The emissions projections that I have compiled are interesting in their own right in terms of gaining insight into what is driving methane emissions, how the various sources are projected to change in the future, and which of the analyzed countries are responsible for the majority of emissions by source and year. Using the spreadsheet model that I have created, one can generate numerous alternate methane emissions pathways in order to better understand the impacts of improving methane capture for certain sources and, more importantly, the challenge of reducing emissions such that the business as usual (BAU) pathway is not realized. However, to gain further insight into what this implies for the climate, we need to understand how anthropogenic methane emissions will behave on a global scale. I can make some assumptions that take the emissions from our six countries and six sources and scale up to a global level. To understand the climate impacts, I use the simple climate model MAGICC (Model for the Assessment of Greenhouse Gas Induced Climate Change) developed by Tom Wigley at NCAR and subsequently used in the IPCC to determine concentrations of certain atmospheric gases as well as the associated global temperature and sea-level rise.

Global Emissions

To extrapolate the calculated methane emissions to global values so that one can observe climate implications, I must “scale up” the total country-specific values to include not only the remaining unaccounted-for anthropogenic emissions (since I only analyzed the 6 main sources) but also the rest of the world.

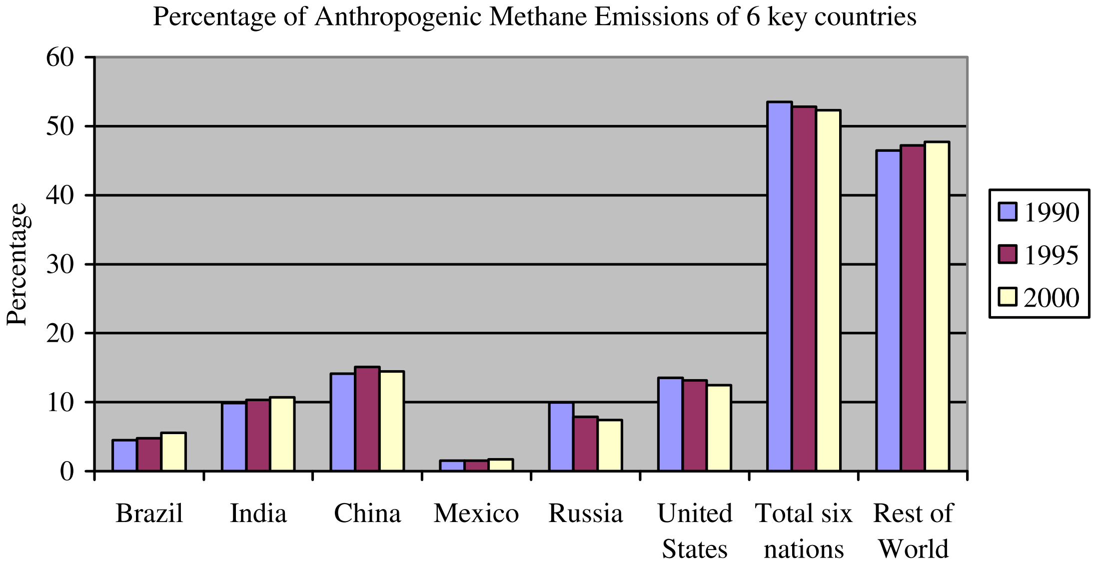
To account for the other remaining anthropogenic methane emissions sources, I can again use the EPA and EDGAR databases, which have documented emissions levels per country for all known anthropogenic sources. I use the year 2000 breakdown to account for the remaining anthropogenic methane emissions per country (Table 17). This percentage breakdown is maintained throughout the projection period (i.e. through 2050) implying that the un-modeled sources grow at the same rate as the modeled sources. As indicated in the table, the six modeled anthropogenic sources represent the vast majority of total anthropogenic methane sources per country with values greater than 90 % with the exception of Brazil. Deforestation is so rampant in Brazil and is considered a large source of anthropogenic methane emissions and thus accounts for a larger percentage of unaccounted anthropogenic emissions source.

Table 17 – Proportion of modeled anthropogenic six sources to total emissions

YEAR 2000	**BRAZIL**	**CHINA**	**INDIA**	**MEXICO**	**RUSSIA**	**UNITED STATES**
% of total anthropogenic	70	90	87	90	93	95
Scaling factor	1.3	1.1	1.13	1.1	1.07	1.05

Now that we have total anthropogenic methane emissions for the six analyzed nations, we need to account for the rest of the world and scale up to a global anthropogenic methane emissions value per year. Again, I refer to the EDGAR and EPA databases for the year 2000 and calculate the sum of the six nations total anthropogenic methane emissions and find the percentage they represent. Both datasets agree that these six nations represent between 45-50 % of the total global anthropogenic methane emissions. Therefore, I "scale up" the summed country total values to a global scale by a 100 % increase throughout the projection period. Again, the assumption here is that the rest of the world anthropogenic emissions will grow at the same rate as our six key nations. This assumption seems reasonable based on historical observations (Figure 12)

Figure 12 – Contribution of anthropogenic methane emissions compared to world



Since we have projections of methane emissions within the IPAT framework, we can see how our Business as Usual emissions scenario compares with the projections in the IPCC Special Report on Emissions Scenarios (SRES, 2001). Here, simple assumptions are made about economic and population growth as well as global trade and various emissions pathways are projected. The 40 scenarios are categorized based and future global "storylines" and separated into 4 main types labeled A1, A2, B1, and B2. Basically, the A storylines describe a world where market forces dominate development that lead to higher emissions pathways whereas the B storylines focus more on sustainable development and technology sharing that lead to lower emissions. Further distinction between "1" and "2" imply higher and lower economic growth and homogenous and heterogeneous technology scenarios. (Table 18)

Table 18 – SRES scenario mode description

A1: Rapid economic growth, global convergence, more equal per capita income *High Emissions*	**A2:** Slow convergence, self-preservation, Slower economic growth, regionally oriented *High Emissions*
B1: Rapid economic growth, global convergence, shift to service/information economy, more efficient technologies *Low Emissions*	**B2:** Localized solutions to improvement of economy/environment, intermediate growth *Low Emissions*

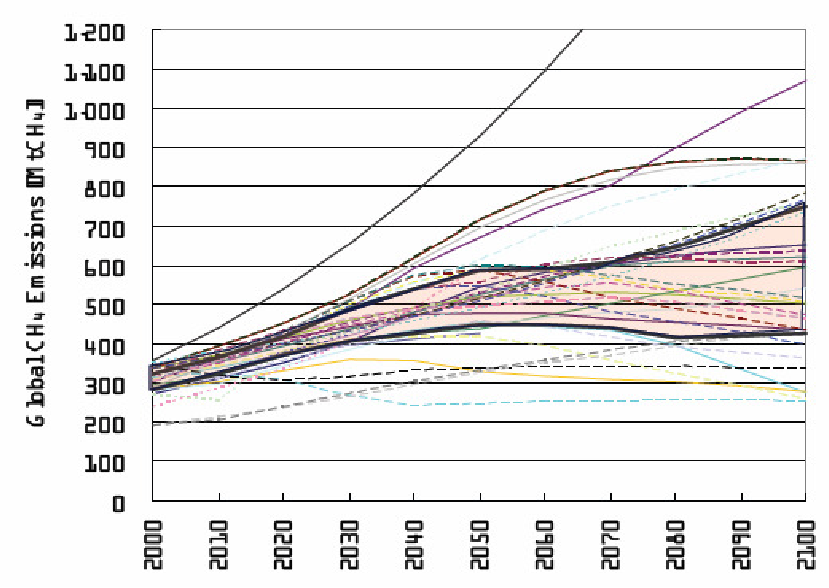
For our analysis, we will focus on the A2 scenarios since our world appears to be more fitting to this market driven, technologically heterogeneous storyline. MAGICC contains 6 scenarios within the A2 storyline that comprise a wide range of emissions pathways. These include A2A1MI, A2AIM, A2-ASF, A2GIM, A2MES, and A2MIN. All these scenarios use the assumptions in the A2 SRES description but are analyzed using different climate models. The "marker" scenario for the A2 storyline is the A2-ASF scenario and the maximum (A2MES) and minimum (A2GIM) emissions scenarios in terms of methane emissions.

Since the SRES scenarios illustrate emissions pathways through 2100, I need to take the global IPAT CH_4 emissions values, which go only out to 2050, and extrapolate out to the year 2100. This extrapolation is highly uncertain but for this analysis I determine a range of possibilities. I first take the BAU pathway and linearly extrapolate to 2100 from the 2050 level. This will be considered a maximum BAU scenario. Then I logarithmically extrapolate the IPAT 2050 projections and consider this the minimum BAU scenario. In other words, I assume a logarithmic fit to the projections through 2100.

This analysis of anthropogenic methane emissions underestimates the amount of global emissions in the year 2000 compared to the SRES scenarios. The reasons for this are as follows. First, the scaling factors used to obtain country-level emissions accounting for the other anthropogenic sources are constant which could mean that other sources actually constitute a larger percentage of total anthropogenic emissions per country. Secondly, the scaling factor for the rest of the world is also a constant. This could mean that our 6 countries represent a smaller fraction of the world total than we have analyzed here. Finally, although the global emissions underestimate the value in the year 2000, the trend quickly approaches the SRES predictions and thus closes the emissions difference. This is due to the exponential growth inherent in the parameters used to project emissions (i.e. population and affluence).

It is important to note that there is much uncertainty in assessing anthropogenic methane emissions and the IPCC states this uncertainty is at least 25 % (IPCC, 2001). Even in the year 2000, the largest deviation of global emissions, these estimates are within 30 % of the SRES predictions. To give some context of other total global anthropogenic methane emissions projections we can look at the full range of pathways (Figure 13). The figure below illustrates that there is a wide range of estimated anthropogenic methane emissions though time starting with values as low as 200 Tg in the year 2000 (Hanaoka 2006).

Figure 13 – Estimates of total global anthropogenic methane emissions pathways (Hanaoka, 2006)



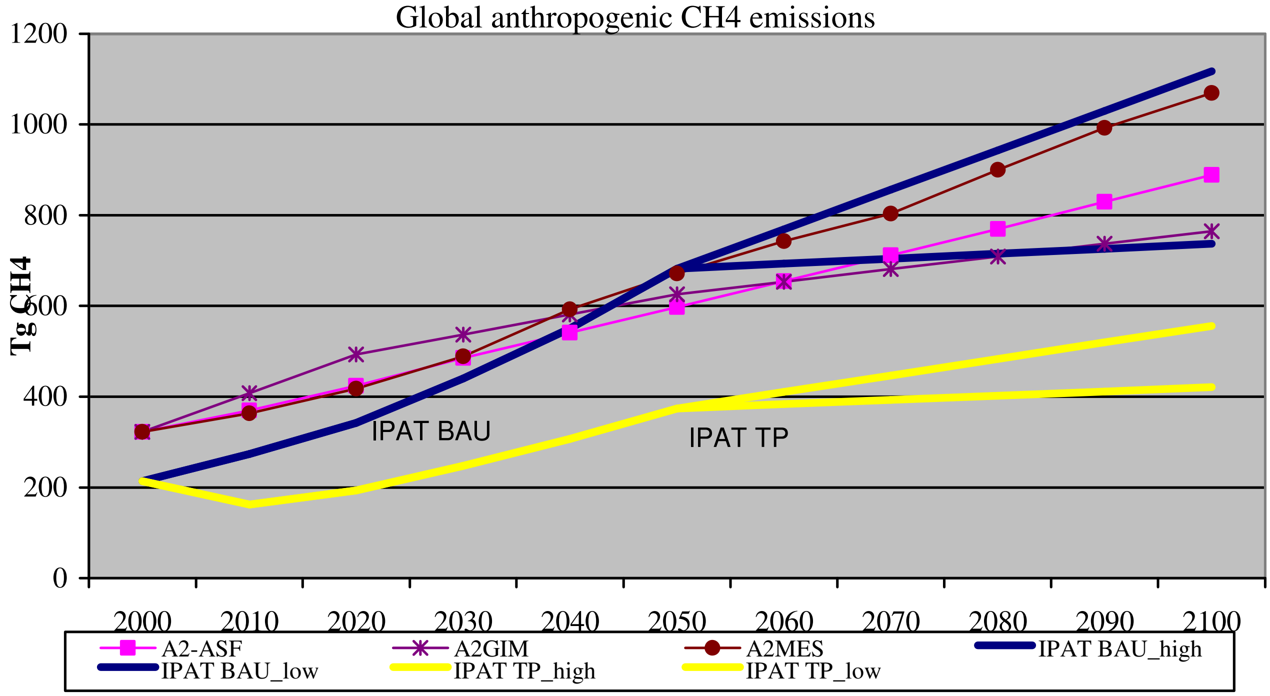
Building on the Business as usual projection of anthropogenic methane emissions out to 2050, I compile the individual source and country information and establish a "Technological Potential" (TP) methane emissions scenario. The following table outlines and summarizes the overall reduction in methane emissions for each source. The full description of the reduction is located in the "Materials and Methods" section previously.

Table 19 – Reduction of methane emissions per source from BAU projection

Overall Reduction from BAU 2010 through 2050 in the Technological Potential						
Source	Rice cultivation	Enteric Fermentation	Coal Mining	Natural Gas and Oil Systems	Landfills	Wastewater
6 nations	50-75 %	44 %	43 %	26 %	25 %	50-55%

Using the assumptions to scale to the global level, I obtain the following as the business as usual (BAU) and technological potential (TP) emissions pathways (Figure 14). The graph below shows the full comparison between the two BAU scenarios and the marker, maximum, and minimum SRES emissions pathways (Figure 14). It is clear that the linear extrapolation is directly comparable to the maximum SRES pathway (i.e. A2MES) and the logarithmic extrapolation is directly comparable to the minimum SRES pathway (i.e. A2GIM). The marker scenario (A2-ASF) represents the mid range of the maximum and minimum scenarios.

Figure 14 – Comparison of global anthropogenic methane emissions pathways



As can be seen above, my technological potential projections offer reductions of roughly 40 % from the baseline. It is important to note that in my simple analysis, my business as usual projections match nicely with the maximum and minimum SRES IPCC scenarios.

Global Concentrations

Now that we have established emissions pathways for methane that are consistent with the IPCC SRES pathways, I use MAGICC to generate concentration levels and the associated radiative forcing that occur over time. Ideally, I compare the two BAU scenarios with the maximum and minimum SRES scenario pathways. To do this, I take the IPAT projections and replace the methane values in the marker A2-ASF scenario. I use the high case (i.e. linear extrapolation to 2100) and low case (i.e. logarithmic extrapolation to 2100) to illustrate a range of emissions pathways. Note that the other emissions associated with A2-ASF such as CO_2, SO_2, HFCs, etc will remain as they are in the original A2-ASF scenario and thus only the methane emissions are changed. Also note that MAGICC applies a default natural methane emissions value to each year, which does not change throughout the projection period. MAGICC adds a certain amount of natural emissions per year to the input anthropogenic methane emissions to account for all natural sources, which remain constant through time. This assumption is likely to underestimate the total future methane emissions pathway since natural emissions will likely increase as the climate warms (Wuebbles, 2002).

The objective here is to establish a baseline maximum and minimum global emissions scenario such that one can observe the impact of a methane emissions pathway change on radiative forcing and ultimately on temperature fluctuations over time. Once this baseline is established with a maximum and minimum concentration range identified, the IPAT methane emissions can be changed to reflect technological improvements by country or source.

It is important to digress into how MAGICC calculates the concentration of methane in the atmosphere based on input emissions over time. Just as in the IPCC assessment, MAGICC uses an empirical global mass-balance equation to determine concentration of methane.
The change in concentration of methane is mediated by the emissions and the three known sinks (reaction with the OH radical, loss to the stratosphere, and absorption by the earth's soil)

$$(1)\ d\mathrm{C}/dt = E/2.78 - C/\tau_{\mathrm{OH}} - C/\tau_{\mathrm{STRAT}} - C/\tau_{\mathrm{SOIL}}$$

- C → global-mean tropospheric abundance of CH_4 in ppb
- E → total (natural + anthropogenic) CH_4 emissions in Tg/year
- τ_{STRAT} → stratospheric sink lifetime of 120 years
- τ_{SOIL} → soil sink lifetime of 160 years
- τ_{OH} → OH radical sink that is determined by equation (2)

The OH sink which determines the concentration of methane in the troposphere is in turn determined by the relative abundance of other reactive gas concentrations, namely CH_4, VOC, CO and NO_x.

$$
\begin{aligned}
(2)\ d(\ln \tau_{OH})dt = -0.32d(\ln C)/dt + 0.0042dE(NO_x)/dt \\
- 0.000105\ dE(CO)/dt \\
- 0.000315\ dE(VOC)/dt
\end{aligned}
$$

- CO, VOC → Tg/year where natural emissions remain constant
- NO_x → Tg/year of N
- For the year 2000 as a baseline, $\tau_{OH} = 9.6$ years, C = 1764 ppbv, $dC/dt = 8$ ppb/year

Now, for all of the SRES scenarios, the baseline year 2000 values are used to balance equation (1) such that the total emissions reflect this balanced initial budget. The reason for this is that in the year 2000 the concentration of methane was relatively stable and considered at steady-state meaning that the sinks essentially were exactly counteracting the sources in this year. In other words, the known concentration loss rate (8ppbv/year) was compared directly to the known CH_4 concentration in the year 2000 (i.e. 1764 ppbv) as well as the known atmospheric lifetimes of the sinks and the total emissions was back-calculated using equation (1).

$$(1)\ dC/dt = E/2.78 - C/\tau_{OH} - C/\tau_{STRAT} - C/\tau_{SOIL}$$

$$8\text{ppbv/yr} = E/2.78 - 1764\text{ ppbv}/9.6\text{ yr} - 1764\text{ ppbv}/120\text{yr} - 1764\text{ ppbv}/160\text{yr}$$

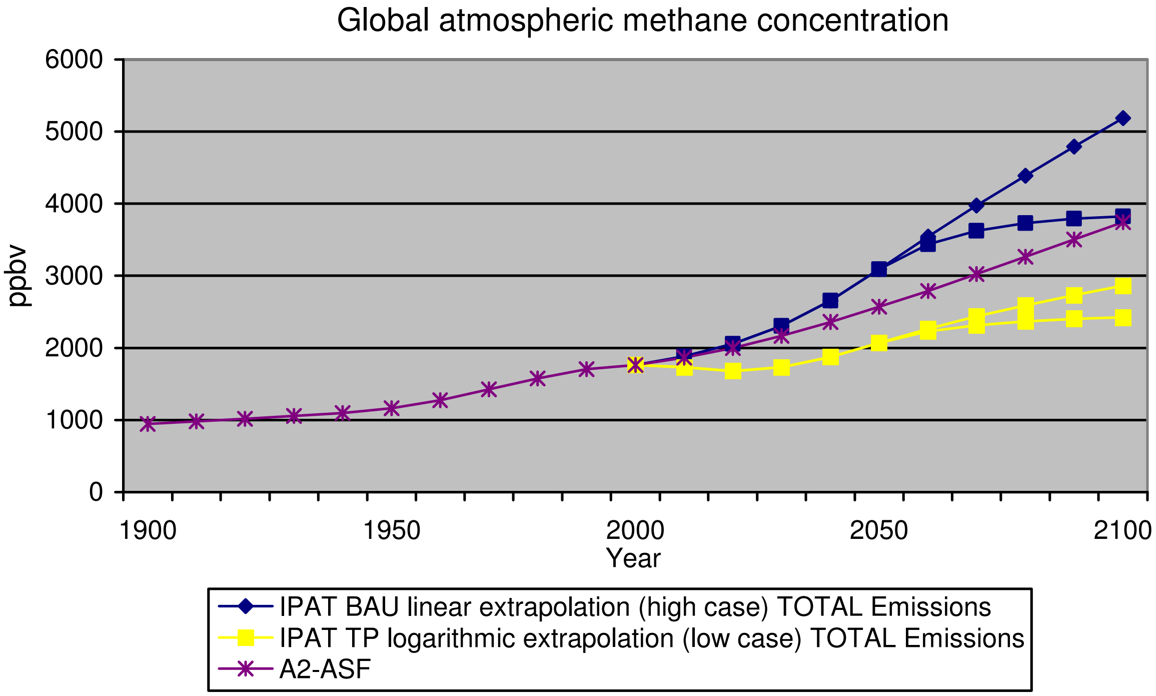
Total CH_4 Emissions → 604.5805 Tg in 2000

Therefore, the total emissions of methane in the year 2000 are ~605 Tg according to this mass-balance equation. Initially, for the A2-ASF scenario and all other A2 MAGICC scenarios, the anthropogenic input methane emissions are 323 Tg for the year 2000 meaning that the “natural” emissions must equal ~282 Tg. This constant offset is added to all future values of input anthropogenic emissions to give the total per year.

For the IPAT projections, the initial year 2000 value of global anthropogenic methane emissions is different from the IPCC SRES at only 214 Tg. This difference is due to the fact that this framework contains assumptions that scale the modeled six sources into a global level. In other words, not all sources are explicitly accounted for and thus the IPAT projections slightly underestimate total anthropogenic emissions, at least initially. The mass-balance equation represents the total emissions (natural + anthropogenic), which is known because of the measured concentration level. More of the uncertainty lies in the ratio of natural to anthropogenic emissions. In other words, in the IPAT model, I calculate a smaller amount of initial anthropogenic emissions at 214 Tg and thus assume more natural emissions to achieve the total 605 Tg.

I calculate the total methane concentration using the mass-balance equation with the same initial conditions as the SRES scenarios (Figure 15). However, note that MAGICC adds a higher level of natural emissions (390 Tg) to the inputted anthropogenic emissions. This value is added to each year throughout the projection period. This should not affect our analysis since it is a constant added to each year. Also, this may be conservative considering that natural emissions will likely increase in the future due to changes in the climate itself.

Figure 15 – Global atmospheric methane concentration



The resulting difference between the high and low business as usual (BAU) methane projection cases can be seen in Figure 15. Again, all other gas emissions have remained as they are in the scenario A2-ASF and the only difference is in the anthropogenic methane emissions. Using equations (1) and (2) through MAGICC the methane concentration of the scenario emissions pathways is calculated while assuming the same emissions of VOC, NOx, and CO used in the A2 scenario.

Climate Implications

In the technological potential (TP) scenario, the projections indicate that fugitive methane emissions from the 6 main sources will be reduced through the implementation of feasible and existing technologies and options. This reduced overall methane emissions by roughly 40 % starting in 2010 throughout 2050. Depending on the assumed pathway out from 2050-2100, the linear (high) case offers reductions of up to 50% through 2100 and the logarithmic (low) case offers reductions of up to 40 % in 2100.

The “avoided” methane emissions that are captured in the technological potential (TP) scenario are assumed to be used as an energy source. I take the captured methane emissions from only the energy and waste sectors from 2010 through 2050 and sum them for the six countries. Again, assuming the rest of the world follows suit, I double the captured methane emissions to obtain a global captured methane emissions potential. I then assume that 100 % of the avoided emissions are combusted in electricity generation. Thus, using the captured methane emissions as the fuel source can offset a certain amount of CO_2 that is projected in the A2 scenarios that came from fossil fuel combustion. Thus, I am essentially replacing the CO_2 coming from coal plants with CO_2 coming from the combustion of the captured methane emissions. Since burning methane for fuel is twice as efficient in terms of CO_2 per kWh electricity generated, there will be a certain amount of reduction of CO_2 in the overall carbon profile.

I can provide an example of this calculation using the Business as Usual (BAU) low case and the Technological Potential (TP) low case. In these scenarios, the difference in anthropogenic methane emissions is roughly 40 % from 2010-2100. This assumes that the reductions achieved in the 6 analyzed nations are reflected globally such that the rest of the world achieves similar reductions. Now, these emissions reduction include those from the agriculture sector (enteric fermentation and rice cultivation). I do not consider them here since these reductions would not be used as an energy source and instead are “consumed” through increased productivity. Thus, I take the difference in methane emissions from the energy and waste sectors only from the 6 analyzed nations and double this to account for the globe.

Avoided Methane emissions from globe →

$$2 \times [(\text{Waste Sector, Energy Sector})_{BAU} - (\text{Waste Sector, Energy Sector})_{TP}]$$

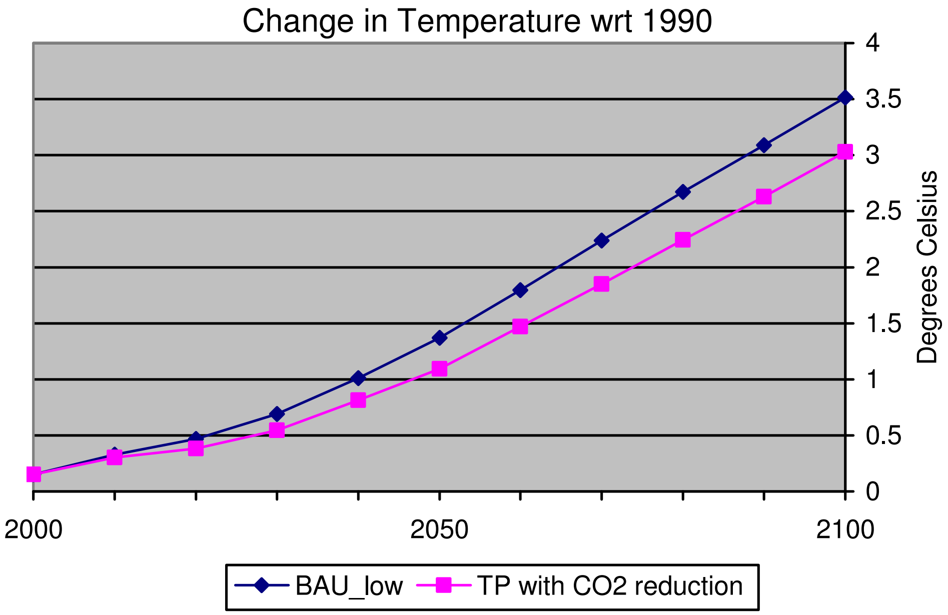
After obtaining the captured emissions per year, I translate this into available energy (BTU) through a conversion factor assuming this methane is 100% natural gas. The BTU is then translated into electricity potential (kWh) assuming a conversion factor of 10000 BTU per kWh. This is typical amount of energy required to create a kWh of electricity from a natural gas fired power plant. This amount of electricity from natural gas combustion generates CO_2. However, I assume that this CO_2 displaces a larger amount that would have been created from coal-burning plants. Since natural gas-fired electricity is twice as carbon efficient at generating electricity than coal, I obtain an avoided CO_2 number per year (Table 20). This can be subtracted from the CO_2 profile in the SRES A2 scenario for analysis in the temperature change profile. The avoided CO_2 from 2050 -2100 is the same as the 2050 level since we assume that methane emissions have stabilized at that point.

Table 20 – Global captured carbon emissions from methane reductions (2010-2100)

Year	Global captured methane emissions from Waste + Energy Sectors $(BAU - TP)_{low}$ (Gg methane)	Decrease in CO_2 if used to displace coal electricity production ($Gg\ CO_2$)	CO_2 reduction (Pg)	Carbon reduction (Pg)
2010	59955	3224803	3.22	0.88
2020	76312	4104573	4.10	1.12
2030	103638	5574374	5.57	1.52
2040	130202	7003155	7.00	1.91
2050	160296	8621795	8.62	2.35
2060	160296	8621795	8.62	2.35
2070	160296	8621795	8.62	2.35
2080	160296	8621795	8.62	2.35
2090	160296	8621795	8.62	2.35
2100	160296	8621795	8.62	2.35

Once again, using MAGICC I take the BAU (low case) and TP (low case) methane emission pathways and determine the resulting global temperature changes using the A2-ASF SRES emissions profile. The emissions for CO_2 are left as is for the BAU (low case) but I subtract the avoided carbon in the TP (low case). (Figure 16).

Figure 16 – Estimated temperature change from BAU and TP emissions pathways



The temperature difference in 2100 reflects a 0.5 degree Celsius reduction from the Business as Usual pathway. In other words, the reduction of methane emissions (roughly 40%) along with the reduction of carbon dioxide via the use of the avoided methane as an energy source displacing coal-fired electricity produced a global temperature decrease of ½ a degree Celsius. The temperature decrease due to methane reductions themselves (with no CO_2 displacement from the A2 scenario) offers about half of the observed temperature decrease. In other words, without using the captured methane from the waste and energy sectors to displace otherwise coal-generated CO_2 would still reduce global temperatures by 2100 but only by about 0.25 degrees Celsius. This would make less sense realistically since the captured methane from the waste and energy sectors would most likely be used to generate electricity or combusted for some other usable purpose.

Discussion and Conclusion

There are significant uncertainties in factors that affect methane emissions and how these factors will change over time. As a consequence of this, the concentration of methane in the atmosphere through time is also highly uncertain. This analysis does not take into account the fact that natural emissions of methane emissions will likely change over time simply due to climate change itself. However, using this simple framework enables one to gain insight into the macroscopic influences that shape emissions coming from major anthropogenic sources and how these sources affect different nations. One of the limitations of this simple bookkeeping framework is that the individual parameters are not, in fact, independent. The feedbacks and interdependence between factors exist such that changes in population will likely impact economic status as well as certain production projections used in this analysis. This framework sacrifices these dynamical interactions for simplicity and transparency. Rather than being used to accurately predict emissions profiles, it is a tool that sheds light on the main drivers of anthropogenic methane emissions and provides a platform for decision-makers to discover how much impact certain policies will likely have in the future given a perceived rate of growth.

Of course, the idea of reducing methane emissions from anthropogenic sources in order aid in mitigating global warming is not new. James Hansen has described the need for reducing methane emissions from anthropogenic sources by 30 % in order to provide a negative forcing of 0.2 W/m^2 that would counteract some of the future increases in global warming from the build up of CO_2 (Hansen, 2000). However, he describes how "a better understanding of the CH_4 cycle, especially CH_4 sources" is needed.

Recently, Paul Lucas et. al published work that describes the long-term potential for reducing methane citing global abatement potentials per source in 2050 and 2100. My results using IPAT obtain similar percentage reductions and in fact are conservative compared to their abatement reductions (Lucas, 2007). Still, my work projects methane abatement potential on a country-specific basis as opposed to global level.

It is clear that future increases in methane emissions from anthropogenic sources can and will significantly impact our climate. In terms of climate policy, it makes sense to incorporate non-CO_2 greenhouse gas reduction strategies, especially for methane, for many reasons. These include (1) the relatively short lifetime (8-12 years) of methane in the atmosphere enabling for quick concentration reductions; (2) the direct economic benefit of using the captured methane as a feedstock for electricity generation; (3) the associated CO_2 offset via using the captured methane in electricity generation as opposed to dirtier sources like coal; (4) the air quality connection between increasing methane concentrations and tropospheric ozone.

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