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ABSTRACT

There is a growing public consensus that the primary cause of climate change is anthropogenic greenhouse gas (GHG) emissions and that it will be necessary for the global community to use low-carbon technologies in both the energy and industrial sectors (IEA, 2013). As a result of the recent focus on GHG emissions, the U.S. Environmental Protection Agency (EPA) and state agencies are implementing policies and programs to quantify and regulate GHG emissions from sources in the United States. These policies and programs have generated a need for a reliable source of information regarding GHG mitigation options. In response to this need, EPA developed a comprehensive GHG mitigation options database (GMOD). The database is a repository of data on available GHG technologies in various stages of development for several industry sectors. It can also be used to assess the performance, costs, and limitations of various mitigation control options. This paper further describes the objectives of GMOD, the data available in GMOD, and functionality of GMOD as an analysis tool. In addition, examples are provided to demonstrate GMOD's usability and capabilities. A comparison of GMOD to other existing GHG mitigation databases is also provided along with the recommended next steps for GMOD.

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1. Introduction

Concern regarding greenhouse gas (GHG) emissions has grown over the past quarter century, and a heightened awareness has occurred over the past 5–10 years amidst new policies, programs, and regulations. A brief description of current GHG policies, programs, and regulations is provided in this section.As outlined below, the most significant regulation of GHGs has occurred in the past 2–3 years, and additional regulations are anticipated in the near future.

Started in 1990, the inventory of U.S. GHG emissions and sinks tracks the national trend in GHG emissions and removals. The national GHG inventory is submitted to the United Nations in accordance with the Framework Convention on Climate Change. The inventory is compiled using a "top-down" approach and is designed to develop aggregated emissions for a source type or sector. The inventory shows that since 1990 GHG emissions have increased by 10.5%.

The Greenhouse Gas Reporting Program (GHGRP) mandates a more refined estimate of GHG emissions from large industrial sources (direct emitters) in the United States than the GHG inventory. The program requires facilities within regulated source categories that emit GHGs above a certain reporting threshold to report GHG emissions at the facility level. The goal of the reporting program is to help the U.S. Environmental Protection Agency (EPA) understand where anthropogenic GHGs are coming from so that EPA can make informed policy, business, and regulatory decisions. In total, 41 source categories reported GHG emissions data for

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Table 1
Greenhouse gas reporting program – 2011 data highlights.[a]

Industry sector	Number of reporters	Emissions (million metric tons CO_2 emissions)	Percentage of total
Power plants	1594	2221	67.0
Petroleum and natural gas systems	1880	225	6.8
Refineries	145	182	5.5
Chemicals	458	180	5.5
Other industrial	1377	126	3.8
Waste (including landfills)	1593	103	3.1
Metals (including iron and steel)	297	115	3.5
Minerals (including cement)	362	98	3.0
Pulp and paper	230	44	1.3
Total		3300	

[a] Data from EPA's Greenhouse Gas Reporting Program (data current as of 1/16/13). Biogenic emissions and emissions from suppliers are not included in the table. The majority of the GHG emissions associated with the transportation, residential, and commercial sectors are accounted for by suppliers. http://www.epa.gov/ghgreporting.

calendar year 2011, which accounts for 85–90% of U.S. GHG emissions from large industrial sources. The first reports were submitted in 2011 and contained estimates of GHG emissions from calendar year 2010. Annual reporting is required for facilities subject to the rule.

The data in Table 1 summarize the GHG emissions reported from various industry sectors for calendar year 2011 and show the percentage of total emissions for each of the nine sectors. Over 70% of the total GHG emissions reported in 2011 through the GHG reporting program are associated with sectors currently included in the GHG mitigation options database (GMOD). As the table indicates, power plants accounted for approximately 67% of reported emissions in 2011. The iron and steel industry accounted for 1.75% of total GHG emissions (roughly one-half of the emissions from the metals sector). The cement industry accounted for 0.75% of total GHG emissions (roughly one-quarter of the emissions from the minerals sector), and the pulp and paper industry accounted for 1.3% of total GHG emissions in 2011 (US EPA, 2013a). [In 2008, the United States had the second highest emissions of CO_2 worldwide from fossil fuel combustion, cement manufacturing and gas flaring. Emissions from the U.S. were almost 20% of global emissions (U.S. EPA, September 2013).]

In addition, other programs have been developed at the state or regional level, such as the Regional Greenhouse Gas Initiative (RGGI), that established a cap-and-trade program for CO_2 for states in the Northeast, with some eastern Canadian provinces also participating as observers. The first RGGI auction was held in 2008. Also, in the later part of 2012, California developed a cap-and-trade program. Cap and trade is an environmental policy tool that delivers emission reduction results with a mandatory cap on emissions while providing sources flexibility in how they comply. Examples of successful cap-and-trade programs include the nationwide Acid Rain Program, the regional NO_X Budget Trading Program in the Northeast that resulted from the NO_X State Implementation Plan Call, and the NO_X and SO_2 trading programs under the Clean Air Interstate Rule. The RGGI and California carbon cap-and-trade programs include an enforceable GHG cap that will decline over time. RGGI holds auctions for allowances with proceeds used to promote energy conservation and renewable energy. The California Air Resources Board will distribute allowances, which are tradable permits, equal to the emissions allowed under the cap.

Permitting requirements are also emerging for facilities emitting GHGs. On April 2, 2007, the U.S. Supreme Court found that GHGs are air pollutants covered by the Clean Air Act (US EPA, 2012). In December 2009, EPA made the endangerment findings under the Clean Air Act regarding GHGs, both for the public health and public welfare of current and future generations (US EPA, 2009). In the years that followed, EPA undertook a series of actions and rulemakings in response to those rulings to begin regulating GHGs under the Clean Air Act (US EPA, 2012). As part of this effort, on May 13, 2010, EPA signed the Prevention of Significant Deterioration (PSD) and Title V GHG Tailoring Rule to tailor the applicability of the New Source Review (NSR)/PSD and Title V air permitting programs to GHG emissions (US EPA, 2012). The rule "tailors" the permitting requirements to determine which new and existing facilities will need to obtain PSD or Title V operating permits for GHGs (US EPA, 2011). Facilities meeting the PSD thresholds defined in this rule will need to perform a best available control technology (BACT) analysis and potentially apply BACT control.

On September 20, 2013, EPA proposed a rule to limit GHGs from new power plants. The proposed standards are the first uniform national limits on the amount of carbon pollution that a source category is allowed to emit. Another rule that will be designed to limit carbon emissions from existing power plants is scheduled to be proposed in June 2014. The proposed limits for natural gas-fired and coal-fired units are different in the rule proposed in September 2013. New coal-fired units will require carbon control in order to meet the proposed limits.

The RGGI, California's Cap and Trade Rule, the GHG Tailoring Rule, and the Power Sector Rule are the first regulations designed to limit emissions of GHGs in the United States. To comply with these rules and future rulemakings, the utilities and industry sectors subject to regulation are in need of a reliable source of information and a supporting tool to identify and analyze GHG control options. Regulatory agencies are also in need of a reliable source of information when establishing GHG emission limits or control requirements for rulemakings or when establishing facility-specific permit limitations or control requirements for a permit (i.e., BACT requirements for a PSD permit). Such a supporting tool and data source will help regulatory decision makers identify the status and availability of each mitigation option. In addition, technology developers and evaluators could use such information to critically assess the performance, costs, and limitations of technologies by comparing various mitigation control scenarios. Because of the emissions distribution (shown in Table 1), future GHG regulations will most likely focus on the power industry as a starting point, so reliable mitigation information for this sector is especially relevant. GMOD is designed to address these information needs, serving as a comprehensive data repository and analytical tool for evaluating alternative GHG mitigation options.

2. Methodology

2.1. GMOD and tool

EPA developed a comprehensive GMOD and tool that provides cost and performance information for GHG mitigation options for the power, cement, and pulp and paper sectors. Characteristics, costs, and emissions information on technologies and mitigation options were collected from credible sources, including publications produced by government agencies, journal articles, conference proceedings, and data from technology vendors. The GMOD includes approximately 350 records obtained from nearly 80 different studies for all three sectors. The goal when collecting the data was to gather all available data from well-known sources at the time of the study. GMOD database includes information on the source studies each record. The database compiles and organizes the collected data, and the GMOD tool enables the user to analyze and compare mitigation options using cost and emission reduction

Table 2
Summary of source types in the power sector in GMOD.

Source type	New	Existing	Total
Biomass boiler	6	3	9
Biomass IGCC[a]	1	–	1
Coal boiler	42	93	135
Coal IGCC[a]	22	–	22
NGCC[b]	5	–	5
Advanced NGCT[c]	1	–	1
Oil boiler	–	2	2
Waste coal boiler	1	–	1
Nuclear	1	–	1
Geothermal	4	–	4
Solar thermal	22	–	22
Wind turbine	10	–	10
Total power sources	115	98	213

[a] IGCC, Integrated Gasification Combined Cycle.
[b] NGCC, Natural Gas Combined Cycle.
[c] NGCT, Natural Gas Combustion Turbine.

criteria. For a particular emission reduction strategy under consideration, GMOD can estimate the cost of CO_2 emission reductions, the level of CO_2 emitted per unit of facility output, and other important parameters based on user-defined criteria. The GMOD tool helps compare two or more emission reduction strategies on the basis of key metrics, such as CO_2 emitted per unit output, cost per unit output, and cost of CO_2 reduced compared with a benchmark uncontrolled source.

Data were collected for various industrial sectors that included different means for generating power or producing Portland cement or pulp and paper products. These "sources" are potential sources of CO_2 that produce the product of interest (e.g., a megawatt hour [MWh] of electricity or a ton of clinker). In the GMOD database, "sources" are the source of the GHG emissions (or source of the product). For the power industry, sources identified in the data references include boilers, integrated gasification combined-cycle (IGCC) plants, solar power plants, wind turbines, natural gas combustion turbines (NGCT), geothermal plants, and nuclear power plants. Sources for the cement sector include long dry kilns, wet kilns, preheater kilns, and precalciner kilns. Sources for the pulp and paper sector include the pulp and paper mill, boilers, digesters, and lime kilns. Note that many of the GHG pollution sources in the cement and pulp and paper sectors are fossil fuel-fired energy sources. Table 2 presents the distribution of source types related to the power sector that are available in GMOD.

The number of unique power sector sources included in GMOD totals 213, of which 115 sources are new construction and 98 are existing sources. New construction sources are hypothetical plants that would be constructed at some point in the future. Existing sources represent facilities already operating, where the GHG control technology was retrofitted based on the existing facility design. GMOD includes both traditional fossil fuel-fired systems as well as more advanced technologies including integrated biomass for IGCC, advanced NGCT, and NGCC plant types. GMOD also includes nuclear sources and new-construction utility-scale renewable sources including four geothermal sources, 22 solar sources, and ten wind sources. GMOD is capable of incorporating additional sources as new studies are published.

Data on GHG mitigation control options were also collected. Control options for GHG emissions identified in the references include add-on controls (e.g., carbon capture and sequestration), energy-efficiency measures (e.g., equipment upgrading or rebuilding a pulp and paper mill water distribution system to use available heat to offset steam usage), or other pollution prevention measures (e.g., raw material or fuel substitution) that may be applied to a source. Each control option specific to a study was assigned a stage of development based on its level of maturity. The six stages of development assigned in GMOD are concept, laboratory, pilot, demonstration, commercial, and mature in order of least to most mature. These stages of development are assigned based on the literature and are aligned with the U.S. Department of Energy's (DOE's) *Technology Readiness Assessment Guide* (DOE, 2009). The degree of certainty in any cost or performance information in the database will increase as the stage of development approaches maturity. As a result, for those control options that are in early development stages, cost and performance information should be regarded as very preliminary, while cost and performance information for commercial or mature control technologies should be regarded as reliable.

Table 3
Literature data – GMOD.

Source/control data from study	Capital cost data	Operating cost data[a]	Emissions data
New sources (with or without control)	Total	Total	Total
Existing sources retrofitted with control	Delta	Delta	Delta
Existing sources retrofitted with control	Delta	Total	Total
Existing sources without control	None	Total	Total

[a] For GMOD, operating costs and fuel costs are estimated independently, giving the user the flexibility to account for differences in fuel prices.

2.2. GMOD database

Studies found in the GHG mitigation literature frequently provide a characterization of the mitigation technology evaluated and report the associated economic and emissions performance data. However, the presentation of data and results varies across studies. As shown in Table 3, data were generally presented in the studies in four different ways. Data in the studies included new source and existing source data. Some of the sources presented in the literature are controlled and some of the sources are uncontrolled. Cost and emissions are either expressed as a total (for the source and control) or as the change that results in applying the control (delta, control only).

The data are used to estimate the cost of mitigation in a number of different ways depending on the emitting source type and mitigation technology evaluated. The economic data were standardized, making the data comparable between studies. Data on capital and operating costs are generally normalized with respect to output or, in some cases, heat input. Furthermore, the costs presented in each study were adjusted to a common base year using the Chemical Engineering Plant Cost Indices. The base year can be changed so that costs are presented in the year chosen by the user.

GMOD also includes default parameters defined for economic life, lifetime utilization rates, administrative costs, insurance, taxes, and interest rates. These defaults can be modified, which will affect the annualized cost of the control option. The default economic life is typically either 30 or 40 years, and there are a wide range of default utilization rates because they are equipment specific. Using the default data, administrative costs, insurance, and taxes are assumed to be 3% of capital costs per year. The interest rate is expressed as a fraction and the default value is 0.1.

Pollutant data from many of the studies were also provided in different ways and, thus, also had to be standardized. As with cost, emissions data are generally normalized with respect to output or, in some cases, heat input, to make the data comparable. All of the studies provided data for CO_2 emissions either quantifying total CO_2 emissions from the source and control or quantifying the change in CO_2 emissions from applying a control option to an existing source for retrofitted sources. Some of the studies provide emissions for non-GHGs such as SO_2, NO_X, and particulate matter

(PM). These pollutants are included in the analysis on controlled sources when available and reflect the co-benefits of applying GHG control to non-GHG pollutants. For example, most carbon capture and sequestration technologies also result in large reductions of non-GHG pollutants.

GMOD contains extensive data for fuel costs and fuel heating values. Fuels costs are presented starting in the year 1990 based on the U.S. Energy Information Administration's historical data and forecasts. For some fuels, fuel costs are estimated through the year 2050; however, limited information is available on future fuel prices, and projected fuel prices are highly uncertain. Annual operating costs for fuel-fired sources are affected by fuel prices, and GMOD will adjust fuel costs to reflect the cost year chosen by the user. The user has the ability to input fuel cost information as well.

Source and control data from the literature were separated to create "baseline" sources. For both the new and existing categories, a baseline source is a new or existing source with no control. This designation was made so that the GMOD user can always compare the cost and emissions from applying no control to a source to the cost and emissions of applying the available control options to that same source. The studies that supplied new and existing source data with no control can be used as a baseline to compare cost and emission data for a similar source with control. Control devices not designed to reduce emissions of GHGs are considered part of the baseline source (e.g., an electrostatic precipitator on a coal-fired boiler is part of the source and is not a GHG control). This designation is especially relevant for sources required to meet emission limits from rules designed to reduce emissions of criteria pollutants or hazardous air pollutants (e.g., many pulverized coal-fired boilers include a combination of pollution control technologies sufficient to meet current New Source Performance Standards and BACT requirements).

2.3. Data quality and limitations

The data collection and availability limitations associated with GMOD are as follows:

- Cost performance information was collected from government publications and other reputable peer-reviewed sources. All compiled secondary source data were evaluated relative to GMOD data quality objectives, and the potential bias of each source was considered.
- Because data was collected from different sources that performed estimates at different times and perhaps using different methods, adjustments were made in an effort to account for this; however, the adjustments may not have fully accounted for the differences in the estimates. This introduces a degree of uncertainty that is difficult to estimate. As a result, care should be used when comparing two control options.
- The cost and performance of energy efficiency estimates are often based upon studies with limited data – in some cases only one data point from an actual facility. As a result, this data does not account for all of the differences in condition or operation that may exist between various facilities of the same type. For this reason there is significant uncertainty in any predictions of cost and performance of energy efficiency methods for a particular facility, and care should be exercised when using these predictions.
- Research into GHG mitigation strategies and the associated technologies for GHG mitigation is a very active area. Cost and performance estimates are continually being updated; therefore, other sources may show different estimates of cost or performance for a GHG mitigation method. GMOD users who are interested in learning more about the technology, the basis of the cost estimate, or performance estimates are encouraged to read the source document that is identified in the database.
- To calculate a reduction in GHG emissions, the user must identify both a baseline uncontrolled unit and one with GHG mitigation and compare emission rates. A similar comparison is necessary to estimate the additional fuel consumption (i.e., heat input) or parasitic load of a GHG control device retrofit.

2.4. GMOD tool (interface)

Fig. 1 illustrates the conceptual design of GMOD, which can be used to access the data, develop mitigation options from existing and new sources, enter a new source, modify or delete a source,

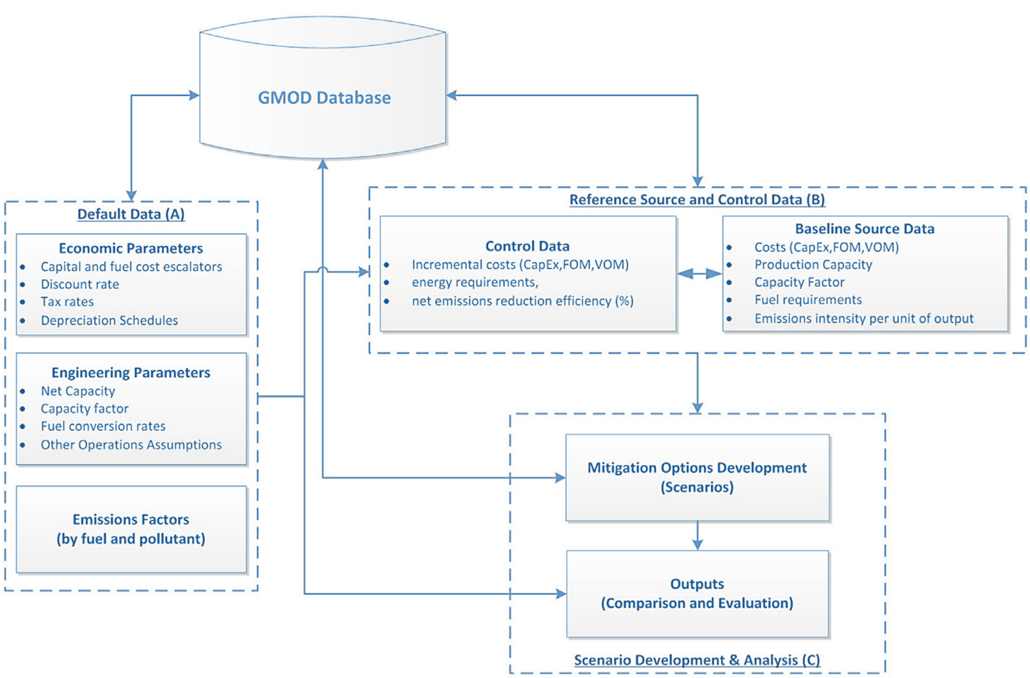

Fig. 1. Conceptual design of the GMOD.

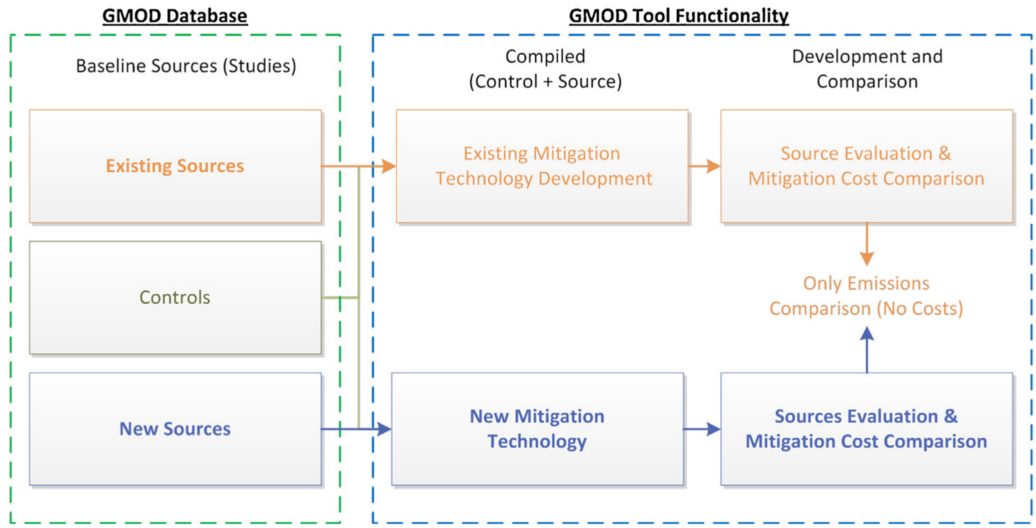

Fig. 2. Database structure.

compare mitigation options, and evaluate data. GMOD's architecture is divided into three components: default data (A), reference source and control data (B), and scenario development and analysis (C). The default data component allows the user to review and modify the economic, engineering, and emissions factor parameters. The reference source and control database component includes new and existing sources and controls data.[1] The GMOD tool allows the user to manipulate existing data and create new source or control data records. The scenario development and analysis component allows the user to develop a mitigation scenario by selecting an existing source from the dataset and compatible mitigation options of interest. The analysis phase allows the user to compare two or more sources including technologies characteristics, costs, and associated emissions data. In addition, the supporting tool allows the user to perform an environmental analysis of selected sources.

Data are structured in a Microsoft SQL database, and the input data are pre-processed to arrive at suitable input parameters for use in the model's equations explained in a later section. As shown in Fig. 1, to develop a mitigation option, the user selects an existing source and compatible controls from the database to evaluate the benefits. The options for environmental or economic evaluation by the tool will be real or potential future mitigation options for a given industrial sector. The user-defined mitigation options (controls) allow for calculating changes in cost and emissions data when changes are made to default parameters or source parameters.

2.5. GMOD functionality

The primary goal for developing GMOD is to give the user the ability to generate realistic control scenarios for a chosen source (baseline) and provide an economic and environmental analysis for each control scenario. The data obtained in the literature were used to generate a comprehensive list of GHG sources for the power, cement, and pulp and paper sectors and provide a corresponding dataset of available control options for each of those sources. Control scenarios can include a single control option or multiple control options in a series. Applicability of a control option considers dynamics of the source, including any existing control (GHG or non-GHG). For most sources in the database, multiple control options are available to the user. There are limitations to "mix and match" controls; the GMOD interface was developed to prevent mismatches between sources and controls or mismatches between multiple controls. Fig. 2 illustrates the interaction between sources and controls. As shown in the diagram, only emissions can be compared for new and existing sources because capital cost data for new and existing sources are not directly comparable. (Frequently, the capital cost of an add-on control for a new source is more cost-effective than the capital cost of an add-on control for an existing source.)

For a particular control strategy under consideration, the GMOD tool can estimate the cost of CO_2 emission reductions, the level of CO_2 emitted per unit of facility output, and other important parameters based on user-defined criteria. The GMOD tool can also generate data to compare two or more control strategies on the basis of key metrics, such as CO_2 emitted per unit output, cost per unit output, and cost of CO_2 reduced compared with a benchmark uncontrolled source. The user can also compare cost and emissions data for a controlled versus uncontrolled source or comparison of two or more controlled sources as is necessary in a BACT analysis. The literature data are accessible using the interface if the user chooses to obtain the specific data from the study.

In the GMOD tool scenario analysis, the user must first define the baseline source (e.g., source without GHG control) including the size of the source, the fuel type, and whether the source is new or existing. The user can review GMOD's default data (data already available in the database) and adjust the parameters as needed. Finally, the user may pick one or multiple control options from a list of available control options in the default database applicable to the selected baseline source; if the user chooses multiple control options in a series, the order of the control devices must be specified. The user must also specify any existing control devices (GHG or non-GHG) as this will impact the effectiveness of new controls. These steps define one control scenario. If the user wishes to compare two or more control scenarios, the user must define each control scenario. GMOD has been built with a user interface that includes pull-down menus, mouse support, and point-click activation features to facilitate scenario development.

The following three examples highlight various applications of GMOD based on different key metrics. The most basic application available in GMOD is presented in example 1, which presents cost and performance results for an individual option. Examples

[1] "New and existing sources" refer to the baseline facilities as defined in the literature and included in GMOD before any control option has been applied; "controls" refer to the GHG mitigation options that would be applied to the new or existing baseline facility.

Table 4
Cost analysis for existing 200 MW cyclone boiler.

Cost variable	Cost change	Units
Normalized capital cost base year (2006)	31,500	$/MW
Normalized capital cost chosen year (2007)	33,127	$/MW
Total capital cost chosen year (2007)	6625,340	$
Annualized capital cost	901,571	$
Annualized capital cost	4507	$/MW-year
Annual fixed operating cost	0.04	$
Annual variable operating cost	1658,228	$
Annual variable operating cost	1.26	$/MW-year
Change in primary fuel cost	−3945,942	$
Change in primary fuel cost	−3	$/MW-year
Change is secondary fuel cost	4379,562	$
Change is secondary fuel cost	3.33	$/MW-year
Total generation cost	2993,419	$
Total generation cost	2.28	$/MW-year

2 and 3 illustrate more advanced comparative analyses of mitigation options for a new source (example 2) and an existing source (example 3).

2.5.1. *Example 1: individual option analysis – existing coal-fired cyclone boilers*

Tables 4 and 5 show the data available in GMOD for a particular source and control scenario obtained from one source of literature. The scenario is an existing 200 MW bituminous coal-fired subcritical cyclone boiler that is retrofitted to co-fire wood [The boiler in this example is hypothetical and the results are based on existing operational co-fired boilers (EPRI, 2007)]. The technology summary in GMOD indicates that the control scenario is in the mature stage of development and that the boiler will be equipped to co-fire wood and other waste biomass. Biomass is commonly defined as material derived from living organic matter and the biofuel in the study is wood sawdust at 30% moisture (EPRI, 2007). The resource summary in GMOD indicates that fly ash, bottom ash, and slag are generated as solid waste. Data from the cost summary and emissions summary in GMOD are summarized in Tables 3 and 4, respectively. Because this is an existing source, the cost and emissions data are presented as changes due to retrofitting the source. Emissions for the primary fuel (coal, shown as fossil fuel in Table 5) are shown as negative because the source will burn less coal as a result of the retrofit; therefore, emissions from burning coal will decrease. Emissions for the secondary fuel (wood, shown as biogenic fuel in Table 5) are shown as an increase because the source is being retrofitted to burn wood.

Table 5
Emissions analysis for existing 200 MW cyclone boiler.

Pollutant Name	Change in emissions (tons/year)	Fuel
CO_2	−251,105	Fossil fuel
NO_X	−478	Fossil fuel
SO_X	−299	Fossil fuel
Biogenic CO_2	291,971	Biogenic fuel
NO_X	199	Biogenic fuel
SO_X	133	Biogenic fuel
PM	53	Biogenic fuel

2.5.2. *Example 2: multioption analysis – new 550 MW power source coal-fired power generator*

This example involves an owner of a facility that needs additional generating capacity to meet demand. The facility owner has determined that because of the facility's location and other geographical limitations, the wind turbine, geothermal, and solar options are not viable, and the owner does not wish to build a nuclear plant in light of site selection difficulties. The facility owner is considering building a new coal-fired supercritical pulverized coal (PC) boiler with a net capacity of at least 550 MW. (There is no existing combustion source at the facility that can be modified or expanded to provide the additional power requirement.) The owner has determined that an economic life of 40 years and a utilization rate of 0.80 along with a base year for costing of 2007 are sufficient for the analysis. The mitigation options available for this case scenario are the following:

- building a new coal-fired supercritical PC boiler with no GHG control
- building a new coal-fired supercritical PC boiler with oxy-firing and an air separation unit plus carbon capture and storage (cryogenic distillation for 95% oxygen purity; energy requirements supplied by the PC boiler and subtracted from the gross output)
- building a new coal-fired supercritical PC boiler with post-combustion using MEA[2] carbon capture and storage
- building a new coal-fired supercritical PC boiler with post-combustion chilled NH_3 carbon capture and storage
- building a new coal-fired supercritical PC boiler with post-combustion dry carbonate carbon capture and storage
- building a new coal-fired supercritical PC boiler with post-combustion with Econamine FG Plus carbon capture and storage

The facility owner is only interested in control options that are at least at the demonstration level, thus eliminating the post-combustion chilled NH_3 and the post-combustion dry carbonate capture options because they are only at the pilot level. This leaves four options: no GHG control, oxy-firing with air separation plus capture and storage, post-combustion MEA capture and storage, and post-combustion Econamine FG Plus capture and storage.

The results of the analysis from GMOD are shown in Table 6 (for the sake of simplicity, all of the data available in GMOD as shown in example 1 are not provided in Table 6). Because the source is new, all cost and emissions data shown are the totals. As shown in Table 6, overall, post-combustion MEA is the most cost-effective (i.e., normalized annual total generation costs ranging from $71 to $82 per MWh) for a PC boiler in the 300–700 MW capacity range. The analysis also shows that oxy-firing has the lowest CO_2 emission rate (approximately 170 lb/MWh), while the CO_2 emission rates for post-combustion MEA and post-combustion Econamine FG Plus are higher (closer to 250 lb/MWh). The emission reduction associated with oxy-firing for this example is estimated to be up to 4 million tons of CO_2 per year. The data also show the relative cost of

[2] MEA refers to monoethanolamine, one of the chemical absorption methods for post combustion CO_2 capture.

Table 6
Cost and emission analysis for new 550 MW coal-fired PC boiler.

Type of control	Technology development status	CO_2 emissions (lb/MWh)	Normalized annual total generation cost ($/MWh)	Source size range (MW)
No control	Commercial/mature	1709–1899	41–79	200–600
Oxy-firing	Demonstration	168	85	549
MEA capture	Demonstration	239–258	71–82	329–666
Econamine FG Plus	Demonstration	244–266	90–116	379–550

Table 7
Cost and emission analysis for existing 315 MW coal-fired PC boiler.

Type of control[a]	Change in emissions (lbs/MWh)	Change in emissions (ton/yr)[b]	Normalized overnight cost ($/MW)	Source size range (MW)
Excess oxygen control in boiler	−5.25 to −13.6	−20,000 to −50,000	556–1000	500–900
Decreased boiler air heater leakage	−0.834 to −5.25	−900 to −20,000	529–1300	250–900
New turbine seals	−3.13	−3000	1500	250
Boiler feed pump overhaul	−7.87	−8500 to −31,000	833–1500	200–900
Install intelligent soot blowers	−12.6 to −18.9	−16,000 to −50,000	556–1500	200–900
Boiler condenser cleaning	−10.5	−9000 to −41,000	0	200–900
Ductwork upgrade	−0.315	−600	556	450
Modify ESP	−0.525	−450 to 2000	444–500	200–900
Modify SCR	−1.05	−900 to 4000	1000–1250	200–900

[a] The stage of development for all energy-efficiency measures is mature.
[b] Assumes operation 8760 h per year.

constructing an uncontrolled source versus the cost of constructing a controlled source, as well as the emission benefits of constructing a controlled source. It is important to note that because none of the control methods in this example are commercial or mature, there is significant uncertainty in the cost and performance estimates. However, the estimates represent the best information available.

This example could be expanded to compare data for different boiler types if the facility owner had not yet decided what type of boiler to build. A comparison of data for a particular control type on different boiler types can also be done using the data in GMOD.

2.5.3. Example 3: multioption analysis –existing coal-fired PC boiler

This example involves a facility with an existing 315 MW PC boiler, and the owner wishes to reduce GHG emissions from the boiler. The owner has a capital expenditure budget of $600,000, or a normalized budget of $1905/MW (normalized overnight cost). The owner also has an imminent timeline for the project, so the stage of control development must be mature; which leaves only energy-efficiency control options. As with the previous example, the owner has determined that the defaults for an economic life of 30 years and a utilization rate of 0.75 for an existing PC boiler are sufficient for the analysis. The chosen year for the analysis is 2007. The control options available for this scenario are the following:

- excess oxygen control in boiler
- decreased boiler air heater leakage
- new turbine seals
- boiler feed pump overhaul
- install intelligent soot blowers
- boiler condenser cleaning
- ductwork upgrade
- modify electrostatic precipitator (ESP)
- modify selective catalytic reduction (SCR)

The results of the analysis for example 3 are shown in Table 7. The data show that, over a broad range of boiler sizes, installing intelligent soot blowers provides the most emission reduction of CO_2. As shown in Table 7, the boiler condenser cleaning option provides a high level of emission reduction relative to the other energy-efficiency options with no capital expenditure. ESP modification has the lowest normalized overnight cost but does not provide much of an emissions reduction. The remaining seven options (aside from condenser cleaning and ESP modification) have similar normalized overnight costs ranging from approximately $500/MW to $1500/MW. Although energy-efficiency options result in emission reduction levels lower than an add-on control, they are important pollution reduction options to assess in light of President Obama's initiative to double the nation's energy efficiency by 2030 (Green Productivity, 2013). Also, as discussed earlier with regard to data limitations, when considering energy efficiency options, the degree of energy improvement that GMOD estimates should be considered exemplary rather than absolute. The actual improvement in efficiency will vary significantly from one facility to the next based upon the condition of the particular facility. For example, there is less room for improvement for facilities that have been very well maintained and kept up to date than facilities that have not been maintained as well. The manner in which the facility operates (base loaded versus load following) will also impact the efficiency improvement that is possible.

3. GMOD and other GHG mitigation databases and tools

Several other EPA databases currently compile information on GHG mitigation techniques, including EPA's RACT/BACT/LAER/Clearinghouse (RBLC) database [available online at: http://cfpub.epa.gov/rblc/]. Other examples include, the International Institute for Applied Systems Analysis's (IIASA) *Carbon Dioxide (Technology) Database* (CO2DB), and Carnegie Mellon University's *Integrated Environmental Control Model* [IECM]. However, none of these other databases are as comprehensive as GMOD.

The RBLC database contains GHG mitigation data for facilities required to obtain a PSD/NSR permit for GHG gases. The RBLC database contains basic information on control measures and emission limits but provides limited costing data. It also has very little information at this time because the NSR program for GHGs is still evolving, and it takes time for the regulatory agencies to transfer the information from permits into the database. Most importantly, the RBLC database does not contain information on prospective technologies that may be applied in the future.

IIASA's CO2DB contains nearly 3000 technologies and can be used to analyze techno-economic data on carbon dioxide mitigation technologies applied to a number of energy generation technologies. IECM, while somewhat more limited in scope, the IECM model provides high resolution cost information and systems analysis capabilities for analyzing alternative fossil fuel power plant types (i.e., PC, NGCC, IGCC, and Oxyfuel combustion). IECM has the capability to model the alternative plants with and without CO_2 capture and storage (CCS), enabling users to quantify the costs and potential emissions reductions for each system.

While these databases offer a great wealth of information on CO_2 mitigation technologies available to the power sector. GMOD seeks to cover a broader scope, expanding beyond the power sector to include energy intensive industries as well as major emitters of non-CO_2 GHG emitting sources (e.g. oil and natural gas production systems, coal mining, waste management, and industrial processes). GMOD fills information gaps that are present in existing mitigation databases, provides a centralized location for mitigation cost and performance data, and provides a standardized system to compare multiple mitigation options.

4. Conclusions

GMOD is a decision support database and tool that is designed to evaluate mitigation options to support permitting activities and independent research. GMOD's primary goal is to give the decision maker an option to generate realistic technology choices that are comparable for engineering and economic analyses. It allows evaluation of multiple mitigation options with respect to emissions reductions and co-benefits and supports decision making in permitting activities and technology investments. It is designed to address multisector GHG emissions from stationary sources and help the user determine the most attractive options from performance and cost perspectives.

GMOD's objective is to provide the user with information on real-life examples from the literature and control options for various sectors. It provides a tool to analyze and evaluate changes in the environmental and economic performance metrics as a result of combining the user-specified base sources (e.g., energy generation unit, kiln) and control techniques (i.e., mitigation options). The user can specify combinations of sources and control techniques (scenarios) to ensure the relevance and applicability of the results. GMOD is designed to provide multiple GHG control options for various sectors. It can be used for analyses of various air pollution control technology options and their implications on sector-specific output, economics, and environmental parameters.

GMOD serves as a comprehensive information source on GHG control options, and the tool provides users with the capability to develop a host of alternative scenarios by constructing a conceptual-based source with suitable alternative control technologies. For the mitigation technologies' analysis strategies under consideration, the GMOD supporting tool provides information on the following:

- the best mitigation option (control) for a selected (base) technology,
- the most cost-effective mitigation option, and
- the amount of emissions reduction that can be achieved over the time period of interest using one or more mitigation options.

5. Availability and requirements

GMOD is a downloadable executable database and tool that can be used to access and develop GHG mitigation options. A zipped file including database and executable files will be available on EPA's website to download. The application requires one of the following operating systems to be installed on the user's machine: Microsoft (Windows XP, Vista, or Windows 7 or 8) or OS X. Users can make new contributions to the database using this tool. However new content will need to be vetted by EPA staff to resolve conflicts and evaluate the reliability of the information submitted by the user. EPA plans to make periodic updates to GMOD that will incorporate new information as it becomes available.

6. Future research work

A future goal for GMOD is to provide a more extensive list of control/mitigation choices to the user for a given source type. This can be done by using the cost and emission data for a given source/control option combination from the literature and making engineering assumptions to apply that data to a different source/control option combination (e.g., using the literature data for energy-efficiency measures applied to a 250 MW PC boiler to estimate the cost and emission reduction of energy-efficiency measures applied to a 500 MW oil-fired boiler). Basically, cost and emission curves could be developed from the current data so that the data can be applied to scenarios outside of the literature studies. The data could also be adjusted to apply several different efficiency measures to one source concurrently (e.g., overhauling the boiler feed pump and installing intelligent soot boilers from example 3) or expanding the pollutant list from one study using more extensive pollutant data from another study. Cost and emission curves could also be developed to compare new and existing data (e.g., a facility owner that is deciding between building a new source and expanding an existing source).

Because many of the important technologies are in the development stage, updating the database with new information as it becomes available and populating the database for other industrial sectors (e.g., iron and steel, landfills, transport) would also prove useful to keep GMOD current. Refinements can be made to the interface to provide flexibility to the user when developing scenarios (e.g., retrieve all data on a particular control technology for different types of sources). Finally, cost and emissions data could be integrated to further help the user make decisions regarding control (e.g., \$/ton CO_2 reduced).

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