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US ENERGY SECTOR ANALYSIS OF NON-CO_2 GHG EMISSION ABATEMENT

Report on the Methane Sub-Model for the US EPA National MARKAL Model

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1. Introduction and Purpose

The Environmental Protection Agency's (EPA) Coalbed Methane Outreach Program has requested that the EPA US-national MARKAL (EPA-MARKAL)[1,2] model be augmented to include the ability to track methane emissions from the energy system, and limited other sources (landfills and manure handling). This Methane sub-model includes a wide range of methane emission sources and handling options that could be introduced to mitigate methane emissions[3]. The Methane sub-model has been careful added as an alternate scenario to the current EPA national model and integrated with the BASE scenario and other model scenarios[4]. This enables easy running of the model with or without the Methane subsystem.

The methane sub-model in the EPA-MARKAL model has been developed and calibrated to perform the following functions:

- Provide projections of future methane emissions from the energy system out to 2030;
- Assess potential mitigation levels of methane emissions by energy system component;
- Evaluate the benefit and costs of policies, programs, and actions to reduce methane and/or Greenhouse Gas (GHG) emissions;
- Help to prioritize emission reduction opportunities in terms of cost-effectiveness and ancillary benefits, and
- Produce emission abatement cost curves.

The Methane sub-model does not make any substantive changes to the EPA-MARKAL model resource supply depictions, which have been partially calibrated to AEO2003 by EPA Office of Research and Development (ORD). As mentioned below, the introduction of the Methane sub-model to the national model had only a very slight impact on the reference scenario.

There are four components that fully document the methane subsystem. The first is this report, which describes the Methane sub-model, the data sources, methodology and model calibration results. It is intended to serve as a reference manual and user guide for EPA staff who wish to use the model for various analyses, and other interested parties.

The second component is a comprehensive 37-sheet data workbook[5] which contains all the data on methane emissions and mitigation technology options provided to this effort by EPA staff. This workbook contains all the transformations to convert the basic input data into model input parameters. The workbook, which is described below, allows model users to modify basic EPA data in their normal form and automatically translate this to that appropriate for the model. The modified Methane sub-model can then be rather easily moved into the EPA-MARKAL model database maintained under ANSWER[6].

The third piece of the documentation is a report describing the initial analyses that were performed to test the operation of the sub-model and to investigate the effectiveness of various technologies and policies for reducing methane emissions. The report[7] documents the results of the mitigation abatement cost analysis presented by means of various types of abatement cost curves, and measure ranking of the effectiveness of the mitigation options.

The final component of the document is the actually EPA-MARKAL database, which contains the Base and associated calibration scenarios for the initial model, as well as the methane sub-model and all methane-related model runs[8].

2. Modeling Approach and Subsystem Descriptions

The Methane sub-model is characterized according to five methane generating sectors:

1) Municipal waste and landfills;
2) Natural gas production, transmission/storage, and distribution;
3) Coal production;
4) Oil production, and
5) Manure management.

In each sector, a subsystem was developed that simulates activities that produce methane, derives emission estimates from these activities, provides alternatives for handling the produced methane, and implements methane mitigation technologies as appropriate, based on least-cost and in response to policy constraints applied by the user. The approach employed for modeling each subsystem within the Methane sub-model is described in this section.

Data on historical and projected future methane emissions is developed from various EPA documents[9], the AEO 2002[10], and a few other sources[11]. The approach employed for modeling each of the five methane sectors is described below. In each sectors, the model simulates activities that produce methane, derives emission estimates from these activities, provides alternatives for handling the produced methane, and implements methane mitigation technologies as appropriate, based on least-cost and in response to policy constraints applied by the user. Reference Energy System (RES) network flow diagrams are employed to present each subsystem visually, identifying the various commodities (energy carriers and emissions) and technologies (methane sources and mitigation options) encompassing each subsystem[12].

Table 1 summarizes the numbers of emission and mitigation technologies that comprise the methane sub-model. These are described in more detail below, and details of the input parameters (investment cost, operating cost, emission reduction efficiency, lifetime, etc.) are provided for each technology in the associated data workbook. An index page with hyperlinks to the different data sheets facilitates easy access to specific data for each subsystem. The rest of this chapter describes each of the subsystem in detail.

Table 1: Summary of Technologies in the Methane Sub-Model

Methane Sector	Emission technologies	Mitigation technologies
MSW / Landfills	5	11
Natural Gas	3	33
Coal	40	19
Oil	4	8
Manure	4	5
Total	**56**	**76**

2.1 Municipal Solid Waste (MSW) and Landfills

In the MSW and landfill subsystem methane is generated through a biological process, which breaks down the organic materials, ferments the materials and then methane-producing bacteria converts these materials to biogas (approximately 50% methane) through an anaerobic process. As shown in Figure 1, the emissions from landfills have been divided into two categories for modeling this subsystem. First are methane emissions from the pre-2005 landfills, which are based on the known amount of waste in place that is still active. The model includes a variety of mitigation technologies that can capture landfill gas to reduce emissions from these landfills. After 2005, the model tracks MSW utilization, and mitigation options are expanded to include landfills and diversion of MSW to other types of use such as anaerobic digestion, composting, mechanical biological treatment, etc.

Figure 1 also illustrates the conventions used in the methane subsystem RES diagrams: the blue arrows represent energy flows, the red arrows represent methane emissions (MTHAIR) and emission reductions (MTHCAP), and the green arrows represent other emissions (mostly CO_2). In this figure and the diagrams to follow, MTHCAP is used to signify the capture of methane that would otherwise be emitted. However, within the actual model MTHCAP is specified as a negative MTHAIR so that the sum of all the MTHAIR values represents the net methane emissions. The diagrams also provide the MARKAL name for the technologies and energy carriers involved in each of the subsystems.

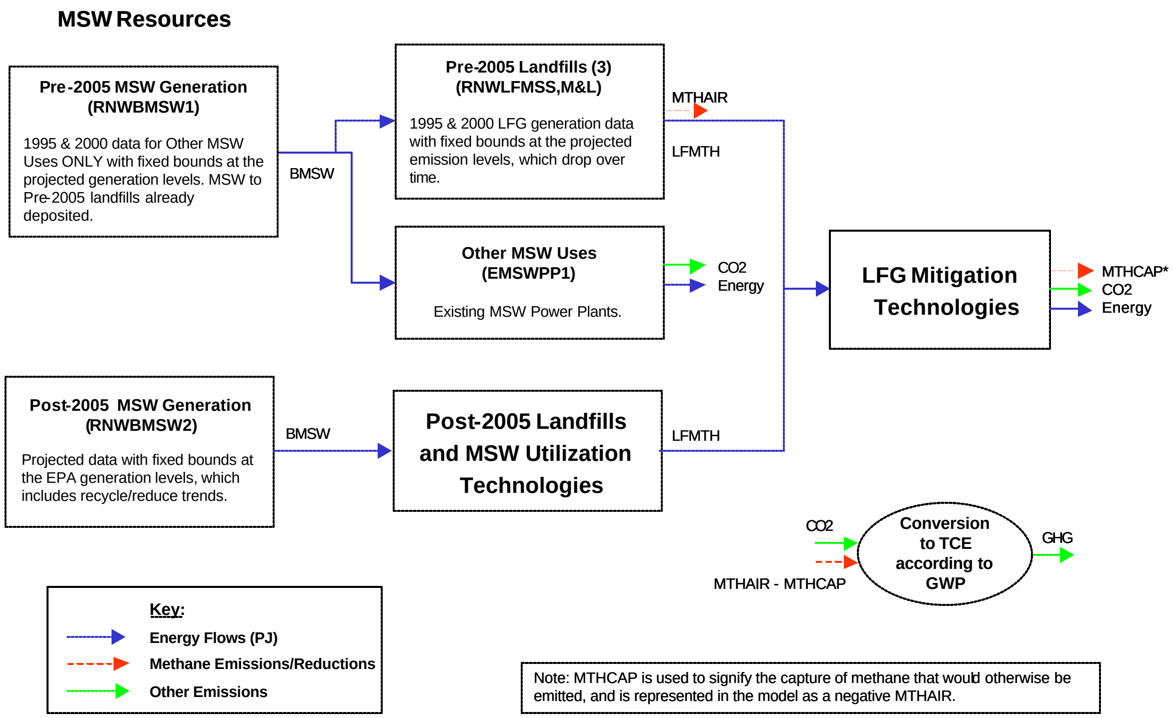

Figure 1: Overall Modeling of MSW / LFG Subsystem

Figure 2 illustrates the modeling of methane emissions from the pre-2005 landfills. These landfills generate methane emissions based on the known amount of waste in place that is still active, and a variety of mitigation technologies that capture landfill gas (LFG) can be applied to emissions from these landfills. The list of mitigation technologies for captured landfill gas includes flaring of landfill gas, capture and upgrade of landfill gas for pipeline injection, landfill gas used for supplemental fuel, electricity generation using landfill gas, and co-generation using landfill gas. If the landfill gas is not captured, the default (no mitigation) is the normal landfill cap, whereas an increased oxidation cap option represents another mitigation technology.

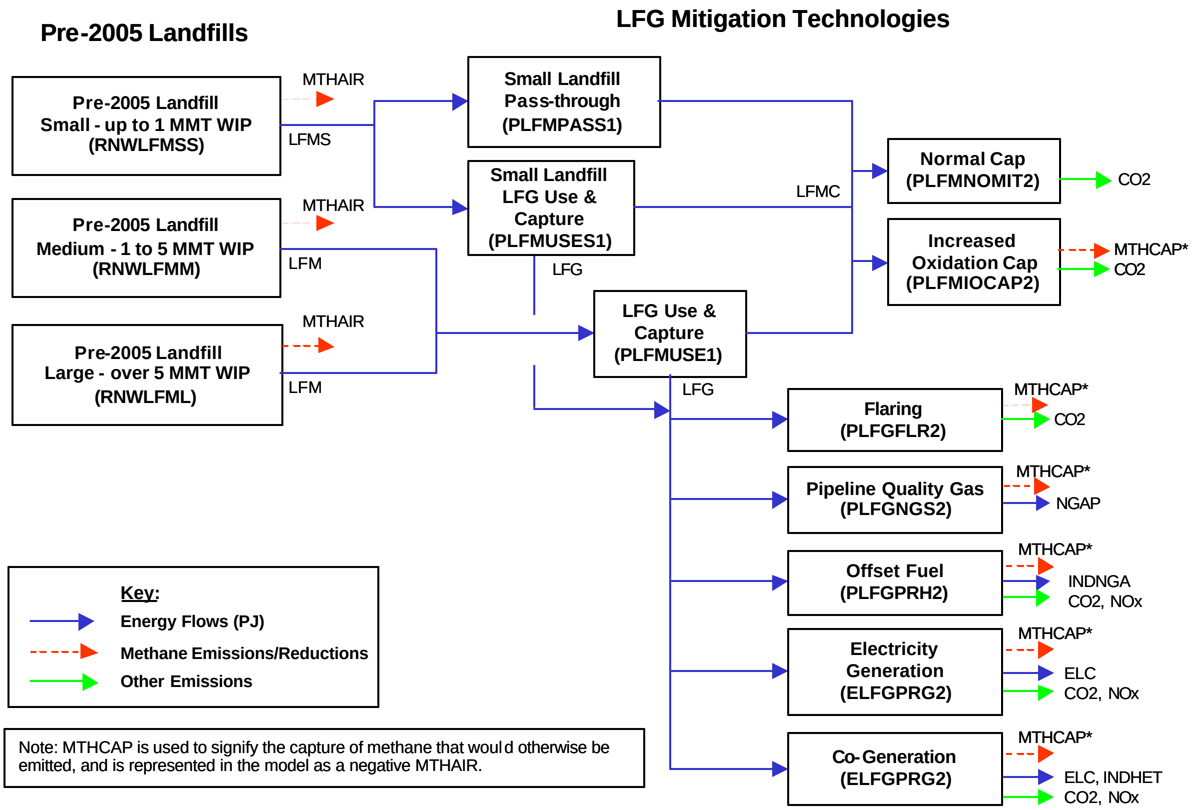

Figure 2: RES Flow Diagram for LFG Emissions from Pre-2005 Landfills

The pre-2005 landfills are modeled as large, medium and small to account for different methane generation rates and the applicability of the Landfill Rule[13] to large and medium landfills. The waste in place at the pre-2005 landfills has an age distribution, and we assumed this was uniform, which results in a 30-year linear decay of LFG emissions from these landfills as shown in Table 2.

Table 2: Projected Methane Emissions from Existing (Pre-2005) Landfills (Gg/yr)

	1995	2000	2005	2010	2015	2020	2025	2030	2035
Small Landfills	5,686	6,667	6,667	5,556	4,445	3,334	2,222	1,111	-
Medium Landfills	6,971	7,427	7,427	6,189	4,951	3,713	2,476	1,238	-
Large Landfills	1,508	1,591	1,591	1,326	1,061	796	530	265	-

The diagram in Figure 3 illustrates the post-2005 MSW and LFG model structure. After 2005, MSW is modeled as a potential energy resource, and mitigation options are expanded to include diversion of MSW to other types of uses. Because MSW deposited in landfills will generate methane over a 30-year period the post-2005 landfills are modeled to accept a one-time input of MSW which continues to generate methane for their full lifetime (30-years). This is then repeated as the landfill is expanded (or new ones built) to accommodate waste generated in each period. Characteristics for the MSW and LFG mitigation technologies were developed from EPA and other sources[14].

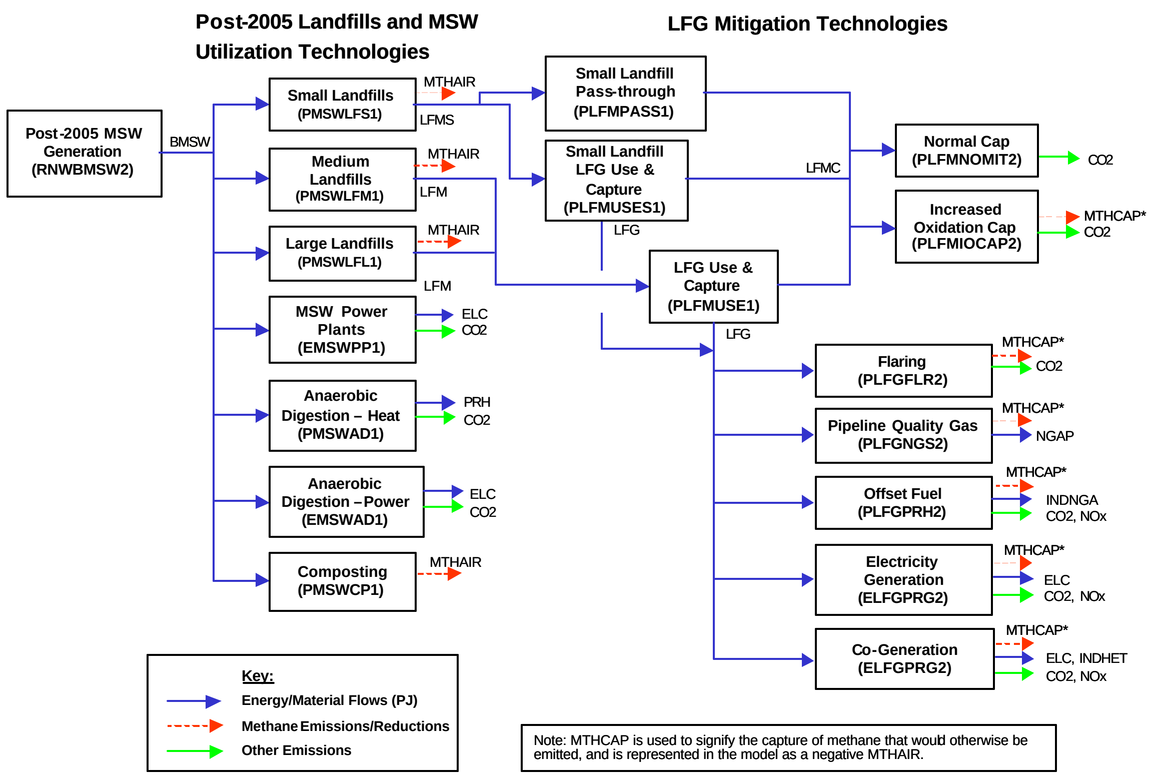

Figure 3: RES Flow Diagram for New MSW Utilization and LFG Mitigation

Figure 3 shows that MSW can flow into a choice of small landfills, medium-sized landfills, large landfills or several possible utilization technologies including power plants, anaerobic digestion (for heat and power), composting or mechanical biological treatment. LFG that is generated in the post-2005 landfills can either be ignored (leading to emissions through the normal cap), or it may be captured and used by the same LFG mitigation technologies as described for Figure 2.

The methane generation rates for new MSW placed into landfills were developed from Annex Q of the 2002 Emissions Inventory[15], and these are given in Table 3. The emissions from the new landfills were assumed to be constant over a 30 year period. The Excel data and calculation workbook contains a complete description of these technologies along with the full set of input parameters for each.

Table 3: Methane Generation Rates from New Landfills

Type	m3/min/MMT
Small landfills	7.43
Medium landfills	8.558
Large landfills	8.558

2.2 Coal Mining

Methane emissions from coal mining result when methane is liberated from the coal and surrounding strata during mining. Emissions also occur during production and transport of coal. Methane emissions from the production of surface-mined coal are accounted for in the model, but have no mitigation options. Likewise, methane emissions that occur during coal transport (surface or underground) are accounted for in the model, but have no mitigation options. However, the production of underground-mined coal has several mitigation options including degasification required prior to mining, ventilation air methane capture and use, and gob gas upgrading for pipeline injection. The coal (both surface and underground) is tracked by major basins as the methane release rates vary by region. The modeling is complicated by the need to differentiate between existing and new mines in order to properly account for degasification of new mines, as well as the need to represent the distinctive basins and their associated supply step curves (quantity available of each coal type from each basin at a given price).

Figure 4 shows the methodology used to model coal mining methane emissions and the mitigation options for the Appalachian underground high sulfur coal resource, which is only one of over 10 coal basins and types modeled. Similar approaches were used for the other coal resources.

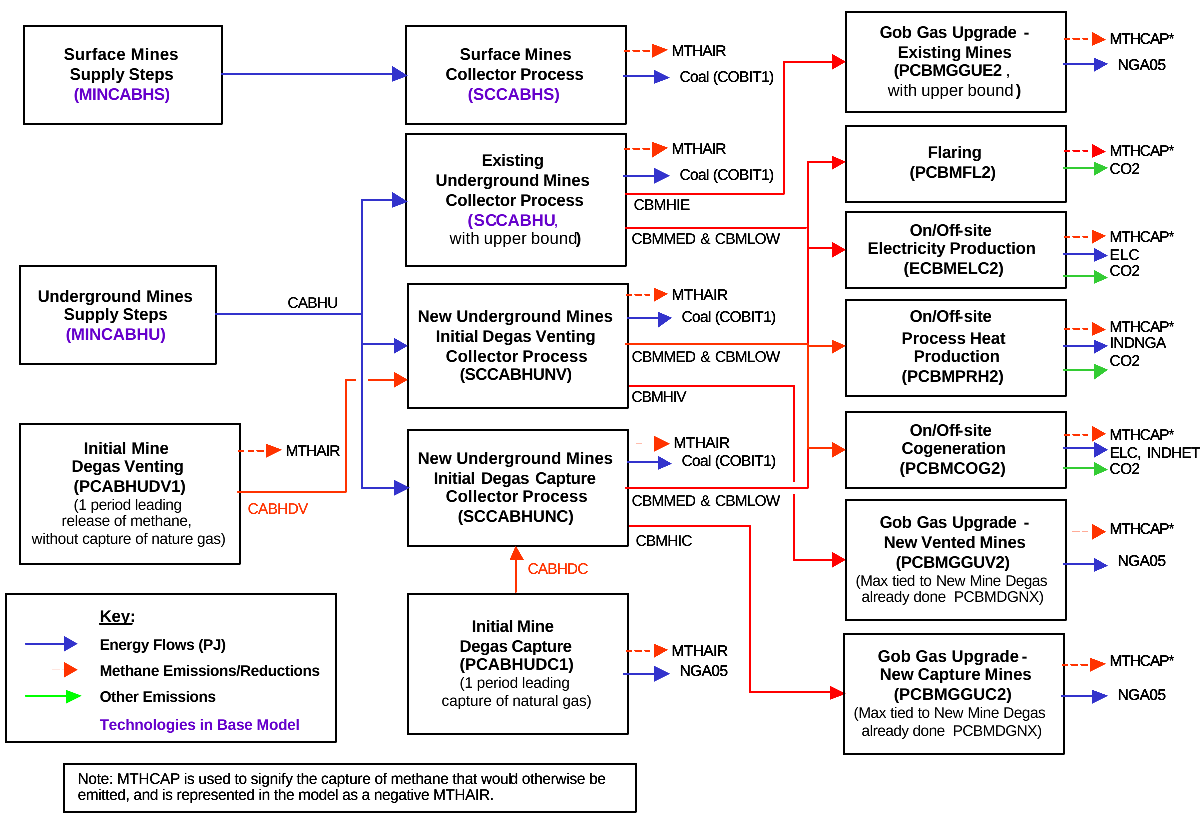

Figure 4: RES Flow Diagram for Coal Mine Methane Emissions and Mitigation Options Example: Appalachian Underground High Sulfur Coal

An approach was developed to accommodate the time lag required between the initial mine degas and the start of new coal mining. The initial mine venting activities were modeled as processes that produced a degas output "dummy" material that lags by one period (5 years). The new coal mining collector process requires this lagging degas material in order to produce new coal. The result of such an approach is that the model must schedule degas activities to take place the period prior to actual delivery of the first coal from new mines. Two processes were required to differentiate between initial degas that involves capture and pipeline injection (Initial Mine Degasification and Capture, a mitigation option) and initial degas that only involves venting (Initial Mine Degasification and

Venting). The cost of Initial Mine Degasification and Venting was estimated at one-third the cost of Initial Mine Degasification and Capture. The Excel data and calculation workbook contains a complete description of these technologies along with the full set of input parameters for each.

2.3 Natural Gas Production, Transmission and Distribution

Natural gas is mostly methane, and emissions of natural gas (or methane) generally occur from a variety of natural gas processing steps, during normal operations, routine maintenance activities, and during systems upsets. All three major sub-sectors of natural gas use were modeled: domestic gas production, processing, transport and storage of domestic and imported natural gas, and distribution to end-users. Each of the three major sub-sectors (production, transmission and distribution) is modeled separately, though each is fully inter-connected, as is shown in Figure 5.

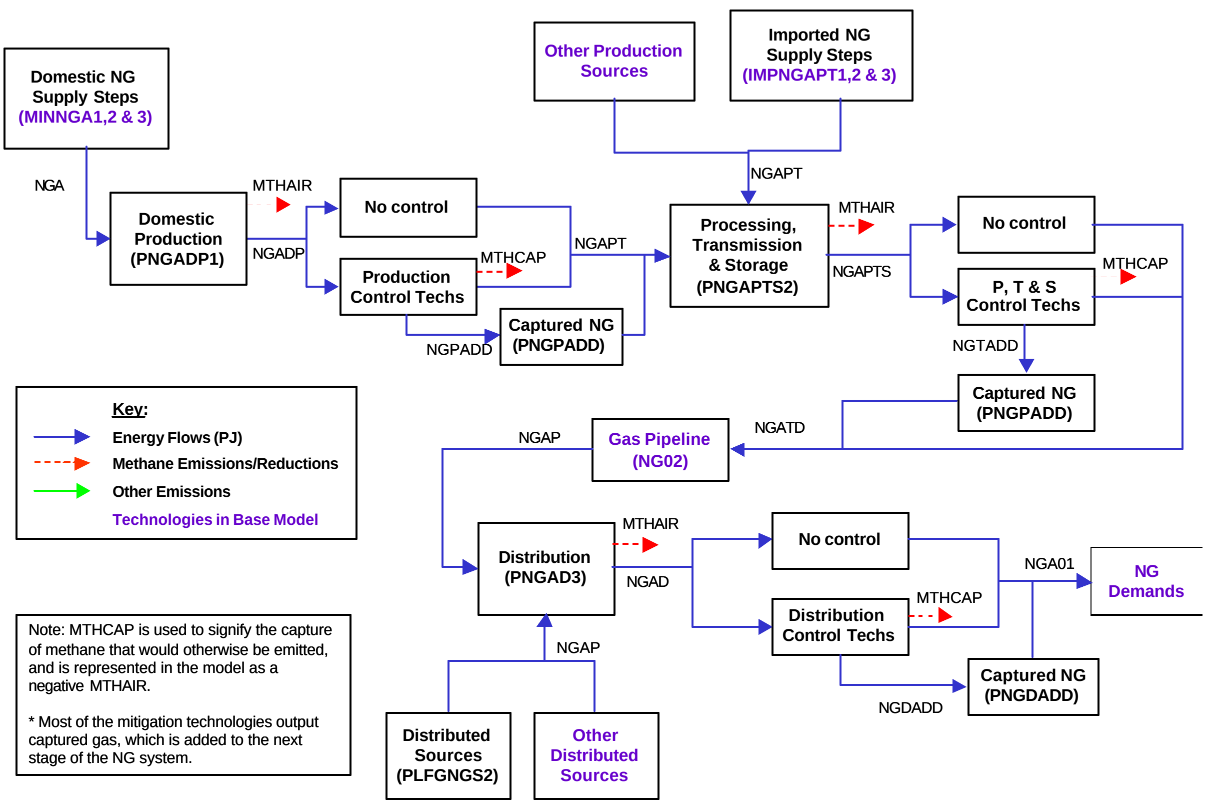

Figure 5: Overview Flow Diagram for the Natural Gas Subsystem

For each sub-sector, the overall emissions (MTHAIR) are calculated, then either "no control" or particular control technologies can be selected. The control technologies will mitigate the normal methane emissions (producing MTHCAP, or negative MTHAIR). For some mitigation technologies, the methane is captured (or not released) and is added back to the flow in the next sub-sector of the natural gas subsystem. This is represented by the "Captured NG technology,", and is referred to as NGxADD where x = P/T/D for process/transportation/distribution sub-sector on each of the natural gas sub- system RES diagrams. However, with other technologies, the mitigated methane emission is assumed to be flared or used for fuel within the facility implementing the option, and these technologies will show a CO_2 emission.

Within each sub-sector, the emission mitigation control technologies are modeled using a framework of series and parallel options as illustrated in Figure 6 for the natural gas production sub-sector. For this sub-sector, the possible mitigation options were characterized according to eight technologies that mitigate a portion of the potential methane emissions. The modeling approach allows the competing and complimentary mitigation technologies to be selected or not independent of other decisions. For each of the mitigation technologies, there is a limit on what percentage of baseline methane emission from the sub-sector that can be captured by each mitigation technology.

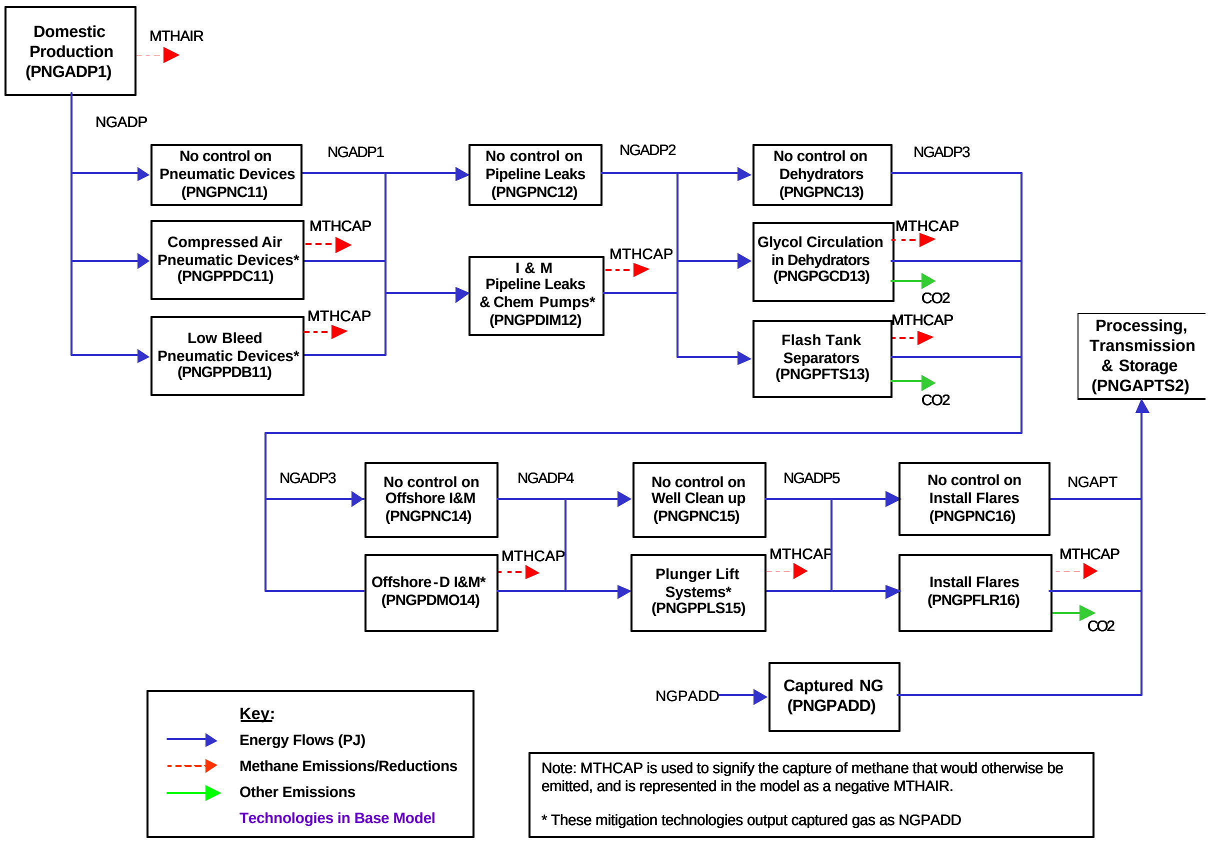

Figure 6: Flow Diagram for Mitigation Options in the Natural Gas Production Sub-sector

As shown in Figure 5, imported natural gas and other pipeline quality gas (e.g. from coal mining) are introduced into the natural gas sector after the production sub-sector, and the combined gas flow goes to the process, transmission and storage sub-sector, which is shown in Figure 7 and Figure 8. The transmission and storage sub-sector is represented by 18 mitigation technologies, ranging from hardware modification to process improvements to enhanced inspection and maintenance. The Excel data and calculation workbook contains a complete description of these technologies along with the full set of input parameters for each.

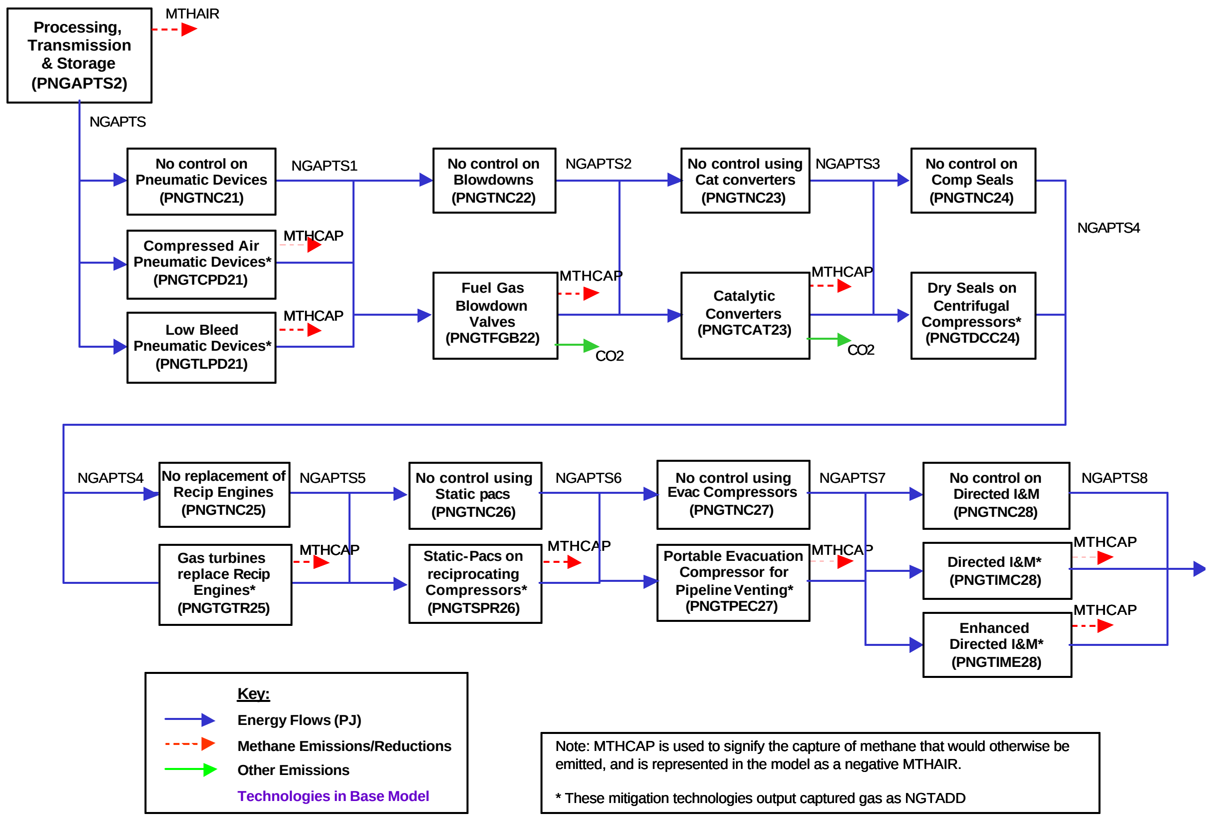

Figure 7: Flow Diagram for Mitigation Options in the Natural Gas Transmission Sub-sector-1

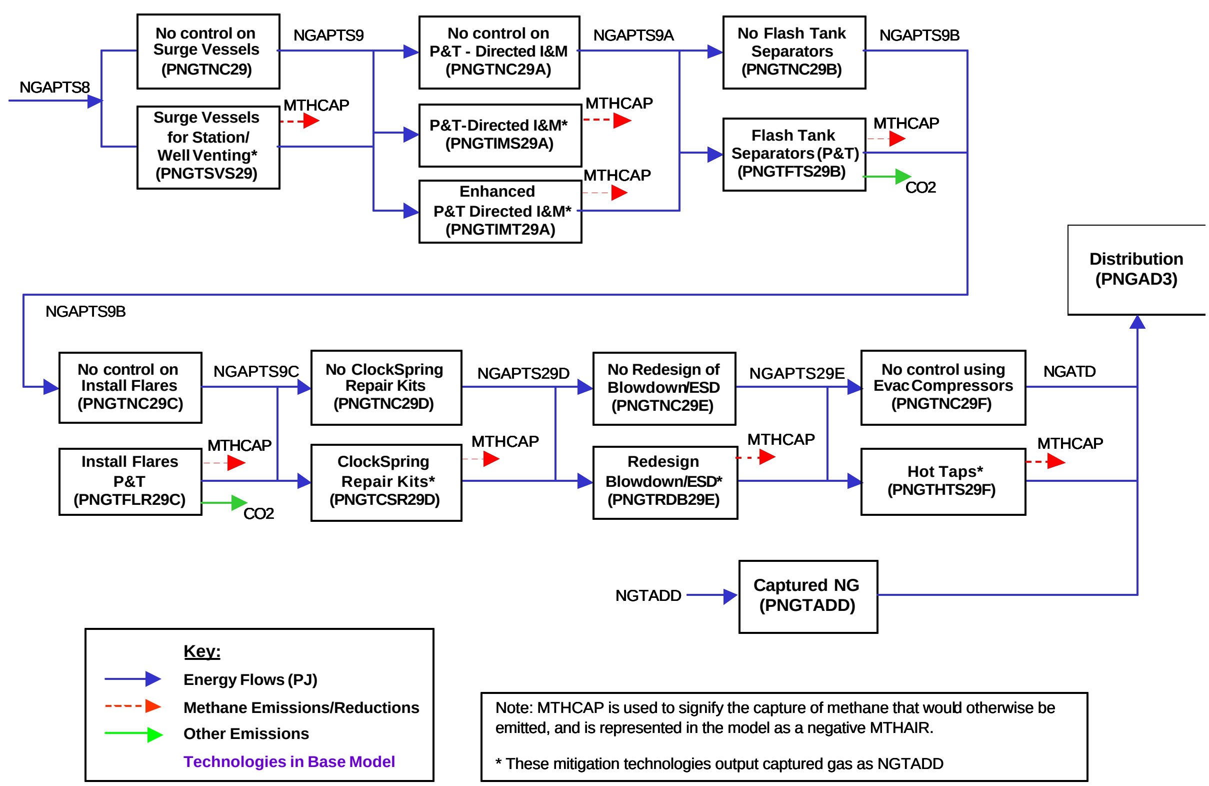

Figure 8: Flow Diagram for Mitigation Options in the Natural Gas Transmission Sub-sector-2

As shown in Figure 5, pipeline quality gas from distributed sources, such as landfills, is combined with gas from the process, transmission and storage sub-sector and introduced into the natural gas distribution sub-sector, which is shown in Figure 9. The natural gas distribution sub-sector is represented by 7 mitigation technologies. The Excel data and calculation workbook contains a complete description of these technologies along with the full set of input parameters for each.

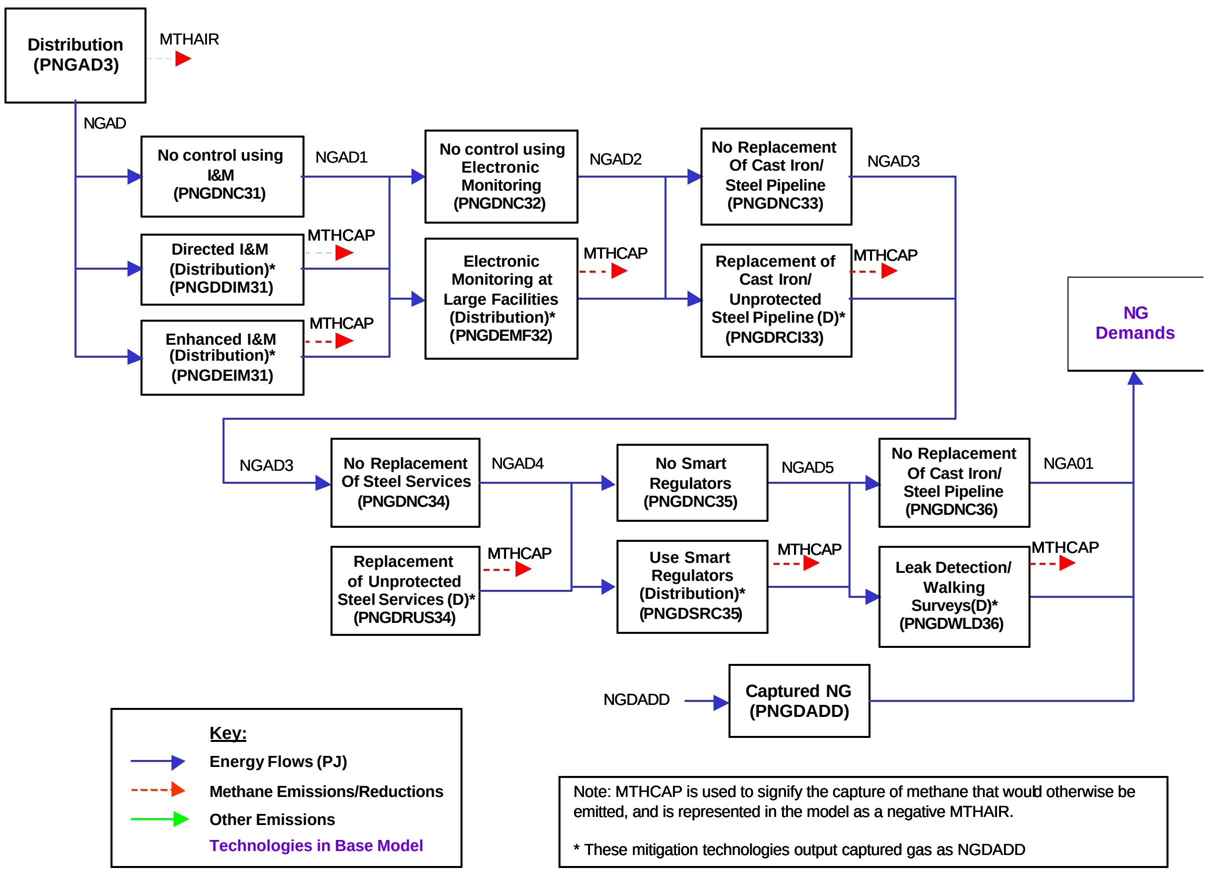

Figure 9: Flow Diagram for Mitigation Options in the Natural Gas Distribution Sub-sector

2.4 Oil Production

Within the oil supply subsystem, methane emissions mostly occur during crude oil production as a fugitive or vented emission. Methane emissions from oil transport and refining are small and are ignored in this sub-model. Emissions and mitigation options from domestic oil production are modeled for the Lower 48 and Alaska separately to allow for different emission factors and mitigation costs for these two regions. Both domestic oil sources are further segregated into on-shore and off-shore production, so that different mitigation options can be applied appropriately.

The emission factors for the onshore production are very similar for Lower 48 and for Alaska, but the offshore emission factors for Alaska are lower because the Mineral Management Service requires (as in mandates) offshore drillers reuse the methane released. Figure 10 illustrates the modeling of methane emissions and mitigation options for oil production from the Lower 48 states. The modeling of methane emissions and mitigation options for Alaska oil production is the same, but the two sources are independent, and different sources, technologies and energy carrier names are used to allow for the different cost and performance characteristics between these two oil sources.

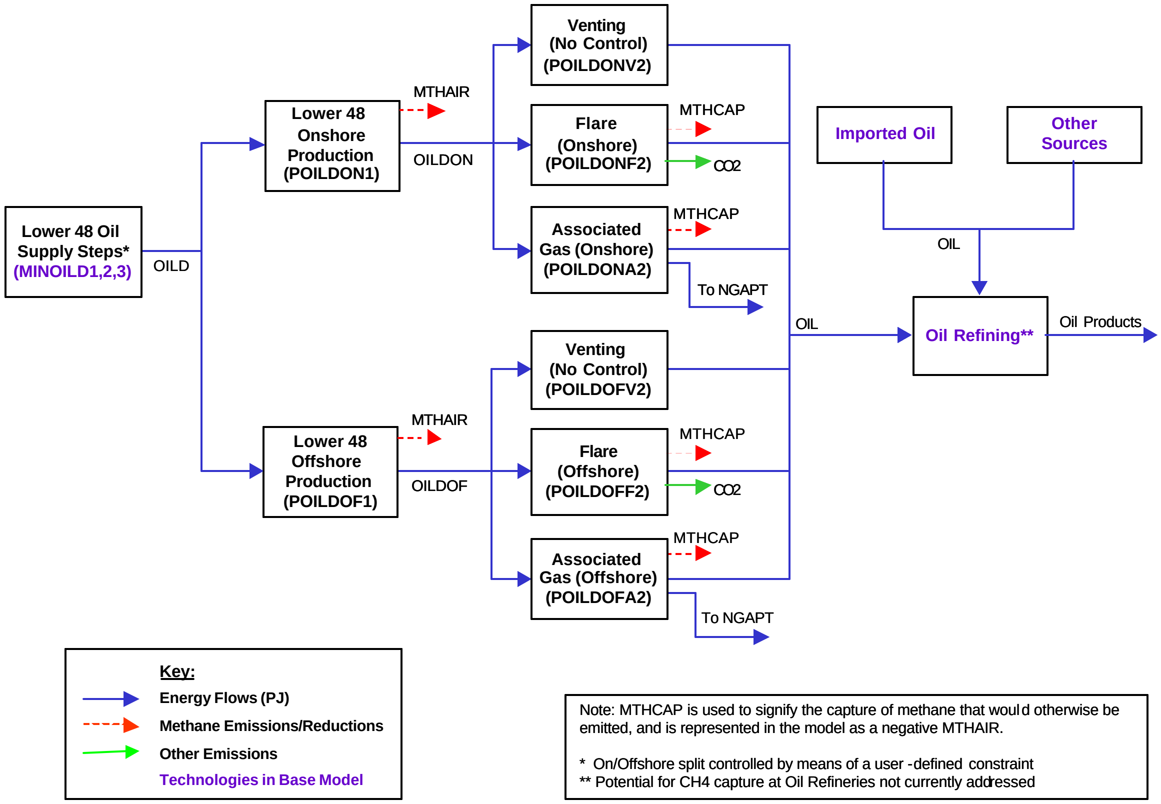

Figure 10: RES Flow Diagram for Methane Emissions from the Oil Subsystem - Lower 48 States

Table 4 provides the emission factors for both onshore and offshore oil production for Alaska and the Lower 48 states. In addition, it provides the percentage of offshore production for both resources. The ratio of onshore to offshore production for the lower 48 was taken from the Oil and Gas Supply Table of AEO 2004. For the Lower 48, onshore production is expected to decline, but offshore production is expected to increase.

Table 4: Input Parameters for Methane Emissions from Oil Production

Emission Factors for Oil Production - Lower 48, kt CH4/PJ oil										
	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035
On Shore	0.0821	0.0808	0.0791	0.0791	0.0791	0.0791	0.0791	0.0791	0.0791	0.0791
Off Shore	0.0821	0.0808	0.0791	0.0791	0.0791	0.0791	0.0791	0.0791	0.0791	0.0791
Ratio of Domestic Oil Production Offshore, %										
	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035
Lower 48	14.7%	23.2%	30.5%	41.5%	47.9%	48.2%	48.0%	50.2%	50.2%	50.2%
Alaska	14.7%	23.2%	29.9%	29.9%	29.9%	29.9%	29.9%	29.9%	29.9%	29.9%
Emission Factors for Oil Production - Alaska, kt CH4/PJ oil										
	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035
On Shore		0.0765	0.0765	0.0765	0.0765	0.0765	0.0765	0.0765	0.0765	0.0765
Off Shore		0.0456	0.0456	0.0456	0.0456	0.0456	0.0456	0.0456	0.0456	0.0456

2.5 Manure Treatment

Methane emissions from livestock manure management are generated from the anaerobic decomposition of the manure and are dependent on three principal factors: the manure source (including climate differences), the manure management system and the emission mitigation technology. Because liquid management systems promote anaerobic processes that generate methane, while dry management systems maintain greater exposure of the manure to air and do not promote methane generation, the manure sources were grouped according to their likelihood of using liquid or slurry management systems.

Figure 11 shows that dairy cows and swine were modeled as the dominant manure sources that could use liquid manure management systems, and all other livestock were modeled as using dry treatment systems. The methane emissions from dry treatment have no mitigation options, while the liquid management systems have several options available. As in the other subsystems, once waste flow was divided between liquid or slurry management, the appropriate treatment and/or mitigation technologies can be applied.

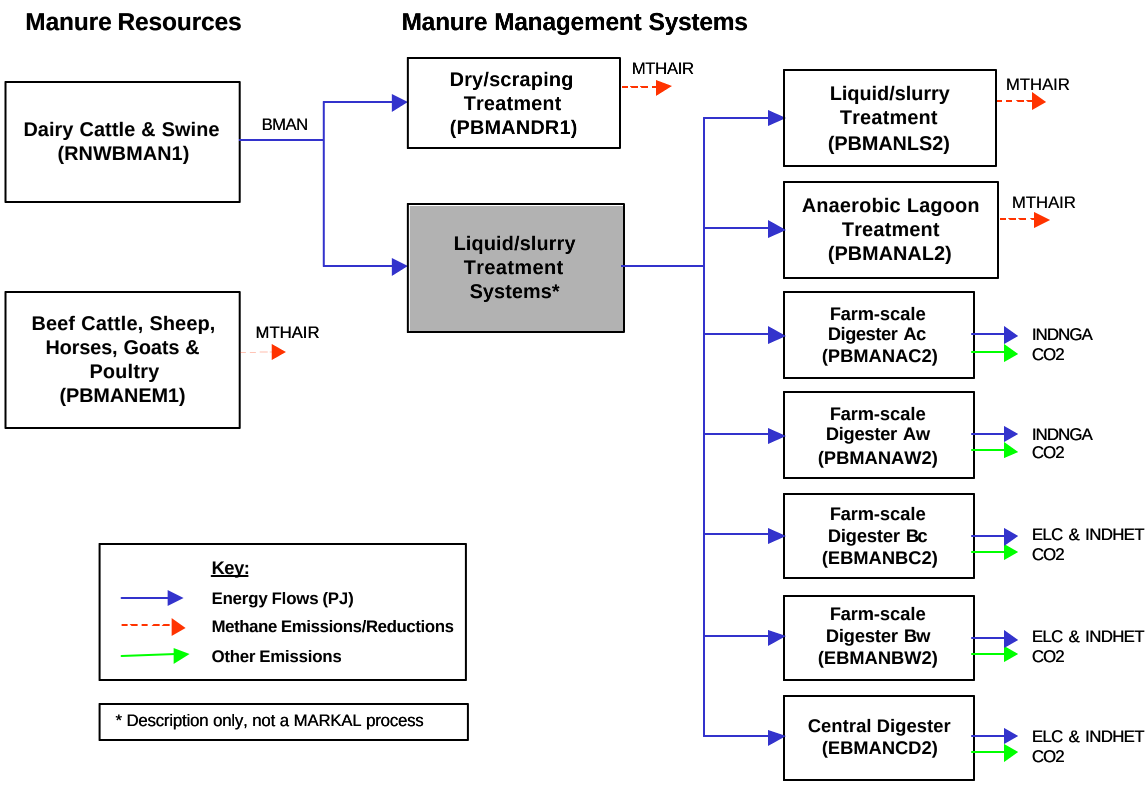

Figure 11: RES Flow Diagram for the Manure Handling Subsystem

There is a portion of poultry manure that goes to liquid treatment systems, but the added complexity of modeling two liquid waste streams was not considered necessary considering the small size of this emission subsystem. Table 5 provides the basic data used for he manure subsystem, including the assumed split between cattle and swine manure, the relative methane conversion factors and the ratio of solid to liquid treatment systems.

Table 5: Manure System Emissions Data for Liquid Treatment Systems

		Weighted-average CH4 Generation Potential (m3 CH4/kg VS)								
	2001 Data	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**
Dairy Cattle	0.2113	0.3245	0.3303	0.3384	0.3447	0.3513	0.3548	0.3581	0.3620	0.3658
Swine	0.48									
	2001 Data	**Methane conversion factors**								
Dry	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%
Liquid Slurry	29.57%	29.6%	29.6%	29.6%	29.6%	29.6%	29.6%	29.6%	29.6%	29.6%
Anaerobic Lagoon	69.97%	69.9%	69.9%	69.9%	69.9%	69.9%	69.9%	69.9%	69.9%	69.9%
	2001 Data	**% of Liquid treatment systems**								
Dairy Cattle	20%	18%	20%	21%	23%	26%	28%	31%	34%	38%
Swine	30%	28%	30%	32%	34%	36%	38%	40%	43%	45%
Weighted average %		22%	24%	26%	28%	31%	33%	36%	39%	42%

3. Data Specification Spreadsheet Workbook[5]

The EPA data on methane release and mitigation options have been assembled in to comprehensive Excel data and calculation workbook. The workbook contains three basic groups of spreadsheets briefly described here.

1) Index, conversion and commodities/units

   These three sheets respectively serve to:

   - Provide an index and quick link to the main data sheets (3) associated with each of the six methane subsystems;
   - Provide the conversion factors most commonly used to transform the source data to model units, and
   - Define each of the commodities (energy carriers and emissions) and their model units involved in the entire methane sub-model.

2) Calibration

   - This sheet contains the results of the sub-model calibration to the baseline EPA methane emission estimates. The results of the calibration run are discussed in the next section.

3) Subsystem specification sheets, usually consisting of:

   - EPA resource supply and emission information, (<sector> Source), for example details on MSW collection and methane release rates, the coal basin composition associated release methane rates, etc.
   - EPA methane mitigation technology options data (<sector> Data) providing the name, description and technical (efficiency, mitigation rate) and economic (investment and O&M cost) characterization information for each technology, and
   - MARKAL technology sheets (<sector> Tech) identifying each model parameter (time series and time independent) transformed as required into the model units and ready for input to the model database.

4. Methane Sub-Model Calibration

4.1 Running the Methane Sub-Model

All of the data for the Methane sub-model is contained within the METHALL scenario within the EPA US-national MARKAL model. The run the methane sub-model, this scenario is added to other model scenarios maintained in the current EPA-MARKAL ANSWER database. The following scenarios are combined to make the non-methane base case for the model:

- BASE - the complete RES for the core national energy system depicted in the model;
- CALIB - various refinements to the BASE scenario made by EPA-ORD in the process of calibrating the reference scenario to EIA data;
- CARSPLTS - an updated representation of the model's transportation sector; and
- INDSAGE - the expanded representation of the industrial sector adopted from that used in the SAGE model.

The methane calibration run was by including the three additional scenarios:

- FIXCO2 - adjustments made to the BASE scenario during the methane work to correct errors in the CO2 accounting and add coal technologies with CO_2 sequestration;
- METHALL - the full methane subsystem, and
- METHCAL - all the methane mitigation technologies in METHALL are prevented from operating so that the methane emissions calculated by the model can be calibrated to the EPA baseline estimates.

For the Reference methane run, only FIXCO2 and METHALL are added to the base set of scenarios, and for various sensitivity cases, one or more additional scenarios are added to the model runs.

4.2 Methane Calibration Results

Figure 12 shows the calibration of each sector of the Methane sub-model to the EPA baseline methane emission projections[9]. In the model calibration run, the methane mitigation options were deactivated so that the model produced only methane emission and did not use any mitigation technologies. The model's projected emissions (to 2030) were then compared to the EPA methane inventory for 1995 and 2000 and the EPA baseline emission projections (to 2020 only).

As can be seen in the figure, the methane emissions reported by the model from the coal, oil and manure sources closely match the EPA baseline data and projections. However, starting in 2005 there are some divergences with in the landfills and natural gas subsystems in particular. For landfills, the age distribution of waste in place in existing landfills is not known, and the LFG emissions are assumed to have a linear decay rate. This is likely the reason for the difference between the baseline and base case landfills emissions. Natural gas emissions as calculated by the model are slightly different from EPA projections because the future projection for natural gas demand in the model is slightly different from that used in the EPA projection of baseline methane emissions[16]. The difference in the emissions calculated by the model is directly proportional to the difference in the natural gas demand. The smaller differences in the coal and oil sectors are also largely due to slightly different projections of energy use.

The conclusion of this calibration effort is that the methane sub-model is precise for the 1995 and 2000 periods, and that the differences beyond that time are clearly explainable in terms of the model's behavior. A more detailed discussion of the calibration of each of the subsystems follows.

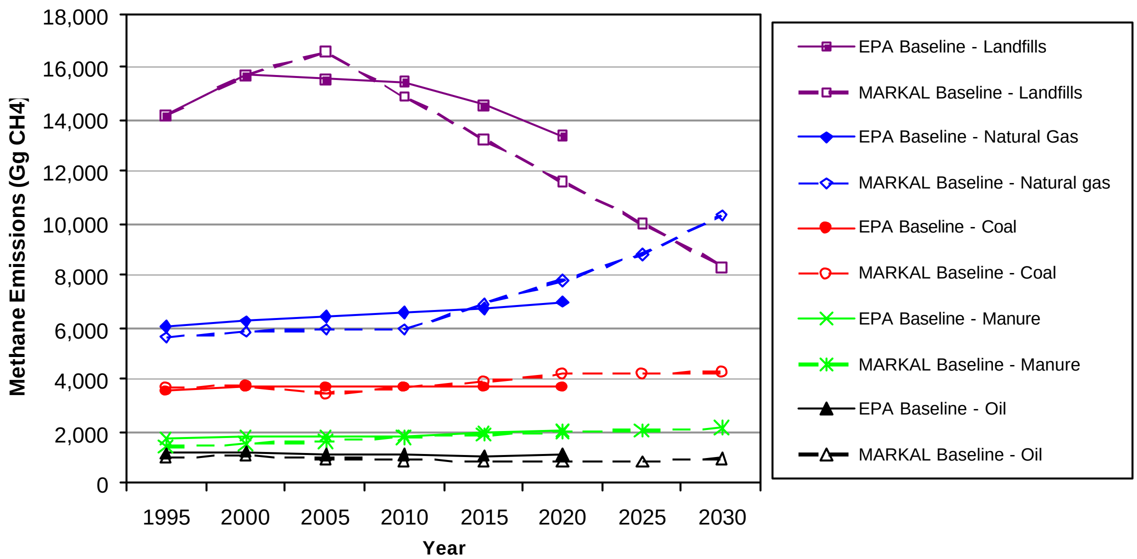

Figure 12: Methane Subsystem Calibration to EPA Baseline Projections

4.2.1 MSW and Landfill Subsystem

For the 1995 and 2000 periods, the model accurately gives the baseline methane emissions because these are known emissions from existing landfills. The future emissions from these pre-2005 landfills were assumed to follow a 30 year linear decay based on the assumption that the age distribution of the waste in place (WIP) in these landfills is relatively uniform. It is possible that an improvement in the projection for this emission component could be made if the emissions were adjusted relative to the age distribution of the pre-2005 WIP.

In 2005 and later years, the model over predicts landfill emissions by about 6%. This is probably due to the assumed emission profile from existing landfills, which may be over predicting in the early years (and under predicting the later years).

Following 2005, the landfill emissions drop faster than EPA projections (from 4% to 13%). This is probably due to a combination of two factors. The first is the assumed emission profile from existing landfills, and second is the projected diversion of MSW from landfills to MSW power plant technology. No other alternate uses for MSW were allowed in the calibration run.

4.2.2 Natural Gas Subsystem

For the natural gas subsystem, emissions from the model track the EPA baseline emissions from 1995 to 2010 but run about 6% lower than the EPA projection for the later periods. The reason for this difference is that the EPA baseline projection is slightly higher than the projection from the EPA-MARKAL. Table 6 and Table 7 show the breakdown of the natural gas emissions by sub-sectors, where it can be seen that the ratio of natural gas use between the EPA projection and the model (Energy ratio) and the ratio of methane emissions

(Methane ratio) are very close for both the production and the transmission sub-sectors. However, for the distribution sub-sector, the methane emissions are about 3 percentage points below what would be expected by the energy ratio.

Table 6: Natural Gas System Emissions Calibration for 1995

	1995 CH_4 emissions (Gg)	1995 Model Results (Gg)	Calibration Deltas	EPA NG Use (PJ)	Mode NG Use (PJ)	Energy ratio	Methane ratio
NG Production	1,583	1,481	-102	19,616	18,351	93.6%	93.6%
NG Transmission	2,904	2,740	-165	22,612	21,328	94.3%	94.3%
NG Distribution	1,572	1,423	-149	22,612	21,328	94.3%	90.6%
NG Total	6,059	5,644	-415				

Table 7: Natural Gas System Emissions Calibration for 2000

	2000 CH_4 emissions (Gg)	2000 Model Results (Gg)	Calibration Deltas	EPA NG Use (PJ)	Model NG Use (PJ)	Energy ratio	Methane ratio
NG Production	1,633	1,675	43	20,037	20,765	103.6%	102.6%
NG Transmission	2,996	2,740	-257	23,604	21,328	90.4%	91.4%
NG Distribution	1,622	1,423	-198	23,604	21,328	90.4%	87.8%
NG Total	6,251	5,838	-412				

4.2.3 Coal Subsystem

Coal mining emissions run from the model track the EPA baseline emissions generally within about 4% of the EPA projection. Because coal production in the model is higher than the value of coal production used to calculate the methane emission factor, there may be some under-prediction by the model of the coal mining methane emissions. This can be seen in Table 8. One cause of the variances may be the difference in the splits between underground and surface coal production used by EPA and predicted by the model.

Table 8: Coal Mining Emissions Calibration for 1995 and 2000

	1995 CH_4 emissions (Gg)	1995 Model Results	Calibration Deltas	EPA NG Use (PJ)	Model NG Use (PJ)	Energy ratio	Methane ratio
Coal Mining	3,519	3,671	152	23,761	28,132	118.4%	104.3%
	2000 CH_4 emissions (Gg)	**2000 Model Results**	**Calibration Deltas**	**EPA NG Use (PJ)**	**Model NG Use (PJ)**	**Energy ratio**	**Methane ratio**
Coal Mining	3,702	3,762	61	23,761	28,177	118.6%	101.6%

4.2.4 Manure Subsystem

Manure system emissions predicted by the model are low relative to EPA baseline emissions by as much as 19%. The difference is likely to be due to the calculation of liquid treatment emissions, because the calculation of the dry treatment emissions is quite straightforward. The main factor contributing to the difference is most likely to be due the decision to exclude the portion of poultry manure that goes to liquid treatment systems. It's also possible that some difference is due to the assumed split between cattle/swine and solid/liquid treatment systems.

4.2.5 Oil Production Subsystem

Oil system emissions from the model run about 15% below the baseline projections. These differences could be due to our assumed splits between onshore and offshore oil and our split between Lower 48 and Alaska oil, which are both based on the year 2000 data.

4.3 Possible Calibration Improvements

Calibration of the EPA-MARKAL model is not complete yet by ORD, and as a result it is not practical at this time to pursue some of the possible measures to improve the calibration of the methane sub-model. Based on the results discussed above, the items listed below could be pursued after further calibration of the full model

1. We currently have very little data on existing capacity in place (RESID) for the mitigation technologies. Data for existing technologies will be needed to improve the model calibration.
2. Develop a new projection of emissions from pre-2005 landfills based on data and assumptions regarding the WIP age distribution of typical landfills.
3. Improve the modeling of Other Natural Gas Sources entering the Transmission and Storage sub-sector and Distributed Natural Gas Sources entering the Distribution sub-sector.
4. Examine the emission factors for natural gas distribution sub-sector.
5. Examine the model projections of underground and surface mined coal and the relative emissions from both sources of methane emissions.
6. Further examine the splits of Lower 48 and Alaska oil production and the ratio of onshore to offshore oil production.
7. Examine the cost of manure management systems, and consider adding liquid treatment systems for poultry manure.

5. Results from the Reference Mitigation Run

With the preliminary calibration of the methane subsystem accomplished the task of evaluating the performance of the model in response to emission caps was undertaken. Table 9 below presents the picture of the Methane options in the reference run. Details on the results arising from the calibration, reference and a series of mitigation runs can be found in the Analysis report[7].

Table 9: Summary of Methane Mitigation Options

Methane Subsystem	Technology Description	MARKAL Name[1]	Limit Introduced	Reference Results and Comment
5.1.1.1.1 Manure	Centralized Digesters (cool climate)	EBMANBC2	GROWTH = 30% per year, dropping to 10% later, starting from 0.01 GW.	• 0.01GW in 2000 only. • Not of much interest to the model.
	Farm Scale Digesters-B (warm climate)	EBMANBW2	GROWTH = 30% per year, dropping to 10% later, starting from 0.01 GW.	• 0.01GW in 2000, then runs at growth limit for the rest of the modeling horizon. • Need to limit growth, which is binding in all periods, particular the early ones.
	Farm Scale Digesters-B (cool climate)	EBMANCD2	GROWTH = 30% per year, dropping to 10% later, starting from .01 GW.	• 0.01GW in 2000 only. • Not of interest to the model.
	Farm Scale Digesters-A (cool climate)	PBMANAC2	GROWTH = 5% per year, starting from .01 PJ/a.	• Does not enter. • Not of interest to the model.
	Anaerobic Lagoon	PBMANAL2		• Investment in 1995 only. • Not of much interest to the model.
	Farm Scale Digesters-A (warm climate)	PBMANAW2		• Does not enter. • Not of interest to the model.
	Manure Dry Handling	PBMANDR1	Dry handling percent of total exogenous.	• Invests heavily every 15 years. • Share of dry handling fixed to %, varying over time, of all manure produced.
	Beef Cattle, Sheep, Goat, Horse & Poultry Emission	PBMANEM1	Exogenously fixed to EPA production estimates.	• At fixed levels.
	Liquid Slurry Treatment	PBMANLS2		• Does not enter. • Not of interest to the model.
Coal	On/offsite CoGen	ECBMCOG2	GROWTH = 30% per year, dropping to 10% later, starting from 0.1 GW.	• Investment throughout modeling horizon, growth constrained until 2020. • Operated at full utilization in all periods.
	On/offsite Power	ECBMELC2	GROWTH = 30% per year, dropping to 10% later, starting from 0.1 GW.	• Does not enter. • Not of interest to the model.

[1] Ordered by subsystem stage, then technology type (E=electric power plant, P=non-electric process) and name (<E/P-prefix>, commodity in, technology type, and index).

Methane Subsystem	Technology Description	MARKAL Name[1]	Limit Introduced	Reference Results and Comment
	Degas Capture (New): <basin and coal type>	PCABHUDC1	Only can be done for new coal mines.	• Minor interest in late periods of the model for Appl. Medium sulfur mines. • MARKAL commodity LAG used to delay coal production by 1 period (5-years). • Similar process exists for each coal-basis.
	Degas Venting (New): <basin and coal type>	PCABHUV1	Only can be done for new coal mines.	• Enters at levels corresponding to the opening of new mines. • MARKAL commodity LAG used to delay coal production by 1 period (5-years). • Similar process exists for each coal-basis.
	Flaring of Coal Mine Methane	PCBMFLR2		• Not of interest to the model.
	Gob gas upgrade - New Capture	PCBMGGUC2	Limited to new mines that did degas initially. GROWTH = 5% per year, climbing to 20% later, starting from .1PJa.	• Done whenever gob is captured in order to inject into the natural gas system. • Minor interest in late periods of the model for Appl. Medium sulfur mines.
	Gob gas upgrade - Existing	PCBMGGUE2	Limited to existing mines that did degas initially. GROWTH = 30% per year, dropping to 10% later, starting from 1PJa.	• Done whenever gob is captured in order to inject into the natural gas system. • Enters to growth limit out until 2020, then still of interest but below limit.
	Gob gas upgrade - New Vented	PCBMGGUV2	Limited to existing mines that did degas initially. GROWTH = 30% per year, dropping to 10% later, starting from 1PJa.	• Done whenever gob is vented in order to inject into the natural gas system. • Enters late hitting growth limit.
	Enhanced Degas (Existing)	PCBMEDBE2	Capped at a .5 – 2.8% of existing mines.	• Likes it in 1995 and 2010.
	Enhanced Degas (New)	PCBMEDBN2	Limited to those that did degas initially. GROWTH = 30% per year, dropping to 10% later, starting from 1PJa.	• Takes it to the limit except for last period. • Need to limit growth, which is binding when MTHAIR limit imposed in some periods.
	On/Off site Process Heat	PCBMPRH2		• Not of interest to the model.
Municipal Solid Waste	Landfill Gas Co-Generation	ELFGCOG2	GROWTH = 30% per year, starting from 1.0GW.	• Invests off and on throughout the model horizon. • Hits the growth limit in 2005.
	Landfill Gas Electricity Generation	ELFGPRG2	GROWTH = 10% per year, rising to 20% later, starting from .1GW.	• Invests lightly in 1995 and 2000, but not beyond.

Methane Subsystem	**Technology Description**	**MARKAL Name[1]**	**Limit Introduced**	**Reference Results and Comment**
	Anaerobic Digest 2 – Electric Generation	EMSWAD1	GROWTH = 30% per year, dropping to 10% later, starting from 0.05GW.	• Modest investment in 2005, but not beyond.
	MSW Power Plant	EMSWPP1	GROWTH = 5% per year.	• Growth limited investment in all periods. • Growth limit estimated in consultation with EPA.
	Flaring	PLFGFLR2	GROWTH = 20% per year, beginning from 1Pj.	• Not of interest to the model.
	Direct Gas Use (at base price for gas)	PLFGNGS2	GROWTH = 20% per year, beginning from 1Pj.	• Investment in 2005 and then from 2020 - 2030.
	Heat Generation	PLFGPRH2	GROWTH = 20% per year, beginning from 1Pj.	• Not of interest to the model.
	Increased Oxidation Cap	PLFMIOCAP2	GROWTH = 20% per year, beginning from 1Pj.	• Not of interest to the model.
	Normal Cap	PLFMNOMIT2		• 1st period investment does it all.
	Anaerobic Digest 1 – Process Heat	PMSWAD1	GROWTH = 2% per year, starting from 1PJa.	• Invests modestly.
	Composting 1	PMSWCP1	GROWTH = 30% per year, dropping to 10% later, starting from 1PJa.	• Not of interest to the model.
	Large Landfills	PMSWLFL1	Large landfills must be <= 47% of total landfill capacity.	• Large landfills are the vehicle of choice for handling the MSW, constrained by the 47% limit.
	Medium Landfills	PMSWLFM1		• Medium landfills take whatever is left after large hits limits, smalls forced in, and cost-effective capture and use options exhausted.
	Small Landfills	PMSWLFS1	Large landfills must be => 7% of total landfill capacity.	• Small landfills are expected to be at least 7% of total MSW generated, and sit on this lower bound in all periods.
	Mechanical Biological Treatment	PMSWMB1		• Not of interest to the model.
Natural Gas[a]	All distribution related options	PNGD<tech_qual>	Each mitigation option is limited to a maximum percent of total distribution.	• Each mitigation option named PNGDxxx3i, where i = the technology index within the group. • The PNGDNC3i options are the pass thru no control routes, and are the only ones used.
	All production related options	PNGP<tech_qual>	Each mitigation option is limited to a maximum percent of total production.	• Each mitigation option named PNGPxxx1i, where i = the technology index within the group. • The PNGPNC1i options are the pass thru no control routes, and are the only ones used.

Methane Subsystem	Technology Description	MARKAL Name[1]	Limit Introduced	Reference Results and Comment
	All transmission related options	PNGT<tech_qual>	Each mitigation option is limited to a maximum percent of total production.	• Each mitigation option named PNGTxxx2i, where i = the technology index within the group. • The PNGTNC2i options are the pass thru no control routes and dominate, except for PNGTDCC24 below.
	Dry Seals on Compressors (Trans)	PNGTDCC24	Limit <= 3.68% of transmission	• Investment constrained by the limit percentage.
Oil	Associated Gas (vented) Mix with Other (Off/Onshore), Alaska	POILAOFA2 / POILAONA2		• Not of interest to the model.
	Flare instead of venting (Off/Onshore), Alaska	POILAOFF2 / POILAONF2		• Not of interest to the model.
	Venting or no control (Off/Onshore), Alaska	POILAOFV2 / POILAONV2		• Chosen when no incentive to do otherwise.
	Associated Gas (vented) Mix with Other (Off/Onshore), Lower 48	POILDOFA2 / POILDONA2		• Not of interest to the model.
	Flare instead of venting (Off/Onshore), Lower 48	POILDOFF2 / POILDONF2		• Not of interest to the model.
	Venting or no control (Off/Onshore), Lower 48	POILDOFV2 / POILDONV2		• Chosen when no incentive to do otherwise.

a - There are an extensive set of natural gas mitigation options. The reader is referred to the Excel database[5] or Analysis report[7] for a complete indication of the options available to the model.

Review of these reference case results identified two items that might warrant further investigation. First, the model reports very high marginal costs for coal mine methane on/offsite power generation (ECBMELC2). The investment and O&M cost inputs for this technology should be reviewed by an EPA expert. Second, the model also reports very high marginal costs for anaerobic digestion of MSW for electric generation (EMSWAD1). The EPA data for this technology (and a few other technologies) has a large negative O&M cost, which represents a non-energy related revenue stream (in this case the fertilizer by-product). This non-energy revenue was not included in the technology characterization, and this decision should be reviewed with EPA.

6. Conclusions

This report describes the details of the methane sub-model that has been added to the EPA US-national MARKAL model. The report and its companion documents provide all the data and assumptions behind the modeling approach. The methane sub-model can be used to investigate policies and strategies to encourage the use of cost-effective energy supply options embedded within the methane system and it can examine the relative effectiveness of possible programs looking to mitigate GHG emissions. From the modeling point of view the complexities of the methane emission sectors and their interactions with the energy system are represented in appropriate detail. The scenarios investigated in this paper were exploratory and serve to illustrate the possible technology and policy options that can be investigated with the model; and the continuous and cumulative mitigation cost curves providing insight into programs that might stimulate the market to more quickly adopt the more cost-effective mitigation options.

A very powerful capability of the EPA-MARKAL model is its ability to model technology and policy options for both CO_2 and CH_4 mitigation based on their relative global warming potential. The results of the mitigation scenarios performed for this paper illustrate the increased cost-effectiveness of such combined strategies. To this end, expanding the emission coverage to include the rest of the GHG contributors is planned, permitting a complete picture of options and opportunities to reduce GHG emissions in the most cost-effective manner to be examined with the model.

References

[1] See www.etsap.org for a summary of MARKAL, its applications and its user community.

[2] The documentation on the EPA-MARKAL national model is pending, though being assembled by EPA-ORD. For information on the EPA-MARKAL national model contact Carol Shay (shay.carol@epamail.epa.gov).

[3] "*Feasibility Study for the Inclusion of Industrial and Municipal Methane Sources in a MARKAL Model*". Preliminary concept developed by Lorna A. Greening, deliverable under U.S. Environmental Protection Agency Contract No. 68-W7-0067, TO 4004, Task #5, September 26, 2001.

[4] The methane subsystem as model is essentially self-contained, and can be hooked into most MARKAL models by simply renaming the energy carriers at the subsystem borders (e.g., mined coal, oil production, pipeline gas, etc.). Emission profiles for landfills and manure treatment, and the technology costs, need to be adjusted to the local circumstances.

[5] The current Excel data and calculation workbook is "Methane MAC Data_Rev4.xls." It contains the original source data, conversion tables, and transformation operations that result data ready for entering into ANSWER.

[6] Need to add reference to ANSWER user's manual.

[7] "Analysis of Methane Mitigation Options using the US-EPA MARKAL Model," International Resources Group Report to USEPA, September 2004.

[8] ANSWER database file name: EPANM_INDSAGE+METH.mdb.[0]"

[9] U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions, USEPA Office of Air and Radiation, EPA-430-R-99-013, September 1999.

Addendum to the U.S. Methane Emissions 1990-2020: 2001 Update for Inventories, Projections, and Opportunities for Reductions, December 18, 2001.

Assessment of Abatement Cost of Emissions Reductions Options for Greenhouse Gases, EU Report, 2000.

U.S. HGWPs Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions. USEPA, 2001.

Abatement of Other Greenhouse Gases-Engineered Chemicals, Report Number PH3/35, EC February 2001.

U.S. Adipic and Nitric Acid N2O Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions, USEPA, 2001.

Draft report, International Mitigation of Adipic and Nitric Acid Emissions, ICF 2002.

[10] Annual Energy Outlook 2002 with Projections to 2020, US Energy Information Administration, DOE/EIA-0383(2002), December 2001.

[11] Technical and Economic Assessment: Mitigation of Methane Emissions from Coal Mine Ventilation Air, USEPA, Office of Air and Radiation, EPA-430-R-001, February 2000.

[12] Editable versions of the flow diagrams presented in this report are also provided in a Power Point file: Methane Model Flow Diagrams Version 1.0.ppt.

[13] The U.S. Landfill Rule requires landfills with a certain level of waste-in-place to flare landfill gas in order to control for Volatile Organic Compounds (VOCs).

[14] Judith Bates and Ann Haworth, "Economic Evaluation of Emission Reductions of Methane in the Waste Sector in the EU: Bottom-up Analysis," Final Report (Updated version), AEA Technology Environment, March 2001.

[15] USEPA GHG Emissions inventory (Fix this reference)

[16] The EPA projection of baseline methane emissions were developed in 1999 and used data from AEO 1998. Initial calibration of the EPA US-national MARKAL model was performed in 2003 and used data and projections from AEO 2003.