Summary of Expansions and Revisions in GREET1_2011[*] Version

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This release of GREET1_2011 model includes the following major updates:

1. Added shale gas (SG) production pathway, including well drilling, SG recovery and processing. Added/updated flaring of associated gas, CO_2 and CH_4 emissions from flaring, and CH_4 leakage from NG recovery, SG recovery, NG processing and NG transportation and distribution. These updates are documented in a completed Argonne study. (Reference: Burnham, A., Han, J., Clark, C., Wang, M., Dunn, J., Palou-Rivera, I., 2011. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal and petroleum. Environmental Science & Technology, under review.)
   a. Updated the NG recovery efficiency taking into account the increased NG feed loss.
   b. Shared the same downstream assumptions with conventional NG pathways.
   c. Updated NG fuel production pathways to include compressed natural gas (CNG), liquefied natural gas (LNG), natural gas (NG) as a process fuel, and NG as an intermediate feed to produce methanol, dimethyl ether (DME), liquefied petroleum gas (LPG), Fistcher-Tropsch diesel (FTD), Fistcher-Tropsch naphtha (FTN) and hydrogen from SG sources.
2. Updated petroleum recovery assumptions including flaring associated gas in crude oil recovery and venting CH_4 from tailing pond in oil sands recovery. These updates are documented in a completed Argonne study. (Reference: Ignasi Palou-Rivera and Michael Wang, 2011, "Updated Estimation of Energy Efficiencies of U.S. Petroleum Refineries," Center for Transportation Research, Argonne National Laboratory)
3. Updated overall petroleum refinery efficiency and models (including the conversion of inputs and the combustion of intermediate) on the basis of 2009 petroleum refinery data from the Energy Information Administration's (EIA's) annual survey. Also, revised the allocation of refinery energy use among the different refinery products.
   a. Updated petroleum refinery model taking into account the conversion of inputs and the combustion of intermediate (Reference: Ignasi Palou-Rivera and Michael Wang, 2011, "Updated Estimation of Energy Efficiencies of U.S. Petroleum Refineries," Center for Transportation Research, Argonne National Laboratory)
   b. Updated petroleum refinery process fuel use on the basis of EIA Refinery Capacity Report 2010 on fuel consumed at refineries by Petroleum Administration for Defense (PAD) districts in 2009
   c. Updated merchant and captive hydrogen consumption at refineries on the basis of 2006 data found in The Chemical Economics Handbook, 743.5002
   d. Revised refinery energy-intensity ratios for gasoline, diesel, jet, LPG, naphtha, and residual oil to reflect actual energy use and emissions for each fuel product and hydrogen-producing and -consuming sources within a refinery. This revision was based largely on Larry Bredeson, Raul Quiceno, Xavier Riera-Palou, and Andrew Harrison, 2010 ("Factors Driving Refinery CO2 Intensity, with Allocation into Products," The International Journal of Life Cycle Assessment, DOI 10.1007/s11367-010-0204-3)

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[*] New GREET naming convention is now defined by its purpose as well as the year associated with its release. Since GREET1 is the fuel cycle model and 2011 is the year of this release, the name for this release became GREET1_2011.

4. Added renewable natural gas (RNG) production and processing from anaerobic digestion (AD) and conventional manure management. Included CH_4 leakage in RNG processing from both AD of manure and landfill gas sources. The RNG pathways are documented in a completed Argonne study. (Reference: Han, J., Mintz, M., Wang, M., 2011. Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model. Center for Transportation Research, Argonne National Laboratory)
   a. Updated NG and hydrogen fuel production pathways to include compressed natural gas (CNG), liquefied natural gas (LNG), and natural gas (NG) as an intermediate feed for methanol, dimethyl ether ($_D$ME), liquefied petroleum gas (LPG), Fistcher-Tropsch diesel (FTD), Fistcher-Tropsch naphtha (FTN) and hydrogen from RNG sources.
5. Added pyrolysis-based renewable gasoline and diesel production by including fast-pyrolysis of corn stover and forest residue, and the subsequent stabilization and upgrading of pyrolysis oil. The pathways are documented in a completed Argonne study. (Reference: Han, J., Elgowainy, A., Palou-Rivera, I., Dunn, J. and Wang, M., 2011. Well-to-Wheels Analysis of Fast Pyrolysis Pathways with GREET. Center for Transportation Research, Argonne National Laboratory)
   a. Pyrolysis and upgrading assumptions with corn stover as feedstock are based on an Iowa state university study (Reference: Wright, M.M., 2010, Techno-Economic Analysis of Biomass Fast Pyrolysis to Transportation Fuels, NREL/TP-6A20-46586, National Renewable Energy Laboratory, Golden, Colo.)
   b. Pyrolysis and upgrading assumptions with forest residue as feedstock are based on a Pacific North National Laboratory study (Reference: Jones, S.B., et al., 2009, Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case, PNNL-18284, Pacific Northwest National Laboratory, Richland, Washington.)
   c. Added vehicle technologies for pyrolysis-based renewable gasoline and diesel which share the same vehicle technology assumptions as bio-oil-based renewable gasoline and diesel.
6. Added algae pathways to produce bio-oil, including the algae growth, dewatering and oil extraction stages. More detailed assumptions for these stages are included in a separate spreadsheet known as the algae process description (APD) which is linked to GREET. The pathways are documented in a completed Argonne study.
   a. Added algae growth, dewatering and oil extraction modules (Reference: Frank, E., Han, J., Palou-Rivera, I., Elgowainy, A., Wang, M., 2011. Life-Cycle Analysis of Algal Lipid Fuels with the Greet Model. Center for Transportation Research, Argonne National Laboratory, Available at: http://greet.es.anl.gov/files/algal_lipid_fuels)
   b. Added process-level displacement, energy-based allocation, market value-based allocation and hybrid methods for algae growth, dewatering and oil extraction modules.
   c. An algae process description (APD) is created with a user manual (Reference: Frank, E., Han, J., Palou-Rivera, I., Elgowainy, A., Wang, M., 2011. User Manual for Algae Life-Cycle Analysis with GREET: Version 0.0. Center for Transportation Research, Argonne National Laboratory)
   d. Added pathways for the following new fertilizers based on a completed Argonne study: sodium chloride (NaCl), potassium chloride (KCl), potassium hydroxide (KOH), sodium nitride ($NaNO_3$), langbeinite ($K_2SO_4.2MgSO_4$), ammonium chloride (NH_4Cl), potassium nitrate (KNO_3), calcium nitride ($Ca(NO_3)_2$), calcium nitride ($Ca(NO_3)_2.4H_2O$), potassium phosphates (K_2HPO_4), potassium phosphates ($K_2HPO_4.3H_2O$), potassium phosphates (KH_2PO_4), diammonium phosphate ($(NH_4)_2HPO_4$), potassium sulfate (K_2SO_4), superphosphate ($Ca(H_2PO_4)_2+2CaSO_4$), triple superphosphate (Ca(H2PO4)2), triple superphosphate (Ca(H2PO4)2.H2O). (Reference: Frank, E., Han, J., Palou-Rivera, I., Elgowainy, A., Wang, M., 2011. Life-Cycle Analysis of Algal Lipid Fuels with the Greet Model. Center for Transportation Research, Argonne National Laboratory, Available at: http://greet.es.anl.gov/files/algal_lipid_fuels)

7. Added five new feedstocks (palm, rapeseed, jatropha, cemelina and algae), in addition to updating soybean farming estimates, for bio-oil production and the subsequent production of biodiesel, renewable diesel and renewable gasoline based on studies by Argonne, Massachusetts Institute of Technology (MIT) and Michigan Technical University, and a study co-worked by University of Idaho and USDA
   a. Algae pathways assumptions are based on a completed Argonne study (Reference: Frank, E., Han, J., Palou-Rivera, I., Elgowainy, A., Wang, M., 2011. Life-Cycle Analysis of Algal Lipid Fuels with the Greet Model. Center for Transportation Research, Argonne National Laboratory, Available at: http://greet.es.anl.gov/files/algal_lipid_fuels)
   b. Updated farming assumptions (farming energy and fertilizer and pesticide inputs) for soybean based on a study co-worked by University of Idaho and USDA. (Reference: Pradhan, A., Shrestha, D. S., McAloon, A., Yee, W., Haas, M., Duffield, J. A., 2011. Energy Life-Cycle Assessment of Soybean Biodiesel Revisited. Transactions of the American Society of Agricultural and Biological Engineers 54(3), 1031-1039)
   c. Added farming, harvesting, transportation and oil extraction modules of five additional feedstocks including palm, rapeseed, jatropha, cemelina and algae (Reference: Elgowainy, A., Han, J., Wang, M., Carter, N. and Hileman, J., 2011. Life cycle analysis of alternative aviation fuels. Center for Transportation Research, Argonne National Laboratory)
   d. Palm, rapeseed, jatropha pathways assumptions are based on a MIT study (Reference: Stratton, R.W., Wong, H.M., Hileman, J.I., 2010. Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels. Partnership for AiR Transportation Noise and Emissions Reduction. Massachusetts Institute of Technology, Cambridge, MA.)
   e. Camelina pathway assumptions are based on a Michigan Technical University study (Reference: Shonnard, D.R., Williams, L., Kalnes, T.N., 2010. Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. Environmental Progress & Sustainable Energy 29, 382-392.)
8. Added jet fuel pathways by including the refining of conventional petroleum and hydrotreated pyrolysis oil to produce jet A and ultra low sulfur jet. Also added the production for Fischer-Tropsch jet from NG, coal and cellulosic biomass, and the production of (hydroprocessed) renewable jet from soybean, palm, rapeseed, jatropha, cemelina and algae, based on a completed Argonne study co-worked with Massachusetts Institute of Technology (MIT).
   a. Added jet fuel pathways producing jet A and ultra low sulfur jet from conventional petroleum and hydrotreated pyrolysis oil, Fistcher-Tropsch jet from NG, coal and cellulosic biomass, and hydroprocessed renewable jet from soybean, palm, rapeseed, jatropha, cemelina and algae (Reference: Elgowainy, A., Han, J., Wang, M., Carter, N. and Hileman, J., 2011. Life cycle analysis of alternative aviation fuels. Center for Transportation Research, Argonne National Laboratory)
   b. HRJ production assumptions are based on a Pearlson's thesis (Reference: Pearlson, 2007. A Techno-Economic and Environmental Assessment of Hydroprocessed Renewable Distillate Fuels. MIT)
9. Updated geothermal power plant cycle with energy and emissions burdens associated with plant and equipment composition and onsite construction activities for the following three geothermal power plant technologies.
   a. Hydrothermal Flash: Steam or hot water delivered to the surface to provide steam to drive a turbine generator for producing electricity.
      i. Plant cycle burdens for above ground plant structure, enclosures, and power generating equipment and 2.5 km deep wells.
      ii. CO_2 emissions from the geofluid released to the atmosphere are accounted for.
   b. Hydrothermal Binary: Subsurface hot water is used to flash a secondary fluid (typical organic liquids like pentane) to drive a closed loop turbine generator system for producing electricity. The cooled water is reinjected back into the reservoir.

        i. Plant cycle burdens for above ground plant structure, enclosures, and power generating equipment and 1.5 km deep wells.

        ii. CO_2 emissions from the geofluid released to the atmosphere are accounted for.

  c. <u>Enhanced Geothermal Systems</u>: Hot water from very deep below the surface is used to flash a secondary fluid like pentane to drive a closed loop.

        i. Plant cycle burdens for above ground plant structure, enclosures, and power generating equipment and 6 km deep wells.

        ii. CO_2 emissions from the geofluid released to the atmosphere are accounted for.

        iii. Burdens for fracturing subsurface rock to enhance heat exchange and fluid flow are accounted for.

10. Updated farming assumptions (farming, harvesting and collection energy and fertilizer and pesticide inputs) for corn stover, forest residue, switchgrass and sugarcane based on completed Argonne studies.

  a. Updated farming assumptions (farming, harvesting and collection energy and fertilizer and pesticide inputs) of switchgrass (Reference: Dunn, J., Eason, J. and Wang, M., 2011. Updated Sugarcane and Switchgrass Parameters in the GREET Model. Center for Transportation Research, Argonne National Laboratory)

  b. Updated farming assumptions (farming, harvesting and collection energy and fertilizer and pesticide inputs) of sugarcane (Reference: Dunn, J., Eason, J. and Wang, M., 2011. Updated Sugarcane and Switchgrass Parameters in the GREET Model. Center for Transportation Research, Argonne National Laboratory)

  c. Updated farming assumptions (farming, harvesting and collection energy and fertilizer and pesticide inputs) of corn stover (Reference: Han, J., Elgowainy, A., Palou-Rivera, I., Dunn, J. and Wang, M., 2011. Well-to-Wheels Analysis of Fast Pyrolysis Pathways with GREET. Center for Transportation Research, Argonne National Laboratory)

  d. Updated farming assumptions (farming, harvesting and collection energy and fertilizer and pesticide inputs) of forest residue (Reference: Han, J., Elgowainy, A., Palou-Rivera, I., Dunn, J. and Wang, M., 2011. Well-to-Wheels Analysis of Fast Pyrolysis Pathways with GREET. Center for Transportation Research, Argonne National Laboratory)

11. Revised the emission calculations of ammonia production for fertilizer applications. The upstream emissions of non-combusted NG in ammonia production are now included, which were not taken into account in the previous versions.

12. Updated the projections of U.S., California (CA), and northeastern (NE) electricity generation mixes on the basis of EIA's Annual Energy Outlook 2011. (Reference: U.S. EIA, 2011. <u>Annual Energy Outlook 2011</u> (DOE/EIA-0383(2011)). U.S. Energy Information Administration, Washington, D.C.). Previous and updated average generation mixes in the U.S. are shown in the following tables.

GREET 1_2011	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Others
2010	1.0%	22.9%	46.4%	20.3%	0.2%	9.2%
2015	0.9%	21.5%	44.2%	21.0%	0.5%	11.8%
2020	0.9%	20.2%	45.1%	21.1%	0.9%	11.7%
GREET 1.8d	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Others
2010	1.0%	20.2%	46.7%	21.0%	0.3%	10.7%
2015	1.0%	14.8%	49.2%	20.5%	1.2%	13.3%
2020	1.0%	15.6%	48.0%	20.6%	2.0%	12.7%

13. Added options to account for energy uses and emissions associated with the construction of petroleum and NG wells, and coal mines based on a completed Argonne study. (Reference: Burnham, A., Han, J., Clark, C., Wang, M., Dunn, J., Palou-Rivera, I., 2011. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal and petroleum. Environmental Science & Technology, under review.)