Supplementary Information to:

Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model

Lena Höglund-Isaksson, Adriana Gomez-Sanabria, Zbigniew Klimont, Peter Rafaj, Wolfgang Schöpp

2020-02-21

Content:

S1: Activity source sectors of the CH_4 module in the GAINS model

Table S1-1: GAINS model source sectors for anthropogenic CH_4 emissions.

Major source sector	Source sector	Activity unit	Further sub-sectors in GAINS
Agriculture	Beef cattle	M heads	Solid/Liquid manure management; Enteric fermentation/Manure management modelled separately only for animals on liquid manure management; Animals by farmsize (0-15 LSU, 15-50 LSU, 50-100 LSU, 100-500 LSU, > 500 LSU)
	Dairy cows	M heads	
	Sheep Goats etc	M heads	
	Pigs	M heads	
	Poultry	M heads	Laying hens/Other poultry
	Rice cultivation	M Ha	Continuously flooded/intermittently dried out/upland
	Agr waste burning	Mt crop residuals	no further sub-sectors
Energy	Coal mining	Mt coal mined	hard coal/brown coal; pre-mining/during mining/post-mining
	Abandoned coal mines	kt CH4	no further sub-sectors
	Domestic energy use firewood	PJ energy use	By woodstove type
	Domestic energy use other	PJ energy use	By boiler type; by fuel
	Industry energy use other	PJ energy use	By boiler type; by fuel
	Powerplant energy use other	PJ energy use	By boiler type; by fuel
	Domestic energy use gas	PJ energy use	combustion/fugitive emissions; by boiler type
	Industry energy use gas	PJ energy use	combustion/fugitive emissions; by boiler type
	Powerplant energy use gas	PJ energy use	combustion/fugitive emissions; by boiler type
	Gas transmission	PJ gas transported	no further sub-sectors
	Gas production	PJ gas produced	conventional natural gas/shale gas/coal bed methane/tight gas; fugitive emissions from intended venting and unintended equipment leakage estimated separately
	Oil production	PJ crude oil produced	fugitive emissions from intended venting and unintended equipment leakage estimated separately; heavy/conventional and on-shore/off-shore reflected in emission factor assumptions
	Oil refinery	PJ crude oil refined	no further sub-sectors
	Transport Road	PJ energy use	By fuel; by vehicle type (bus/truck/car/light-duty van); by EURO class
Industry	Industry Brick kilns	Mt brick	no further sub-sectors
Waste	Solid waste industry	Mt waste	By manufacturing industry: food, beverages, tobacco/pulp & paper/textile & footwear/wood & wood products/rubber & plastics/other
	Solid waste municipal	Mt waste	By waste category: food & garden/paper/textile/wood/rubber & plastics/other
Wastewater	Wastewater industry	kt COD	By manufacturing industry: food, fat, sugar & beverages/pulp & paper/organic chemical
	Wastewater domestic	M people	centralized collection/decentralized collection of wastewater

S2: GAINSv4 bottom-up CH$_4$ emission inventory 1990-2015 by sector and major World region

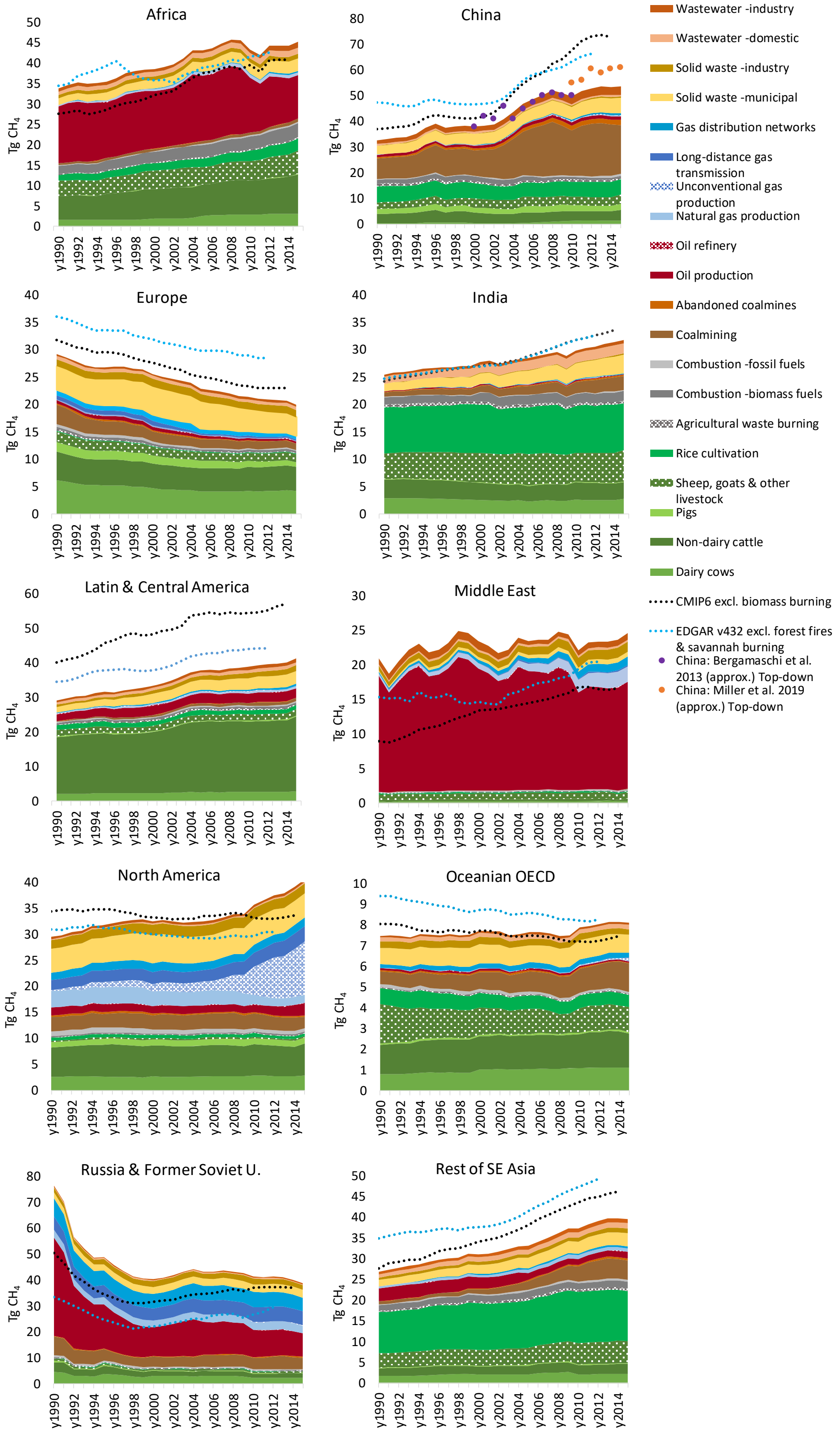

Figure S2-1: GAINSv4 bottom-up emission inventory for CH$_4$ emissions 1990-2015 by major World region.

S3: GAINSv4 baseline CH_4 emissions 1990-2050 by sector and major World region

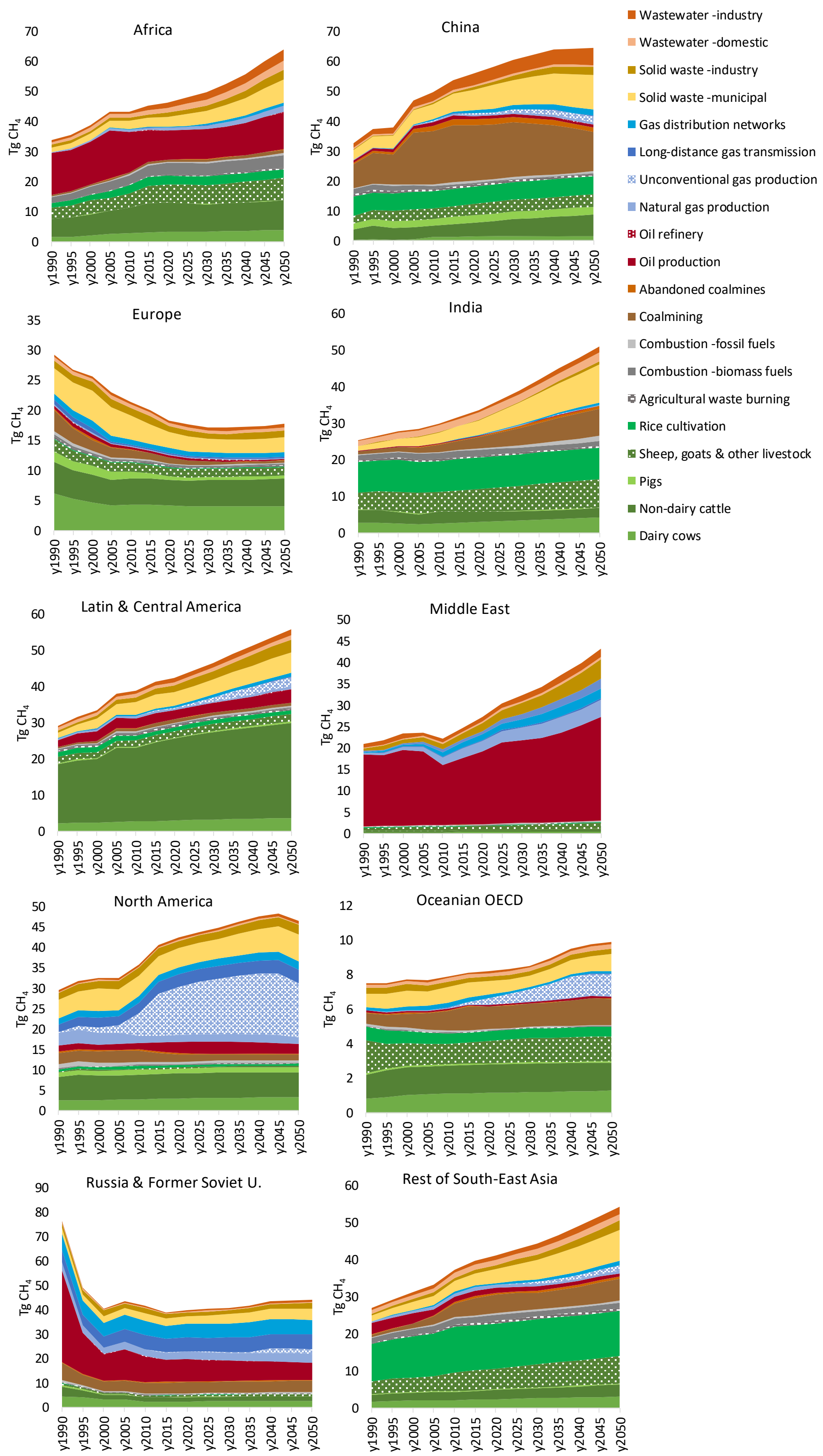

Figure S3-1: Baseline CH_4 emissions 1990-2050 by sector and World region as estimated in GAINSv4.

S4: Current legislation addressing CH_4 emissions implemented in GAINSv4

Table S4-1 provides a list of implemented national and regional legislation with direct or indirect impacts on CH_4 emissions, which have been considered in the GAINSv4 baseline scenario.

Table S4-1: Current legislation implemented in the GAINSv4 Baseline scenario.

Country	Sector	Policy or voluntary initiative	Date of publication/implementation
Algeria	Solid waste	Law relating to the management, control and disposal of waste. In GAINS assumed only partially enforced.	Law No. 01-19 of 12/12/2001
Argentina	Solid waste	Law relating to the management, control and disposal of waste. In GAINS assumed only partially enforced.	Law 25916 of 7/09/04
Australia	Solid waste	Region level legislation. Western Australia: Waste Avoidance and Resource Recovery Act 2007 (WARR Act); Canberra: ACT Waste Management Strategy: Towards a sustainable Canberra 2011-2025; Northern Territory: Waste Management Strategy 2015-2022; Queensland: Waste Avoidance and Resource Productivity Strategy 2014–2024	Regional implementation dates.
Colombia	Solid waste	Integrated waste management plans; Household waste collection, separation and landfill. In GAINS assumed only partially enforced.	Decree 1713/2002. Environment, Housing and development Ministry.
Costa Rica	Solid waste	Law on waste management: collection, separation and final disposal. In GAINS assumed partially enforced.	Law 8839 from 2010
Canada	Oil & gas systems	Requirements for oil and gas producers in the provinces of Alberta, British Columbia, Newfoundland to limit flaring and venting resulting in, e.g., a 40% reduction in venting and a 60% reduction in flaring of solution gas in Alberta. Recently implemented requirements in Saskatchewan and New Brunswick are expected to achieve similar reductions.	Alberta Energy Regulator (2013, 2014); BC Oil and Gas Commission (2013); Canadian Minister of Justice (2009); Saskatchewan Ministry for Energy and Resources (2011); New Brunswick Department of Energy and Mines (2013)
	Solid waste	Provincial regulations in British Columbia, Manitoba, Ontario, Quebec and Prince Edward Island require the collection and utilization and/or flaring of landfill gas (although requirements may depend upon facility size, age, etc.). Under the Provincial regulations in Alberta, facilities can reduce their emissions physically, use offsets or contribute to the Climate Change and Emissions Management Fund.	BC Ministry of Environment (2008); Manitoba Ministry of Conservation and Water Stewardship (2009); Ontario Ministry of Environment (2007); Quebec MDDELCC (2011); PEI Ministry of Environment, Labour and Justice (2009); Alberta Energy Regulator (1998); Ontario Ministry of Energy (2009)
		Province of Ontario has feed-in tariff in support of landfill gas electricity generation.	
	Livestock	Voluntary provincial greenhouse gas offset protocols in Alberta and Quebec address methane emissions from the anaerobic decomposition of agricultural materials (Alberta) and covered manure storage facilities (Quebec).	Alberta Environment (2007); Quebec MDDELCC (2009)
China	Coal mining	Various administrative provisions and programs to increase control and utilization of coal mine gas	Implemented 2005-2007, see Cheng, Wang & Zhang (2010); Miller et al. (2019)
	Solid waste	Law on the Prevention and Control of Environmental Pollution by Solid Waste. In GAINS assumed enforced in Hong-Kong, Shanghai and Beijing, with partial enforcment in other provinces.	Implemented 1995 with Amendment in 2004
Ecuador	Solid waste	Integrated waste management plans; Household waste collection, separation and landfill. In GAINS assumed only partially enforced.	Official registry No 316 -May 2015
Egypt	Solid waste	Law requring solid waste collection, treatment and disposal. In GAINS assumed only partially enforced.	Law 38/1967 on General Public Cleaning and Law 4/1994 for the Protection of the Environment.

Continued Table S4-1: Current legislation implemented in the GAINS Baseline scenario.

Country	Sector	Policy or voluntary initiative	Date of publication/implementation
European Union (EU-28)	EU-wide Climate policies	EU Climate and Energy package 2020: At least 20% cut in GHG emissions from 1990 level. Indirect effect on CH$_4$ through targets in the energy sector, e.g., 20% renewable energy in 2020 affect CH4 through incentives to extend anaerobic treatment of manure and food waste for recovery of biogas. The Effort-sharing decision provide binding national reduction targets for non-ETS sectors (housing, agriculture, waste, transport).	Adopted May 2009
		EU Climate and Energy framework 2030: At least 40% cut in GHG emissions from 1990 level. Indirect effect on CH4 through targets in the energy sector, e.g., 27% renewable energy, trigger incentives to extend anaerobic treatment of manure and food waste for recovery of biogas. Binding national reduction targets for non-ETS sectors (housing, agriculture, waste, transport) still to be adopted.	Adopted Nov 2018
	Oil & gas systems	EU Fuel Quality Directive: Reduce life-cycle greenhouse gas emissions of fossil fuels by 10% between 2010 and 2020 incl. reductions of flaring and venting at production sites.	EU Directive 2009/30/EC
		Gas flaring is only allowed with specific permission of the government and venting is only permitted in case of emergency.	GMI & EC (2013)
	Solid waste	EU Landfill Directive: Until 2016 reduce landfill disposal of biodegradable waste by 65 percent from the 1995 level and implement compulsory recovery of landfill gas from 2009.	EU Directive 1999/31/EC
		EU Waste Management Framework Directive: The waste hierarchy must be respected, i.e., recycling and composting preferred to incineration/energy recovery, which in turn is preferred to landfill disposal.	EU Directive 2008/98/EC
		Austria, Belgium, Denmark, Germany, Netherlands, Sweden: National bans on landfill of untreated biodegradable waste.	In effect 2005 or earlier.
		Slovenia: Decree on landfill of waste beyond the EU Landfill Directive. Includes a partial ban on landfill of biodegradable waste.	In effect Feb 2014
		Portugal: Target set to reduce landfill of biodegradable waste to 26% of waste landfilled in 1995.	Date of enforcement unclear, but policy in place in 2014.
	Wastewater	EU Urban Wastewater treatment Directive: "Appropriate treatment" of wastewater from urban households and food industry must be in place by 2005 and receiving waters must meet quality objectives.	EU Directive 1991/271/EEC
	Livestock	Denmark: National law on the promotion of renewable energy, which includes subsidy on biogas generated e.g., from manure.	Lov 1392, 2008
Iceland	All sources	No policies specifically addressing methane. Emissions likely small because of small population and cold climate.	Personal info (P. K. Jonsson, 2014)
Indonesia	Solid waste	Current state of waste management implemented in GAINS. Law assumed partially enforced in terms of waste collection and handling.	Waste Management Law of 2008 (No 18/2008)
Japan	Solid waste	High collection rates, appropiate separation systems and adequate waste treatment including recycling, composting and incineration of waste.	Law for Promotion of Utilisation of Recycled Resources (2002)
Kenya	Solid waste	Although Kenya has laws targeted to waste collection and management, implementation and enforcement is weak.	The Environmental Management And Coordination Act (EMCA), 1999
Malaysia	Solid waste	Current waste handling dominated by mostly unmanaged landfills with low collection and recycling rates	Solid Waste and Public Cleansing Management Corporation (SWPCMC) Act, 2007
Mozambique	Solid waste	Current waste treatment is poor with low collection rates	Environment Act (Law 20/97 of October1st)
New Zealand	Solid waste	Waste collection, separation and treatment systems are in place and enforced. Waste minimization assumed partially implemented in GAINS.	Waste Minimisation Act 2008
Norway	Oil & gas systems	Gas flaring is only allowed with specific permission of the government and venting is only permitted in case of emergency.	GMI & EC (2013)
	Solid waste	National ban on deposition of biodegradable waste in covered landfills from 2004.	FOR-2004-06-01-930

Continued Table S4-1: Current legislation implemented in the GAINS Baseline scenario.

Country	Sector	Policy or voluntary initiative	Date of publication/implementation
Peru	Solid waste	Current state of waste treatment systems reflected in GAINS Baseline. Landfills only partially managed, collection rates low in particular in small cities and rural areas.	General Law on Solid Waste Management (Ley General de Residuos Sólidos, 27314)
Phillipines	Solid waste	The GAINS Baseline reflects the current situation. Low collection rates, mainly unmanaged landfills.	Ecological Solid Waste Management Act, known as the Pepublic Act No 9003 (RA 9003)
Russia	Oil & gas systems	In the April 2007 state of the union address, president Putin announced an intent to make better utilization of associated gas a national priority.	Carbon Limits (2013)
		"Estimation of fines for release of polluting compounds from gas flares and venting of associated gas from oil production." (Translation from Russian by A. Kiselev, 2014)	Decree No.1148, Nov 8, 2012 of the Russian Fed. Governm.
		As of 2012, all flared associated gas must be metered or the methane fine increases by a factor of 120.	Evans and Roshchanka (2014)
	Other sources	"About greenhouse gases emission reduction." General policy addressing greenhouse gases, but unclear how methane is specifically addressed.	Decree No.75, Sep 30, 2013 of the Russian Fed. Governm.
Rwanda	Solid waste & wastewater	The GAINS Baseline reflects the current situation. Low collection rates, poor waste & wastewater handling.	National Policy and Strategy for Water Supply and Sanitation Services
Singapore	Solid waste	High collection rates and appropiate waste treatment including recycling, composting, incineration and sanitary landfills.	Environmental Public Health Act, Environmental Public Health (General Waste Collection & Waste Disposal Facilities) Regulations
South Africa	Solid waste	Current waste management shows partial implementation of the law in terms of collection rates, separation of waste and treatment.	National Environmental Management: Waste Act, 2008 (Act 59 of 2008)
Sri Lanka	Solid waste	The GAINS Baseline reflects the current situation. Low collection rates and generally poor management and treatment.	Solid Waste Act 2011
Tanzania	Solid waste	The GAINS Baseline reflects the current situation. Low collection rates and generally poor management and treatment.	Environmental Management Act of 2004
Tunisia	Solid waste	The GAINS Baseline reflects the current situation. Low collection rates and generally poor management and treatment.	Decree no 97-1102 of 2 Juin 1997
United States	Oil & gas systems	EPA's Natural Gas STAR Program: voluntary partnership that encourages oil and natural gas companies to adopt cost-effective technologies and practices that improve operational efficiency and reduce emissions of methane.	USEPA (2014a)
		New Source Performance Standards 2016 for methane from oil and gas systems sources, including Amendment from Sep 2018. Initially requiring oil and gas well owners to schedule monitoring and to repair leakages. The 2018 Amendment significantly relaxed requirements and provided possibilities for exceptions.	USEPA (2018)
	Coal mining	EPA's Coalbed Methane Outreach Program: voluntary program whose goal is to reduce methane emissions from coal mining activities.	USEPA (2014b)
	Solid waste	All landfills fullfill requirements for sanitary landfills. EPA's Landfill Methane Outreach Program: voluntary assistance program that helps to reduce methane emissions from landfills by encouraging the recovery and beneficial use of landfill gas as an energy resource.	USEPA (2014c); Resource Conservation and Recovery Act 1976, 1986
	Livestock	EPA's AgSTAR Program: voluntary outreach and educational program that promotes the recovery and use of methane from animal manure.	USEPA (2014d)
Vietnam	Solid waste	GAINS assumes partially implemented waste separation systems with proper handling and treatment in larger cities, Low collection rates and lack of proper treatment in rural areas.	Law on Environmental Protection 2005

S5: Assumptions on impacts of technological development

Table S5-1 presents GAINSv4 assumptions on impacts of technological development on future emission reduction potentials and costs for CH_4 abatement technologies. For details, see Höglund-Isaksson et al. (2018). Note that the “Technical removal efficiency” refers to the removal potential of emissions in a given country and sector relative a “no control situation”, which is defined as before any abatement technology has been adopted. If a technology has been adopted to some extent already in the baseline, then the remaining removal efficiency will be smaller than the technical removal efficiency. The same applies if there are physical or technical limitations to full applicability in a sector, e.g., animal feed changes are only assumed applicable to animals that are housed indoor. The technical removal efficiency then refers to the removal efficiency for the subset of animals housed indoor.

Table S5-1: Technological development effects 2020-2050 assumed in GAINSv4 for CH_4 mitigation options.

Sector	Methane mitigation options in GAINS	Technical removal efficiency (relative no control when technology is applicable)		Technological development effect on investment and O&M costs
		Current technology	Technology in 2050 (incl. technological development effect)	
Livestock	Anaerobic digestion of manure from cattle and pigs on farms with 100-500 LSU	60% (of manure emissions)	70% (of manure emissions)	-35%
	Anaerobic digestion of manure from cattle and pigs on farms with > 500 LSU	75% (of manure emissions)	82% (of manure emissions)	-35%
	Small-scale biogas digester for farm households in developing countries	50% (of manure emissions)	63% (of manure emissions)	-35%
	Breeding through selection for cows, cattle and sheep > 100 LSU (from 2030)	~ 10% (of enteric fermentation emissions)	~ 26% (of enteric fermentation emissions)	-28%
	Intensive systems: breeding in combination with feed additives > 100 LSU (from 2030)	20-30% (of enteric fermentation emissions)	34-43% (of enteric fermentation emissions)	-28%
	Extensive systems: breeding combined with inter-seeding of natural pastures > 100 LSU (from 2030)	30% (of enteric fermentation emissions)	43% (of enteric fermentation emissions)	-28%
Rice cultivation	Combined option: intermittent aeration of continuously flooded fields, alternative hybrids and sulphate amendments	33%	51%	-35%
Municipal solid waste	Food & garden waste: source separation and anaerobic digestion with biogas recovery and utilization	90%*	93%*	-35%
	Food & garden waste: source separation and treatment in household compost	80%*	85%*	-35%
	Food & garden waste: source separation and treatment in large-scale compost	89.5%*	92%*	-35%
	Paper waste: source separation and recycling	93%*	95%*	-35%
	Textile waste: source separation and reuse/recycling	100%*	100%*	-35%
	Wood: source separation and recycling for chip board production	95%*	96%*	-35%
	All waste categories: well managed incineration of mixed waste with energy recovery	>99%*	>99%*	-35%
Industrial solid waste	Food industry: Anaerobic digestion with biogas recovery and utilization	90%*	93%*	-35%
	Pulp & paper industry: incineration of black liqour for energy utilization	>99%*	>99%*	-35%
	Textile industry: incineration with energy recovery	>99%*	>99%*	-35%
	Wood industry: chipboard production	95%	96%	-35%
	All industries: well managed incineration with energy recovery	>99%*	>99%*	-35%
Domestic wastewater	Upgrade of primary treatment to secondary/tertiary anaerobic treatment with biogas recovery and utilization	93% (of primary treatment emissions)	95% (of primary treatment emissions)	-35%
Industrial wastewater	Upgrade of treatment to two-stage treatment, i.e., anaerobic with biogas recovery followed by aerobic treatment	99% (of primary treatment emissions)	99.3% (of primary treatment emissions)	-35%
Coal mining	Pre-mine degasification on both surface and underground coal mines	90%	93%	-35%
	Oxidation of ventilation air methane (VAM) on underground mines	50%	63%	-35%
	VAM oxidation combined with improved ventilation systems on underground mines	70%	78%	-35%
Oil & gas production	Extended recovery and utilization of vented associated gas	98%	99%	-35%
	Monitoring of temporary flare shutdowns	99%	99%	-35%
	Reducing unintended leakage through Leak Detection and Repair (LDAR) programs	67%	76%	-35%
Gas transmission	Reducing unintended leakage through Leak Detection and Repair (LDAR) programs	75%	82%	-35%
Gas distribution networks	Replacement of grey cast iron pipes and doubling of control frequency	97%	98%	-35%
	Reducing unintended leakage through Leak Detection and Repair (LDAR) programs	50%	63%	-35%
Combustion	Ban on open burning of agricultural waste	100%	100%	-35%

*Reduction relative a no control case defined as disposal to an unmanaged landfill with compacting

S6: Detailed source sector documentation

This section provides additional details on methodologies to estimate CH_4 emissions at the sector level in GAINSv4. The methodology described here builds on the documentation provided in the Supplement of Höglund-Isaksson (2012).

S6.1. Coal mining

The methodology for estimating global CH_4 emissions from coalmines in GAINSv4 has been described in detail in the Supplement of Höglund-Isaksson (2012). In short, emissions are estimated separately for brown coal and hard coal and using separate emission factors for pre-mining degasification, during mining and post-mining activities. In addition, country-specific information about the fractions of coal surface mined and mined underground has been collected and considered in emission estimations. Resulting implied emission factors and estimated emissions in 2010 and 2015 for all coalmining sources are presented in Table S6-1 by country. Emissions from Chinese coal mines make up over half of global CH_4 emissions from this source. Three recent studies (Peng et al., 2016; Miller et al., 2019; Sheng et al., 2019) quantify CH_4 emissions bottom-up from Chinese coalmines with Miller et al. and Sheng et al. also verifying bottom-up estimates with top-down atmospheric measurements and satellite observations. In GAINSv4, we align emissions from coal mining with the findings of these three studies as shown in Table S6-2.

Table S6-1: Implied emission factors for coal mining in GAINSv4 and in comparison to most recent reporting to the UNFCCC (2018).

		Implied emission factors ($Gg CH_4/Mt$ coal)		Emissions in year 2010 ($Tg CH_4$)		Emissions in year 2015 ($Tg CH_4$)	
World region	Country	Brown coal	Hard coal	GAINS	UNFCCC (v2018)	GAINS	UNFCCC (v2018)
Africa	South Africa	n.a.	2.36	0.60	n.a.	0.61	n.a.
	Other Africa	0.87	8.38	0.04	n.a.	0.12	n.a.
China		n.a.	5.61	17.7	n.a.	19.1	n.a.
European Union	Bulgaria	0.83	8.56	0.03	0.04	0.02	0.04
	Czech Rep.	0.59	8.26	0.17	0.18	0.12	0.14
	France	n.a.	13.74	0.004	0.00	0.003	0.0004
	Germany	0.07	7.51	0.13	0.13	0.08	0.12
	Greece	1.13	n.a.	0.06	0.05	0.06	0.04
	Italy	n.a.	12.84	0.001	0.001	0.001	0.001
	Poland	0.09	5.94	0.50	0.62	0.50	0.66
	Romania	1.72	13.50	0.06	0.06	0.05	0.04
	Slovak Rep.	2.61	n.a.	0.01	0.02	0.01	0.01
	Spain	0.32	4.44	0.03	0.01	0.02	0.003
	United Kingdom	n.a.	7.66	0.14	0.08	0.08	0.04
	Other EU countries	0.87	8.38	0.01	0.01	0.008	0.006
Eastern Europe	Former Yugoslav republics	0.87	8.38	0.10	n.a.	0.10	n.a.
	Turkey	1.68	8.90	0.15	0.24	0.11	0.09
Western Europe	Norway	n.a.	1.56	0.003	0.002	0.002	0.002
Russia & Former Soviet Union	Russian Fed.	4.53	9.51	2.47	2.23	2.98	2.45
	Kazakhstan	4.01	6.67	0.72	0.97	0.70	0.89
	Ukraine	1.22	22.97	1.26	0.93	0.69	0.56
	Other Former Soviet republics	0.87	8.38	0.01	n.a.	0.02	n.a.
India		0.87	3.84	2.05	n.a.	2.46	n.a.
Latin & Central America		0.87	8.38	0.80	n.a.	0.92	n.a.
Middle East	Iran	1.32	n.a.	0.01	n.a.	0.01	n.a.
North America	Canada	0.54	0.61	0.04	0.05	0.04	0.04
	United States	0.76	2.98	2.75	3.29	2.26	2.45
Oceanian OECD	Australia	1.12	2.89	1.13	0.98	1.37	1.00
	New Zealand	0.81	2.88	0.01	0.02	0.01	0.01
Rest of South-East Asia		0.87	8.38	3.62	n.a.	4.67	n.a.
Global				34.6		37.1	

Table S6-2: GAINSv4 estimate of CH_4 emissions from coalmining in China in comparison to other recent studies.

	China coal mining emissions (Tg CH_4/year)			
Year	GAINS (this study)	Peng et al., 2016	Miller et al., 2019 (approx. adapted from Fig.5)	Sheng et al., 2019
1990	7.9	6.8 (6.0-7.5)		
1995	10.1			
2000	10.1	6.0 (5.3-6.7)		
2005	17.1			11.0
2010	17.7	17.7 (16.7-20.3)	16	15.2
2015	19.1		19	15.9

Emissions from both surface and underground mines can be reduced if CH_4 is recovered through pre-mine drainage up to ten years before the mining starts (USEPA, 2008). Currently in the US, at least 90 percent of degasification emissions from underground coalmines are recovered and utilized (USEPA, 2010). In GAINSv4, this is assumed technically possible in other countries as well. There is, however, only one project known to be recovering and utilizing CH_4 from pre-mine drainage at a surface mine and details about the removal efficiency of this option are uncertain (Sino-US New Energy Sci-Tech Forum, 2009). In GAINSv4, it is considered technically possible to recover 90 percent of the drainage gas also from surface mines. Costs for degasification are taken from Thakur (2006) and include costs for in-mine drilling, underground pipeline costs, and hydraulic fractioning of vertical wells and other gob wells.

Ventilation air methane (VAM) from underground coal mines can be recovered and oxidized through installation of VAM oxidizers (Mattus and Källstrand, 2010). Although the application on coalmines is still in an early phase, the technology is well known from control of odor and VOC emissions worldwide. The technology oxidizes at least 95 percent of VAM when applied to a ventilation shaft. It uses the energy released during the oxidation to keep the process running, which keeps fuel costs limited to the initial start-up phase. For a thermal oxidation process to run without interruptions the CH_4 concentration in the ventilation air needs to be at least 0.3 percent. For some recent installations in China a catalytic oxidation process is in use, which operate with CH_4 concentration rates in the ventilation air as low as 0.2% (Somers and Burklin, 2012). Securing this concentration level without increasing explosion risks (i.e. CH_4 concentrations in the air should never be in the explosive range between 5 and 15 percent), may in some mines require investments in more efficient ventilation systems. A general assumption is made in GAINSv4 that it is technically possible to keep CH_4 concentration levels at a steady rate of at least 0.3 percent, and therefore to install self-sustained VAM oxidizers (Mattus and Källstrand, 2010), on 50 percent of the ventilation air emitted from underground coal mines in all countries. Combining a catalytic oxidation VAM technology with an improved ventilation system is assumed to extend the feasible application of VAM oxidizers to 70 percent of VAM emitted from underground mines in all countries. An improved ventilation system is taken to double the ventilation capacity of the mine compared with a conventional system, thereby doubling the amount of electricity used for ventilation. Costs for VAM oxidation technology and installation are taken from USEPA (2003, p.30) and GMI (2008) and refer to installations in the US and China. Costs for increased electricity use for ventilation in mines are based on information from Unruh (2002) and Papar et al. (1999). No mitigation potential is assumed for post-mining emissions.

S6.2. Abandoned coal mines

Countries reporting CH_4 emissions to the UNFCCC in the Annex-1 category are expected to enter emissions from abandoned coal mines in the Common Reporting Formats (CRFs). The reported emissions make up the activity data for this source sector in GAINSv4. For non-Annex-1 countries, a default assumption is made that emissions from abandoned coal mines corresponds to 10% of active hard coal mining emissions. This assumption is based on US estimates of CH_4 emissions from abandoned coal mines corresponding to 13% of active coal mining CH_4 emissions in 2015 (USEPA, 2017a). Applying this default assumption to China means between 1200 and 1900 kt CH_4 released per year between 2005 and 2015 from this source. In a study funded by USEPA, Collings et al., (2012) analyze CH_4 emissions from 44 abandoned coal mines in the Shanxi province and find that these alone emit an estimated 0.5 bcm or about 350 kt CH_4 per year. Considering that the same report mentions there are likely thousands of abandoned coal mines in China, our estimate for all of China, is likely conservative.

The release of CH_4 emissions from abandoned coal mines typically depends on the status of the abandoned mine, i.e., whether it is left open for venting in order to prevent build-up of explosive CH_4 pockets underground, flooded to prevent CH_4 emissions from escaping, or sealed through cement plugging (USEPA, 2004). For the modelling in GAINSv4, it is assumed that without regulation the no control case is venting. The control option considered is flooding, which is assumed to prevent 90% of emissions compared to the venting case. Sealing is not considered a CH_4 control option in GAINSv4, because to effectively prevent gas leakage, at least 95% of shafts must be sealed (USEPA, 2004), which likely makes it relatively expensive. In contrast, the cost of flooding abandoned coal mines is likely low or even profitable, as abandoned mines can potentially fill an important role in a future transformation to renewable energy. Abandoned coal mines can be used as pumped storage hydroelectric plants (Pujades et al., 2016; Jessop et al., 1995) or flooded and converted to giant floating solar farms as in Huainan, China (China Daily, 2017).

S6.3. Oil and gas production

The methodology for deriving country-specific emission factors for CH_4 from oil and gas systems is described in Höglund-Isaksson (2017). In summary, separate emission factors are derived for emissions from the handling of associated gas, for fugitive emissions from unintended leakages of the equipment, and from downstream leakages from transmission pipelines and consumer distribution networks. Unintended leakages from upstream sources are estimated using IPCC (2006) default emission factors, while emissions from downstream sources use a combination of emission factors from IPCC (2006) and national reporting to the UNFCCC (2016) when available. Emission factors linked to the management of associated gas are derived in a consistent manner across countries using country- and year- specific data on the total generation of associated gas 1990-2012 and the managerial practices for handling of the associated gas. These include the fraction of associated gas recovered, utilized and reinjected, and the volumes of gas not recovered and therefore either flared or vented.

For this study, a few updates were made to take account of additional information provided for Russia, the USA and Canada. For Russia, assumptions on the average composition of the associated gas generated from oil production have been revised based on information provided in Huang et al. (2015). Huang et al. provide information for three different separation stages. Although not completely clear from the source reference, we have interpreted the different stages as stage 1 representing the associated gas flared or vented directly at the wellhead with stages 2 and 3 representing subsequent processing stages. We further assume that the associated gas relevant for our estimations here is to 90% from stage 1 and to 10% from stage 2. The corresponding weighted average composition in vol% is 60.1% CH_4, 8.6% ethane, 17.9% propane, 12.0% other heavier hydrocarbons, and the rest being nitrogen gas and carbon dioxide. This is in contrast to the assumption in Höglund-Isaksson (2017), where the vol% composition of Russian associated gas was taken to be 81% CH_4, 5.5% ethane, 6.6% propane and 5.4% heavier hydrocarbons. Another update concern the recovery rate for Russian associated petroleum gas (APG), which with the recent data from NOAA (Elvidge et al., 2016) suggest that the volume of gas flared from Russian sources is 24.6

bcm in 2016, down from 35.2 bcm in 2010. Using this information to extend Table 5 of the Supplement to Höglund-Isaksson (2017), the resulting recovery rate for Russian APG becomes 68% and is in GAINSv4 applied to all Russian oil production from 2015 onwards.

For the US and Canada, we need to distinguish emission factors for conventional gas production as well as for unconventional shale gas extraction, which has increased rapidly since 2006 due to the development of hydraulic fracturing technology, as illustrated in Figure S6-1. For the US, total gas production increased by 47% between 2006 and 2017.

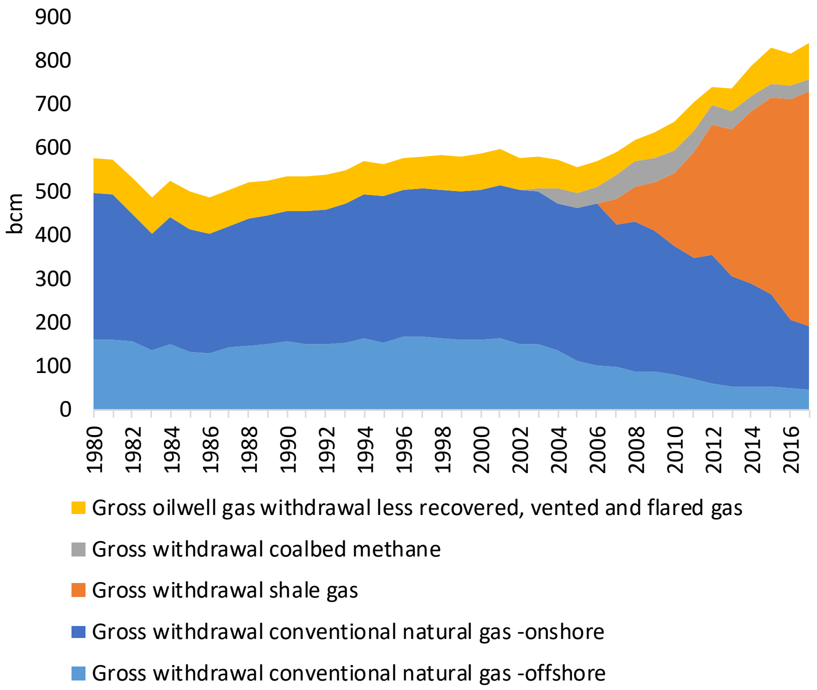

Figure S6-1: US natural gas production by type of gas 1980-2017. Adapted from data retrieved from EIA (July 11, 2019).

There is considerable uncertainty in the literature regarding the average emission factor for fugitive emissions from both conventional and unconventional gas extraction. A general conclusion appears to be that an important reason for the high uncertainty is the highly skewed distribution of emissions with rare super-emitting events contributing to a majority of emissions (Brandt et al. 2013; Zavala-Ariza et al. 2015; Alvarez et al. 2018). Inverse model results show contradicting results concerning whether North American shale gas extraction has contributed to an increase in CH_4 emissions or not. E.g., Turner et al. (2016), Hausmann et al. (2016) and Franco et al. (2016) find strong increases in recent US CH_4 emissions suggesting that unconventional gas extraction could be a likely culprit as much of the increase is measured over regions with such activities. Turner et al. estimate a more than 30% increase in US CH_4 emissions between 2002-2014, with maximum emissions in the South-Central US where unconventional hydrocarbon production is high. However, also livestock production is high in these regions, which adds to the uncertainty in source attribution. Supporting the attribution of recent emission increases to unconventional gas production is a measured simultaneous increase in the atmospheric concentration of ethane (Franco et al., 2016; Vinciguerra et al., 2015), which is consistent with the particularly high vol% of ethane found in US shale gas. In contrast, Bruhwiler et al. (2017) and Lan et al. (2019) find smaller increases in oil and gas emissions than Turner et al., Hausmann et al., and Franco et al., and no firm evidence of a large increase in total US CH_4 emissions 2006-2015. The controversy in the literature also extends to whether conventional and unconventional gas release similar emissions per unit of gas produced or whether considerable differences exist. Few studies (Kirchgessner et al., 1997) are available that measure the average leakage rate from US gas production before 2005 when the boom in shale gas production took off. Comparisons of measured leakage rates before and after the shale gas boom are further complicated by the technological advances in both extraction and emission control technology, as well as the introduction of emission regulations such as 'green completions' (USEPA, 2011). The GAINSv4 upstream emission estimates for US oil and gas sources in 2015 are presented in Tables S6-3 and S6-4. The US upstream emission factors for oil and gas production have been aligned with the average nation-wide estimates of Alvarez et al. (2018, Table 1). Alvarez et al. do not specify emission factors by type of gas produced. This split is in GAINSv4 based on activity data from other references (IEA-WEO, 2018 and EIA, 2019). The leakage rates assumed in GAINSv4 for the US are 0.19% for conventional offshore gas production (Skone et al., 2011), 1% for conventional onshore gas production (Kirchgessner, 1997; Skone et al., 2011; Allen et al., 2013; Cathles, 2012), and 1.65% and 0.58% for tight gas and coalbed methane, respectively (Skone et al., 2011). The leakage rate for shale gas extraction is assumed to 2.66% on average. This assumption was derived by matching the average leakage rate from Alvarez et al. of 1.95% for all upstream oil and gas production in the US in year 2015. An average leakage rate for shale gas of 2.66% is within the relatively large range reported in the literature for shale gas (e.g., Karion et al., 2013; Caulton et al., 2014; Schneising et al., 2014; Peischl et al., 2015; Howarth, 2019). The same average upstream leakage rates by types of gas produced have been assumed for Canadian gas production.

Table S6-3: US emissions (Tg CH_4) from oil and gas systems in year 2015 as estimated by Alvarez et al. (2018), USEPA (2017b) and GAINSv4.

	Alvarez et al., 2018 Table 1		**USEPA (2017b)**	**GAINSv4**
Emission source	**Bottom-up estimate**	**Range**		
Upstream -Production	7.6	6-9.5	3.5	11.85
Upstream -Gathering	2.6	2.42-3.19	2.3	
Downstream -Processing	0.72	0.649-0.92	0.44	2.58
Downstream -Transmission & storage	1.8	1.58-2.15	1.4	
Downstream -Local distribution	0.44	0.22-0.91	0.44	1.55
Oil refinery & transportation	0.034	0.026-0.084	0.034	0.014
Total US Oil & Gas supply	**13.2**	**10.896-16.794**	**8.1 (6.7-10.2)**	**16.0**

Table S6-4: GAINSv4 estimate for US upstream oil and gas emissions in year 2015.

Hydrocarbon produced	**Tg CH_4**	**Leakage as % of gas produced**	**Principal references for current leakage rates**	**MFR leakage rates in 2015**	**References for MFR leakage rates**
Crude oil	1.45	n.a.	Höglund-Isaksson (2017)	n.a.	n.a.
Conventional gas -offshore	0.05	0.19%	Skone et al. (2011) for all gases except shale. Shale leakage rate derived to match Alvarez et al. (2018) for upstream oil & gas CH_4.	0.18%	Skone et al. (2011) 'new technology'; USEPA (2016); Saunier et al. (2017)
Conventional gas -onshore	1.12	1.00%		0.50%	
Shale gas	7.90	2.66%		1.33%	
Coalbed methane	0.14	0.58%		0.29%	
Tight gas	1.19	1.65%		0.83%	
Sum upstream	**11.85**	**1.95%**	Alvarez et al., 2018	**0.98%**	

There are several cost-effective and low cost options available to reduce unintended leakage during extraction and processing of oil and natural gas (USEPA, 2016; ICF International, 2016). Addressing leakages first requires detection. With recent development of Leak Detection and Repair (LDAR) programs, in particular the use of infrared cameras, has lowered the cost of leak detection significantly (ICF International, 2016; USEPA, 2016; McCabe and Fleischmann, 2014). In a survey of LDAR programs in Europe installed to reduce unintended leakages from gas production, transportation and storage facilities, Saunier et al., (2017) find that when used regularly and systematically, LDAR effectively detects leakages. Out of detected leakages, 61 percent are successfully repaired leading to emission reductions of at least 90 percent, while 31 percent are less successfully repaired, reducing emissions by less than 50 percent and sometimes even increasing emissions. In an industry survey of US oil and gas facilities, ICF International (2016) finds that if all facilities are subject to annual LDAR emission surveys, an overall emission reduction of 40 percent is feasible. Drawing on these two studies, we assume in GAINSv4 that it is technically feasible to reduce emissions from unintended leakages by on average 50% when LDAR technology is implemented across all facilities. The cost of LDAR programs is likely to be highly site-specific and to vary with the gas price as reduced gas leakages mean higher profits from gas sales. After detection of leakages, there is a long list of possible repairs that are available at a wide range of costs (see e.g., Table 3-1 in ICF International, 2016). As we do not have access to industry data on the incidence of different types of leakages in global oil and gas systems, it is not possible to make an assessment of the expected number and types of repairs that will be needed and the associated costs. Such assessments exist for US gas and oil systems, based on detailed data reported by industry to the USEPA and complemented by industry surveys (USEPA, 2014e; ICF International, 2016). To estimate costs for gas leakage repairs in GAINSv4, we have sought to align the assumptions on costs with the ranges for the US marginal abatement costs estimated for different industry segments (i.e., production, processing, transmission and distribution).

Maximum technically feasible reduction of CH_4 emissions from the handling of associated gas generated during oil (and to a limited extent gas) production assumes it possible in all countries to recover and utilize at least 98 percent of the associated gas generated. This high level of associated gas recovery is already exceeded in Norway (Husdal et al., 2016a,b; EIA, 2015) and therefore assumed possible to achieve in other countries as well. Costs are taken from OME (2001) and refer to the costs of recovering and processing the gas and transporting it to the nearest EU border either through pipeline or ship, for details see the Supplement of Höglund-Isaksson (2012). In addition to extending associated gas recovery rates to 98 percent, it is assumed technically feasible to further reduce gas venting by making sure as much as possible of the two percent of associated gas not recovered is flared off. Through LDAR programs (USEPA, 2016; McCabe and Fleischmann, 2014), infrared cameras can be installed to continuously monitor flares of associated gas, thereby allowing for the identification and remedy of 'super-emitters', reduce routine venting as well as reduce the number and duration of temporary flare shut-downs caused by unfavorable weather and wind conditions (Husdal et al., 2016b, p.31). To our knowledge, LDAR programs have until now been introduced in Europe to control unintended fugitive leakages from gas processing plants and transmission and distribution networks (Saunier et al., 2017), however, not to control venting of associated gas. The applicability and cost of the technology for this purpose is therefore highly uncertain. As a conservative assumption we assume it possible to reduce venting of unrecovered associated gas by 30 percent if LDAR is implemented across all oil and gas production facilities. The marginal cost is very high (exceeding 500 €/t CO_2eq) as LDAR is assumed applied on top of a 98 percent recovery rate of associated gas and therefore only addressing emissions from the two percent associated gas not being recovered.

S6.4. Livestock

The general methodology used in GAINSv4 to estimate CH_4 emissions from livestock is described in the Supplement of Höglund-Isaksson (2012). Recent revisions concern updates of activity data and reported emission factors to latest statistics (FAOSTAT, 2018; UNFCCC, 2016; 2018) and a review of available technical abatement options for CH_4 described in detail in Höglund-Isaksson et al. (2018). Emissions are estimated by animal types, i.e., dairy cows, non-dairy cattle, pigs, poultry, sheep and goats, buffaloes, and horses, by whether emissions stem from enteric fermentation or manure management, and for dairy cows, non-dairy cattle and pigs, by whether animals are subject to liquid or solid manure management. A recently introduced improvement in the CH_4 module of the GAINS model is a split of the animal categories dairy cows, non-dairy cattle, pigs, sheep and goats by five farm size classes, i.e., less than 15 livestock units (LSU), 15 to 50 LSU, 50 to 100 LSU, 100 to 500 LSU, and above 500 LSU. Information on historical farm-size distributions are taken from EUROSTAT (2015), Ashton et al. (2016), Australian Government (2018), USDA (2011a; 2011b; 2013; 2015; 2016), Arelovich et al. (2011), Beef2Live (2018), Montaldo et al. (2012), Hengyun et al. (2011). Projections of the future development in farm-size classes have been produced for Europe by applying a multi-nominal logistic function weighing in the development observed in historical years from 1990 onwards. To reflect the recent fast-growing development of large dairy and cattle farms in China (Bai et al., 2017), it is assumed in GAINSv4 that the entire future stock increase as projected by FAO (Alexandratos and Bruisma, 2012) is allocated to farms with more than 100 LSU (Bai et al., 2017). For other World regions, farm-size class shares are kept constant in future years due to a lack of historical time-series on which to base a future development in farm size classes. The future development in farm-size classes has implications for future fractions of animals on liquid and solid manure management and on the future applicability of control technology options.

In GAINSv4, country- and animal- specific emission factors have been aligned with the implied emission factors reported to UNFCCC-CRF (2016; 2018) for the year 2010. For dairy cows, both enteric fermentation and manure management emissions per animal are affected by the milk productivity of the cow. This effect is accentuated for highly productive milk cows. To capture this, the no control emission factor for dairy cows is specified as the sum of a fixed emission factor per animal for cows producing up to 3000 kg per head per year and an additional term describing the emission factor per milk yield for milk production exceeding the productivity level of 3000 kg per animal per year. For further details see the Supplement of Höglund-Isaksson (2012).

Technical options to reduce CH_4 emissions from livestock exist for emissions from enteric fermentation and from the handling of manure. The options identified in GAINSv4 are breeding through selection with the dual target of increasing animal productivity while maintaining animal health and fertility, various options to change animal feed, and anaerobic digestion of manure for the production of biogas. A detailed description of these options with references and including expected removal efficiency and costs, is provided in Höglund-Isaksson et al. (2018). Due to limitations posed by economies of scale, the options listed above are considered feasible for large farms (above 100 LSU) with liquid manure management systems and with application limited to the time animals spend indoor. Such intensive systems are typically prevalent in Europe, North America and for a fast growing segment of large industrial farms in parts of Asia, notably China (Bai et al., 2017). In Latin America, parts of the USA, Australia and New Zealand, large-scale extensive dairy and cattle farming dominate, with animals typically grazing outdoor or staying outdoor in feedlots. In GAINSv4, there are no CH_4 mitigation options considered to control manure management emissions from such systems, however, there is assumed to be a potential to reduce enteric fermentation emissions by 10% through breeding and by maximum 30% if breeding is combined with inter-seeding of natural pastures with grass legumes, adding fodder crops and grass legume mixtures. The objective of the latter options is to improve animal productivity by increasing the quantity and quality of the fodder (FAO, 2017). Addressing CH_4 emissions from sheep and goat populations through breeding and changes in animal fodder is only considered feasible for animal on large farms (>100 LSU) in OECD countries. In all other parts of the world, sheep and goat rearing is assumed operated in extensive systems with animals grazing outdoor, genetically well adapted to local conditions, and without feasible technical potential to control emissions.

In GAINSv4, we assume no technical abatement potential for CH_4 from substitution of indigenous low-yielding breeds with highly productive imported breeds for the large number of cows and cattle kept on smallholder farms in Africa and South-East Asia. The reason is that milk and meat production is one out of a number of reasons for keeping livestock, where keeping herds as a mean for storing assets and manage risks over time may exceed productivity in importance (Udo et al., 2011). As smallholder farmers often lack access to formal credit markets and governmental support when faced with incidents of failed crops or illness, keeping large herds of livestock becomes one of few options for managing the risk of life-threatening unforeseen events over time. Substituting robust and to the climate genetically well adapted indigenous breeds with less robust but more productive imported breeds, is under such circumstances unlikely to be attractive to smallholder farmers. Addressing CH_4 emissions from smallholder livestock farmers is likely to require more fundamental economic and institutional reforms aimed at mitigating the risks currently facing this group of farmers.

Figure S6-2 illustrates the limited technical abatement potential for CH_4 emissions from livestock for different animal categories. As shown, technical abatement is almost only limited to large farms with more than 100 LSU. This means that the technical options are only applicable to about one third of global CH_4 emissions from livestock. Another third is estimated from smallholder cattle farms and extensive sheep and goat farms, primarily found in Africa and South-East Asia. No technical options have been found feasible to address these emissions, as explained above. The residual third of global livestock CH_4 is attributed to medium sized farms of 15-100 LSU. With the exception of limited potential from breeding and feeding options applicable to cattle farms with liquid manure management in the 50-100 LSU farm size class, we do not consider the available technical options economically feasible for farms below 100 LSU. Hence, deep future reductions in livestock CH_4 emissions will require additional policy incentives to limit the consumption of meat and milk, e.g., through economic instruments like taxes or by changing consumer preferences by promoting reduced meat and milk consumption for health reasons.

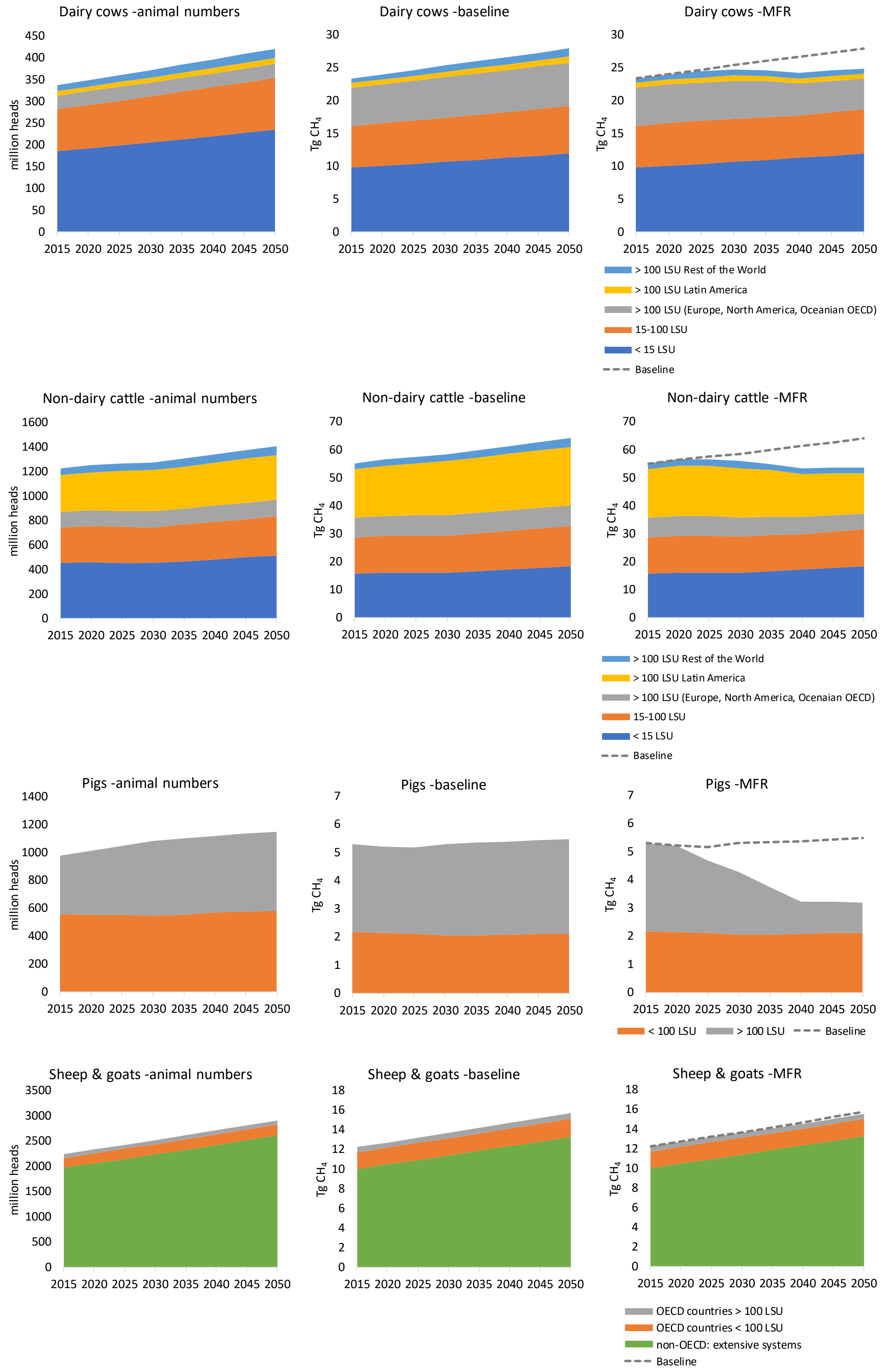

Figure S6-2: Global livestock animal numbers, baseline CH$_4$ emissions and emissions after Maximum technically Feasible Reduction (MFR), as estimated in GAINSv4.

S6.5. Rice cultivation

CH_4 emissions from rice cultivation result from anaerobic decomposition of organic material in flooded rice fields. Emissions depend on many factors e.g., on the season (wet or dry and season length), soil characteristics, soil texture, use of organic matter and fertilizer, climatic conditions such as temperature and humidity, and agricultural practices (IPCC, 2006, Vol.4, p. 5.45). The emission calculation methodology used in GAINSv4 follows the IPCC guidelines (2006, p. 5.49) and adopts IPCC default emission factors for given water management regimes. The IPCC method is based on the annual harvested area with scaling factors for different water regimes. In GAINSv4, these translate into three cultivation activities:

- *Continuously flooded cultivation area:* fields have standing water throughout the growing season and only drying out for harvest.
- *Intermittently flooded cultivation area:* fields have at least one aeration period of more than three days during the growing season. Compared with continuously flooded rice fields, IPCC suggests that intermittently flooded rice fields emit 27 to 78 percent of continuously flooded fields, where the range depends on if the fields are rainfed or irrigated. GAINSv4 uses the assumption of 50 percent emissions per hectare from intermittently flooded compared with continuously flooded fields.
- *Upland rice cultivation area:* fields are never flooded for a significant period of time and are not assumed to emit CH_4.

Activity data for rice cultivation is measured in million hectares of land cultivated for rice production (FAOSTAT, 2015) and cross-checked with information provided by countries in national reporting to the UNFCCC (2015; 2018). From the same source, we take data on country-specific application of different water regimes, complemented with information from IRRI (2007). For each cultivation activity, country- and technology- specific CH_4 emission factors are identified. CH_4 emissions from rice cultivation in country *i* in year *t* are calculated as follows:

$$E_{it} = \sum_{sm} A_{it} * ef_{i;\, flood}^{IPCC} * h_i * \beta_s * V_{is} * \left(1 - remeff_{sm}\right) * Appl_{itsm} \ ,$$

where	A_{it}	is the rice cultivation area in country *i* in year *t*,
	$ef_{i;\, flood}^{IPCC}$	is the IPCC default emission factor for CH_4 emissions from flooded rice fields (1.3 kg CH_4 ha^{-1} day^{-1}),
	h_i	is the duration of the growing season expressed in days per year (=185 days per year),
	β_S	is an emission scaling factor for water regime *s* (=1 for continuously flooded, =0.5 for intermittently flooded, and =0 for upland rice).
	V_{is}	is the fraction of rice cultivated land under water regime *s*,
	$remeff_{sm}$	is the removal efficiency of technology m when applied to water regime s, and
	$Appl_{itsm}$	is the application rate of technology *m* when applied to water regime *s*.

CH_4 mitigation options implemented in GAINSv4 to control emissions from rice cultivation include employment of improved water management regimes, use of alternative rice hybrids increasing yields while suppressing methane generation e.g., through shorter stems, and use of soil amendments e.g., biochar or sulphate-containing amendments.

There are several ways to reduce CH_4 emissions through improved water management; single mid-season drawdown, alternative wetting and drying, aerobic rice production and dry direct seeding (WRI, 2014). A common feature of all water management options is that they reduce CH_4 emissions through decreasing the time that fields are flooded. Differences in local conditions e.g., climatic conditions, traditional farming customs and access to herbicides, water regulation mechanisms or fertilizers, will affect the impact of different water management regimes on yield, labour requirements and methane emissions (WRI, 2014). The choice of preferred water management regime is closely linked to these local conditions. Due to lack of information, we are not able to make a full-fledged assessment of the effectiveness of individual water management regimes in different regions of the world, but will have to resort to making broad assumptions about the effectiveness of water management regimes in general and their associated costs. According to a literature survey by WRI (2014), implementing improved water management regimes on continuously flooded fields have shown to achieve CH_4 emission reductions between 30-90%, with the higher relative reductions found for well-managed fields in the US. As a general assumption in GAINSv4 across all flooded rice fields, an average abatement potential of 20% is assumed achievable in the next ten years, extending to 40% on an annual basis in 2050. If improved water management is combined with other options e.g., low-CH_4 hybrids or different soil amendments (see below for details), the average global abatement potential assumed in GAINSv4 for continuously flooded fields extends to 50%. This estimate takes into account that some areas may be difficult to subject to improved water management due to heavy rainfall during the wet season (e.g., in the Phillippines) or due to unreliable water supply systems or fields that are not well levelled (WRI, 2014). These assumptions are somewhat conservative in comparison to Beach et al. (2015) who estimate an overall abatement potential for global rice cultivation in 2030 at 26.5% below baseline and Harmsen et al. (2019) who estimate 61% below baseline in 2050 for the same source.

A cost estimate of improved water management through drying out of continuously flooded rice fields will have to consider associated operation costs, including cost-savings from reduced water use and higher labour costs due to increased weed growth. In particular in poorer regions where farmers lack access to herbicides, longer periods of dry fields increase weed growth (WRI, 2014; Barrett et al. 2004; Ferrero and Nguyen 2004). According to estimates by Barrett et al. (2004), weed growth increases labour costs by an estimated 20 percent, which is equivalent to about 60 additional work hours annually per hectare in developing countries (Heytens, 1991) and 12 additional work hours annually per hectare in developed countries, where herbicides are used for controlling weed (Shibayama, 2001). Dry direct seeding of rice seedlings have shown to be very effective (45-90% reductions in emissions) for reducing CH4 emissions in the US compared with transplanting seedlings into flooded fields (WRI, 2014; Linquist et al., 2015). The abatement effect is attributed to the one month shorter period of flooding as seedlings grow in dried out fields. The option also contributed to reduced labour input and costs, however, this result appears to be conditional on unrestricted access to herbicides and well managed water tables and may therefore be difficult to replicate in many developing countries. According to IRRI (2007), intermittent aeration of continuously flooded rice fields may reduce water use by 16 to 24 percent. Assuming that continuously flooded rice fields need 1000 mm water input per year (Bouman, 2001) and the global average cost of irrigated water is 0.02 US$ per m^3 (FAO, 2004), then saving 22 percent of water corresponds to a cost-saving of about 30 Euro per ha. In Europe and North America, the cost of irrigated water is higher than the global average, converting into a higher cost-saving of about 70 Euro per ha.

Certain rice hybrids may affect CH_4 emissions. By careful selection of low-CH_4 producing hybrids, emissions can be ten percent lower (ADB 1998). ADB (1998) estimates that Chinese rice yields may increase by as much as 10 to 20 percent from switching to low-CH_4 hybrids. In other parts of the world, where high yield rice hybrids are already in extensive use, potentials for additional yield increases are likely lower. In GAINSv4, the assumption is that the potential reduction in CH_4 emissions from switching to alternative rice hybrids is 10 percent with a 3 percent increase in crop yield, when applied as the sole option. When applied in combination with other options, like improved water management of continuously flooded fields, the removal efficiency of this option is set to 5 percent.

Application of sulphate-containing substrates to rice fields reduces CH_4 emissions because CH_4 producing bacteria compete for the same substrate as the sulphate reducing bacteria (van der Gon et al. 2001). Likewise, application of biochar to soils in rice fields improves soil fertility while contributing to reduced CH_4 emissions because carbon is added in a stabilized form, which inhibits the abundance and activity of methanogens (Han et al., 2016). The costs associated with these options are the costs of acquiring the sulphate-containing substrates or biochar and spreading them on the fields. In GAINSv4, a conservative assumption is that application of these types of CH_4 inhibitors can remove on average 20 percent of CH_4 emissions when applied as a stand-alone option and 5 percent when applied in combination with other options like improved water management.

The country-specific marginal abatement cost estimated for mitigation of CH_4 emissions in rice cultivation in year 2050 ranges from -10 to 40 €/t CO_2eq in GAINSv4.

S6.6. Solid waste

CH_4 from municipal and industrial solid waste is formed and emitted when biodegradable matter is decomposed under anaerobic conditions in landfills or during temporary storage of waste aimed for different types of treatment. CH_4 may also be released during loading or emptying of the reactor when organic waste is treated in anaerobic digesters to produce biogas or during treatment of organic waste in composts. In developing countries, it is common to scatter waste e.g., along riverbeds with the waste eventually ending up in the oceans, or to burn it openly in order to reduce its volume (Wiedinmyer et al., 2014). In both cases anaerobic conditions are unlikely and therefore CH_4 emissions remain very low, however, open burning of waste contribute to high air pollution emissions e.g., PM2.5 and NOx (Andersson et al., 2016; Anenberg et al., 2012; Das et al., 2018). In addition, waste contains a lot of carbon that could be harvested as a source of energy, making scattering and open burning a loss of potentially valuable renewable energy (Gómez-Sanabria et al., 2018). The activity data used in GAINSv4 is the total amount of waste generated before diversion to different types of treatment like recycling, energy recovery or landfill. Amounts of waste generated are first split by municipal or industrial solid waste and then by waste composition for municipal solid waste and by manufacturing industry sub-sector for industrial solid waste. Starting point for emission estimations are historical reported waste generation rates for municipal solid waste and industry waste reported to EUROSTAT (2015) for the EU countries and to the World Bank (Hoornweg and Bhada-Tata, 2012) and various national studies (see Gómez-Sanabria et al. 2018) for other regions. The methodology used to project future generation of waste by estimating waste generation elasticities is described in detail in the Supplement of Gómez-Sanabria et al (2018). The driver for industrial solid waste is growth in value added in the relevant manufacturing industry sectors. It can be expected that municipal solid waste generation per capita is positively related to per capita income (Hoornweg and Bhada-Tata, 2012) and that relative changes in income have a relatively larger effect on waste generation in high-income than in low-income countries. The reason for this being that food waste make up the major part of household waste generated in low-income countries and as countries become richer, it is primarily the generation of non-food waste (paper, plastics etc.) that grows and with per capita food waste generation remaining relatively stable. We used country-level data to estimate waste generation elasticities for different average per capita income intervals using data on income, urbanization rate and historical waste generation for 34 European and 10 non-European countries in the years 1995-2014 (EUROSTAT, 2015; OECD, 2016). Applying the estimated elasticities, future relative growth in the generation of municipal solid waste (MSW) per capita is estimated as a function of the relative growth in GDP per capita and urbanization rate (UNstat, 2014).

CH_4 from waste deposited on landfills is formed and released with a time delay of up to several decades. IPCC (2006, Vol. 5, Ch. 3) recommends the use of a First-order-decay model taking up to fifty years disposal into account. The GAINS model structure does not allow for implementation of a full First-order-decay model. Instead, a simplified structure is used, where the delay between waste disposal on landfills and CH_4 release is accounted for as a lag in the activity data of 10 years for fast degrading organic waste like food and garden waste and 20 years for more slowly degrading waste like paper, wood and textile. The lags correspond to approximate average half-life values for the respective waste types (IPCC, 2006, Vol.5, Tables 3.3 and 3.4).

Table S6-5 presents a summary of the various waste treatment options available in GAINSv4 model structure. The options considered preferable for a given waste category on the basis of overall environmental impacts are indicated with an asterisk. When constructing the marginal abatement cost curves for the solid waste sectors it has been necessary to extend the environmental objectives beyond only minimization of CH_4 emissions, as several of the options available (e.g. scattering and open burning) have dire environmental consequences on air quality and ocean life despite generating minimal CH_4 emissions. Instead the approach has been to identify 'preferred options' and apply them to a maximum technically feasible extent. In the long term, i.e. a timeframe long enough to allow for major infrastructural investments, the reduction potential accounted for in the marginal abatement cost curve for the solid waste sectors reflect the potentials and costs for moving from the current system to a system with an infrastructure supporting maximum source separation for reuse, recycling or treatment in biogas digesters. Any organic waste that cannot be source separated is to be combusted in a well managed (i.e., controlling for dioxins and other air pollutants) incinerator with energy recover and utilization. Hence, in the maximum technically feasible reduction (MFR) scenario, no untreated organic waste is assumed to go to landfills. Information on costs is provided in Höglund-Isaksson et al. (2018).

Table S6-5: GAINSv4 model structure for estimating CH_4 emissions from solid waste sectors.

Options and organic waste source categories		Waste management options included in the GAINS model	Max feasible reduction (MFR) application of preferred option
Options available to all organic waste categories		Incineration with energy recovery (well managed)*	In the MFR scenario is assumed that all waste that is not possible to separate, reuse, recycle or treat in an anaerobic digester, is combusted in a well managed incinerator with energy recovered and utilized
		Incineration to reduce volume (not well managed)	
		Landfill with gas recovery and flaring	
		Landfill with gas recovery and utilization	
		Landfill with compacting	
		Landfill with cover of earth	
		Unmanaged landfill -predominantly warm/humid conditions	
		Unmanaged landfill -predominantly cold/dry conditions	
		Open burning	
		Scattering (no control option)	
Options available to specific organic waste categories	MSW -available to food and garden waste	Source separation & anaerobic digestion with gas recovery & utilization*	100%
		Source separation & household composting	Current composting levels maintained to 2030, thereafter move to AD with biogas recovery
		Source separation & large-scale composting	
	MSW -available to paper waste	Source separation & paper recycling*	90%
	MSW -available to wood waste	Source separation & recycling for chip board production*	90%
	MSW -available to textile waste	Source separation & reuse or recycling*	90%
	Food industry waste	Anaerobic digestion with gas recovery and utilization*	100%
	Pulp and paper industry waste	Black liquor recovered and incinerated for energy purposes*	100%
	Textile industry waste	Incineration with energy recovery*	100%
	Wood industry waste	Incineration with energy recovery*	100%

* Preferred option for given waste category

S6.7. Wastewater

CH_4 emissions are formed when wastewater with a high organic content is handled under anaerobic conditions. Wastewater treatment plants serve to decompose compounds containing nitrogen and phosphor as well as carbon before discharge to a water body. Main gaseous products from wastewater treatment are CO_2 and molecular nitrogen, but also some CH_4. In the GAINS model, wastewater emissions from households and industry are accounted for separately. The activity data used to estimate emissions from domestic wastewater is number of people connected to centralized or decentralized collection of wastewater, respectively. This basically refers to wastewater from

urban and rural populations, except for most industrialized countries where wastewater collection services often include some rural areas as well. Country-specific data on population fractions of wastewater collected centrally are taken from UNFCCC (submission 2014), EUROSTAT (version as of June 26, 2013) and OECD (2015). Country-specific values for the biochemical oxygen demand per person (BOD) are used when available from UNFCCC-CRF (2014). When unavailable, an IPCC (2006, Vol.5, Table 6.4) default factor is used for the maximum CH_4 producing capacity (B_0).
Industry sectors identified by IPCC (2006, Vol.5, p.6.19) as potential sources for CH_4 emissions from wastewater are food, pulp- and paper industry and other manufacturing industries generating wastewater with an organic content, i.e., textile, leather, organic chemicals etc. The activity data for estimating CH_4 emissions from industrial wastewater is the amount of COD present in untreated industrial wastewater. These amounts are derived from production volumes combined with COD generation factors as specified in Table S6-6. Production volumes in ton product are taken from FAOSTAT (2015). Growth in value added by industry is used as driver for future projections. For the pulp- and paper industry, wastewater and COD generation rates reported in literature differ considerably between processes and between developed and developing countries. By comparing reported values from different sources, process specific generation rates are derived as presented in Table S6-6. It should be noted that when using process specific generation rates, for some food industries and pulp- and paper industry the estimated amounts of COD and CH_4 generated from industry come out several times lower than if using the IPCC default factor (2006, Vol.5, Table 6.9). Values for the maximum CH_4 production capacity (B_0^{COD}) of wastewater from different industrial sectors are based on a literature review presented in Table S6-6. Weighted averages of the values for each process/product for the year 2010 were used to calculate the CH_4 production capacity by sector and country. An IPCC (2006, Vol.5, Table 6.2) default factor of 0.25 kt CH_4/kt COD is applied for the maximum CH_4 producing capacity (B_0^{COD}) when no value was available from literature.

The methanogenic process in the treatment of wastewater is sensitive to daily/seasonal temperature variations as temperature affects the microbiological community and the degradation rate of organic matter (Dhaked, Singh and Singh, 2010). With temperature being a relevant factor for the formation of CH_4 during treatment of domestic wastewater (Luostarinen et al. 2007), the GAINS model includes a country-specific temperature correction factor when deriving emission factors. Data on the rates of methanogenesis at different temperature intervals is adopted from Lettinga, Rebac, and Zeeman (2001), while daily data of the maximum temperature for years 2000, 2005 and 2010 at 25km resolution was taken from the Agri4 Cast Data Portal (JRC, 2015) for Europe and from NOAA (2018) for other parts of the World. No temperature correction factors are applied to emission factors for industrial wastewater, because the temperature is likely to be process-specific rather than determined by the outdoor temperature.

Current applications of different treatment practices for domestic and industrial wastewater are taken from UNFCCC (2014) CRF tables complemented with information from EUROSTAT (version as of June 26, 2013), OECD (data downloaded July 2015) and IPCC (2006, Vol.5, Table 6.5). There are no wastewater options available that primarily target CH_4 emissions. There are, however, several different ways of treating wastewater, which have different implications for CH_4 emissions (Pohkrel and Viraraghavan, 2004 and Thompson et al., 2001). When domestic wastewater is centrally collected and emitted to a water body with only mechanical treatment to remove larger solids, plenty of opportunities for anaerobic conditions and CH_4 formation are created. For this type of treatment, the CH_4 correction factor (MCF) used in GAINS is 1. With well managed aerobic or anaerobic treatment, the CH_4 formation is effectively mitigated and CH_4 emissions can be kept on a negligible level. MCF used in GAINS is 0.01 for aerobic treatment and 0.005 for well managed anaerobic treatment. With less well managed systems the occurrence of anaerobic conditions increase as well as CH_4 formation (IPCC 2006, Vol.5, Tables 6.3 and 6.8). Anaerobic treatment has advantages over aerobic treatment like lower costs, smaller volumes of excess sludge produced, and the possibility of recovering useful biogas, which can be upgraded to gas grid quality (Lettinga, 1995; Thompson et al., 2001). For industrial wastewater, it is assumed that the most effective way to reduce CH_4 emissions is to apply a two-stage process where the water is treated anaerobically with recovery of the biogas in a first stage, which is then followed by an aerobic treatment in a second stage (Latorre et al., 2007). The assumed MCF for this type of treatment is 0.05. In rural areas, domestic wastewater can be collected and treated in latrines, septic tanks or similar anaerobic treatment (USEPA, 1999). Investment costs for sewage treatment are taken from EEA (2005) and operation and maintenance costs from Hernandez-Sancho and Sala-Garrido (2011). Rural wastewater treatment costs are from USEPA (1999).

Table S6-6: GAINSv4 model assumptions for deriving CH_4 emission factors for industrial wastewater sources.

Industry	Product	Wastewater genertion in m3/ton. (range over different studies)	[COD] in kg/m3 Untreated wastewater. (range over different studies)	Maximum CH_4 producing capacity in kg CH_4/kgCOD. (range over different studies)	References
Food	Beer	4.95^{a} (1.98 - 7.92)	4^{a} (2-6 /1.2 - 125 UK)	0.23 ^{a}(0.19-0.27)	Debik and Coskun 2009; Kobya, Senturk, and Bayramoglu 2006; Fountoulakis et al. 2008; Şentürk, İnce, and Onkal Engin 2010; Azbar et al. 2004; Azbar et al. 2009; Healy, Rodgers, and Mulqueen 2007; Brito et al. 2007; Rodgers, Zhan, and Dolan 2004; Sharda, Sharma, and Kumar 2013; Shivayogimath and Jahagirdar 2015; Maya-Altamira et al. 2008.
	Vegetables oils^{c}	0.8^{a} (0.4 - 1.2)	45.5^{a} (5 -804)	0.17^{a} (0.11 -0.24	
	Wine	2^{b} (0.8-14)	30.4^{b} (3.1-150)	0.18^{d}	
	Sugar Refining	0.69^{a} (0.16-1.0)	6.15 ^{a} (2.3 -10)	NR	
	Meat	13 (IPCC)	5.4 ^{b} (3 -11)	0.22	
	Dairy Products^{e}	3.05$^{b\ f}$(0.19-10)	8.8^{b} (0.18 -25.6)	0.22 ^{b} (0.16 -0.27)	
Pulp	Bleached sulphate pulp	70^{a} (30 -110)	1.55^{a} (0.10-3.0)	NR	Janssen et al. 2009; Ekstrand et al. 2013; Larsson et al. 2015; Karlsson et al. 2011; Tezel et al. 2001; Chaparro and Pires 2011; Dufresne, Liard, and Blum 2001; Arshad and Hashim, 2012; Thompson et al. 2001.
	Unbleached sulphate pulp	50^{a} (20 -80)	1.43^{b} (1.35 -2.44)	NR	
	Bleached sulphite pulp	70^{a} (40-100)	2.10^{b} (0.62 - 8)	0.22^{b}(0.20-0.24)	
	Unbleached sulphite pulp	70^{a} (40-100)	0.80^{a} (0.20 - 1.4)	NR	
	Mechanical wood pulp	20^{a} (5-50)	6.9^{b} (2.71 - 10.37)	0.19^{a} (0.12 - 0.27)	
	Semi-Chemical pulp	50^{a}(20-80)	2.19^{a} (0.67 -3.71)	0.19^{a} (0.11-0.27)	
	Recovered pulp^{g}	20	3	NR	
	Other fibre pulp	20^{g}	8.20^{a} (7.7 -8.7)	NR	
Paper	Newsprint	9^{a} (5-15)	3.5	NR	
	Printing and writing paper	60^{h} (60-227)	0.81^{a} (0.5-1.11)	NR	
	Recovered paper	12^{a} (8 - 16)	0.51^{a} (0.43 -0.58) ^{i}	0.22^{a} (0.16-0.27)	
	Household/sanitary/tissue	8.50^{a} (5-12)	1.02^{a} (0.05-2)	NR	
	Wrapping papers^{g}	20	0.08	NR	
	Paper and paperboard other	12^{a} (8 - 16)	0.95^{b} (0-11)	NR	

a Average

b Median

c Olive oil (Centrifugation and Pressing production processes (most of the data)), sunflower and cotton seed oil

d One study

e Including milk production, cheese, cheese whey, ice cream and butter

f Most of the data (11 total) are below 4.0 (8)

g based on Höglungd - Isaksson .2012

h 60 for UK 227 for Thailand

i Collected after the clarifier

S7: World region aggregations of GAINS model regions

Table S7-1: 174 GAINS model regions used in this study to model global CH_4 emissions.

World regions	174 GAINS model regions used in the modelling of global CH_4 emissions in this study
Africa	Egypt, North Africa (Algeria, Morocco, Tunisia, Libya), South Africa, Other Africa (All other African countries)
China	China (32 provinces)
Europe	EU-28 (28 countries), Norway, Iceland, Switzerland, Albania, Bosnia-H., Kosovo, North Macedonia, Montenegro, Serbia, Turkey
India	India (23 provinces)
Latin & Central America	Argentina, Bolivia, Brazil, Carribean (The Bahamas, Barbados, Cuba, Dominican Rep., Guyana, Haiti, Jamaica, Suriname, Trinidad and Tobago), Central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama), Chile, Colombia, Ecuador, Mexico, Paraguay, Peru, Uruguay, Venezuela
Middle East	Iran, Israel, Saudi Arabia, Rest of Middle East (Bahrain, Iraq, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Syria, United Arab Emirates, Yemen)
North America	United States of America, Canada
Oceanian OECD	Australia, New Zealand, Japan (6 provinces)
Russia & Former Soviet Union	Russian Federation (2 regions), Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgizistan, Moldavia, Ukraine, Other Former Soviet Union (Uzbekisthan, Tajikistan, Turkmenistan)
Rest of South-East Asia	Afghanistan, Bangladesh (2 regions), Bhutan, Brunei, Cambodia, Indonesia (4 regions), North Korea, South Korea (4 regions), Laos, Malaysia (3 regions), Mongolia, Myanmar, Nepal, Pakistan (4 regions), Philippines (3 regions), Singapore, Sri Lanka, Taiwan, Thailand (5 regions), Vietnam (2 regions)

References

ADB (1998): ALGAS -Asia least cost greenhouse gas abatement strategy -People's Republic of China, Asia Development Bank, Manila.

Alberta Energy Regulator, 1998. Alberta Environmental Protection: Code of practices for landfills. Government of Alberta, Canada.

Alberta Energy Regulator, 2013. Upstream petroleum industry flaring and venting report. Government of Alberta, Canada.

Alberta Energy Regulator, 2014. Directive 060: Upstream petroleum industry flaring, incinerating and venting. Government of Alberta, Canada.

Alberta Environment, 2007. Quantification protocol for the anaerobic decomposition of agricultural materials. Government of Alberta, Canada.

Alexandratos, N. and J. Bruinsma, 2012. World Agriculture Towards 2030/2050. ESA Working Paper No.12-03. Food and Agriculture Organization of the United Nations (FAO), Rome.

Allen, D. T., V. M. Torres, J. Thomas, D. W. Sullivan, M. Harrison, A. Hendler, S. C. Herndon, C. E. Kolb, M. P. Fraser, A. D. Hill, B. K. Lamb, J. Miskimins, R. F. Sawyer and J. H. Seinfeld, 2013. Measurements of methane emissions at natural gas production sites in the United States. *Proceeding of the National Academy of Sciences* of the United States of America, 110 (44):17768–17773.

Alvarez, R.A., D. Zavala-Araiza, D.R.Lyon, D.T. Allen, Z. R. Barkley, A. R. Brandt, K.J. Davis, S.C. Herndon, et al., 2018. Assessment of methane emissions from the US oil and gas supply chain. *Science* 21 June 2018.

Andersson, K., Rosemarin, A., Lamizana, B., Kvarnström, E., McConville, J., Seidu, R., Dickin, S., Trimmer, C., 2016. Sanitation, Wastewater Management and Sustainability: from Waste Disposal to Resource Recover. Nairobi and Stockholm: United Nations Environment Programme and Stockholm Environment Institute.

Anenberg, S., Schwartz, J., Shindell, D., Amann, M., Faluvegi, G., Klimont, Z., Janssens-Maenhout, G., Pozzoli, L., Van Dingenen, R., Vignati, E., et al., 2012. Global air quality and health benefits of mitigating short-lived climate forcers. *Environmental Health Perspectives* 120(6):831-839.

Arelovich, H. M., R. D. Bravo, M.F. Martinez, 2011. Development, characteristics, and trends for beef cattle production in Argentina. *Animal Frontiers* 1(2):37-45

Arshad, A. and N. H. Hashim, 2012. Anaerobic Digestion of Nssc Pulping Effluent. *Int. J. Environ. Res.* 6(3):761-768.

Ashton, D., Oliver, M. and Valle, H.: Australian beef, Financial performance of beef farms, 2013–14 to 2015–16. Research by the Australian Bureau of Agricultural and Resource Economics and Sciences, September 2016.

Australian Government, 2018. Department of Agriculture and Water Resources ABARES, http://www.agriculture.gov.au/abares.

Azbar, Nuri, Abdurrahman Bayram, Ayse Filibeli, Aysen Muezzinoglu, Fusun Sengul, and Adem Ozer, 2004. A Review of Waste Management Options in Olive Oil Production. *Critical Reviews in Environmental Science and Technology* 34 (3): 209–47. doi:10.1080/10643380490279932.

Azbar, Nuri, F. Tuba Çetinkaya Dokgöz, Tugba Keskin, Kemal S. Korkmaz, and Hamid M. Syed, 2009. Continuous Fermentative Hydrogen Production from Cheese Whey Wastewater under Thermophilic Anaerobic Conditions. *International Journal of Hydrogen Energy*, IWBT 2008IWBT 2008, 34 (17): 7441–47. doi:10.1016/j.ijhydene.2009.04.032, 2009.

Bai, Z., M. R. F. Lee, L. Ma, S. Ledgard, O. Oenema, G. L. Velthof, W. Ma, M. Guo, Z. Zhao, S. Wei, S. Li, X. Liu, P. Havlik, J. Luo, C. Hu, F. Zhang, 2017. Global environmental cost of China's thirst for milk. *Global Change Biology* 24:2198-2211.

Barrett, C. B., C. M. Moser, O. V. McHugh and J. Barison (2004): Better technology, better plots, better farmers? Identifying changes in productivity and risk among Malagasy rice farmers, American Journal of Agricultural Economics, Vol.86 (4), pp.869-888.

BC Ministry of Environment, 2008. Landfill gas management regulation. Government of British Columbia, Canada.

BC Oil and Gas Commission, 2013. Flaring and venting reduction guideline. Government of British Columbia, Canada.

Beach, R. H., Creason, J., Bushey Ohrel, S., Ragnauth, S., Ogle, S., Li, C., Ingraham, P., Salas, W.: *Journal of Integrative Environmental Studies*, 12(Suppl. 1), 87-105, 2015.

Beef2Live, 2018. Feedlot production & Farmsize: FarmCentric. Paraguay Beef & Cattle Outlook 2018, 21 Feb 2018. http://beef2live.com/story-paraguay-beef-cattle-report-0-107341

Bergamaschi, P. et al., 2013. Atmospheric CH4 in the first decade of the 21st century: inverse modeling analysis using SCIAMACHY satellite retrievals and NOAA surface measurements. *J. Geophys. Res. Atmos.* 118: 7350-7369.

Bouman, B.A.M.(2001): Water-efficient management strategies in rice production", IRRI Mini Review 26.2, International Rice Research Institute, Los Banos, Philippines.

Brandt, A. R., G. A. Heath, E. A. Kort, F. O'Sullivan, G. Petron, S. M. Jordaan, P. Tans, J. Wilcox, A. M. Gopstein, D. Arent, S. Wofsy, N. J. Brown, R. Bradley, G. D. Stucky, D. Eardley, R. Harriss, 2014. Methane Leaks from North American Natural Gas Systems. *Science* 343:733-735.

Brito, António G., João Peixoto, José M. Oliveira, José A. Oliveira, Cristina Costa, Regina Nogueira, and Ana Rodrigues, 2007. Brewery and Winery Wastewater Treatment: Some Focal Points of Design and Operation. In *Utilization of By-Products and Treatment of Waste in the Food Industry*, edited by Vasso Oreopoulou and Winfried Russ, 109–31. 3. Springer US. http://link.springer.com/chapter/10.1007/978-0-387-35766-9_7.

Bruhwiler, L. et al., 2017. US CH_4 emissions from oil and gas production: Have recent large increases been detected? *J. Geophys. Res. Atmos*. 122:4070-4083.

Canadian Minister of Justice, 2009. Newfoundland offshore petroleum drilling production regulations. Government of Canada, Canada.

Carbon Limits, 2013. Associated Petroleum Gas Flaring Study for Russia, Kazakhstan, Turkmenistan and Azerbaijan, Carbon Limits AS, Oslo. Available at http://www.ebrd.com/downloads/sector/sei/ap-gas-flaring-study-final-report.pdf.

Caulton, D., P. B. Shepson, R. L. Santoro, J. P Sparks, R. W. Howarth, A. R. Ingraffea, M. O. L. Cambaliza, C. Sweeney, A. Karion, K. J. Davis, B. H. Stirm, S. A. Montzka and B. R. Miller, 2014. Toward a better understanding and quantification of methane emissions from shale gas development. Proceedings of the National Academy of Sciences of the United States of America *PNAS* 111:6237-6242.

Chaparro, T. R., and E. C. Pires, 2011. Anaerobic Treatment of Cellulose Bleach Plant Wastewater: Chlorinated Organics and Genotoxicity Removal. *Brazilian Journal of Chemical Engineering* 28 (4): 625–38. doi:10.1590/S0104-66322011000400008

Cathles, L. M., 2012. Assessing the greenhouse impact of natural gas, *Geochemistry, Geophysics, Geosystems G3* 13(6).

Cheng, Wang & Zhang, 2010. Environmental impact of coal mine methane emissions and responding strategies in China. *International Journal of Greenhouse Gas Control* 5:157-166.

China Daily, 2017. World's largest floating solar farm starts operating. China Daily 2017-08-15. http://www.chinadaily.com.cn/china/2017-08/15/content_30631248.htm

Collings, R., K. L. Doran, R. Murray, 2012. Methane Emissions from Abandoned Coal Mines in China. EPA Project No. EPAOARCCD0903. Global Methane Initiative, United States Environmental Protection Agency, Washington D.C.

Das, B., Bhave, P.V., Sapkota, A., Byanju, R.M., 2018. Estimating emissions from open burning of municipal solid waste in municipalities of Nepal. Waste Management 79, 481–490. https://doi.org/10.1016/j.wasman.2018.08.013

Debik, E., and T. Coskun, 2009. Use of the Static Granular Bed Reactor (SGBR) with Anaerobic Sludge to Treat Poultry Slaughterhouse Wastewater and Kinetic Modeling. *Bioresource Technology* 100 (11): 2777–82. doi:10.1016/j.biortech.2008.12.058

Dhaked, R.K., Singh, P., Singh, L., (2010). Biomethanation under psychrophilic conditions. Waste Management 30, 2490–2496. https://doi.org/10.1016/j.wasman.2010.07.015

Dufresne, Robert, Alain Liard, and Murray S. Blum, 2001. Anaerobic Treatment of Condensates: Trial at a Kraft Pulp and Paper Mill. *Water Environment Research* 73 (1): 103–9

EEA: Effectiveness of urban wastewater treatment policies in selected countries: an EEA pilot study, European Environment Agency, Copenhagen, 2005.

EIA, 2015. Country Analysis Briefs. US Energy Information Administration, US Department of Energy, Washington D.C., webpage: http://www.eia.doe.gov/.

EIA, 2019. International Energy Statistics. US Energy Information Administration, US Department of Energy, Washington D.C., webpage: http://www.eia.doe.gov/.

Ekstrand, Eva-Maria, Madeleine Larsson, Xu-Bin Truong, Lina Cardell, Ylva Borgström, Annika Björn, Jörgen Ejlertsson, Bo H. Svensson, Fredrik Nilsson, and Anna Karlsson, 2013. Methane Potentials of the Swedish Pulp and Paper Industry – A Screening of Wastewater Effluents. *Applied Energy* 112 (December): 507–17. doi:10.1016/j.apenergy.2012.12.072.

Elvidge C. D., Zhizhin, M., Baugh, K., Hsu, F.-C., and Ghosh, T.: Methods for global survey of natural gas flaring from Visible Infrared Imaging Radiometer Suite Data, *Energies*, doi.org:10.3390/en9010014, 2016.

EUROSTAT database. European Commission, Brussels, 2013. http://epp.eurostat.ec.europa.eu/

EUROSTAT database. European Commission, Brussels, 2015. http://epp.eurostat.ec.europa.eu/

EUROSTAT database. European Commission, Brussels, 2016. http://epp.eurostat.ec.europa.eu/

Evans, M. and Roshchanka, V.: Russian policy on methane emissions in the oil and gas sector: A case study in opportunities and challenges in reducing short-lived forcers, *Atmospheric Environment*, 92, 199-206, 2014.

FAO: Water charging in irrigated agriculture –an analysis of international experience, FAO water reports 28, Food and Agriculture Organization, Rome, 2004.

FAOSTAT. Food and Agriculture Organization, Rome, 2015. http://faostat.fao.org,

FAOSTAT. Food and Agriculture Organization, Rome, 2016. http://faostat.fao.org

FAOSTAT. Food and Agriculture Organization, Rome, 2018. http://faostat.fao.org

FAO, 2017. Low emissions development of the beef cattle sector in Uruguay –Reducing enteric methane for food security and livelihoods. Food and Agricultural Organization of the United Nations, Rome. http://www.fao.org/3/a-i6749e.pdf

Ferrero, A. and N. V. Nguyen: Constraints and opportunities for the sustainable development of rice-based production systems in Europe in . N. V. Nguyen (ed.) Proceedings of the FAO Rice Conference, Food and Agriculture Organization, Rome, 2004.

Fountoulakis, M. S., S. Drakopoulou, S. Terzakis, E. Georgaki, and T. Manios, 2008. Potential for Methane Production from Typical Mediterranean Agro-Industrial by-Products. *Biomass and Bioenergy* 32 (2): 155–61. doi:10.1016/j.biombioe.2007.09.002.

Franco, B. et al., 2016. Evaluating ethane and methane emissions associated with the development of oil and natural gas extraction in North America. *Environ. Res. Lett.* 11 DOI:10.1088/1748-9326/11/4/044010.

GMI: VAM Utilization Project at Xiaodongshan Shaft of Sihe Mine, Jincheng Anthracite Mining Group, Jincheng Mining Area, Shanxi Province, China, Global Methane Initiative, Washington D. C., 2008.

GMI and EC, 2013. European Commission Global Methane Reduction Actions. Ref. Ares (2013)2843722-06/08/2013. Global Methane Initiative and European Commission. Online at: www.globalmethane.org/documents/EC_GMI_reduction_actions.pdf

Gómez-Sanabria, A., Höglund-Isaksson, L., Rafaj, P., Schöpp, W.: Carbon in global waste and wastewater flows – its potential as energy source under alternative future waste management regimes, *Advances in Geosciences*, 45, 105-113, 2018.

Han, X., Sun, X., Wang, C., Wu, M., Dong, D., Zhong, T., Thies, J.E., Wu, W.: Mitigating methane emission from paddy soil with rice-straw biochar amendment under projected climate change. Scientific Reports DOI:10.1038/srep24731, 2016.

Harmsen, M. J. H. M., van Vuuren, D. P., Nayak, D. R., Hof, A. F., Höglund-Isaksson, L. Lucas, P. L., Nielsen, J. B., Smith, P., Stehfest, E.: Long-term marginal abatement cost curves of non-CO2 greenhouse gases, *Environmental Science and Policy*, Accepted/In Press, 2019.

Hausmann, P., R. Sussmann and D. Smale, 2016. Contribution of oil and natural gas production to renewed increase of atmospheric methane (2007-2014): Top-down estimate from ethane and methane column observations. *Atmos. Chem. Phys.* 16:3227-3224.

Healy, M. G., M. Rodgers, and J. Mulqueen, 2007. Treatment of Dairy Wastewater Using Constructed Wetlands and Intermittent Sand Filters. *Bioresource Technology* 98 (12): 2268–81. doi:10.1016/j.biortech.2006.07.036.

Hengyun, M., L. Oxley, S. Gao, H. Tang, Y. Wu, J. Huang, A. Rae and S Rozelle, 2011. Chinese Dairy Farm Performance and Policy Implications in the New Millenium. Working Paper No. 21/2011, Department of Economics and Finance, College of Business and Economics, University of Christchurch, New Zealand.

Hernandez-Sancho, F., Molinos-Senante, M., Sala-Garrido, R., 2011. Cost modelling for wastewater treatment processes. Desalination 268, 1–5. https://doi.org/10.1016/j.desal.2010.09.042

Heytens, P.: Chapter 6: Technical change in wetland rice agriculture, in S. Pearson, W.Falcon, P. Heytens, E. Monke and R. Naylor (eds.) Rice Policy in Indonesia, Cornell University Press, Ithaca and London, 1991.

Höglund-Isaksson, L., 2012. Global anthropogenic methane emissions 2005-2030: technical mitigation potentials and costs. *Atmospheric Chemistry and Physics* 12:9079-9096.

Höglund-Isaksson, L., A. Thomson, K. Kupiainen, S. Rao, G. Janssens-Maenhout, 2015. Chapter 5: Anthropogenic methane sources, emissions and future projections in AMAP Assessment 2015: Methane as an Arctic climate forcer. Arctic Monitoring and Assessment Programme (AMAP) of the Arctic Council, Oslo.

Höglund-Isaksson, 2017: Bottom-up simulations of methane and ethane from global oil and gas systems. *Environmental Research Letters* 12(2), http://iopscience.iop.org/article/10.1088/1748-9326/aa583e

Höglund-Isaksson, L., W. Winiwarter, P. Purohit, A Gómez-Sanabria, P. Rafaj, W. Schöpp, J. Borken-Kleefeld, 2018. Non-CO2 greenhouse gas emissions in the EU-28 from 2005 to 2070: GAINS model methodology. Report produced by IIASA for the European Commission DG-Climate Action under the EUCLIMIT4 project financed by the European Commission Service Contract for Modelling of European Climate Policies No.: 340201/2017/766154/SER/CLIMA.C1, 30 October 2018. https://ec.europa.eu/clima/sites/clima/files/strategies/analysis/models/docs/non_co2_methodology_report_en.pdf

Hoornweg, D., Bhada-Tata, P., 2012. What a waste. A global review of solid waste management (Urban development series knowledge papers). The World Bank.

Howarth, R.: Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane? Biogeosciences 16:3033-3046, 2019. doi.org/105194/bg-16-3033-2019.

Huang, K. et al., 2015. Russian anthropogenic black carbon: Emission reconstruction and Arctic black carbon simulation. *Journal of Geophysical Research: Atmospheres* DOI:10.1002/2015JD023358.

Husdal, G., L. Osenbruch, Ö. Yetkinoglu and A. Østebrøt, 2016a. Cold venting and fugitive emissions from Norwegian offshore oil and gas activities, Summary report prepared for the Norwegian Environment Agency M-515/2016. Add Novatech AS, 12 April 2016a.

Husdal, G., L. Osenbruch, Ö. Yetkinoglu and A. Østebrøt, 2016b. Kaldventilering og diffuse ytslipp fra petroleumvirksomheten på norsk sokkel, Delrapport 2: Utslippsmengder og kvantifiseringsmetodikk. Rapport utarbeidet for Miljødirektoratet M-511/2016. Add Novatech AS, 15 March 2016b.

ICF International, 2016. Economic Analysis of Methane emission Reduction Potential from Natural Gas Systems. Report prepared by ICF International, Fairfax VA, USA.

IEA-WEO: International Energy Agency –World Energy Outlook 2018, International Energy Agency, Paris, 2018.

IPCC: IPCC Guidelines for National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change, Japan, 2006.

IRRI: Distribution of rice crop area by environment 2004-2006, International Rice Research Institute, Los Banos, the Philippines, 2007.

Janssen, Albert J. H., Piet N. L. Lens, Alfons J. M. Stams, Caroline M. Plugge, Dimitri Y. Sorokin, Gerard Muyzer, Henk Dijkman, Erik Van Zessen, Peter Luimes, and Cees J. N. Buisman, 2009. Application of Bacteria Involved in the Biological Sulfur Cycle for Paper Mill Effluent Purification. *Science of The Total Environment* 407 (4): 1333–43. doi:10.1016/j.scitotenv.2008.09.054.

Jessop, A. M., J. K. MacDonald, H. Spence, 1995. Clean energy from abandoned mines in Springhill, Nova Scotia. *Energy Source*s 17:93-106.

JRC. Agri4 Cast Data Portal. https://agri4cast.jrc.ec.europa.eu/DataPortal/RequestNETCDFResource.aspx?idResource=19. Retrieved 2015.

Karion, A., C. Sweeney, G. Pétron, G. Frost, R. M. Hardesty, J. Kofler, B. R. Miller, T. Newberger, S. Wolter, R. Banta, A. Brewer, E. Dlugokencky, P. Lang, S. A. Montzka, R. Schnell, P. Tans, M. Trainer, R. Zamora and S.

Conley, 2013. Methane emissions estimate from airborne measurements over a western United States natural gas field. *Geophysical Research Letters*, 40:4393-4397.

Karlsson, Anna, Xu-Bin Truong, Jenny Gustavsson, Bo H. Svensson, Fredrik Nilsson, and Jörgen Ejlertsson, 2011.Anaerobic Treatment of Activated Sludge from Swedish Pulp and Paper Mills – Biogas Production Potential and Limitations. *Environmental Technology* 32 (14): 1559–71. doi:10.1080/09593330.2010.543932.

Kirchgessner, D. A., R. A. Lott, R. M. Cowgill, M. R. Harrison, T. M. Shires, 1997. Estimate of methane emissions from the U.S. natural gas industry. *Chemosphere*, 35(6):1365-1390.

Kobya, Mehmet, Elif Senturk, and Mahmut Bayramoglu, 2006. Treatment of Poultry Slaughterhouse Wastewaters by Electrocoagulation. *Journal of Hazardous Materials* 133 (1–3): 172–76. doi:10.1016/j.jhazmat.2005.10.007.

Lan, X. et al., 2019. Long-term measurements show little evidence for large increases in total U.S. methane emissions over the past decade. *Geophysical Research Letters* 46:4991-4999.

Larsson, Madeleine, Xu-Bin Truong, Annika Björn, Jörgen Ejlertsson, David Bastviken, Bo H. Svensson, and Anna Karlsson, 2015. Anaerobic Digestion of Alkaline Bleaching Wastewater from a Kraft Pulp and Paper Mill Using UASB Technique. *Environmental Technology* 36 (12): 1489–98. doi:10.1080/09593330.2014.994042

Latorre, A., A. Malmqvist, S. Lacorte, T. Welander, D. Barcelo, 2007. Evaluation of the treatment efficiencies of paper mill whitewaters in terms of organic composition and toxicity, Environmental Pollution, Vol.147, pp.648-655,

Lettinga, G., 1995. Anaerobic digestion and wastewater treatment systems. Antonie van Leeuwenhoek, International Journal of General and Molecular Microbiology 67, 3–28.

Lettinga, G., Rebac, S., Zeeman, G., 2001. Challenge of psychrophilic anaerobic wastewater treatment. Trends in Biotechnology 19, 363–370. https://doi.org/10.1016/S0167-7799(01)01701-2

Linquist, B., Anders, M.A., Adviento-Borbe, M., Chaney, R.L., Nally, L., Da Rosa, E., Van Kessek, C. 2015. Reducing greenhouse gas emissions, water use and grain arsenic levels in rice systems. *Global Change Biology*. 21(1);407-417. doi: 10.1111/GCB.12701.

Luostarinen, S., Sanders, W., Kujawa-Roeleveld, K., Zeeman, G., 2007. Effect of temperature on anaerobic treatment of black water in UASB-septic tank systems. Bioresource Technology 98, 980–986. https://doi.org/10.1016/j.biortech.2006.04.018

Manitoba Ministry of Conservation and Water Stewardship, 2009. Prescribed landfills regulation, Government of Manitoba, Canada.

Mattus, R. and Å. Källstrand (2010), Chapter 12: Fossil Energy and Ventilation Air Methane, in Reay, D. et al. (eds) Methane and Climate Change, Earthscan, London.

Maya-Altamira, L., A. Baun, I. Angelidaki, and J. E. Schmidt, 2008. Influence of Wastewater Characteristics on Methane Potential in Food-Processing Industry Wastewaters. *Water Research* 42 (8–9): 2195–2203. doi:10.1016/j.watres.2007.11.033.

McCabe, D. and L. Fleischmann, 2014; Quantifying Cost-effectiveness of Systematic Leak Detection and Repair Programs Using Infrared Cameras. Power point presentation by Carbon Limits and Clean Air Task Force, 13 May 2014.

Miller, S.M., A.M. Michalak, R.G. Detmers, O.P. Hasekamp, L.M.P. Bruhwiler and S. Schwietzke, 2019. China's coal mine methane regulations have not curbed growing emissions. *Nature Communications* 10:303.

Montaldo, H.H., E. Casas, J. B. Sterman Ferraz, V. E. Vega-Murillo, S. I. Roman-Ponce, 2012. Opportunities and challenges from the use of genomic selection for beef cattle breeding in Latin America. *Animal Frontiers* 2(1):23-29

New Brunswick Department of Energy and Mines, 2013. Responsible environmental management of oil and natural gas activities in New Brunswick: Rules for industry. Government of New Brunswick, Canada.

NOAA, 2018. Gridded Climate Datasets: Surface Temperature. ESRL, Physical Science Division. National Oceanic and Atmospheric Administration, US Department of Commerce, USA.

OECD. Statistical Database. Organization for Economic Co-operation and Development (OECD), Paris http://stats.oecd.org/, 2015.

OECD. Statistical Database. Organization for Economic Co-operation and Development (OECD), Paris http://stats.oecd.org/, 2016.

OME: Assessment of internal and external gas supply options for the EU, evaluation of the supply costs of new natural gas supply projects to the EU and an investigation of related financial requirements", Observatoire Mediterraneen de l'Energie, Nanterre, 2001.

Ontario Ministry of Energy, 2009. FIT and MicroFIT Program. Government of Ontario, Canada.
Ontario Ministry of Environment, 2007. Landfill gas collection and control regulation. Government of Ontario, Canada.

Papar, R., A. Szady, W. D. Huffer, V. Martin, A. McKane: Increasing energy efficiency in mine ventilation systems, Industrial Energy Analysis, Lawrence Berkeley National Laboratory, University of California, 1999.

PEI Ministry of Environment, Labour and Justice, 2009. Waste resource management regulations (article 22). Government of Prince Edward Island, Canada.

Peischl, J., T.B. Ryerson, K. C. Aikin, J. A. de Gouw, J. B. Gilman, J. S. Holloway, B. M. Lerner et al., 2015. Quantifying atmospheric methane emissions from the Haynesville, Fayetteville, and northeastern Marcellus shale gas production regions. *J. Geophysical Research: Atmospheres* 120:2119-2139.

Peng, S., S. Piao, P. Bousquet, P. Ciais, B. Li, X. Lin, S. Tao, Z. Wang, Y. Zhang and F. Zhou, 2016. Inventory of anthropogenic methane emissions in mainland China from 1980 to 2010. *Atmos. Chem. Phys.* 16 :14545-14562.

Pokhrel, D., Viraraghavan, T., 2005. Municipal solid waste management in Nepal: practices and challenges. Waste Management 25, 555–562. https://doi.org/10.1016/j.wasman.2005.01.020

Pujades, E., P. Orban, A Dassargues, 2016. Underground pumped storage hydroelectricity using abandoned works (deep mines or open pits) and the impact on groundwater flow. *Hydrogeology Journal*, April 2016. DOI: 10.1007/s10040-016-1413-z.

Québec MDDELCC, 2009. Issuance of offsets credits protocol 1: Covered manure storage facilities – CH_4 destruction. Québec Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, Gouvernement du Québec, Canada.

Québec MDDELCC, 2011. Règlement sur l'enfouissement et l'incinération de matières Résiduelles. Québec Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques, Gouvernement du Québec, Canada.

Rodgers, Michael, Xin-Min Zhan, and Brian Dolan, 2004. Mixing Characteristics and Whey Wastewater Treatment of a Novel Moving Anaerobic Biofilm Reactor. *Journal of Environmental Science and Health, Part A* 39(8):2183–93. doi:10.1081/ESE-120039383.

Saunier, S., 2017. Statistical Analysis of Leak Detection and Repair Programs in Europe. Carbon Limits AS, Oslo.

Saskatchewan Ministry for Energy and Resources, 2011. Upstream petroleum industry associated gas, Conservation Directives S-10 and S-20. Government of Saskatchewan, Canada.

Schneising, O., J. P. Burrows, R. R. Dickerson, M. Buchwitz, M. Reuter, and H. Bovensmann, 2014. Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations. Earth's Future 2(10):548-558.

Şentürk, E., İnce, M., Onkal Engin, G., 2010. Kinetic evaluation and performance of a mesophilic anaerobic contact reactor treating medium-strength food-processing wastewater. *Bioresource Technology* 101, 3970–3977.

Sino-US New Energy Sci-Tech Forum: Summary Report –Conference on Coalmine Methane Recovery and Utilization, Jincheng, China, February 24-27, 2009.

Sharda, Avinash, M. P. Sharma, and Sharwan Kumar, 2013. Performance Evaluation of Brewery Waste Water Treatment Plant. *International Journal of Engineering Practical Research* 2(3):105-112.

Sheng, J., Song, S., Zhang, Y., Prinn, R.G., Janssens-Maenhout, G.: Bottom-up estimates of coal mine methane emissions in China: A gridded inventory, emission factors, and trends. *Environmental Science and Technology* 6:473-478, 2019.

Shibayama, H.: Weeds and weed management in rice production in Japan, *Weed biology and management*, Vol. 1, pp. 53-60, 2001.

Shivayogimath, C. B., and Rashmi Jahagirdar, 2015. Treatment Of Sugar Industry Wastewater Using Electrocoagulation Technique. *Int. J. Research in Engineering and Technology*, IC-RICE Conference Issue, November 2013.

Skone, T. J., J. Littlefield and J. Marriott, 2011. Life cycle greenhouse gas inventory of natural gas extraction, delivery and electricity production, Report prepared by National Energy Technology Laboratory for the U. S. Department of Energy, October 24.

Somers, J. and C. Burklin, 2012. A 2012 update on the world VAM oxidizer technology market. 14th United States/North American Mine Ventilation Symposium, 2012. University of Utah, Department of Mining Engineering.

Tezel, Ulas, Engin Guven, Tuba H Erguder, and Goksel N Demirer, 2001. Sequential (anaerobic/aerobic) Biological Treatment of Dalaman SEKA Pulp and Paper Industry Effluent. *Waste Management* 21(8):717–24. doi:10.1016/S0956-053X(01)00013-7.

Thakur, P. C.: Coal seam degasification, in Kissell, F.N. (ed.) Handbook for Methane Control in Mining, Information Circular 9486, Department of Health and Human Services, National Institute for Occupational Safety and Health, Pittsburgh, US, 2006.

Thompson G., J. Swain, M. Kay and C.F. Forster, 2001. The treatment of pulp and paper mill effluent: a review, *Bioresource Technology* 77:275-286.

Turner, A. J., D. J. Jacob et al., 2016. A large increase in US methane emissions over the past decade inferred from satellite data and surface observations. *Geophys. Res. Lett.* 43:2218-2224.

Udo, H.M.J., H.A. Aklilu, L.T. Phong, R.H. Bosma, I.G.S. Budisatria, B.R. Patil, T. Samdup and B.O. Bebe, 2011. Impact of intensification of different types of livestock production in smallholder crop-livestock systems. *Livestock Science* 139:22-29.

UNFCCC (2014), "National Inventory Submissions 2014." Retrieved 2014, from https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2014

UNFCCC (2015), "National Inventory Submissions 2015." Retrieved 2015, from https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2015

UNFCCC (2016), "National Inventory Submissions 2016." Retrieved 2016, from https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2015

UNFCCC (2017), "National Inventory Submissions 2015." Retrieved 2018, from https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories/submissions-of-annual-greenhouse-gas-inventories-for-2017/submissions-of-annual-ghg-inventories-2015

UNFCCC (2018), "National Inventory Submissions 2015." Retrieved 2018 from https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/submissions/national-inventory-submissions-2018

Unruh, B.: Delivered energy consumption projections by industry in the Annual Energy Outlook 2002, US Energy Information Administration, Washington D. C., 2002.

UNStat (2014). United Nations Statistics Division. Statistical databases. https://unstats.un.org/unsd/databases.htm. Retrieved 2016.
USDA, 2011a. Farms, Land in Farms, and Livestock Operations, 2010 Summary, United States Department of Agriculture ISSN: 1930-7128, Feb 2011.

USDA, 2011b. Small-scale US Cow-calf operations, USDA, Fort Collins CO, USA. https://www.aphis.usda.gov/animal_health/nahms/smallscale/downloads/Small_scale_beef.pdf

USDA, 2013. Foreign Agricultural Service, Report from the Global Agricultural Information Network. United States Department of Agriculture, Washington D.C. https://www.fas.usda.gov/databases/global-agricultural-information-network-gain

USDA, 2015. Ecuador Livestock Annual 2015 –Cattle Numbers Up. USDA Foreign Agricultural Service, Report from the Global Agricultural Information Network. United States Department of Agriculture, Washington D.C. https://www.fas.usda.gov/databases/global-agricultural-information-network-gain

USDA, 2016. Building a Competitive and Inclusive Livestock Sector in Nicaragua -A Case Study of the Ganadería Empresarial Project (2012-2016). Technoserve Inc. and United States Department of Agriculture, Washington D.C.

USEPA: Decentralized systems technology fact sheet –septic tank –soil absorption systems, EPA 932-F-99-075, US Environmental Protection Agency, Washington D.C., 1999.

USEPA, 2003. “Assessment of the Worldwide Market Potential for Oxidizing Coal Mine Ventilation Air Methane”, EPA 430-R-03-002, United States Environmental Protection Agency, July 2003.

USEPA, 2004. Methane emissions from Abandoned Coal Mines in the United States: Emissions inventory methodology and 1990-2002 emission estimates. USEPA Coalbed Methane Outreach Programme, United States Environmental Protection Agency, Washington D.C.

USEPA, 2008. US surface coal mine methane recovery project opportunities", EPA Publication 430R08001, US Environmental Protection Agency, Washington D. C., July 2008.

USEPA, 2010. Coalbed methane outreach program, http://www.epa.gov/cmop/, US Environmental Protection Agency, Washington D.C.

USEPA, 2011. Reduced emissions completions from hydraulically fractured natural gas wells. Lessons learned from Natural gas STAR partners. United States Environmental Protection Agency, Washington D.C. https://www.epa.gov/sites/production/files/2016-06/documents/reduced_emissions_completions.pdf

USEPA, 2014a. Natural Gas STAR Program. United States Environmental Protection Agency, Washington D.C. https://www.epa.gov/

USEPA, 2014b. Coalbed Methane Outreach Program. United States Environmental Protection Agency, Washington D.C. https://www.epa.gov/cmop

USEPA, 2014c. EPA's Landfill Methane Outreach Program. United States Environmental Protection Agency, Washington D.C. https://www.epa.gov/

USEPA, 2014d. EPA's AgSTAR Program. United States Environmental Protection Agency, Washington D.C. https://www.epa.gov/

USEPA, 2016; Control Techniques Guidelines for the Oil and Natural Gas Industry. EPA-453/B-16-001, United States Environmental Protection Agency, Washington D.C.

USEPA, 2017a. Abandoned Coal Mine Opportunities Database. USEPA Coalbed Methane Outreach Programme, United States Environmental Protection Agency, Washington D.C.

USEPA, 2017b. Inventory of US greenhouse gas emissions and sinks, United States Environmental Protection Agency, Washington D.C.

USEPA, 2018. New Source Performance Standards 2016 with Amendment 2018. United States Environmental Protection Agency, September 2018. https://www.epa.gov/controlling-air-pollution-oil-and-natural-gas-industry/proposed-improvements-2016-new-source

Van der Gon, H. A. D., P. M. Van Bodegom, R. Wassmann, R. S. Lantin and T. M. Metra-Corton: Sulphate-containing amendments to reduce methane emissions from rice fields: mechanisms, effectiveness and costs, *Mitigation and Adaptation Strategies for Global Change*, Vol.6, pp.71-89, 2001.

Vinciguerra, T. S. et al., 2015. Regional air quality impacts of hydraulic fracturing and shale natural gas activity: Evidence from ambient VOC observations. *Atmos Environ* 110:144-150.

Wiedinmyer, C., Yokelson, R.J., Gullett, B.K., 2014. Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants from Open Burning of Domestic Waste. *Environ. Sci. Technol*. 48, 9523–9530. https://doi.org/10.1021/es502250z

WRI, 2014. Wetting and drying: Reducing greenhouse gas emissions and saving water from rice production. World Resources Institute Working Paper, Installment 8 of "Creating a Sustainable Food Future". World Resources Institute, Washington D.C.

Zavala-Araiza, D., D.R. Lyon, R.A. Alvarez, K.J. Davis, R. Harriss et al., 2015. Reconciling divergent estimates of oil and gas methane emissions. *PNAS* 112(51):15597-15602.