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Multiregional environmental comparison of fossil fuel power generation—Assessment of the contribution of fugitive emissions from conventional and unconventional fossil resources

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ABSTRACT

In this paper we investigate the influence of fugitive methane emissions from coal, natural gas, and shale gas extraction on the greenhouse gas (GHG) impacts of fossil fuel power generation through its life cycle. A multiregional hybridized life cycle assessment (LCA) model is used to evaluate several electricity generation technologies with and without carbon dioxide capture and storage. Based on data from the UNFCCC and other literature sources, it is shown that methane emissions from fossil fuel production vary more widely than commonly acknowledged in the LCA literature. This high variability, together with regional disparity in methane emissions, points to the existence of both significant uncertainty and natural variability. The results indicate that the impact of fugitive methane emissions can be significant, ranging from 3% to 56% of total impacts depending on type of technology and region. Total GHG emissions, in CO_2-eq./kWh, vary considerably according to the region of the power plant, plant type, and the choice of associated fugitive methane emissions, with values as low as 0.08 kg CO_2-eq./kWh and as high as 1.52 kg CO_2-eq./kWh. The variability indicates significant opportunities for controlling methane emissions from fuel chains.

1. Introduction

With the increasing interest in power generation from unconventional fossil fuel resources, such as shale gas, and the large push for gas fired power plants as a clean form of electricity production (Stephenson et al., 2012), a more complete quantification of the (potential) environmental impacts of fossil fuel power generation life cycle is needed. Though the environmental impacts of the operation of most power generation technologies are relatively well described and quantified in life cycle assessment (LCA) literature (Corsten et al., 2013; Heath et al., 2014; O'Donoughue et al., 2014; Whitaker et al., 2012), we argue here that attention should also be directed towards upstream processes, such as the extraction and transport of fossil fuel resources (Alvarez et al., 2012; Burnham et al., 2012; Weber and Clavin, 2012). The fuel supply is especially important when carbon dioxide capture and storage (CCS) technology is applied to reduce the greenhouse gas emissions of the power plant itself, a step which increases fuel consumption due to the inherent energy efficiency penalty related to the carbon dioxide capture and compression processes.

One of the major greenhouse gases (GHGs) emitted in natural gas and coal production is methane. As a major constituent of natural gas, methane emissions occur at all points during the natural gas extraction process: well drilling and completion, well operation, e.g. in the form of purges and vents, and through leakages of the entire natural gas infrastructure, e.g., at intermediate compressor and redistribution stations of the pipeline (Burnham et al., 2012). Coal bed methane is formed from bacterial degradation of coal and biomass residuals, and thermally through devolatilisation within the coalification process of organic matter (Moore, 2012). It is released during coal extraction and removal of overburden. Methane emissions from fossil fuel origin are estimated to represent about 30% of the world anthropogenic methane emissions, although both fossil emissions and total anthropogenic emissions are quite uncertain (Kirschke et al., 2013).

A range of life cycle assessments (LCAs) of fossil fuel power generation with and without CCS has been published previously (Jaramillo et al., 2007; Koornneef et al., 2008; NETL, 2010b,c,d,e; Odeh and Cockerill, 2008; Singh et al., 2011a; Zapp et al., 2012). Most studies were thoroughly reviewed in the papers by Whitaker

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et al. (2012), O'Donoughue et al. (2014), Heath et al. (2014), and Corsten et al. (2013). Whitaker et al. (2012) present a review and harmonization of LCA greenhouse gas emission results for coal based electricity generation. Coal methane emissions are discussed, and an interquartile range of the reviewed studies of 54–73 g CO_2-eq/kWh is presented (median 63 g CO_2-eq/kWh). O'Donoughue et al. (2014) review and harmonize LCA greenhouse gas emission results for conventional gas based electricity generation. Heath et al. (2014) harmonize shale gas life cycle emissions. Methane leakage is discussed and ranges from 0.2% to 6% of natural gas production in the reviewed studies. Corsten et al. (2013) review the LCAs of both coal and natural gas based electricity generation in combination with CCS. They conclude that the upstream emissions of natural gas lead to large impacts on the overall GHG emissions, to the extent that electricity generated by a natural gas combined cycle power plant with CCS appears to have associated GHG emissions of the same order of magnitude as pulverized coal generated electricity with CCS.

Several recent studies focus on fugitive methane emissions from conventional and unconventional fossil fuel production. Weber and Clavin (2012) perform a Monte Carlo analysis based on six previous studies for natural gas from conventional and unconventional sources. Burnham et al. (2012) compare results for emissions related to coal and natural gas, shale gas and petroleum. Both studies conclude that upstream methane leakage and venting can reduce significantly the life cycle benefit from gas compared to coal, and that gas related emissions from conventional or shale production are statistically indistinguishable in a life cycle perspective. Laurenzi and Jersey (2013) study GHG emissions and water consumption of Marcellus shale gas production, but indicate that for certain GHG emissions EPA emission factors are used. They find that the estimated ultimate recovery of shale wells is one of the major determinants in the life cycle GHG emissions of shale gas electricity generation.

Though there are differences between the LCA studies of power plants with and without CCS in the literature, relatively little attention has been paid to fugitive emissions. These are mainly included by application of an emission factor and sometimes discussed as a subject of sensitivity analysis. In addition, most studies have a limited regional scope, evaluating power plants in Europe or the United States, with the shale gas literature focusing almost solely on the United States. This leads to the questions to what extent data are available with respect to fugitive methane emissions for both coal and natural gas, how they vary regionally, and consequentially what that implies for the environmental performance of fossil fuel power generation with and without CCS.

The aim of this paper is to make an inventory of the ranges of fugitive methane emissions available in the literature and assess the consequences these emissions have on the life cycle GHG impacts of fossil fuel power generation. We focus on fugitive methane emissions of coal mining, conventional natural gas production and shale gas production. The hybridized multiregional life cycle assessment model THEMIS (Technology Hybridized Environmental-economic Model with Integrated Scenarios) is used (Hertwich et al., 2014), in combination with a set of life cycle inventories for state-of-the-art fossil fuel power plants, both with and without CCS facilities. We allow for regional variation of fugitive emissions in order to increase understanding of the environmental consequences of implementation of fossil fuel power generation in different regions.

2. Methods

In this section we discuss the approach followed to assemble the fugitive emission datasets with special focus on the data reported in UNFCCC. We continue with a description of the HLCA model employed. The system description for the HLCA and life cycle inventories used are described separately in Section 3 of this paper.

2.1. Dataset assembly fugitive emissions

Three datasets were compiled containing a total of 227 entries for coal fugitive emissions, 34 entries for conventional gas fugitive emissions and 19 entries for shale gas emissions, based on peer reviewed published literature as well as data reported as part of the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC was established in 1992 at the United Nations Conference on Environment and Development in Rio de Janeiro. The treaty has the objective to achieve '*...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system...*' (United Nations, 1992). Annex I countries that have ratified the convention, report national greenhouse gas inventories yearly in the form of a national inventory report (NIR) and the common reporting format (CRF). The NIRs contain detailed information for each country and the CRF is an electronically submitted series of standardized data tables for all greenhouse gas emissions per sector. According to the guidelines governing the reporting on annual inventories, the estimates of emissions should be comparable among parties. In order to do so, countries have to follow the IPCC guidelines (IPCC, 2006) to estimate and report on anthropogenic emissions, but are free to use the different methods included in those guidelines (UNFCCC, 2004). Though data should be comparable between countries, there are different levels of uncertainty related to the UNFCCC data, which are related to the different calculation approaches accepted in the IPCC guidelines. Countries can report data using a tier 1 approach. In this approach, associated with the highest level of uncertainty, total emissions are calculated using a global average range of emissions factors and country-specific activity data. In the tier 2 approach, emissions are calculated using country or basin specific emissions factors. In the tier 3 approach, associated with the lowest level of uncertainty, direct measurements on a mine-specific basis are used (IPCC, 2006). Though not reported in the tables of the CRF, the NIRs contain information about the approaches used by Annex I countries (commonly mixes between tiers 1, 2, and 3) in reporting emissions data.

In this paper, we used the data provided by the Annex I countries in Table 1.B.1 and 1.B.2 of the CRF, that describe the fugitive emissions from solid fuels (1.B.1) and oil, natural gas and other sources (1.B.2) (UNFCCC, 2012). We selected for each country the average, minimum and maximum emissions of the time series from the starting year of reporting (usually 1990, though there are variations between countries) until 2010. These country level data were subsequently aggregated to generate a list of regional estimates of methane emissions related to coal production and conventional natural gas production. The regions correspond to the regional division of our HLCA model, which is described in Section 2.2.

In this study, values larger than 1.5 times the global interquartile range above the (global) 3rd quartile were considered outliers and were removed from the database. This was the case for natural gas data reported by Ukraine and Greece (respectively 1025 and 837 g CH_4/m^3 natural gas) and some of the coal data for Russia and France. Such high numbers may be due to the application of too uncertain emissions factors in the tier 1 method and possibly aggregation of fugitive emissions related to the natural gas transportation infrastructure in the UNFCCC common reporting format.

Because the United States is the only country with significant past shale gas production and because there is no distinction in the UNFCCC natural gas data regarding the source (conventional or shale) of methane emissions, we assumed that UNFCCC natural gas