1. Methods and Data Detail

When studies reported leakage or emission factors as a percentage of total natural gas production, percent methane of total natural gas production, or percent methane of total methane production, the following conversion factors were used:

- Lower Heating Value of Natural Gas = 35.95 MJ/cubic meter (as reported in [1])
- Density of Natural Gas = 0.68 kg/cubic meter (as reported in [2-3])

1.1 Workovers

Many of the same parameters are important for well workovers as for well completions, as they also represent a one-time emission that must be allocated over the lifetime production of a well. Well workovers for shale gas wells consist of a second (or more) hydraulic fracturing of a well to stimulate production after it has decreased over time. Like initial completion, when the fracturing fluid is pulled out of the well as flowback, gas is usually either vented or flared to the atmosphere.

In addition to the uncertainty of how much gas is vented or flared, the flaring rate, and the EUR, workovers add another uncertain parameter of the number of refracturing events that will occur over the lifetime of the well. Two authors assumed refracturing would not occur in their base case (Jiang and Stephenson) and the others made some calculation for workovers based on a typical rate per year (i.e., one workover per 10 years [2, 4]) or based on current data on the number of workovers currently occurring [5]. These different assumptions, when combined with assumed well lifetimes that range from one year to 30 years, translate into different numbers of workovers per well occurring over the lifetime of the well, which is the parameter of interest. As Table 1 shows, this parameter ranges from 0 to ~3.5 across the different studies.

It is impossible to know what the most likely number of workovers per well will be at this point. Relatively few shale gas wells have been fully depleted to increase the information related to EUR, workovers, and completions and considerable variation in wells and basins exists. For our best estimate, we used a discrete probability distribution for number of workovers per lifetime, assuming with no better information a one-third chance of 0, 1, and 2 workovers per lifetime and combined this distribution with the well completion distributions described in the previous section. While it is clear that the eventual number of workovers per well is likely correlated in some way to the average EUR, it is currently unclear what such a correlation looks like and how strong it may be. Thus we assume independence between these parameters but note that this assumption likely increases the overall model uncertainty for shale gas carbon footprint due to a likely positive relationship.

1.2 Liquids Unloading

Liquids unloading are intermittent fugitive emissions that generally occur only from conventional natural gas wells [4-5]. During natural gas production from some mature conventional wells, well operators must intermittently remove water and condensate buildup that impedes the flow of natural gas. Liquids unloading generally occur more frequently and with less emissions per event than the analogous shale gas well workovers. The issues with determining point estimates for liquids unloading and uncertainty ranges