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Working Paper

DEFINING THE SHALE GAS LIFE CYCLE: A FRAMEWORK FOR IDENTIFYING AND MITIGATING ENVIRONMENTAL IMPACTS

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EXECUTIVE SUMMARY

Life cycle assessments of shale gas activities differ in their findings. Among the various studies, researchers estimate different greenhouse gas emissions, rates of water use, and rates of wastewater production.

Some of the variation in findings is due to the parameters of each study, particularly the life cycle boundary. The life cycle boundary determines which life cycle stages—and which processes attributable to those stages—are included in the assessment. For example, a life cycle boundary for shale gas often includes stages for exploration, drilling, fracturing, well production, processing, and combustion. Attributable processes further define the activities in those stages. However, some assessments omit stages—such as exploration, processing, or combustion—or do not delineate between stages and processes at all. The variations make it difficult to compare assessments and begin a constructive dialogue on strategies that reduce impacts.

This working paper proposes a life cycle boundary for shale gas spanning exploration to well closure/site remediation and from natural gas production to use. It follows the boundary setting guidance given in the Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard, which builds and expands on the ISO 14044 standard for life cycle assessment. In addition, WRI compares its life cycle boundary to those in 16 assessments of the environmental impacts of shale gas production. The findings illustrate significant variations in the scope of such studies, which complicate shale gas discussions. WRI will seek feedback on its life cycle boundary and apply it in a forthcoming working

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paper that summarizes the findings of previous assessments on the greenhouse gas emissions of shale gas production; estimates the implications on emissions from the Environmental Protection Agency's revised Greenhouse Gas Reporting Rule; and highlights the potential for additional methane abatement from natural gas systems in the United States.

INTRODUCTION

Rapid development of shale formations due to horizontal drilling and hydraulic fracturing is redrawing the global energy picture but raising concerns about the environmental impacts of production. At least 680 shale formations in 140 basins throughout the world are capable of producing natural gas (WEC 2010). By 2010, dry shale gas production in the United States had increased to 4.80 trillion cubic feet (tcf) from 0.39 tcf in 2000 (USEIA 2011b). Exploration has also occurred in Austria, Australia, Canada, China, Poland, South Africa, the United Kingdom, and other countries. In all countries with shale resources, increased natural gas could provide national security, economic, and environmental benefits. However, environmental impacts also arise from pollutants and activities associated with the production process, including greenhouse gas (GHG) emissions, chemicals used in the hydraulic fracturing process, and land clearance for the development of well sites. For the definition of terms used in this working paper, see Appendix 2.

In early 2012, the World Resources Institute (WRI) initiated projects to promote clarity on some contentious issues associated with shale gas. When following discussions on the environmental impacts of shale gas production, WRI observed in particular a debate over estimates of GHG emissions. This debate is echoed in the academic literature. For example, WRI found that Jiang et al. (2011) estimates GHG emissions from activities in the production stage of the shale gas life cycle to total 9.70 grams CO_2e/MJ.[1] For the same stage, Stephenson et al. (2011) estimates emissions of 1.17 grams CO_2e/MJ.[2] WRI also observed that findings vary for assessments of other environmental impacts, including water withdrawal, wastewater production, and wildlife habitat disruption.[3]

Many factors affect the findings of different assessments on the environmental impacts of shale gas production. Emissions factors, recovery rates, and rates of material leakage[4] affect GHG emission estimates; projected rainfall, the number of drilled wells, and water needs for well completions and workovers affect water use and impact estimates; and the extent of developed well sites, their spatial distribution, and recovery potential at reclaimed sites affect wildlife habitat disruption. Regardless, a consistent factor affecting findings is the boundary of identified shale gas life cycles.[5] Authors vary in how they bound life cycles, including and omitting different stages and their attributable processes as consistent with the scope of their assessments. In addition, authors order life cycle activities differently among assessments. Such variations make it difficult to combine or compare findings.

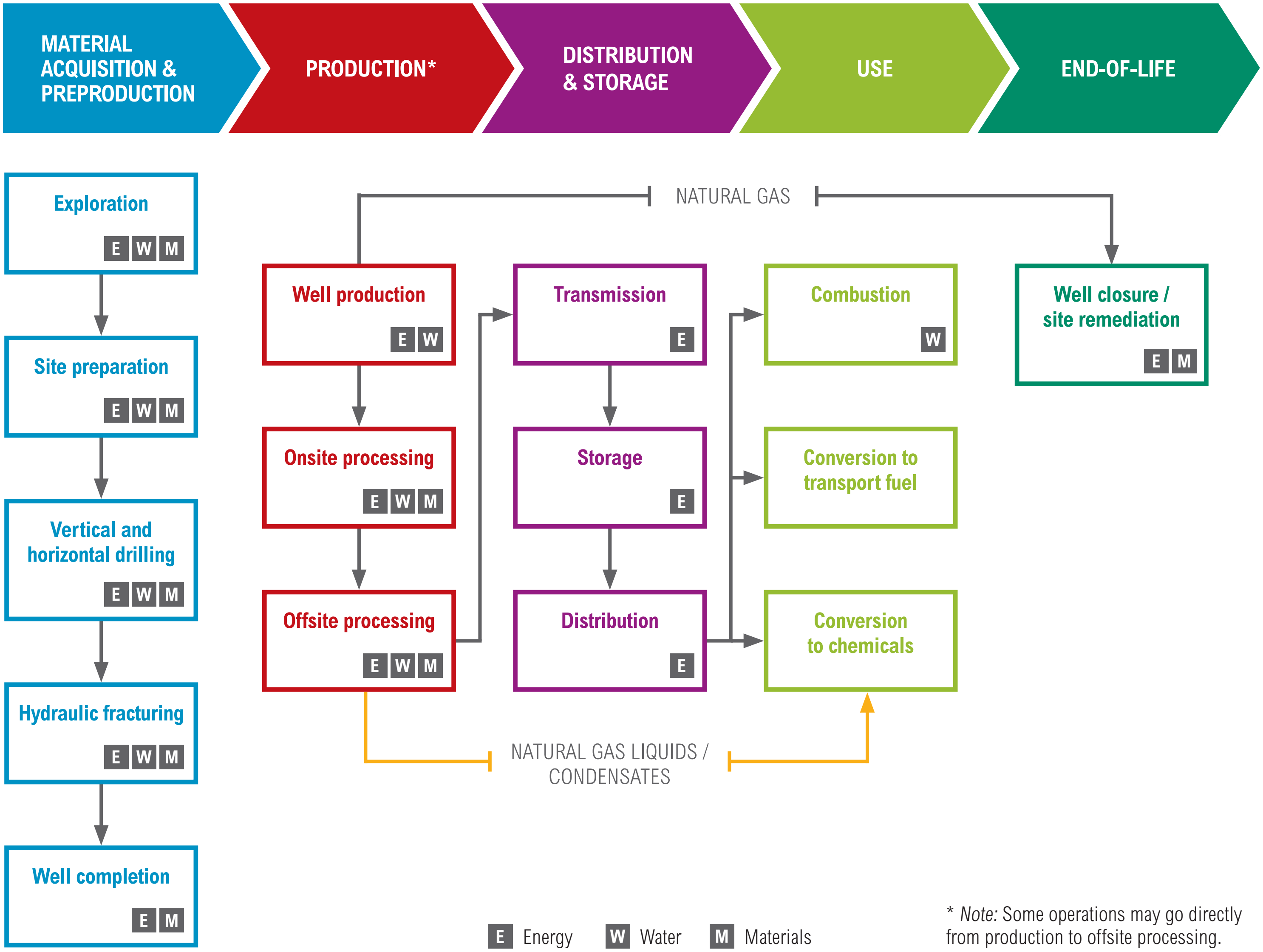
In this working paper, WRI proposes a life cycle boundary for shale gas with applicable stages and attributable processes. The WRI life cycle boundary is based on the boundary-setting guidance of the Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard (product standard). The product standard expands upon the International Organization for Standardization (ISO) 14044 standard for life cycle assessments.[6] The WRI life cycle boundary can thus apply to studies for all environmental mediums—air, water, or land—in all geographic regions. After defining the stages and attributable processes, this working paper compares the life cycle boundary to those in 16 assessments[7] of the environmental impacts of shale gas development. It concludes with recommendations for next steps toward a common understanding of assessment findings.

A common life cycle boundary proved helpful to WRI for understanding existing assessments and planning its future work on shale gas. Other stakeholders—including communities where shale gas development occurs, regulatory agencies, academic or research institutions, and businesses—also may find it helpful. WRI will seek feedback on its process map from potential users. It will then apply the life cycle boundary in its forthcoming quantitative comparison of existing assessments on the GHG emissions of shale gas production. A working paper will present those findings, assess the implications of the revised Greenhouse Gas Reporting Rule on methane emissions from natural gas wells, and discuss the potential for abatement.

METHODS

WRI followed three steps to develop its life cycle boundary. In an initial review, WRI identified the stages and attributable processes of life cycle boundaries in some academic, government, nongovernmental, and private sector literature. It then developed a list of draft attributable processes for standardized life cycle stages. An important

Figure 1 | **The WRI life cycle process map includes life cycle stages and attributable processes**



step was to clearly define each attributable process to avoid "double-counting" the activities that comprise them. Finally, WRI compared its life cycle boundary to those in other assessments and made changes as necessary.

WRI based its life cycle boundary on the product standard.[8] In life cycles for all products, boundary setting is an important component. The product standard recommends that entities present findings in a process map that includes standard life cycle stages and processes attributable to those stages. In figure 1, stages from the product standard are listed horizontally and include (1) material acquisition and preproduction,[9] (2) production, (3) distribution and storage, (4) use, and (5) end-of-life. Attributable processes are listed vertically, occurring in sequential order beginning in the upper left corner (exploration) and ending with the arrow terminus in the lower right corner (well closure/site remediation). Since energy use, water input and output (that is, water use and wastewater production), and use of introduced materials (such as gravel cover, well casing, and perforating explosives) apply in several attributable processes, those activities are represented through cross-cutting symbols (that is, E, W, M) rather than processes occurring in the sequential order.[10,11] Similar to life cycle boundaries in other studies on shale gas environmental impacts, the WRI process map spans the working life of one well.

Comparing life cycle boundaries

After defining its stages and attributable processes, WRI compared its life cycle boundary to those in other assessments of shale gas environmental impacts. Oft-cited studies—such as Skone et al. (2011), Howarth et al. (2011), and Moniz et al. (2011)—were easy to identify because of the media attention they have received. To find other studies, WRI searched for keywords relevant to the natural gas industry and included in major global newspapers from January 2009 to December 2011. Relevant articles referenced 35 assessments. In reviewing those assessments, WRI found 16 with life cycle boundaries that were sufficiently developed to include in the analysis.[12] WRI compared its stages and attributable processes to those in the identified studies, making changes as necessary to produce the following figures.

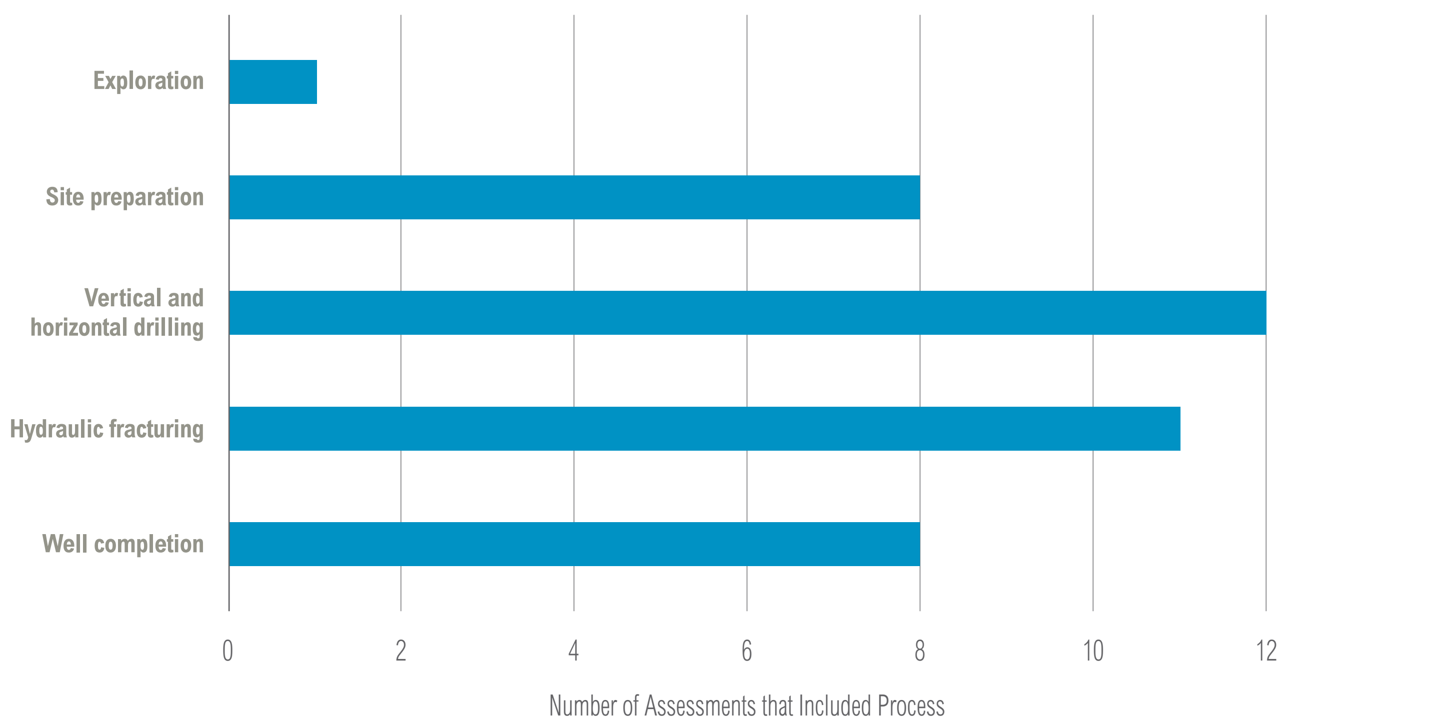
RESULTS

As evident from the following figures and text, assessments have different scopes and goals. For that reason, they bound life cycles differently and include different attributable processes. WRI compares only the life cycle boundaries and not the purpose of the assessment. For example, Jiang et al. (2011), an assessment of GHG emissions, identifies just two stages: (1) preproduction, and (2) after preproduction.[13] The authors describe 22 processes attributable to those stages. Conversely, Olmstead (2011), which presents a framework for all environmental impacts, does not separate activities into stages and attributable processes. It instead identifies nine discrete steps in the development process. While both assessments follow the development process from early site preparation through use, each treats water differently. Jiang et al. (2011) identifies water inputs and outputs as individual attributable processes, while Olmstead (2011) focuses on water outputs, including flowback, produced water storage, and ultimate disposal.

Material acquisition and preproduction stage

In the WRI process map, the material acquisition and preproduction stage includes five attributable processes. Some of the 16 assessments also include those attributable processes (figure 2).

Figure 2 | **Variability in material acquisition and preproduction stage**



The respective first and second WRI attributable processes, exploration and site preparation, are treated differently in the assessments. Only Considine et al. (2009) includes exploration, listing it after leasing.[14] Regarding site preparation, most of the evaluated assessments reference activities associated with the process, such as:

- Permitting (Moniz 2011)
- Preparation of well pad (Jiang et al. 2011)
- Raw materials extraction (Skone et al. 2011)
- Road and well site/pad development/construction (USFS 2007 and NYSDEC 2011)
- Site development and drilling preparation (Olmstead 2011)
- Site preparation (Saiers 2011)
- Well infrastructure (Burnham et al. 2011).

For the third WRI attributable process, vertical and horizontal drilling, most assessments include it directly. Ten assessments refer to "drilling" in the description of a process. Some combine vertical and horizontal drilling, while others, such as NYSDEC (2011) and Olmstead (2011), separate them. For assessments that do not reference drilling directly, the process could be referred to as "well infrastructure" or included as part of the hydraulic fracturing or well completion processes.

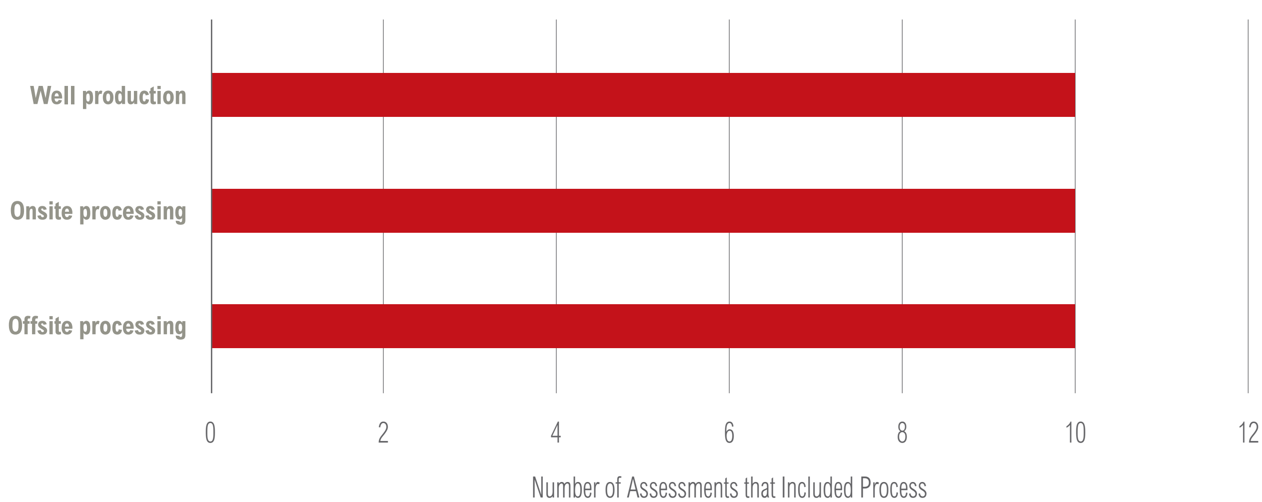
Several assessments identify hydraulic fracturing and well completion, WRI attributable processes four and five, as discrete steps; see USFS (2007), Jiang et al. (2011), NYSDEC (2011), Saiers (2011), and Broderick (2011). The WRI process map separates the two attributable processes because well completion occurs independently of hydraulic fracturing; that is, well completion occurs in conventional natural gas operations. Considine (2009) combines drilling, hydraulic fracturing, and well completion, while Olmstead (2011) considers hydraulic fracturing to be a component of well completion. Jiang et al. (2011) considers well completion as part of the study's preproduction stage. Skone et al. (2011) includes it under a "raw material extraction" stage.

Production stage

The WRI process map includes a production stage with well production, onsite processing, and offsite processing as attributable processes (figure 3).

Most of the reviewed assessments reference attributable processes that WRI includes in the production stage. Ten assessments reference well production, though S&T2 (2010) refers to it as "recovery." All ten assessments listed in figure 3 merge onsite and offsite processing into one category. Skone et al. (2011) specifies a "raw material processing" stage; Stephenson (2011) calls the process "gas treatment;" and Considine (2009) combines transportation, processing, and sales into one process. WRI separates onsite and offsite processing to accommodate any environmental impacts from transportation before the process is complete.

Figure 3 | **Variability in production stage**



Distribution and storage stage

In the WRI process map, the distribution and storage stage includes transmission, storage, and distribution attributable processes (figure 4).

Some of the 16 assessments include the WRI attributable processes. Five assessments—Burnham et al. (2012), Jaramillo (2007), Jiang et al. (2011), S&T 2 (2011), Stephenson et al. (2011), and Fulton (2011)—use the term "pipeline transmission" directly, while two—Skone et al. (2011) and Howarth et al. (2011)—refer to the process as "transport." Five assessments include storage, with Hultman et al. (2011) adding an additional process for liquefied natural gas (LNG). Finally, eight assessments list distribution.

Use stage

WRI includes three attributable processes in the use stage (combustion, conversion to transport fuel, and conversion to chemicals).[15] They are separated because of the diverse impacts of each use (figure 5).[16]

Seven of the assessments assume that natural gas is "combusted." Skone at al. (2011) uses the term "energy conversion facility," which accommodates a broad range of efficiency procedures and technologies in electricity generation. Burnham et al. (2012), Fulton et al. (2011), and Jiang et al. (2011) also account for a range of end-use efficiencies and technologies for combustion for electricity use. Burnham et al. (2012) also accounts for the combustion of natural gas as a transport fuel. No assessments include the WRI attributable process of conversion to chemicals.

End-of-life stage

Concluding the WRI process map is the end-of-life stage. It is described with a single attributable process, well closure/site remediation, which aligns with some of the assessments (figure 6).

Six of the assessments include well closure/site remediation, but use different terms to describe the process. Terms include "well plugging" (Broderick (2011), USFS (2007), and Olmstead (2011)); "decommissioning" (Broderick (2011), Skone et al. (2011)); "abandonment" (Olmstead (2011)); and "reclamation" (USFS (2007)). NYSDEC (2011) also includes well testing and cleanup in the final process.

Figure 4 | **Variability in distribution and storage stage**

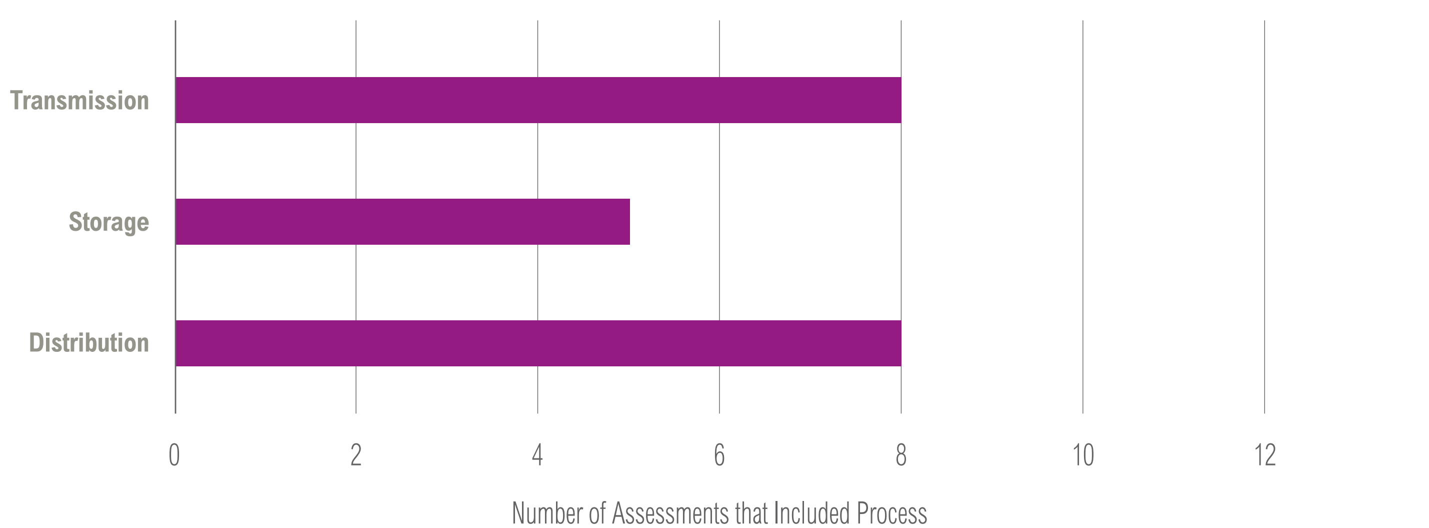


Figure 5 | **Variability in use stage**

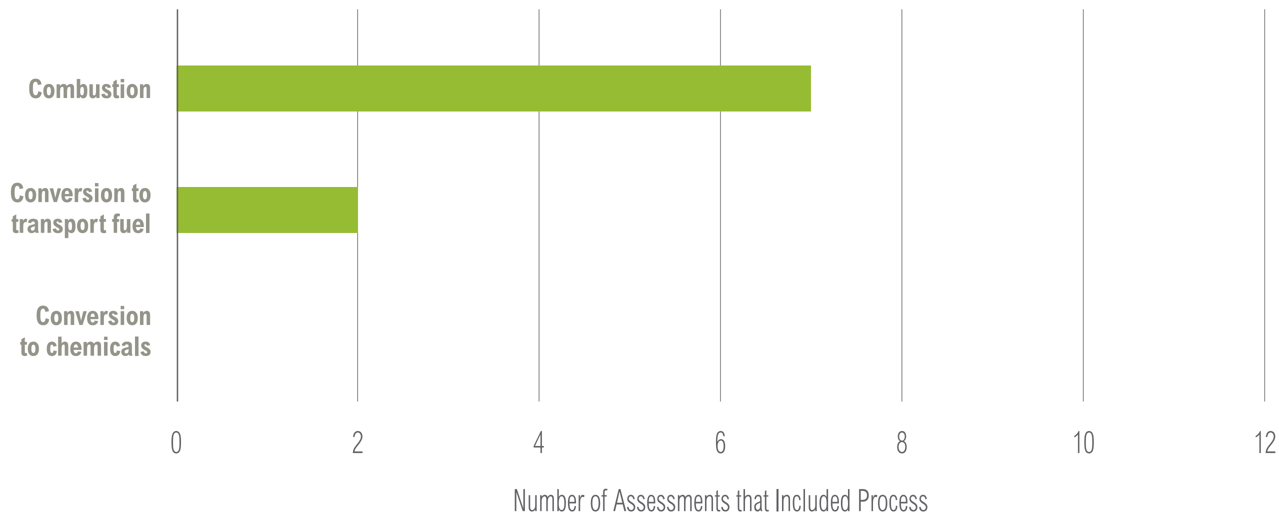


Figure 6 | **Variability in end-of-life stage**

DISCUSSION

The WRI process map and the life cycle boundaries of compared assessments have clear similarities and differences. Likewise, assessments appear to vary among themselves. In part, the differences are due to the aspects of shale gas production most relevant to the specific questions that each author is working to address. For example, an assessment attempting to quantify wastewater production may focus on flowback during the hydraulic fracturing process. However, that assessment might not consider the water outputs from wells drilled for exploration, produced water from a long-term well production process, and wastewater separated from natural gas during onsite and offsite processing. The assessment focusing on hydraulic fracturing may or may not provide readers and researchers with the necessary information. Assessments can complicate discussions on solutions when readers confuse their findings with those of a full life cycle analysis.

In addition to differences among the boundaries of compared assessments, terminology varies significantly. WRI uses the terms "onsite processing" and "offsite processing" to refer to all activities associated with preparing recovered natural gas for its end use. Conversely, one assessment uses the term "raw materials" processing and another "gas treatment" to describe at least some activities in the same process. If terms are ambiguous, researchers might question whether findings are comparable among assessments.

Finally, among assessments, the sequential order of the same activities can vary. For example, WRI proposes a process where vertical and horizontal drilling occurs before hydraulic fracturing, which in turn occurs before well completion. In USFS (2007), a second process of "drilling and completion" occurs before a third process of "fracturing." Such variation may not affect the findings of a full life cycle analysis of environmental impacts and may be due in part to the definitions of terms. Nonetheless, the issue constitutes a considerable finding that is worth discussing.

CONCLUSION

In this working paper, WRI proposed a life cycle boundary for shale gas production and demonstrated how it compares to existing assessments on the environmental impacts of shale gas production. A common life cycle boundary helps readers to understand the findings of existing assessments on the environmental impacts of shale gas production. In addition, it helps to plan future assessments. Going forward, authors preparing an assessment might tailor the process map of their assessment, isolating stages and associated attributable processes as necessary. In addition, users may focus on the definitions of attributable processes, further defining them in an eventual effort to include as many activities associated with shale gas production as possible. Finally, those conducting a full life cycle assessment might adopt the WRI life cycle boundary in its entirety. Multiple assessments using a consistent boundary will advance a common understanding of shale gas environmental impacts. WRI will seek feedback on this working paper from audiences, including community groups and others, and use it in a forthcoming effort to compare estimates of GHG emissions from shale gas production.

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APPENDIX 1: ASSESSMENTS COMPARED TO THE WRI LIFE CYCLE BOUNDARY

Broderick (2011): This assessment from the Tyndall Center for Climate Change Research inventories impacts and regulatory oversights for shale gas production in Europe. The life cycle establishes unconventional gas production as distinctly different from conventional production. In addition, authors use the life cycle to illustrate potential environmental impacts. It focuses on the well site, beginning with a preproduction grouping of drilling and hydraulic fracturing and advancing to production stage, well plugging, and decommissioning.

Burnham et al. (2012): Burnham et al. (2012), prepared by researchers from Argonne National Laboratory, produces a GHG comparison of shale gas, natural gas, coal, and petroleum though life cycle modeling. The life cycle was developed for the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) modeling program, which estimates combined emissions from shale gas activities. The process includes well infrastructure (i.e., preparing the site, drilling, and fracturing); natural gas recovery; processing; transmission and distribution; and end use.

Considine et al. (2009): Considine et al. (2009) conducted an economic analysis of Marcellus shale gas in Pennsylvania, which was published by Pennsylvania State University. The life cycle illustrates the identified economic impacts for each activity. It begins with leasing and site exploration, includes drilling and well completion activities, and ends with transporting, processing, and sales.

Fulton et al. (2011): Deutsche Bank and WorldWatch Institute compare existing literature on GHG emissions from shale and conventional gas. Authors normalize assessment results with emission factors released by EPA in 2011. The life cycle establishes boundaries for normalizing data sets to the 2011 revised emission factors. It begins with production, and advances to processing, transmission, and distribution. It concludes with combustion.

Howarth et al. (2011): Howarth et al. (2011) is a life cycle assessment by Cornell University researchers that compares methane emissions from shale gas to those from coal and petroleum. The GHG calculations suggest a life cycle. Calculations in the assessment begin with well completion and include routine venting and equipment leaks, processing, transport, storage, and distribution.

Hultman et al. (2011): The Hultman et al. (2011) assessment, conducted by University of Maryland researchers, estimates the GHG impact of unconventional gas designated for electricity generation. The identified life cycle establishes the basis for a GHG assessment. It begins with well drilling and completion, and includes periodic well workovers and other routine production activities before continuing to processing, distribution to end user, and storage. Since some natural gas is exported, the life cycle includes storage, processing at an LNG terminal, and final distribution.

Jaramillo (2007): This life cycle assessment—a Ph.D. thesis at Carnegie Mellon University—estimates GHG emissions from several fossil fuels, including natural gas. The life cycle is for natural gas, not specifically shale gas. Activities begin with well production and include the processing, transmission, distribution, and product storage. The life cycle ends with combustion or end use.

Jiang et al. (2011): Jiang et al. (2011), by authors from Carnegie Mellon University, conducts a GHG life cycle assessment of natural gas recovered from Marcellus shale. The authors separate shale gas development into two phases of "preproduction" and "after preproduction." Preproduction includes the investigation and preparation of the well site, as well as the drilling, fracturing, completion, and water/wastewater pathways. After preproduction begins with production and follows the product line through processing, transmission, distribution, and combustion.

Moniz et al. (2011): This assessment by MIT authors contains analysis of the environmental and economic impacts of natural gas development, including shale gas. The bounded life cycle begins with permits and site construction and continues to drilling, casing, perforating, and fracturing the well. It concludes with flowback of fracturing fluid and putting the well into production.

NYSDEC (2011): The Supplemental Generic Environmental Impact Statement identifies potential impacts from shale gas development to New York counties. The life cycle educates readers about the shale gas process and includes sections on environmental impacts. It begins with well pad construction and access roads; continues to the vertical and horizontal drilling process, hydraulic fracturing preparation and completion process, flowback collection and treatment process; and concludes with well cleanup.

Olmstead (2011): At an October 2011 seminar, Sheila Olmstead of Resources for the Future (RFF) presented a life cycle, including impact pathways, or life cycle activities that lead to environmental and social risks. The life cycle has nine stages, including site development and drilling preparation; vertical drilling; horizontal drilling; fracturing and completion; well production and operation; flowback/produced water storage/disposal; shutting-in, plugging and abandonment; workovers; and upstream and downstream activities.

Saiers (2011): In the same RFF seminar, James Saiers of Yale School of Forestry & Environmental Studies discussed shale gas and water quality issues. His presentation identifies seven stages, including site preparation, gas-well drilling, casing, hydraulic fracturing, gas-well production, gas-well plugging, and abandonment.

(S&T)2 (2010): GHGenius, a GHG emissions modeling program maintained by the Natural Resources Department of Canada, estimates emissions from different recovery techniques and end uses of natural gas products. Activities specific to shale gas are included in the model. The life cycle differentiates shale gas from other recovery techniques and includes the processes of natural gas recovery, raw gas processing, and transmission.

Skone et al. (2011): This assessment from the National Energy Technology Laboratory compares GHG emissions from different processes to recover natural gas and extract coal. The study singles out shale gas to account for the unique activities included in its life cycle. Authors use a life cycle that includes raw materials acquisition (site construction, well construction, well completion), raw materials processing, and raw materials transport. In the final stage, authors apply an energy conversion factor to account for different efficiencies in electricity combustion. The accompanying narrative includes distribution to end user and well decommissioning, which the authors do not include in their process map.

Stephenson et al. (2011): Authors of this assessment for Shell Global Solutions, a subsidiary of Royal Dutch Shell plc, use emissions data and factors to compare shale gas (i.e., unconventional) and conventional gas emissions. The study establishes a "Well-to-Wire" (WtW) pathway for both natural gas sources. The WtW pathway for unconventional gas begins with activities specific to shale gas development, including well drilling, well fracturing, and water use and treatment during both activities. A second stage groups together common processes for all recovery techniques, which includes production, pipeline transmission, and end use at a power station.

USFS (2007): The Allegheny National Forest Final Environmental Impact Statement plan provides background and updates on oil and gas development, existing or planned, in the Allegheny National Forest. The purpose of the life cycle is to provide background on oil and gas development and inform further impact analyses. The life cycle begins at road and well site development and includes other construction processes such as drilling, completion, and fracturing. It also includes production and waste disposal (i.e., salt water, brine) and ends with well plugging site reclamation.

APPENDIX 2: DEFINITIONS

Attributable processes: Service, material, and energy flows that become the product, make the product, and carry the product through its life cycle (WRI and WBCSD 2011).

Combustion: The process of igniting a fuel (typically in a boiler, incinerator, or engine/turbine) to release energy in the form of heat.

Conversion to chemicals: A process used to turn a feedstock (in the context of this working paper, natural gas or natural gas derivatives) into chemicals that can be used by various industries.

Conversion to transport fuels: The chemical process used to turn natural gas into a liquid or compressed fuel that can be used in a vehicle (e.g. car, bus, plane).

Distribution: The conveyance of natural gas and associated products to the end user through local pipeline systems (adapted from API 2012). Distribution pipelines are smaller in diameter than transmission pipelines.

Exploration: Generally, the act of searching for potential subsurface reservoirs of gas or oil. Methods include the use of magnetometers, gravity meters, seismic exploration, surface mapping, exploratory drilling, and other such methods (AGA 2012).

Flowback: Used treatment fluid that returns to the surface upon release of pressure on the wellbore in the hydraulic fracturing attributable process.

Hydraulic fracturing: A stimulation treatment in which specially engineered fluids are pumped at high pressure and rate into the reservoir interval to be treated, causing vertical fractures to open. Proppant, such as grains of sand of a particular size, is mixed with the treatment fluid to keep the fractures open once the treatment is complete (adapted from SOG 2012). WRI's definition of the hydraulic fracturing attributable process includes staged perforation of the well casing, flowback of treatment fluid, and wastewater treatment.

Life cycle: Consecutive and interlinked stages of a product system, from raw material acquisition or generation to end-of-life (WRI and WBCSD 2011).

Liquid unloading: The process of removing liquid from the wellbore that would otherwise slow production in a mature well. Some approaches include using a down-hole pump or reducing the wellhead pressure. WRI includes liquid unloading in the production stage.

Mineral leasing: The process of securing a right or permission to conduct exploration and production activities at a specific location.

Process map: Visual representation of a life cycle boundary, including relevant stages and attributable processes.

Processing (onsite and offsite): The act of removing assorted hydrocarbons or impurities such as sulfur and water from recovered natural gas. Initial settling could occur in onsite storage pipes or tanks. Natural gas is then transported offsite through gathering lines, where further processing occurs.

Produced water: Fluid that returns to the surface over the working life of a well.

Site preparation: The act of priming a location for natural gas activities, including securing permits, procuring water and materials, constructing the well pad, preparing access roads, laying gathering lines, and building other necessary infrastructure.

Storage: The process of containing natural gas, either locally in high pressure pipes and tanks or underground in natural geologic reservoirs—such as salt domes, depleted oil and gas fields—over the short or long term (adapted from AGA 2012 and SOG 2012).

Transmission: Gas physically transferred and delivered from a source or sources of supply to one or more delivery points (USEIA 2011a).Transmission pipelines are larger in diameter than distribution pipelines.

Vertical and horizontal drilling: The directional deviation of a wellbore from vertical to horizontal so that the borehole penetrates a productive shale formation in a manner parallel to the formation (adapted from OSHA 2012). WRI's definition of the vertical and horizontal drilling attributable process includes disposal of mud—that is, liquid that circulates in the wellbore during drilling—and placement and cementing of the well casing.

Well closure/site remediation: At the end of a well's working life, the process of ending production by plugging the wellbore, removing equipment, and returning the site to predrilling conditions.

Well completion: A generic term used to describe some of the events and equipment necessary to bring a wellbore into production once drilling operations have been concluded, including but not limited to the assembly of equipment required to enable safe and efficient production from a gas well (adapted from SOG 2012). WRI does not consider placement and cementing of the well casing (see vertical and horizontal drilling) as an activity that occurs in the well-completion stage. Also, hydraulic fracturing constitutes its own stage, so it is not an activity associated with well completion.

Well production: The process that occurs after successfully completing attributable processes in the material acquisition and preprocessing stage, when hydrocarbons are drained from a gas field (adapted from SOG 2012). Recovered hydrocarbons may return produced water to the surface, which requires treatment before disposal. Likewise, liquid unloading may be necessary.

Workover: The performance of one or more of a variety of remedial operations on a producing well to try to increase production (OSHA 2012).

ENDNOTES

1. GHG estimates are reported for 100-year time horizons.
2. The difference is due to the activities authors include in their life cycle boundaries. Additionally, Jiang et al. (2011) includes liquid unloading in the production stage; Stephenson et al. (2011) does not.
3. See New York State Department of Environmental Conservation. 2011. "Revised Draft SGEIS on the Oil, Gas and Solution Mining Regulatory Program: Well Permit Issuance for Horizontal Drilling and High-Volume Hydraulic Fracturing in the Marcellus Shale and Other Low-Permeability Gas Reservoirs"; and U.S. Department of Agriculture Forest Service. 2007. "Alleghany National Forest Final Environmental Impact Statement."(Appendix C: Reserved and Outstanding Oil and Gas Development on the Allegheny National Forest.)
4. Materials leakage includes methane leaks from steel and copper tubing.
5. The ISO 14044 standard notes "decisions shall be made regarding which unit processes shall be included within the life cycle assessment. The selection of the system boundary shall be consistent with the goal of the study." But different boundaries are a consistent challenge to efforts to compare assessments on the environmental impacts of shale gas. For example, in their comparison of six studies on the carbon footprint of shale and conventional natural gas production, Weber and Clavin (2012) note: "The six studies all attempted to study the carbon footprint of shale gas… but each had different specific inclusions or exclusions within its scope." In addition, Fulton et al. (2011) adjusts the identified life cycle boundaries in its effort to assess the state of knowledge about the average GHG footprints of coal and natural gas-fired electricity.The authors had to adjust data sets to include emissions associated with imports, natural gas produced as a petroleum byproduct, and the share of natural gas that passes through distribution lines before reaching power plants.
6. The ISO 14044 standard alone was not as useful, since its boundary-setting requirements are vague and lack the specificity and additional guidance of the product standard.
7. See Appendix 1 for the 16 assessments.
8. Developed over three years by 2,300 participants from 55 countries, the product standard enjoys broad buy-in and covers all steps in the GHG inventory process, from establishing the scope of a product inventory to setting reduction targets and tracking inventory changes.
9. The product standard recommends "nature" as a first life cycle stage. The nature stage acknowledges that every product originates from a natural resource. This study does not include nature, assuming that audiences recognize it as a given presence in the development of fossil fuels.
10. For example, treatment of produced and flowback water does not occur after offsite processing. Wastewater treatment is an ongoing process that occurs as wastewater is generated.
11. The use and management of energy, water, and materials varies greatly from well site to well site. For example, a well operator could recycle flowback water onsite, send it to an industrial wastewater treatment plant, or send it for permanent disposal in an underground injection well. Regarding materials, use could increase in a well that is stimulated more than once over its working life.
12. Included studies are listed in Appendix 1.
13. Jiang et al. (2011), Skone et al. (2011), and Stephenson et al. (2011) are the only assessments that organize processes into groups (or, using the WRI methodology, attributable processes into stages).
14. Saiers (2011) also includes leasing as the first process, though refers to it as "mineral leasing."
15. Conversion to transport fuel and conversion to chemicals will have downstream impacts. However, these impacts are not included in the life cycle boundary.
16. Conversion to chemicals was not included specifically in any of the studies evaluated; however, the authors have included it because of the increasing production of natural gas liquids and use in the chemical industry.

ABOUT WRI

The World Resources Institute (WRI) is a global environmental and development think tank that goes beyond research to create practical ways to protect the Earth and improve people's lives. We work with governments, companies, and civil society to build practical solutions to urgent environmental challenges. WRI's transformative ideas protect the Earth and promote development because sustainability is essential to meeting human needs and fulfilling human aspirations for the future.

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