Lifecycle Analysis of Water Use and Intensity of Noble Energy Oil and Gas Recovery in the Wattenberg Field of Northern Colorado

Prepared by Noble Energy, Inc. and Colorado State University

March 2012
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Executive Summary

Introduction and Project Objectives  Water resources in Colorado and the western U.S. are constantly strained given the historical agricultural needs, burgeoning development, and the semi-arid environment. With continued population increases and the importance of agriculture to the overall economy, the pressure on water and other natural resources is expected to intensify. Even though the oil and gas industry has long been a part of the economy in Colorado and the West, recent technological advances have stimulated considerable growth in oil and gas development and operations and therefore have increased the industry’s need for water resources.

Competition over water resources will continue to escalate to meet expanding municipal and industrial demands, including those associated with the oil and gas industry. In October, 2011 the State Review of Oil and Natural Gas Environmental Regulations (STRONGER) organization issued a report on rules developed by the Colorado Oil and Gas Conservation Commission (COGCC) related to hydraulic fracturing. One of the five recommendations of the report was the following:

“The review team recommends that the COGCC and the DWR jointly evaluate available sources of water for use in hydraulic fracturing. Given the significant water supply issues in this arid region, this project should also include an evaluation of whether or not availability of water for hydraulic fracturing is an issue and, in the event that water supply is an issue, how best to maximize water reuse and recycling for oil and gas hydraulic fracturing.”

Another organization, the Natural Gas Subcommittee of the Secretary of Energy’s Advisory Board (SEAB) stated in its November, 2011 report, “At present neither EPA or the states are engaged in developing a systems/lifecycle approach to water management”. They recommend that new partnerships or mechanisms be developed to study the lifecycle of water resources as one approach to protecting the quality of water resources in the future.

The project described in this report is the first step in addressing the concerns raised by these and other studies. A framework is proposed to assess the lifecycle of water and energy resources of Noble Energy assets in the Wattenberg field. Data from Noble’s Wattenberg wells are used to assess the overall water use and average water intensity in the region as a first application of the general framework.
The specific objectives of this project are:

- Determine water use associated with Noble Energy wells in the Wattenberg field and delineate them with respect to horizontal and vertical, drilling and completion.
- Determine the water intensity of Noble Energy wells and compare with industry averages.
- Compare the water intensity for extraction and processing of Noble Energy wells with other energy sources.
- Compare the lifecycle water intensity by energy source for electric power generation.

In consideration of the potential volume of produced water and treatment requirements, it is possible that the net water consumption and water intensity can be driven to nearly zero (i.e. lifecycle production of non-appropriated, non-tributary water is greater than or equal to the volume consumed). Further work needs to be done to estimate the amount of water produced over the lifetime of the well, as well as treatment scenarios and associated energy requirements but the goal of this work would be to assist industry toward meeting water neutrality (no net life-cycle consumption of water).

**Scope and Methods**  The study is divided into two sections: (1) an assessment of the current water intensity of Noble Energy wells, and (2) a water intensity comparison and discussion of other energy sources, such as coal and renewable energy sources. To determine the water intensity of current Noble Energy wells, the water consumption and estimated ultimate recovery (EUR) is found using a decline curve analysis. This ratio is used as a basis for a discussion and comparison of water intensity. Unlike other water and energy studies, which often provide broad estimates from literature, both water consumption and EUR were determined from field data of several individual wells. To best assess current water use and predict future water needs, sampled wells were limited to wells that have been completed in 2010 and 2011 by Noble Energy. The final sample includes 445 wells: 386 vertical wells and 59 horizontal wells.

Water consumption data were collected using Noble Energy’s WellView® program. Wells were classified as either horizontally or vertically drilled. Directional and deviated wells were classified as vertical wells. Water use is categorized as either drilling water or completion (hydraulic fracturing) water.

Daily oil and gas production from the same 445 wells were collected using Noble Energy’s Carte® program. Data is added to Carte® remotely by the lease operator of the well, who is at each well every day. For this analysis, it was assumed that each well would be economically productive for a 30-year period. The decline curves are extrapolated to estimate future oil and gas production over the expected 30-year lifespan of the well. The EUR is estimated by integrating each decline curve. A trapezoidal integration method with a daily step size was used to integrate the curves.
Water Consumption  Vertical and horizontal wells operated by Noble Energy in the Wattenberg during 2010 and 2011 consumed an average 380,000 and 2,800,00 gallons of water. On average, vertical wells used 77,000 gallons to drill and an additional 310,000 gallons to hydraulically fracture the well. Horizontal wells used 130,000 gallons to drill and 2,700,000 gallons to hydraulically fracture the well.

Estimated Ultimate Recovery  A decline curve analysis was used to estimate the ultimate recovery from each individual well. Exponential and harmonic decline curves were fit to the production data to project low and high production scenarios, respectively. Vertical wells are expected to have an estimated ultimate recovery between 24 and 60 BBtu for oil and between 32 and 84 BBtu for gas. Horizontal wells are expected to have an estimated ultimate recovery between 390 and 1,100 for gas and between 180 and 520 BBtu for oil.

Water Intensity  For this study, water intensity is defined as the ratio of water consumed and energy recovered. A schematic of the water and energy flows of a typical oil and gas well or well-field is shown in Figure 1. A mass and energy balance is used to determine the net water consumed and net energy recovered for each well or a well-field and the boundary for the system defined by the balance is shown in the schematic. Using the materials balance presented in Figure 1, a general equation for the water intensity, the ratio of the net water consumption and net energy recovered can be developed (Eq-1 and Eq-2). For the current project, the water intensity assessment scenario incorporates only water consumed and energy produced.

\[
\text{Water Intensity} = \frac{\text{Volume of Drilling Water}}{\text{Volume of Fracturing Water}} - \frac{\text{Volume of Flowback Water}}{\text{Volume of Produced Water}} - \frac{\text{Volume of Injection Water}}{\text{Volume of Evaporated Water}} 
\]

Eq-1

Equation 1 is reduced to:

\[
\text{Water Intensity} = \frac{V_{\text{drill}} - V_{\text{frac}}}{E_{\text{recovered}} - E_{\text{drilling}} - E_{\text{drilling}} - E_{\text{treatment}}} \quad \Rightarrow \quad \text{Water Intensity} = \frac{|V_{\text{in}}|}{E_{\text{net}}} \quad \text{Eq-2}
\]

Vertical and horizontal wells operated by Noble Energy in the Wattenberg during 2010 and 2011 are expected to have an average water intensity of 6.9 and 4.3 gal/MMBtu, respectively. Vertical wells have an expected water intensity ranging between 5.4 and 14 gal/MMBtu and horizontal wells have an expected water intensity between 2.9 and 9.7 gal/MMBtu.
Figure 1: Material balance defining the water intensity assessment. The red and blue lines represent the flow of energy and water, respectively.
A literature review was performed to compare the water intensities found in the study with a variety of fuel sources, including coal, oil, natural gas, uranium, solar, wind, biofuels, and geothermal energy sources. The water intensities are categorized by life-cycle stages (extraction, processing, transport, etc.) and end-use (electricity generation). This study provides a detailed analysis of the water intensity of shale gas on a per well basis and a comparison of vertical and horizontal wells. Previous studies have reported broad generalization of water intensity for shale gas. Water intensity for electrical generation is presented in Figure 2. Generating electricity with natural gas has a lower water intensity than coal, uranium and concentrating solar power but a greater water intensity than photovoltaic solar and wind energy.

![Consumptive Water Intensity of Recovery by Fuel Source](image)

**Figure 2:** A comparison of the consumptive water intensity for recovery of various energy sources and the water intensity from the sample set from Noble Energy.

Although recovery of unconventional shale gas requires large volumes of water, the water intensity value of recovery is one of the lowest. Horizontal wells, which require the most water, have an average water intensity value that is lower than vertical wells for energy recovery. When processing and end uses (e.g. electricity
Table 1: A comparison of the average consumptive water intensity for the recovery of various energy sources and the water intensity of Noble Energy wells.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Method</th>
<th>Water Intensity (gal/MMBtu)</th>
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<tbody>
<tr>
<td><strong>Coal (gal/MMBtu)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Mining</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Underground Mining</td>
<td>9</td>
<td></td>
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<tr>
<td><strong>Natural Gas (gal/MMBtu)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td><strong>Noble Data Natural Gas (gal/MMBtu)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical: Low</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Vertical: Average</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>Vertical: High</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td>Horizontal: Low</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Horizontal: Average</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>Horizontal: High</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td><strong>Oil (gal/MMBtu)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Conventional Flooding</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Oil Sand</td>
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</tr>
<tr>
<td>Oil Shale</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>Enhanced Recovery</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td><strong>Solar (gal/MMBtu)</strong></td>
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<td></td>
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<tr>
<td>Photovoltaic</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td><strong>Wind (gal/MMBtu)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbine</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td><strong>Biofuels (gal/MMBtu)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biodiesel from soy</td>
<td>45,000</td>
<td></td>
</tr>
<tr>
<td>Ethanol from irrigated corn</td>
<td>16,000</td>
<td></td>
</tr>
<tr>
<td>Biodiesel from rapeseed</td>
<td>16,000</td>
<td></td>
</tr>
</tbody>
</table>

generation) are considered, natural gas has one of the lowest water intensity values. Furthermore, if the large volumes of produced water can be treated for reuse in an energy efficient manner the water intensity may be reduced further.
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Water resources in Colorado and the western U.S. are constantly strained given the historical agricultural needs, burgeoning development, and the semi-arid environment. With continued population increases and the importance of agriculture to the overall economy, the pressure on water and other natural resources is expected to intensify. Even though the oil and gas industry has long been a part of the economy in Colorado and the West, recent technological advances have stimulated considerable growth in oil and gas development and operations and therefore have increased the industry’s need for water resources.

In October, 2011 the State Review of Oil and Natural Gas Environmental Regulations (STRONGER) organization issued a report on the Colorado hydraulic fracturing program and the rules developed by the Colorado Oil and Gas Conservation Commission (COGCC) related to this. [1] The report, which was generally positive, made five recommendations for improvement. One of the key recommendations in this report was regarding the availability of water:

“The review team recommends that the COGCC and the DWR jointly evaluate available sources of water for use in hydraulic fracturing. Given the significant water supply issues in this arid region, this project should also include an evaluation of whether or not availability of water for hydraulic fracturing is an issue and, in the event that water supply is an issue, how best to maximize water reuse and recycling for oil and gas hydraulic fracturing.”

Other recommendations regarding the management of water resources associated with hydraulic fracturing were made by the Natural Gas Subcommittee of the Secretary of Energy’s Advisory Board (SEAB) in November, 2011. [2] The subcommittee was charged in April 2011 to study ways to improve the safety and environmental performance of natural gas hydraulic fracturing from shale formations.

In its final report, the subcommittee stated “At present neither EPA or the states
are engaged in developing a systems/lifecycle approach to water management”. They recommend that new partnerships or mechanisms be developed to study the lifecycle of water resources as one approach to protecting the quality of water resources in the future.

The project described in this report is the first step in addressing the concerns raised by these and other studies. A framework is proposed to assess the lifecycle of water and energy resources of Noble Energy (Noble) assets in the Wattenberg field. Data from Noble Wattenberg wells is used to assess the overall water use and average water intensity in the region as a first application of the general framework.

The specific objectives of this project are:

- Determine water use associated with Noble Energy wells in the Wattenberg field and delineate them with respect to horizontal and vertical, drilling and completion.
- Determine the water intensity of Noble Energy wells and compare with industry averages.
- Compare the water intensity for extraction and processing of Noble Energy wells with other energy sources.
- Compare the lifecycle water intensity by energy source for electric power generation.

The research performed as part of this study will assist Noble, the oil and gas industry, governing agencies and the greater public in making informed decisions regarding future energy development through the use of empirical data.
Chapter 1

Water Intensity

1.1 Literature Review

Gleick [3] provided one of the first broad reviews of water intensity, presenting direct, consumptive water intensity values for each life cycle phase (i.e. mining, fuel preparation, generation, etc.) of several different fuel sources in 1994. Sovacool and Sovacool [4] expanded the scope of a water intensity analysis to separate water use into both water withdrawals and consumption. Fthenakis and Kim [5] were the first to include upstream water use in the analysis, which includes water requirements associated with energy and material inputs to each life-cycle phase of electricity generation technologies.

In recent years, increasing concern about water and energy resources in the U.S. has led to significantly more available literature particularly from government agencies [6–14], most notably, a 2006 report to Congress from the Department of Energy. [6] The report was a response to a Congressional directive asking for “a report on energy and water interdependencies, focusing on threats to national energy production that might result from limited water supplies.”

Perhaps the most comprehensive and recent review of water intensity comes from the Harvard Kennedy School, titled Water Consumption of Energy Resource Extraction, Processing, and Conversion. [15]

Several regional studies [12–14, 16–18] have assessed water resource challenges with increasing demands for water. The majority of these studies provide a broad estimate of water requirements, without a detailed analysis of water use on an individual well basis. An analysis of the water intensity of each individual well provides a more detailed and accurate assessment of the water intensity. Other studies focus solely on electricity generation[7, 10, 19–25] or transportation[26–28], the two largest energy sectors in the United States.

Few studies have been completed that assess the water required for shale gas development and production in the United States [29, 30] and nearly all of the studies provide only broad, general estimates. Recent development of shale gas in the
1.2 Water Intensity Approach For This Study

United States has raised concern about the associated impacts on water resources. The goal of this study is to provide a detailed assessment of water requirements for shale gas in the Wattenberg field. The same water intensity framework, developed by previous studies, will be used and compared with the water intensity assessments from previous studies.

1.2 Water Intensity Approach For This Study

Water intensity can be defined in several ways (e.g. water use by economic activity, water use by sector, water use per person etc.), but by any definition it is a measure of how efficiently a water resource is used. For this study, water intensity is defined as the ratio of water consumed and energy recovered. A schematic of the water and energy flows of a typical oil and gas well or well-field is shown in Figure 1.1. A mass and energy balance is used to determine the net water consumed and net energy recovered for each well or a well-field and the boundary for the system defined by the balance is shown in the schematic.

Using the materials balance presented in Figure 1.1, a general equation for the water intensity, the ratio of the net water consumption and net energy recovered can be developed (Eq-1 and Eq-2).

\[
\text{Water Intensity} = \frac{\text{Volume of Drilling Water} + \text{Volume of Hydraulic Fracturing Water}}{\text{Volume of Flowback Water} + \text{Volume of Produced Water} + \text{Volume of Injected Water} + \text{Volume of Evaporated Water}} 
\]

\[\text{Eq-1}\]

\[
\text{Water Intensity} = \frac{\text{Net Energy from Oil} + \text{Energy from Natural Gas}}{\text{Energy Used for Drilling} + \text{Energy Used for Fracturing} + \text{Energy Used for Water Treatment}} 
\]

\[\text{Eq-2}\]

Equation 1 is reduced to:

\[
\text{Water Intensity} = \frac{\text{Net Water}}{\text{Net Energy}} \Rightarrow \text{Water Intensity} = \frac{\text{Net Water}}{\text{Net Energy}} 
\]

\[\text{Eq-2}\]

Several scenarios can be developed from this general framework. For example, the materials balance of an entire region can be assessed for the complete lifecycle of the wells to quantitatively determine the long-term impact on water resources. A material balance of individual wells can also be assessed to better understand water reuse logistics and optimized treatment strategies. The degree of treatment of flowback and produced water will determine the amount of water available for reuse, additional energy requirements required for treatment, and best practices for lifecycle water management and disposal. Future work can be performed to determine the amount of treatment required to optimize water intensity for individual wells and entire regions.

Inconsideration of the potential volumes of produced water and treatment requirements, it is possible that the net water consumption and water intensity can be driven to nearly zero (i.e. lifecycle production of non-appropriated, non-tributary water is greater than or equal to the volume consumed). Further work needs to be completed to estimate the amount of water produced over the lifetime of the well, as well as treatment scenarios and associated energy requirements but the
1.2. Water Intensity Approach For This Study

goal of this work is to assist the industry toward water neutrality (no net life-cycle consumption of water).

For the current project, the water intensity assessment scenario incorporates only water consumed and energy produced. The general materials balance framework for this scenario is shown and explained in Figure 1.2. This simplified water intensity approach will establish a baseline estimate that can be compared with future water management approaches that may involve treatment and recycling.

For this water intensity scenario, it is assumed that the amount of energy required for drilling is negligible when compared with the amount of energy recovered over the 30-year lifetime of the well. It is also assumed that all the flowback and produced water is presently disposed of through evaporation or deep well injection and the water used for drilling and hydraulic fracturing is the same as the net water consumed, in other other words no water is reused. Based on these assumptions, the materials balance equation can be simplified as shown in Eq-3 and Eq-4.

\[
\text{Water Intensity} = \frac{\text{Volume of Drilling Water} + \text{Volume of Hydraulic Fracturing Water}}{\text{Energy from Oil} + \text{Energy from Natural Gas}}
\]

\[
\text{Energy Used for Drilling} + \text{Energy Used for Hydraulic Fracturing} + \text{Energy Used for Water Treatment} = 0
\]

\[
\text{Volume of Flowback} + \text{Volume of Produced Water} - \text{Volume of Injection} - \text{Volume of Evap} + \text{Volume of Recovered Water} - \text{Energy from Drilling} - \text{Energy from Fracturing Water}
\]

\[
\text{Volume of Produced Water} - \text{Volume of Recovered Energy} = 0
\]

Equation 3 is reduced to:

\[
\text{Water Intensity} = \frac{V_{\text{drill}} \cdot V_{\text{fract}}}{E_{\text{recovered}}} \Rightarrow \text{Water Intensity} = \frac{V_{\text{in}}}{E_{\text{recovered}}}
\]

This scenario simplifies the water intensity to a ratio of the water used for drilling and hydraulic fracturing and estimated ultimate oil and gas recovery (EUR). This scenario is likely to overestimate the water intensity because the large volumes of produced water from the 30-year lifespan of the well are not accounted for in the ratio.
Figure 1.1: Material balance defining the water intensity assessment. The red and blue lines represent the flow of energy and water, respectively.
Material Balance Used to Define Water Intensity Assessment

Figure 1.2: Material balance used to defining the water intensity assessment of Noble Energy oil and gas wells in the Wattenberg field.
1.2. Water Intensity Approach For This Study
2.1 Scope of Analysis

The study is divided into two sections: an assessment of the current water intensity of Noble Energy wells, and a water intensity comparison and discussion of other energy sources, such as coal and renewables. To determine the water intensity of current Noble Energy wells, the water consumption and EUR need to be determined, as shown in Figure 2.1. This ratio is used as a basis for a discussion and comparison of water intensity. Unlike other water and energy studies, which often provide broad estimates from literature, both water consumption and EUR were determined from field data representing 445 Noble Energy wells in the Wattenberg. A complete compilation of the results is contained in Appendix G-K.

Figure 2.1: The scope of analysis and the source of the information, where the blue boxes represent data directly from Noble Energy and the red boxes represent data collected from a review of literature.
2.2 Data Collection

To best assess current water use and predict future water needs, sampled wells were limited to wells that have been completed in 2010 and 2011 by Noble Energy in the Wattenberg field. Older wells that have been refractured to stimulate recovery were not included in the assessment of wells since this circumstance is not equivalent to fracturing a newly drilled well. The issue of re-fracturing wells and the associated water consumption and water intensity should be included in future studies. Water consumption and energy production data were collected and separated by well type and water use, as shown in Figure 2.2. The final sample includes 445 wells: 386 vertical wells and 59 horizontal wells. This dataset represents all of the wells in 2010 and 2011 with complete water consumption and energy production records. A total of 883 wells were drilled in 2010 and 2011. Wells were omitted for a variety of reasons, most did not have water consumption or production data readily available.

Filters Used to Define the Sample Set

![Filters Diagram](image)

**Figure 2.2:** Filters and classifications used to define the sample data set.
2.3 Water Consumption Data

Water consumption values were collected using Noble Energy’s WellView® program (Peloton Computer Enterprises Ltd., Houston, TX). WellView is part of the Peloton suite of software used for collecting and organizing oil field data. Drilling and hydraulic fracturing reports are added to WellView® by a Noble Energy employee that is on-site at each drilling and hydraulic fracturing site. The water consumption totals are verified by Noble Energy’s accounting department and any conflict of values between the field operations and the accounting department are reconciled in WellView®. All of the water consumption data was accessed in November of 2011.

Wells were classified as either horizontally or vertically drilled. Directional and deviated wells are classified as vertical wells, as this is a standard distinction in industry. Horizontal wells are much less common than vertical wells since the technology has only recently been adapted to the Wattenberg field. The final water consumption data set includes water consumed and energy recovered from 386 vertical wells and 59 horizontal wells.

Water use is categorized as either drilling water or completion water. Drilling water is used, with a mixture of clay, to carry cuttings to the surface and to cool and lubricate the drill bit to create the bore hole. Once a bore hole is drilled and perforated, the well is hydraulically fractured. Water used during the hydraulic fracturing phase to expand fractures in the formation and carry proppant down the borehole to hold fractures open when pressure is released.

2.4 Oil and Gas Production Data Collection

Daily oil and gas production from the same 445 wells were collected using Noble Energy’s Carte® program. Carte® is part of the Merrick Systems Software (Merrick Systems Oil and Gas Technology Solutions, Houston, TX) used to track daily operations of each individual well. Data is added to Carte® remotely by the lease operator of the well, who is at each well every day. Daily oil production is measured in the tanks and verified when oil is sold to a third-party and removed from the drill site. Gas production is measured at each well using a total flow meter and reconciled by a third party when sold, due to the use of field gas on drill sites. Gas meters are calibrated every quarter and are equipped with a data logger to track historical data.

Estimates of future production for each well was made using decline curves based on the empirical Arps equation. [31] Decline curve analysis are frequently used for naturally-fractured reservoirs, developed unconventional decline curves have not been well established. An exponential decline curve was used to predict a low production scenario and a harmonic decline curve was used to predict a high production scenario, as shown in Eq-6 and Eq-7. An exponential decline curve assumes constant pressure and the production rate approaches zero. A harmonic decline curve approaches a specific value. For this reason exponential and harmonic decline curves often under and over estimate production values, respectively. The two curves were used to bound possible production scenarios.
2.5 Limitations of the Study

\[
q(t) = \frac{q_i}{(1+Di t)^{1/b}} \quad \text{where} \quad q_i = \text{Future production rate} \\
q_i = \text{Initial production rate} \\
Di = \text{Initial decline rate} \\
t = \text{Time} \\
b = \text{Degree of curvature} \\
\text{Eq-5}
\]

When \( b = 0 \) \( \Rightarrow \) \( q(t) = q_i e^{Di t} \) \text{(Exponential Decline Curve)} \text{(Low Production Scenario)} \text{Eq-6}

When \( b = 1 \) \( \Rightarrow \) \( q(t) = \frac{q_i}{1+Di t} \) \text{(Harmonic Decline Curve)} \text{(High Production Scenario)} \text{Eq-7}

For this analysis, it was assumed that each well would be economically productive for a 30-year period. The decline curves are extrapolated to estimate future oil and gas production over the expected 30-year lifespan of the well. The EUR is estimated by integrating each decline curve using a trapezoidal integration method with a daily step size. The entire analysis was done using MATLAB (2007a, The MathWorks, Natick, MA) and the MATLAB code and an example well can be found in Appendix A.

2.5 Limitations of the Study

For this study water use is reported as average, direct water consumption. Only water quantities are reported and water quality concerns are not addressed for the processes included in this report. Although water quality is a critical factor in the planning, use, and management of water resources this parameter warrants independent analysis that is beyond the scope of this investigation. No comments are made about the source of the water consumed or the transportation requirements.

Water use is typically separated into water withdrawal and water consumption. Withdrawn water is, “water removed from the ground or diverted from a surface-water source for use,” and consumed water is, “the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment.” [32] This study primarily focuses on water consumption; although, some processes (e.g. thermoelectric power generation with once-through cooling) consume only a fraction of the large volumes of water withdrawn. For these types of processes both water consumption and withdrawals are reported.

Water use can also be categorized as direct or indirect water use. Direct water use includes water used directly by the industry (e.g. drilling and hydraulic fracturing water) and indirect water use includes increased water use by an increased population the industry brings. Only direct water use is addressed in this study, but as drilling in Northern Colorado increases a complete assessment of water requirements
needs to address indirect and direct water use.

Similarly, upstream or embedded water consumption (e.g. the water required for drill rig fabrication) is not included in the study. Fthenakis [5] attempts to assess the upstream water consumption and provides a good summary of upstream water consumption analysis.

Similarly to water consumption, energy recovery is reported as average, direct energy recovery. Embedded or upstream energy is not addressed. Environmental impacts beyond water quantities, such as water quality, air emissions, erosion, land impacts, noise, etc., are also not addressed in this study.

The quality or composition of the energy recovered is not included in the study. Every barrel of oil is assumed to contain 5.78 MMBtu of energy and every thousand standard cubic feet of gas is assumed to contain 1.025 MMBtu of energy. [33] No distinctions are made about the quality of oil or gas recovered.
2.5. Limitations of the Study
3.1 Noble Energy Water Use

Water consumption data, collected using Noble Energy’s WellView®, was collected from 445 wells in the Wattenberg Field. The water consumption for each well was categorized as either drilling water or hydraulic fracturing water. The wells were separated as either vertical or horizontal wells. Each well, represented by an individual vertical bar in Figure 3.1, is ordered from least to greatest. Figure 3.2 gives an example of four wells from Figure 3.1, to illustrate how the figure is developed.

On average, vertical and horizontal wells used 380,000 and 2,800,000 gallons of water. Vertical wells used 77,000 gallons to drill the well and an additional 310,000 gallons to hydraulically fracture the well, on average. Horizontal wells used 130,000 gallons to drill the well and 2,700,000 gallons for hydraulic fracturing.
Drilling and Hydraulic Fracturing Water Consumption

- Vertical Hydraulic Fracturing Water
- Vertical Drilling Water
- Horizontal Hydraulic Fracturing Water
- Horizontal Drilling Water

Figure 3.1: The total water consumed per well, represented as individual bars, and separated by water use.
Figure 3.2: An example of the water consumption of four wells to illustrate how Figure 3.1 is constructed.
Average Water Consumption by Water Use and Well Type

Figure 3.3: Average water consumption of 2010 and 2011 Noble Energy wells in the Wattenberg Field.
The water consumption for each well type and water use are summarized in Table 3.1.

Table 3.1: Average water consumption of 2010 and 2011 Noble Energy wells in the Wattenberg Field

<table>
<thead>
<tr>
<th></th>
<th>Drilling Water</th>
<th>Hydraulic Fracturing Water</th>
<th>Total Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>130 thousand</td>
<td>2,700</td>
<td>2,800</td>
</tr>
<tr>
<td>Vertical</td>
<td>77 thousand</td>
<td>310</td>
<td>380</td>
</tr>
</tbody>
</table>

Water consumption of horizontal wells appears to be significantly higher for horizontal wells; however, significantly fewer horizontal wells have been drilled. As the number of horizontal wells drilled increases the water requirements may change. An increased drilling distance and number of frac stages was thought to contribute to increased water requirements. To explore this, a subset of wells was chosen to determine if the additional water consumption was a result of the increased drilling distance, or measured distance. The water consumed was plotted as a function of measured wellbore depth. The measured wellbore depth is the length of the wellbore, as if determined by a measuring stick. Figure 3.4 shows that horizontal wells have much longer measured wellbore depths, but no clear correlation with water consumption. A scatter plot of the true vertical depth and water consumption is also shown in Figure 3.5. True vertical depth is the vertical distance from the bottom of the well to the surface. Vertical and horizontal wells had similar true vertical depths, but also showed no clear correlation with the water consumption.
Water consumption as a function of the measured well bore depth for a subset of the sampled wells.

Figure 3.4: Water consumption as a function of the measured well bore depth for a subset of the sampled wells.
Figure 3.5: Water consumption as a function of the true vertical distance for a subset of the sampled wells.
3.1. Noble Energy Water Use

Water Consumption
4.1 EUR for Noble Energy Wells

Daily oil and gas production data was collected for the same set of 445 wells using Noble Energy’s Carte® program, in the Wattenberg field. Future production was estimated using hyperbolic decline curves and integrated to determine the EUR. The total energy recovered for each well is ordered from least to greatest in Figures 4.1 and 4.2. The low (exponential decline curve) and high (harmonic decline curve) production scenarios are shown in Figure 4.1. The two curves were used to bound possible production scenarios and provide a basic sensitivity analysis. An average of the two production scenarios is shown in Figure 4.2. Each well is represented by an individual vertical bar as described in Chapter 3. The EUR categorized by estimated ultimate oil and gas recovery and well type is shown in Figure 4.3.
Figure 4.1: The estimated ultimate recovery for each well, represented by each vertical bar, for the low and high production scenarios and separated by energy source recovered and well type.

Figure 4.2: The estimated ultimate recovery for each well for the average production scenario.
Estimated Ultimate Recovery by Well Type

Figure 4.3: The average estimated ultimate recovered at each well separated by well type.
A summary of the estimated ultimate recovery for each production scenario and well type is shown in Table 4.1 and 4.2 for vertical and horizontal wells, respectively.

### Table 4.1: Ultimate recovery estimates for vertical wells

<table>
<thead>
<tr>
<th>(Vertical Wells: Estimated Ultimate Recovery (Billion Btu))</th>
<th>Low Production Scenario</th>
<th>Average Production Scenario</th>
<th>High Production Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>24</td>
<td>42</td>
<td>60</td>
</tr>
<tr>
<td>Gas</td>
<td>32</td>
<td>62</td>
<td>84</td>
</tr>
<tr>
<td>Total</td>
<td>56</td>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

### Table 4.2: Ultimate recovery estimates for horizontal wells

<table>
<thead>
<tr>
<th>(Horizontal Wells: Estimated Ultimate Recovery (Billion Btu))</th>
<th>Low Production Scenario</th>
<th>Average Production Scenario</th>
<th>High Production Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>180</td>
<td>350</td>
<td>520</td>
</tr>
<tr>
<td>Gas</td>
<td>390</td>
<td>740</td>
<td>1,100</td>
</tr>
<tr>
<td>Total</td>
<td>570</td>
<td>1,100</td>
<td>1,600</td>
</tr>
</tbody>
</table>

The estimated recovery from horizontal wells is nearly ten times higher than vertical wells. The ratio of oil and gas is similar for both vertical and horizontal wells.
Chapter 5

Water Intensity

5.1 Noble Well Water Intensity

A ratio of the total water consumed and the total estimated energy recovered is used to determine the water intensity, as described in Eq-4 of Chapter 1, for Noble Energy oil and gas production in the Wattenberg. The low, average, and high production scenarios are used to calculate the three separate water intensity values for each individual well. The water intensities are ordered from least to greatest and represented by each individual vertical bar in the chart. The high and low production scenarios are presented in Figure 5.1 and the average production scenario is presented in Figure 5.2.

The water intensity for Noble Energy wells in the Wattenberg is summarized in Table 5.1. The average values are presented along with a one standard deviation error.

<table>
<thead>
<tr>
<th></th>
<th>Low Production Scenario</th>
<th>Average Production Scenario</th>
<th>High Production Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>9.7</td>
<td>4.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Vertical</td>
<td>14</td>
<td>6.9</td>
<td>5.4</td>
</tr>
</tbody>
</table>

Table 5.1: Water Intensity Estimate (gal/MMBtu)
Figure 5.1: Water Intensity estimate for low and high production scenarios.

Figure 5.2: Water Intensity estimate for average production scenarios.
Chapter 6

Water Intensity Comparison by Fuel Source

A literature review was performed to compare the water intensities of a variety of fuel sources, including coal, oil, natural gas, uranium, solar, wind, biofuels, and geothermal. The water intensities are categorized by life-cycle stages (extraction, processing, transport, etc.) and end-use (electricity generation). Consumptive, withdrawn, and embedded water intensities are also presented for each life-cycle stage, if the data is available. The values and literature sources are presented in Appendices B-F.

6.1 Extraction and Processing

Water requirements for extraction and processing can vary by fuel source, as shown in Figure 6.1. An abbreviated table of consumptive water values is also shown in Table 6.1. In general, water requirements for fossil fuel extraction and processing is relatively low, when compared with the water required for electricity generation from fossil fuels. Biofuels use the most water for extraction and processing, particularly when irrigation is required. Most of the water input to biofuels (71 percent) is consumed via evapotranspiration from crops and is lost to surface run-off and groundwater recharge. [15] Other renewables, such as solar and wind, do not require water in the extraction and processing life-cycle stages and are not included in Figure 6.1.

The range of consumptive water intensities required for coal, oil and natural gas is shown in Figure 6.1. The range of values is represented by the height of the box and the most commonly accepted value is represented by the point where the two boxes come together.

The water required for coal mining varies throughout the country and depends on local geology, mining methods, and water resources. The type of coal and extraction process determine the amount of water required to process the coal. Typically underground mining (approximately 65 percent of Appalachian coal mining) re-
6.1. Extraction and Processing Water Intensity Comparison by Fuel Source

Figure 6.1: Consumptive water intensity for extraction and processing by fuel source.

requires more water than surface mining (approximately 90 percent of western coal mining). Underground mining requires one to 16 gal/MMBtu and surface mining requires one to four gal/MMBtu of consumptive water. [11] Water is required for dust suppression and hauling activities, as well as coal cutting in underground mines. [6] Water is also required for reclamation and revegetation after a mine is closed and to wash the coal to improve impurities. Removing impurities increases the heating value of the coal and reduces harmful emissions, particularly sulfur, during coal combustion. Appalachian coal generally requires additional washing to remove sulfur. Western coal requires little to no additional processing.

Water required for oil extraction and processing varies substantially depending on region, geology, recovery method, and reservoir depletion. [6] Enhanced oil recovery methods are the most water intensive methods for oil extraction and account for nearly 80 percent of the total U.S. oil production. [15]

Steam injection and CO₂ injection are the most commonly used enhanced oil recovery methods and have consumptive water intensities of 39 gal/MMBtu and 94 gal/MMBtu, respectively. The water requirements for oil sands mining ranges from 14 to 33 gal/MMBtu, depending on the solvent used to separate the bitumen.
Table 6.1: An abbreviated comparison of the average consumptive water intensity for the recovery of various energy sources and the water intensity of Noble Energy wells. For a more complete summary see Appendix B-F.

<table>
<thead>
<tr>
<th>Coal (gal/MMBtu)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Mining</td>
<td>2</td>
</tr>
<tr>
<td>Underground Mining</td>
<td>9</td>
</tr>
</tbody>
</table>

**Natural Gas (gal/MMBtu)**

<table>
<thead>
<tr>
<th>Conventional</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noble Data Natural Gas</td>
<td></td>
</tr>
<tr>
<td>Vertical: Low</td>
<td>5.4</td>
</tr>
<tr>
<td>Vertical: Average</td>
<td>6.9</td>
</tr>
<tr>
<td>Vertical: High</td>
<td>13.6</td>
</tr>
<tr>
<td>Horizontal: Low</td>
<td>2.9</td>
</tr>
<tr>
<td>Horizontal: Average</td>
<td>4.3</td>
</tr>
<tr>
<td>Horizontal: High</td>
<td>9.7</td>
</tr>
</tbody>
</table>

**Oil (gal/MMBtu)**

| Primary                    | 1.5 |
| Conventional Flooding      | 14  |
| Oil Sand                   | 35  |
| Oil Shale                  | 39  |
| Enhanced Recovery          | 58  |

**Solar (gal/MMBtu)**

| Photovoltaic               | 4   |

**Wind (gal/MMBtu)**

| Turbine                    | 0   |

**Biofuels (gal/MMBtu)**

| Biodiesel from soy         | 45,000 |
| Ethanol from irrigated corn| 16,000 |
| Biodiesel from rapeseed    | 16,000 |

from the sands. [15] Most U.S refineries have water intensities between 7.2 and 13 gal/MMBtu, depending on the refinery configuration. [15]

Conventional natural gas wells consume small amounts of water (zero to three gal/MMBtu) for drilling during the extraction phase. [6] Water consumption for shale gas extraction is front-loaded, requiring large amounts of water for drilling (70 to 800 thousand gallons) and hydraulic fracturing (1 to 6 million gallons) for extraction. However, the water intensity for the lifetime of the well is relatively low (0.8 to 9.7 gal/MMBtu). Coal bed methane has a negligible water intensity; however, production can result in substantial volumes of produced water. [15]

Uranium mining water requirements are very similar to coal mining and depend mostly on geography and mining methods. Underground mining requires approximately six gal/MMBtu and surface mining requires one gal/MMBtu. [3] Refining and enriching uranium in the U.S. has consumptive water intensities of four to eight gal/MMBtu, depending on the enrichment process. [3]

Biofuels require the largest amounts of water for extraction and processing with
significant variation in water intensities depending on geography and associated irrigation requirements. [34] For example, in one study [34] corn ethanol grown in Indiana was reported to have a water intensity of 83 gal/MMBtu and corn ethanol grown in Kansas was reported to have a water intensity of 3,805 gal/MMBtu. [15] However, a more detailed study estimated that the water intensity of biofuels has a range of 2,500 to 29,000 gal/MMBtu. [6]

6.2 Electricity Generation

Electricity generation is the single largest energy sector in the U.S. [35] Water is required to carry heat from the condenser. In 2005, thermoelectric power plants accounted for 45 percent of the freshwater withdrawals in the United States, but only three percent of the freshwater consumed. [32] As shown in Figure 6.2 and Figure 6.3, a wide range of withdrawn and consumed water intensities for electricity generation exist depending on the cooling configurations.

The cooling requirements can be divided by once-through and recirculation configurations. Once-through cooling uses withdrawn water to transfer heat and condense steam from the turbine. The water is returned to the source approximately 20°F warmer. [15] Evaporation accounts for all of the consumed water in this configuration. Once-through cooling has low capital and operating costs, but can impact downstream ecosystems due to the increased temperature and is uncommon for new power plants today. [36]

Recirculating cooling configurations include closed loop or wet cooling (e.g. cooling ponds, wet tower) and dry cooling (e.g. dry cooling tower). These configurations have much lower water withdrawals than once-through cooling, as shown in Figure 6.3, but have often higher consumptive water requirements as shown in Figure 6.2. Dry cooling is the least water intensive, but it is also the most expensive. One study estimates dry cooling to be nearly ten times more expensive than once-through cooling. [36] Closed-loop cooling has become the most common configuration for modern power plants. Low water withdrawals are required, but more water is consumed than a once-through configuration.
Figure 6.2: Consumptive water intensity for electricity generation separated by fuel source.
6.2. Electricity Generation

Electricity Generation Water Intensity by Fuel Source

Figure 6.3: Withdrawn water intensity for electricity generation separated by fuel source.
Efficient use of water, particularly in the Western U.S., is an increasingly important aspect of many activities including agriculture, urban and industry. As population continues to increase and agriculture and energy needs continue to increase, the pressure on water and other natural resources is expected to intensify. Recent technological advances have stimulated growth in oil and gas development and operations, as well as increasing the industry’s need for water resources.

This study has provided an analysis of how efficiently water resources are used for unconventional shale gas and shale oil development and compared the efficiency with other energy sources including coal, natural gas, oil, and renewable energy sources. A general materials balance was used to assess the lifecycle of water and energy resources of Noble Energy assets in the Wattenberg field. Water use data as well as oil and gas production data was collected from Noble Energy wells and separated by well type (horizontal or vertical) and water use (drilling and hydraulic fracturing). The sample set included 445 wells operated by Noble Energy and drilled in 2010 and 2011.

Vertical and horizontal wells operated by Noble Energy in the Wattenberg during 2010 and 2011 consumed an average 380,000 and 2,800,00 gallons of water. On average, vertical wells used 77,000 gallons to drill and an additional 310,000 gallons to hydraulically fracture the well. Horizontal wells used 130,000 gallons to drill and 2,700,000 gallons to hydraulically fracture the well.

A decline curve analysis was used to estimate the ultimate recovery from each individual well. Exponential and harmonic decline curves were fit to the production data to project low and high production scenarios, respectively. Vertical wells are expected to have an estimated ultimate recovery between 24 and 60 BBtu for oil and between 32 and 84 BBtu for gas. Horizontal wells are expected to have an estimated ultimate recovery between 390 and 1,100 for gas and between 180 and 520 BBtu for oil.

A ratio of the water consumed and the estimate ultimate recovery for each well was used to estimate the water intensity of each well. Vertical and horizontal wells operated by Noble Energy in the Wattenberg during 2010 and 2011 are expected to
have an average water intensity of 6.9 and 4.3 gal/MMBtu, respectively. Vertical wells have an expected water intensity ranging between 5.4 and 14 gal/MMBtu and horizontal wells have an expected water intensity between 2.9 and 9.7 gal/MMBtu.

When the water intensity of shale gas extraction was compared other energy sources it was found to be one of the lowest. Only wind (0 gal/MMBtu), solar (4 gal/MMBtu), primary oil recovery (1.5 gal/MMBtu), and conventional natural gas (1.5 gal/MMBtu) had slightly lower water intensities. Essentially all of the water required for shale gas extraction is needed to drill and hydraulically fracture the well. Horizontal wells require much more water for hydraulic fracturing than vertical wells, on average. However, the water intensity is estimated to still be slightly lower for horizontal wells because the water is used in a more efficient manner.

7.1 Future work

The general materials balance approach developed for this project is useful to understand the full life cycle of water in oil and gas development. The volume of water consumed during well drilling and completion is considered the input and will be compared to the output of produced water over the lifetime of the well. A GIS application will be developed that includes water input and a temporal relationship of water output (produced water). Water quality spatial relationships will be included in the GIS application to provide a basis for determining the potential for returning produced water to the water cycle (e.g. reused for fracturing, surface discharge, agricultural reuse).

Part of this future work will consider the energy inputs and outputs of the materials balance. The degree of water reuse and discharge for frac flowback and produced water is dependent on the water quality and level of treatment required. As quality deteriorates, the energy required to treat the water for anything more than pit evaporation or deep well injection increases. Using the general materials balance, energy and cost estimates will be developed for different levels of treatment in the Wattenberg field.

The goal of the of the GIS application is to provide a tool that can be used to estimate the cost, energy requirements and timeframe for returning an amount of water equal to that consumed to the water cycle, thus achieving full water neutrality in oil and gas operations. The value of adopting a water neutrality position in terms of public perception of water stewardship is considered to be high. Since it is possible to exceed water neutrality, produce more water for the hydrosphere than consumed, Noble Energy could be in the unique position to document a plan to positively impact the water balance in the region.


Appendix A

Decline Curve Analysis

The Arps Equation used for the decline curves is shown below:

\[ q(t) = \frac{q_i}{(1 + D_i t)^{1/b}} \]

where

- \( q(t) \): Future production rate
- \( q_i \): Initial production rate
- \( D_i \): Initial decline rate
- \( t \): Time
- \( b \): Degree of curvature

Eq-5

When \( b = 0 \) ⇒ \( q(t) = q_i e^{D_i t} \)  (Exponential Decline Curve)  
(Low Production Scenario)  
Eq-6

When \( b = 1 \) ⇒ \( q(t) = \frac{q_i}{1 + D_i t} \)  (Harmonic Decline Curve)  
(High Production Scenario)  
Eq-7

A least-squares method was used to generate the decline curves for each well. The MATLAB code used to generate, plot and integrate the decline curves is shown:

The Arps Equation used for the decline curves is shown below:
clear
close all
clc
clear
close all
clc

% Oil Gas and Water Production

X=1:length(Y);
x'=';
%z=';

% Least squares method to estimate exponential decay
% Y is an array of the oil or gas production each day
% X is an array of the number of days since the well was first productive.

% Plots actual data
hold on
plot(x,Y, '.')
xlabel('Days of Production')
ylabel('Gas Production Rate (MCF/day)')
title('Tri-State Colorado Well')

% Plots exponential decline curve
z=log(Y);

a0= (sum(x.'^2)*sum(z)-x'*z*sum(x))/(length(x)*sum(x.'^2)-sum(x)^2);
al=(length(x)*x'*z-sum(x)*sum(z))/(length(x)*sum(x.'^2)-sum(x)^2);

b=exp(a0);
a=al;
x=1:1:0950;
x'=';
pe=b*exp(a*x);
plot(x,pe, 'green')

X=1:length(Y);
x='X';

% Plots projected harmonic decline curve
z=1./(Y);

a0= (sum(x.'^2)*sum(z)-x'*z*sum(x))/(length(x)*sum(x.'^2)-sum(x)^2);
al=(length(x)*x'*z-sum(x)*sum(z))/(length(x)*sum(x.'^2)-sum(x)^2);

b=1/a0;
a=al/a0;
x=1:1:0950;
x'=';
ph=b./((1+a*x);
plot(x,ph, 'red')
legend('Field Data', 'Exponential Decline Curve', 'Harmonic Decline Curve')

% Uses trapezoidal integration to estimate ultimate recovery
EUR_exp=trapz(x,pe)
% BOE_exp=EUR_exp*10^3/6000

EUR_har=trapz(x,ph)
% BOE_har=EUR_har*10^3/6000
Decline Curve Analysis

Tri-State Colorado Well

Field Data
Exponential Decline Curve
Harmonic Decline Curve

Student Version of MATLAB
Appendix B

Coal Water Intensity

**Figure B.1:** Water intensity associated with each stage of electricity generation from coal.

<table>
<thead>
<tr>
<th>Coal Extraction</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reclamation</td>
<td>0.014</td>
<td>[29]</td>
</tr>
<tr>
<td>Dust Suppression</td>
<td>0.46</td>
<td>[29]</td>
</tr>
<tr>
<td>Underground Appalachian Mining</td>
<td>1</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Surface Mining: Low</td>
<td>1</td>
<td>[3, 5, 37]</td>
</tr>
<tr>
<td>Western Surface Mining</td>
<td>2</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Surface Mining: Average</td>
<td>2</td>
<td>[3, 5, 37]</td>
</tr>
<tr>
<td>Underground Mining: Low</td>
<td>1</td>
<td>[3, 5, 37]</td>
</tr>
<tr>
<td>U.S. Mining Weighted Average</td>
<td>2</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Surface Mining: High</td>
<td>4</td>
<td>[3, 5, 37]</td>
</tr>
<tr>
<td>Underground Mining: Average</td>
<td>9</td>
<td>[3, 5, 37]</td>
</tr>
<tr>
<td>Underground Mining: High</td>
<td>16</td>
<td>[3, 5, 37]</td>
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</table>

Table B.1: Consumptive water intensity of coal extraction
Coal Water Intensity

Table B.2: Withdrawn water intensity of coal extraction

<table>
<thead>
<tr>
<th>Coal Extraction</th>
<th>Withdrawn Water Intensity (gal/MBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Surface Mining</td>
<td>3</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>U.S. Coal Mining</td>
<td>8</td>
<td>[3, 5, 35]</td>
</tr>
<tr>
<td>Eastern Underground Mining</td>
<td>15</td>
<td>[5, 37]</td>
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</table>

Table B.3: Embedded water intensity of coal extraction

<table>
<thead>
<tr>
<th>Coal Extraction</th>
<th>Embedded Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Surface Mining</td>
<td>1</td>
<td>[5]</td>
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<tr>
<td>Eastern Surface Mining</td>
<td>11</td>
<td>[5]</td>
</tr>
<tr>
<td>Eastern Underground Mining</td>
<td>39</td>
<td>[5]</td>
</tr>
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</table>

Table B.4: Consumptive water intensity of coal processing

<table>
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<tr>
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<th>Consumptive Water Intensity (gal/MBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Preparation</td>
<td>0.26</td>
<td>[29]</td>
</tr>
<tr>
<td>Washing: Low</td>
<td>2.3</td>
<td>[5, 11]</td>
</tr>
<tr>
<td>Benefication: Low</td>
<td>3.3</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Benefication: Average</td>
<td>3.4</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Benefication: High</td>
<td>3.5</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Washing: Average</td>
<td>3.6</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Washing: High</td>
<td>5.0</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Coal Gasification or Liquefacation</td>
<td>10</td>
<td>[29]</td>
</tr>
<tr>
<td>Synfuel Coal Gasification: Low</td>
<td>11</td>
<td>[6, 30]</td>
</tr>
<tr>
<td>Synfuel Coal Gasification: Average</td>
<td>19</td>
<td>[6, 30]</td>
</tr>
<tr>
<td>Synfuel Coal Gasification: High</td>
<td>26</td>
<td>[6, 30]</td>
</tr>
<tr>
<td>Coal-to-Liquids:Low</td>
<td>41</td>
<td>[6, 30]</td>
</tr>
<tr>
<td>Coal-to-Liquids:Average</td>
<td>51</td>
<td>[6, 30]</td>
</tr>
<tr>
<td>Coal-to-Liquids: High</td>
<td>60</td>
<td>[6, 30]</td>
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Table B.5: Withdrawn water intensity of coal processing

<table>
<thead>
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<th>Withdrawn Water Intensity (gal/MBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefication</td>
<td>&gt;3.5</td>
<td>[5, 37]</td>
</tr>
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</table>

Table B.6: Embedded water intensity of coal processing

<table>
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<tr>
<th>Coal Processing</th>
<th>Embedded Water Intensity (gal/MBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefication</td>
<td>4.1</td>
<td>[5]</td>
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</tbody>
</table>
### Table B.7: Consumptive water intensity of coal transport

<table>
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<tr>
<th>Coal Transport</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slurry Pipeline, 70 Percent Recycling: Low</td>
<td>3.3</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Slurry Pipeline, 70 Percent Recycling: Average</td>
<td>5.5</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Slurry Pipeline, 70 Percent Recycling: High</td>
<td>7.2</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Slurry Pipeline, No Recycling: Low</td>
<td>11</td>
<td>[6, 15, 30]</td>
</tr>
<tr>
<td>Slurry Pipeline, No Recycling: Average</td>
<td>18</td>
<td>[6, 15, 30]</td>
</tr>
<tr>
<td>Slurry Pipeline, No Recycling: High</td>
<td>24</td>
<td>[6, 15, 30]</td>
</tr>
<tr>
<td>Slurry Pipeline: Low</td>
<td>33</td>
<td>[3, 5, 37]</td>
</tr>
<tr>
<td>Slurry Pipeline: Average</td>
<td>50</td>
<td>[3, 5, 37]</td>
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<tr>
<td>Slurry Pipeline: High</td>
<td>67</td>
<td>[3, 5, 37]</td>
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### Table B.8: Withdrawn water intensity of coal transport

<table>
<thead>
<tr>
<th>Coal Transport</th>
<th>Withdrawn Water Intensity (gal/MMBtu)</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>Slurry Pipeline</td>
<td>35</td>
<td>[3, 5, 37]</td>
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</table>

### Table B.9: Embedded water intensity of coal transport

<table>
<thead>
<tr>
<th>Coal Transport</th>
<th>Embedded Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train: Low</td>
<td>2</td>
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<tr>
<td>Train: Average</td>
<td>2.5</td>
<td>[5]</td>
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<tr>
<td>Train: High</td>
<td>3</td>
<td>[5]</td>
</tr>
<tr>
<td>Slurry Pipeline</td>
<td>240</td>
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### Table B.10: Embedded water intensity of coal-fired power plant construction

<table>
<thead>
<tr>
<th>Coal Plant Construction</th>
<th>Embedded Water Intensity (gal/MBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.9</td>
<td>[5]</td>
</tr>
<tr>
<td>Average</td>
<td>2.2</td>
<td>[5]</td>
</tr>
<tr>
<td>High</td>
<td>3.5</td>
<td>[5]</td>
</tr>
</tbody>
</table>
### Table B.11: Consumptive water intensity of coal-fired power plant electricity generation

<table>
<thead>
<tr>
<th>Coal Electricity Generation</th>
<th>Consumptive Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry: Low</td>
<td>0</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: Average</td>
<td>15</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: High</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Cooling Pond, Supercritical</td>
<td>64</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Once-Through, Supercritical</td>
<td>120</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Once-Through, Subcritical</td>
<td>140</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Once-Through, Fluidized Bed</td>
<td>250</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Wet Tower, Supercritical</td>
<td>250</td>
<td>[3, 5]</td>
</tr>
<tr>
<td>Cooling Pond: Low</td>
<td>260</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Once-Through: Low</td>
<td>300</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Closed-Loop: Low</td>
<td>300</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Once-Through: Low</td>
<td>300</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Once-Through: Average</td>
<td>300</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Once-Through: High</td>
<td>300</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Once-Through: Average</td>
<td>315</td>
<td>[6, 15, 20, 21, 30, 38]</td>
</tr>
<tr>
<td>Once-Through</td>
<td>320</td>
<td>[3, 5]</td>
</tr>
<tr>
<td>Once-Through: High</td>
<td>330</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Wet Tower, Retrofitted with Carbon Capture</td>
<td>340</td>
<td>[5, 39]</td>
</tr>
<tr>
<td>Cooling Pond: Average</td>
<td>380</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Closed-Loop: Average</td>
<td>405</td>
<td>[6, 15, 20, 21, 30, 38]</td>
</tr>
<tr>
<td>Closed-Loop with Carbon Capture</td>
<td>420</td>
<td>[21, 30]</td>
</tr>
<tr>
<td>Wet Tower: Low</td>
<td>450</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower, Subcritical</td>
<td>460</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Wet Tower: Average</td>
<td>480</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Cooling Pond: High</td>
<td>500</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower: High</td>
<td>500</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower, Western U.S.</td>
<td>500</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Closed-Loop: High</td>
<td>510</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Wet Tower, Supercritical</td>
<td>600</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Wet Tower, Subcritical</td>
<td>680</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Wet Tower, Eastern U.S.</td>
<td>740</td>
<td>[5, 37]</td>
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<tr>
<td>Cooling Pond, Subcritical</td>
<td>800</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Wet Tower</td>
<td>820</td>
<td>[3, 5]</td>
</tr>
<tr>
<td>Wet Tower, Supercritical</td>
<td>1000</td>
<td>[5, 41]</td>
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<tr>
<td>Wet Tower, Subcritical</td>
<td>1200</td>
<td>[5, 41]</td>
</tr>
<tr>
<td>Wet Tower, Supercritical with Carbon Capture</td>
<td>1200</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Wet Tower, Subcritical with Carbon Capture</td>
<td>1330</td>
<td>[5, 40]</td>
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</table>
Table B.12: Withdrawn water intensity of coal-fired power plant electricity generation

<table>
<thead>
<tr>
<th>Coal Electricity Generation</th>
<th>Withdrawn Water Intensity (gal/MWh)</th>
<th>Source</th>
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<tbody>
<tr>
<td>Dry: Average</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: High</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: Low</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Wet Tower, Subcritical</td>
<td>230</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Cooling Pond: Low</td>
<td>290</td>
<td>[5, 36]</td>
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<tr>
<td>Closed-Loop: Low</td>
<td>330</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Cooling Pond: Average</td>
<td>450</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Closed-Loop: Average</td>
<td>480</td>
<td>[6, 15, 20, 21, 30, 38]</td>
</tr>
<tr>
<td>Wet Tower: Low</td>
<td>5000</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower: Average</td>
<td>5600</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Closed-Loop with Carbon Capture</td>
<td>563</td>
<td>[21, 30]</td>
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<tr>
<td>Wet Tower, Supercritical</td>
<td>600</td>
<td>[5, 40]</td>
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<tr>
<td>Cooling Pond: High</td>
<td>610</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Wet Tower: High</td>
<td>610</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Closed-Loop: High</td>
<td>630</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Wet Tower, Supercritical</td>
<td>660</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Wet Tower, Subcritical</td>
<td>690</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Wet Tower, Supercritical</td>
<td>1000</td>
<td>[5, 41]</td>
</tr>
<tr>
<td>Wet Tower, Subcritical</td>
<td>1200</td>
<td>[5, 41]</td>
</tr>
<tr>
<td>Wet Tower, Supercritical with Carbon Capture</td>
<td>1300</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Wet Tower, Subcritical with Carbon Capture</td>
<td>1500</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Wet Tower, Retrofitted with Carbon Capture</td>
<td>9500</td>
<td>[5, 39]</td>
</tr>
<tr>
<td>Cooling Pond, Supercritical</td>
<td>15100</td>
<td>[5, 10]</td>
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<td>Cooling Pond, Subcritical</td>
<td>17900</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Once-Through: Low</td>
<td>20030</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Once-Through: Low</td>
<td>20100</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Once-Through, Supercritical</td>
<td>22700</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Once-Through, Subcritical</td>
<td>27300</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Once-Through: Average</td>
<td>35030</td>
<td>[6, 15, 20, 21, 30, 38]</td>
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<tr>
<td>Once-Through: Average</td>
<td>35200</td>
<td>[5, 36]</td>
</tr>
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<td>Once-Through: High</td>
<td>50030</td>
<td>[6, 15, 20]</td>
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<tr>
<td>Once-Through: High</td>
<td>50300</td>
<td>[5, 36]</td>
</tr>
</tbody>
</table>
Figure B.2: Water intensity and U.S. consumption associated with each stage of electricity generation from coal.
**APPENDIX C**

### Oil Water Intensity

![Diagram of oil production process with water intensity values](image)

**Figure C.1:** Water intensity associated with each stage of crude oil production.

**Table C.1:** Consumptive water intensity of oil extraction

<table>
<thead>
<tr>
<th>Oil Extraction</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>1.4</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>Primary</td>
<td>1.5</td>
<td>[3]</td>
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<tr>
<td>PADD II</td>
<td>2</td>
<td>[34]</td>
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<tr>
<td>PADD III</td>
<td>2.2</td>
<td>[34]</td>
</tr>
<tr>
<td>Steam-Assisted Gravity Drainage</td>
<td>2.2</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>Steam Stimulation</td>
<td>2.5</td>
<td>[42]</td>
</tr>
<tr>
<td>Steam Drive</td>
<td>5</td>
<td>[42]</td>
</tr>
<tr>
<td>PADD V</td>
<td>5.1</td>
<td>[34]</td>
</tr>
<tr>
<td>In-Situ Comustion</td>
<td>5.5</td>
<td>[42]</td>
</tr>
<tr>
<td>Oil Sands: Low</td>
<td>7</td>
<td>[34]</td>
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</tbody>
</table>
## Oil Water Intensity

<table>
<thead>
<tr>
<th>Oil Extraction</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upgrading to Syncrude</td>
<td>7.2</td>
<td>[15, 34]</td>
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<tr>
<td>Oil Shale: Low</td>
<td>7.96</td>
<td>[43]</td>
</tr>
<tr>
<td>Conventional: Low</td>
<td>8</td>
<td>[6, 30]</td>
</tr>
<tr>
<td>PADD I</td>
<td>8</td>
<td>[44]</td>
</tr>
<tr>
<td>PADD IV</td>
<td>8</td>
<td>[44]</td>
</tr>
<tr>
<td>Cyclic Steam Stimulation</td>
<td>8.7</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>SAGD with Upgrade</td>
<td>9.4</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>Saudi Arabia: Low</td>
<td>10</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>Saudi Arabia: Ghawar Field</td>
<td>10</td>
<td>[34, 45]</td>
</tr>
<tr>
<td>Micellar Polymer Injection</td>
<td>11</td>
<td>[42]</td>
</tr>
<tr>
<td>CO2 Miscible Flooding</td>
<td>13</td>
<td>[42]</td>
</tr>
<tr>
<td>Oil Shale: Average</td>
<td>13.61</td>
<td>[43]</td>
</tr>
<tr>
<td>Conventional: Average</td>
<td>14</td>
<td>[6, 30]</td>
</tr>
<tr>
<td>Forward Combustion/Air Injection</td>
<td>14</td>
<td>[3, 15, 34]</td>
</tr>
<tr>
<td>Oil Sands: Low</td>
<td>14</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>CSS with Upgrade</td>
<td>164</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>Bitumen Oil Sands via Surface Mining</td>
<td>16</td>
<td>[34, 46]</td>
</tr>
<tr>
<td>Oil Shale: High</td>
<td>19.25</td>
<td>[43]</td>
</tr>
<tr>
<td>Conventional: High</td>
<td>20</td>
<td>[6, 30]</td>
</tr>
<tr>
<td>Oil Sands: Average</td>
<td>20</td>
<td>[34]</td>
</tr>
<tr>
<td>Enhanced Oil Recovery: Low</td>
<td>21</td>
<td>[6, 30]</td>
</tr>
<tr>
<td>Saudi Arabia: Average</td>
<td>22</td>
<td>[34]</td>
</tr>
<tr>
<td>Oil Shale: Low</td>
<td>22</td>
<td>[30]</td>
</tr>
<tr>
<td>Oil Sands: Average</td>
<td>24</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>Oil Sands: Low</td>
<td>27</td>
<td>[30]</td>
</tr>
<tr>
<td>Caustic Injection</td>
<td>28</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>Surface Mining (Athabasca)</td>
<td>28</td>
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<td>Bitumen Oil Sands via Surface Mining</td>
<td>29</td>
<td>[34, 47]</td>
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<tr>
<td>Upgrading</td>
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<td>[34, 47]</td>
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<tr>
<td>Caustic Flooding</td>
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<tr>
<td>CO2 Injection</td>
<td>31</td>
<td>[3, 34]</td>
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<tr>
<td>Saudi Arabia: High</td>
<td>33</td>
<td>[15, 34]</td>
</tr>
<tr>
<td>Saudi Arabia: North ÔAin Dar Field, 2005</td>
<td>33</td>
<td>[34]</td>
</tr>
<tr>
<td>Oil Sands: High</td>
<td>33</td>
<td>[15, 34]</td>
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<td>34</td>
<td>[34]</td>
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<td>Bitumen Oil Sands via Surface Mining</td>
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<td>[3, 34]</td>
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<tr>
<td>CSS (Cold Lake)</td>
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<tr>
<td>Steam Injection</td>
<td>39</td>
<td>[15, 34]</td>
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<tr>
<td>Oil Shale: Average</td>
<td>39</td>
<td>[30]</td>
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<tr>
<td>Polymer Assisted Water Flooding</td>
<td>40</td>
<td>[42]</td>
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<tr>
<td>Saudi Arabia: North ÔAin Dar Field, 1999</td>
<td>43</td>
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### Oil Extraction

<table>
<thead>
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<th>Source</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
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<tr>
<td>Multi-Scheme (Peace River)</td>
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<td>[15, 34, 48]</td>
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<td>Oil Shale: High</td>
<td>56</td>
<td>[30]</td>
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<td>2005 U.S. On-Shore Average Recovery</td>
<td>58</td>
<td>[34]</td>
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<tr>
<td>Secondary Conventional</td>
<td>62</td>
<td>[15, 34]</td>
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<tr>
<td>Enhanced Oil Recovery</td>
<td>62</td>
<td>[34]</td>
</tr>
<tr>
<td>Other</td>
<td>63</td>
<td>[15, 34]</td>
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<td>Oil Sands: High</td>
<td>68</td>
<td>[15, 42, 48]</td>
</tr>
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<td>CO2 Injection</td>
<td>94</td>
<td>[15, 34, 42]</td>
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<tr>
<td>SAGD (Athabasca)</td>
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<td>[34]</td>
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<tr>
<td>CO2 Injection</td>
<td>178</td>
<td>[42]</td>
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<tr>
<td>Micellar Polymer Injection</td>
<td>2485</td>
<td>[15, 34]</td>
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<td>Enhanced Oil Recovery: High</td>
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<td>[6, 30]</td>
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### Oil Processing

<table>
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<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
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<tbody>
<tr>
<td>U.S. Refineries: Low</td>
<td>7.2</td>
<td>[3, 15, 34]</td>
</tr>
<tr>
<td>U.S. Refineries: Average</td>
<td>10</td>
<td>[15, 34]</td>
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<tr>
<td>U.S. Refineries: High</td>
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<td>[15, 34]</td>
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<td>Oil Shale Petroleum: Low</td>
<td>22</td>
<td>[30]</td>
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<td>Oil Sands: Low</td>
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<tr>
<td>Oil Shale Petroleum: Average</td>
<td>39</td>
<td>[30]</td>
</tr>
<tr>
<td>Oil Sands: Average</td>
<td>48</td>
<td>[30]</td>
</tr>
<tr>
<td>Oil Shale Petroleum: High</td>
<td>56</td>
<td>[30]</td>
</tr>
<tr>
<td>Oil Sands: High</td>
<td>68</td>
<td>[30]</td>
</tr>
</tbody>
</table>
Figure C.2: Water intensity and U.S. consumption associated with each stage of U.S. crude oil production.
APPENDIX D

Natural Gas Water Intensity

Figure D.1: Water intensity associated with each stage of electricity generation from conventional natural gas.

Figure D.2: Water intensity associated with each stage of electricity generation from shale natural gas.
**Table D.1:** Consumptive water intensity of natural gas extraction

<table>
<thead>
<tr>
<th>Gas Extraction</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>0</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>On-Shore</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>Off-Shore</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>Shale Gas: Low</td>
<td>0.6</td>
<td>[15]</td>
</tr>
<tr>
<td>Typical Minimum</td>
<td>0.6</td>
<td>[15, 30]</td>
</tr>
<tr>
<td>Haynesville</td>
<td>0.8</td>
<td>[15, 30]</td>
</tr>
<tr>
<td>Shale Gas: Low</td>
<td>0.84</td>
<td>[30]</td>
</tr>
<tr>
<td>Conventional: Low</td>
<td>1</td>
<td>[30]</td>
</tr>
<tr>
<td>Marcellus</td>
<td>1.2</td>
<td>[15]</td>
</tr>
<tr>
<td>Barnett, Vertical Wells</td>
<td>1.2</td>
<td>[15]</td>
</tr>
<tr>
<td>Marcellus</td>
<td>1.3</td>
<td>[15, 30]</td>
</tr>
<tr>
<td>Typical Maximum</td>
<td>1.3</td>
<td>[15, 30]</td>
</tr>
<tr>
<td>Barnett</td>
<td>1.5</td>
<td>[15, 30]</td>
</tr>
<tr>
<td>Fayetteville</td>
<td>1.7</td>
<td>[15, 30]</td>
</tr>
<tr>
<td>Typical Average</td>
<td>1.8</td>
<td>[15, 30]</td>
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<tr>
<td>Conventional: Average</td>
<td>2</td>
<td>[30]</td>
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<tr>
<td>Shale Gas: Average</td>
<td>2.08</td>
<td>[30]</td>
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<tr>
<td>Shale Gas: Average</td>
<td>2.2</td>
<td>[15]</td>
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<tr>
<td>Shale Gas: High</td>
<td>2.4</td>
<td>[15]</td>
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<tr>
<td>Conventional: High</td>
<td>3</td>
<td>[30]</td>
</tr>
<tr>
<td>Barnett, Horizontal Wells</td>
<td>3.1</td>
<td>[15]</td>
</tr>
<tr>
<td>Shale Gas: High</td>
<td>3.32</td>
<td>[30]</td>
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</table>

**Table D.2:** Withdrewn water intensity of natural gas extraction

<table>
<thead>
<tr>
<th>Gas Extraction</th>
<th>Withdrawn Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-Shore</td>
<td>10</td>
<td>[5]</td>
</tr>
<tr>
<td>Off-Shore</td>
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</table>

**Table D.3:** Embedded water intensity of natural gas extraction

<table>
<thead>
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<th>Gas Extraction</th>
<th>Embedded Water Intensity (gal/MMBtu)</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>On-Shore</td>
<td>23</td>
<td>[5]</td>
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<tr>
<td>Off-Shore</td>
<td>0</td>
<td>[5]</td>
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### Table D.4: Consumptive water intensity of natural gas processing

<table>
<thead>
<tr>
<th>Gas Processing</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing and Transport: Low</td>
<td>0</td>
<td>[15, 30]</td>
</tr>
<tr>
<td>Processing and Transport: Average</td>
<td>1</td>
<td>[15, 30]</td>
</tr>
<tr>
<td>Processing and Transport</td>
<td>2</td>
<td>[3, 15]</td>
</tr>
<tr>
<td>Processing and Transport: High</td>
<td>2</td>
<td>[15, 30]</td>
</tr>
<tr>
<td>Gas-to-Liquids: Low</td>
<td>19</td>
<td>[15, 49]</td>
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<tr>
<td>Gas-to-Liquids: Average</td>
<td>42</td>
<td>[15, 49]</td>
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<tr>
<td>Gas-to-Liquids: High</td>
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<td>[15, 49]</td>
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</table>

### Table D.5: Consumptive water intensity of natural gas transport

<table>
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<th>Gas Transport</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport: Low</td>
<td>0</td>
<td>[30]</td>
</tr>
<tr>
<td>Transport: Average</td>
<td>1</td>
<td>[30]</td>
</tr>
<tr>
<td>Transport: High</td>
<td>2</td>
<td>[30]</td>
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<tr>
<td>Pipeline</td>
<td>2.3</td>
<td>[5]</td>
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### Table D.6: Withdrawn water intensity of natural gas transport

<table>
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<th>Gas Transport</th>
<th>Withdrawn Water Intensity (gal/MMBtu)</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>Pipeline</td>
<td>0.1</td>
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### Table D.7: Embedded water intensity of natural gas transport

<table>
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<th>Embedded Water Intensity (gal/MMBtu)</th>
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</tr>
</thead>
<tbody>
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<td>Pipeline</td>
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Table D.8: Consumptive water intensity of natural gas power plant electricity generation.

<table>
<thead>
<tr>
<th>Gas Electricity Generation</th>
<th>Consumptive Water Intensity (gal/MWh)</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>Dry: Low</td>
<td>0</td>
<td>[6, 15, 20]</td>
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<tr>
<td>Combined-Cycle Gas Dry: Low</td>
<td>0</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: Average</td>
<td>15</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Combined-Cycle Gas Dry: Average</td>
<td>15</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Combined-Cycle Once-Through</td>
<td>20</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Dry: High</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Combined-Cycle Gas Dry: High</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Once-Through</td>
<td>90</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Combined-Cycle Gas Once-Through: Low</td>
<td>100</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Combined-Cycle Gas Once-Through: Low</td>
<td>100</td>
<td>[5, 40]</td>
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<tr>
<td>Combined-Cycle Gas Once-Through: Average</td>
<td>100</td>
<td>[5, 40]</td>
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<tr>
<td>Combined-Cycle Gas Once-Through: High</td>
<td>100</td>
<td>[5, 40]</td>
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<tr>
<td>Cooling Pond</td>
<td>110</td>
<td>[5, 10]</td>
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<tr>
<td>Combined-Cycle Gas Once-Through: Average</td>
<td>115</td>
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<td>130</td>
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<tr>
<td>Wet Tower</td>
<td>130</td>
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<tr>
<td>Combined-Cycle Gas Closed-Loop: Low</td>
<td>180</td>
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<tr>
<td>Combined-Cycle Wet Tower</td>
<td>180</td>
<td>[5, 40]</td>
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<tr>
<td>Combined-Cycle Gas Closed-Loop: Low with Carbon Capture</td>
<td>190</td>
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<tr>
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<td>195</td>
<td>[5, 40]</td>
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<td>210</td>
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<td>Combined-Cycle Gas Cooling Pond</td>
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<tr>
<td>Once-Throug</td>
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<td>[5, 37]</td>
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<tr>
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<td>270</td>
<td>[5, 40]</td>
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<td>Once-Through: Average</td>
<td>315</td>
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<td>330</td>
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<td>510</td>
<td>[6, 15, 20]</td>
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<td>820</td>
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## Natural Gas Water Intensity

<table>
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<th>Gas Electricity Generation</th>
<th>Consumptive Water Intensity (gal/MWh)</th>
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<td>Dry: Low</td>
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<td>Dry: Average</td>
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<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: High</td>
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<td>[6, 15, 20]</td>
</tr>
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<td>Combined-Cycle Gas Dry: Low</td>
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<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Combined-Cycle Gas Dry: Average</td>
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<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Combined-Cycle Gas Dry: High</td>
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<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Combined-Cycle Wet Tower</td>
<td>150</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Combined-Cycle Gas Closed-Loop with Carbon Capture</td>
<td>217</td>
<td>[5, 40]</td>
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<tr>
<td>Combined-Cycle Wet Tower</td>
<td>230</td>
<td>[5, 40]</td>
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<tr>
<td>Wet Tower</td>
<td>250</td>
<td>[5, 10]</td>
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<tr>
<td>Combined-Cycle Gas Closed-Loop: Low</td>
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<td>[5, 40]</td>
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<td>Combined-Cycle Gas Closed-Loop: Average</td>
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<td>[5, 40]</td>
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<tr>
<td>Combined-Cycle Gas Closed-Loop: High</td>
<td>260</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Combined-Cycle Wet Tower</td>
<td>270</td>
<td>[5, 40]</td>
</tr>
<tr>
<td>Closed-Loop: Low</td>
<td>330</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Closed-Loop: Average</td>
<td>480</td>
<td>[6, 15, 20, 21, 30]</td>
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<td>500</td>
<td>[5, 41]</td>
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<tr>
<td>Combined-Cycle Wet Tower with Carbon Capture</td>
<td>560</td>
<td>[5, 40]</td>
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<tr>
<td>Closed-Loop with Carbon Capture</td>
<td>563</td>
<td>[21?]</td>
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<tr>
<td>Closed-Loop: High</td>
<td>630</td>
<td>[6, 15, 20]</td>
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<tr>
<td>Combined-Cycle Gas Once-Through: Low</td>
<td>7400</td>
<td>[5, 40]</td>
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<tr>
<td>Combined-Cycle Gas Once-Through: Low</td>
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<td>[5, 10]</td>
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<tr>
<td>Cooling Pond</td>
<td>7900</td>
<td>[5, 10]</td>
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<td>Combined-Cycle Once-Through</td>
<td>9020</td>
<td>[5, 10]</td>
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<td>13800</td>
<td>[5, 40]</td>
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<td>Once-Through: Low</td>
<td>20030</td>
<td>[6, 15, 20]</td>
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<tr>
<td>Combined-Cycle Gas Once-Through: High</td>
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<td>[5, 10]</td>
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<td>Combined-Cycle Gas Once-Through: High</td>
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<td>Once-Through</td>
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<td>[5, 10]</td>
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<td>Once-Through: Average</td>
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</tr>
<tr>
<td>Once-Through: High</td>
<td>50030</td>
<td>[6, 15, 20]</td>
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</tbody>
</table>
Figure D.3: Water intensity and U.S. consumption of natural gas associated with each stage of electricity generation.
Uranium Water Intensity

**Table E.1:** Consumptive water intensity of uranium extraction

<table>
<thead>
<tr>
<th>Uranium Extraction</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underground Mining</td>
<td>1</td>
<td>[3, 6, 15]</td>
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<tr>
<td>Underground Mining</td>
<td>1</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Surface Mining</td>
<td>6</td>
<td>[3, 6, 15]</td>
</tr>
<tr>
<td>Surface Mining</td>
<td>16</td>
<td>[5, 37]</td>
</tr>
</tbody>
</table>

**Table E.2:** Withdrawn water intensity of uranium extraction

<table>
<thead>
<tr>
<th>Uranium Extraction</th>
<th>Withdrawn Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underground Mining</td>
<td>3</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Surface Mining</td>
<td>3</td>
<td>[5, 37]</td>
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</table>

**Table E.3:** Embedded water intensity of uranium extraction

<table>
<thead>
<tr>
<th>Embedded Extraction</th>
<th>Embedded Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
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<tbody>
<tr>
<td>Underground Mining</td>
<td>1</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Surface Mining</td>
<td>1</td>
<td>[5, 37]</td>
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Table E.4: Consumptive water intensity of uranium processing

<table>
<thead>
<tr>
<th>Uranium Processing</th>
<th>Consumptive Water Intensity (gal/MMBtu)</th>
<th>Source</th>
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<tbody>
<tr>
<td>Uranium Ore Milling</td>
<td>0</td>
<td>[29]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: Low</td>
<td>0.1</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Fuel Fabrication</td>
<td>0.9</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: Average</td>
<td>1</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: High</td>
<td>1.5</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Conversion</td>
<td>3</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: Low</td>
<td>3</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: Low</td>
<td>4</td>
<td>[3, 6, 15]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: Average</td>
<td>5</td>
<td>[3, 6, 15]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: High</td>
<td>5</td>
<td>[3, 6, 15]</td>
</tr>
<tr>
<td>Milling: Low</td>
<td>6</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: Low</td>
<td>7</td>
<td>[3, 6, 15]</td>
</tr>
<tr>
<td>Milling: Average</td>
<td>7</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: Average</td>
<td>7</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: Average</td>
<td>8</td>
<td>[3, 6, 15]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: High</td>
<td>8</td>
<td>[3, 6, 15]</td>
</tr>
<tr>
<td>Milling: High</td>
<td>8</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Mining and Processing: Low</td>
<td>8</td>
<td>[5, 37]</td>
</tr>
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<td>Enrichment with Diffusion: High</td>
<td>10</td>
<td>[5, 37]</td>
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<tr>
<td>Mining and Processing: Average</td>
<td>11</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Mining and Processing: High</td>
<td>14</td>
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Table E.5: Withdrawn water intensity of uranium processing

<table>
<thead>
<tr>
<th>Uranium Processing</th>
<th>Withdrawn Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spent Fuel Disposal</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>Fuel Fabrication</td>
<td>0.2</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: Low</td>
<td>1</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: Average</td>
<td>1</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: High</td>
<td>1</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Conversion</td>
<td>1.2</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Milling: Low</td>
<td>1.5</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Milling: Average</td>
<td>1.5</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Milling: High</td>
<td>1.5</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: Low</td>
<td>6</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: Average</td>
<td>6</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: High</td>
<td>6</td>
<td>[5, 37]</td>
</tr>
</tbody>
</table>

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### Table E.6: Embedded water intensity of uranium processing

<table>
<thead>
<tr>
<th>Uranium Processing</th>
<th>Embedded Water Intensity (gal/MMBtu)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Fabrication</td>
<td>0</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Conversion</td>
<td>1</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Spent Fuel Disposal</td>
<td>1.5</td>
<td>[5]</td>
</tr>
<tr>
<td>Milling: Low</td>
<td>5</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Milling: Average</td>
<td>5</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Milling: High</td>
<td>5</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: Low</td>
<td>8</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: Average</td>
<td>8</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Centrifuge: High</td>
<td>8</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: Low</td>
<td>89</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: Average</td>
<td>89</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Enrichment with Diffusion: High</td>
<td>89</td>
<td>[5, 37]</td>
</tr>
</tbody>
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### Table E.7: Consumptive water intensity of uranium electricity generation

<table>
<thead>
<tr>
<th>Electricity Generation</th>
<th>Consumptive Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry: Low</td>
<td>0</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: Average</td>
<td>15</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: High</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Wet Tower (HTGR)</td>
<td>60</td>
<td>[3, 5]</td>
</tr>
<tr>
<td>Once-Through</td>
<td>140</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Once-Through: Low</td>
<td>400</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Closed-Loop: Low</td>
<td>400</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Once-Through: Low</td>
<td>400</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Once-Through: Average</td>
<td>400</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Once-Through: High</td>
<td>400</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Once-Through: Average</td>
<td>415</td>
<td>[6, 15, 20, 21, 30, 38]</td>
</tr>
<tr>
<td>Once-Through: High</td>
<td>430</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Cooling Pond: Low</td>
<td>450</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Closed-Loop: Average</td>
<td>575</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Closed-Loop with Carbon Capture</td>
<td>590</td>
<td>[21, 30]</td>
</tr>
<tr>
<td>Wet Tower</td>
<td>610</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Cooling Pond: Average</td>
<td>680</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower: Low</td>
<td>740</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Closed-Loop: High</td>
<td>750</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Wet Tower: Average</td>
<td>820</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower (PWR)</td>
<td>820</td>
<td>[5, 37]</td>
</tr>
<tr>
<td>Wet Tower (LWR)</td>
<td>850</td>
<td>[3, 5]</td>
</tr>
<tr>
<td>Cooling Pond: High</td>
<td>900</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower: High</td>
<td>900</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower (BWR)</td>
<td>900</td>
<td>[5, 37]</td>
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**Table E.8:** Withdrawn water intensity of uranium electricity generation

<table>
<thead>
<tr>
<th>Electricity Generation</th>
<th>Withdrawn Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry: Low</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: Average</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Dry: High</td>
<td>30</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Cooling Pond: Low</td>
<td>500</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Closed-Loop: Low</td>
<td>530</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Closed-Loop with Carbon Capture</td>
<td>590</td>
<td>[21, 30]</td>
</tr>
<tr>
<td>Cooling Pond: Average</td>
<td>800</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower: Low</td>
<td>800</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Closed-Loop: Average</td>
<td>830</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Wet Tower: Average</td>
<td>950</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Cooling Pond: High</td>
<td>1100</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Wet Tower</td>
<td>1100</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Wet Tower: High</td>
<td>1100</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Closed-Loop: High</td>
<td>1130</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Once-Through: Low</td>
<td>25030</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Once-Through: Low</td>
<td>25100</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Once-Through</td>
<td>31500</td>
<td>[5, 10]</td>
</tr>
<tr>
<td>Once-Through: Average</td>
<td>42530</td>
<td>[6, 15, 20]</td>
</tr>
<tr>
<td>Once-Through: Average</td>
<td>43000</td>
<td>[5, 36]</td>
</tr>
<tr>
<td>Once-Through: High</td>
<td>60030</td>
<td>[6, 15, 20]</td>
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</tbody>
</table>
## Renewables Water Intensity

### Table F.1: Consumptive water intensity of large-scale concentrating solar power

<table>
<thead>
<tr>
<th>Large-Scale CSP</th>
<th>Consumptive Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dish, Stirling</td>
<td>4</td>
<td>[5]</td>
</tr>
<tr>
<td>Dish/Engine</td>
<td>20</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Parabolic Troughs</td>
<td>78</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Parabolic Troughs, Dry Cooling</td>
<td>80</td>
<td>[5]</td>
</tr>
<tr>
<td>Power Tower</td>
<td>90</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Power Tower</td>
<td>500</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Trough</td>
<td>550</td>
<td>[5]</td>
</tr>
<tr>
<td>Concentrating Solar</td>
<td>750</td>
<td>[21, 30]</td>
</tr>
<tr>
<td>Tower</td>
<td>770</td>
<td>[5]</td>
</tr>
<tr>
<td>Parabolic Troughs</td>
<td>800</td>
<td>[15]</td>
</tr>
<tr>
<td>U.S. Weighted Average for CSP: Tower, Wet Cooling</td>
<td>800</td>
<td>[15]</td>
</tr>
<tr>
<td>Parabolic Troughs, Wet Cooling</td>
<td>820</td>
<td>[5]</td>
</tr>
<tr>
<td>Parabolic Troughs, Wet Cooling: Low</td>
<td>820</td>
<td>[5]</td>
</tr>
<tr>
<td>Tower</td>
<td>850</td>
<td>[5]</td>
</tr>
<tr>
<td>Parabolic Troughs, Wet Cooling Average</td>
<td>910</td>
<td>[5]</td>
</tr>
<tr>
<td>: Parabolic Troughs, Wet Cooling</td>
<td>980</td>
<td>[5]</td>
</tr>
<tr>
<td>Fresnal</td>
<td>1000</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Parabolic Troughs, Wet Cooling: High</td>
<td>1000</td>
<td>[5]</td>
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</table>
Table F.2: Withdrawn water intensity of large-scale concentrating solar power

<table>
<thead>
<tr>
<th>Large-Scale CSP</th>
<th>Withdrawn Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dish, Stirling</td>
<td>4</td>
<td>[5]</td>
</tr>
<tr>
<td>Parabolic Troughs, Dry Cooling</td>
<td>8</td>
<td>[5]</td>
</tr>
<tr>
<td>Trough</td>
<td>550</td>
<td>[5]</td>
</tr>
<tr>
<td>Concentrating Solar</td>
<td>760</td>
<td>[21, 30]</td>
</tr>
<tr>
<td>Tower</td>
<td>770</td>
<td>[5]</td>
</tr>
<tr>
<td>Tower, Wet Cooling</td>
<td>820</td>
<td>[5]</td>
</tr>
<tr>
<td>Parabolic Troughs, Wet Cooling</td>
<td>820</td>
<td>[5]</td>
</tr>
<tr>
<td>Parabolic Troughs, Wet Cooling: Low</td>
<td>820</td>
<td>[5]</td>
</tr>
<tr>
<td>Tower</td>
<td>850</td>
<td>[5]</td>
</tr>
<tr>
<td>Parabolic Troughs, Wet Cooling: Average</td>
<td>910</td>
<td>[5]</td>
</tr>
<tr>
<td>Parabolic Troughs, Wet Cooling</td>
<td>980</td>
<td>[5]</td>
</tr>
<tr>
<td>Parabolic Troughs, Wet Cooling: High</td>
<td>1000</td>
<td>[5]</td>
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</tbody>
</table>

Table F.3: Consumptive water intensity of photovoltaic solar power

<table>
<thead>
<tr>
<th>Photovoltaics</th>
<th>Consumptive Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Photovoltaics</td>
<td>0</td>
<td>[6, 15]</td>
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<tr>
<td>Photovoltaic</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>Concentrated Solar Photovoltaics</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>Concentrated Solar Photovoltaics</td>
<td>4</td>
<td>[15, 50, 51]</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>4</td>
<td>[5]</td>
</tr>
<tr>
<td>Concentrated Solar Photovoltaics</td>
<td>4</td>
<td>[5]</td>
</tr>
</tbody>
</table>

Table F.4: Withdrawn water intensity of photovoltaic solar power

<table>
<thead>
<tr>
<th>Photovoltaics</th>
<th>Withdrawn Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>CdTe</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>Concentrated Solar Photovoltaics</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>BOS</td>
<td>0.1</td>
<td>[5]</td>
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<tr>
<td>Photovoltaic</td>
<td>4</td>
<td>[5]</td>
</tr>
<tr>
<td>Concentrated Solar Photovoltaics</td>
<td>4</td>
<td>[5]</td>
</tr>
<tr>
<td>Mono-Si</td>
<td>15</td>
<td>[5]</td>
</tr>
<tr>
<td>Multi-Si</td>
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### Table F.5: Consumptive water intensity of wind power

<table>
<thead>
<tr>
<th>Source</th>
<th>Consumptive Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Power</td>
<td>0</td>
<td>[6, 15]</td>
</tr>
<tr>
<td>Wind</td>
<td>0</td>
<td>[5]</td>
</tr>
<tr>
<td>Wind</td>
<td>1</td>
<td>[5]</td>
</tr>
</tbody>
</table>

### Table F.6: Withdrawn water intensity of wind power

<table>
<thead>
<tr>
<th>Wind</th>
<th>Withdrawn Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>0</td>
<td>[5]</td>
</tr>
</tbody>
</table>

### Table F.7: Embedded water intensity of wind power

<table>
<thead>
<tr>
<th>Wind</th>
<th>Embedded Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark, On Land</td>
<td>130</td>
<td>[5]</td>
</tr>
<tr>
<td>Denmark, Off Shore</td>
<td>130</td>
<td>[5]</td>
</tr>
<tr>
<td>Spain, On Land</td>
<td>160</td>
<td>[5]</td>
</tr>
<tr>
<td>Denmark, Off Shore</td>
<td>180</td>
<td>[5]</td>
</tr>
<tr>
<td>Italy, On Land</td>
<td>190</td>
<td>[5]</td>
</tr>
<tr>
<td>Denmark, On Land</td>
<td>250</td>
<td>[5]</td>
</tr>
</tbody>
</table>

### Table F.8: Consumptive water intensity of geothermal power

<table>
<thead>
<tr>
<th>Geothermal</th>
<th>Consumptive Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geothermal</td>
<td>1400</td>
<td>[6, 15, 20, 30]</td>
</tr>
<tr>
<td>Geothermal: Low</td>
<td>2700</td>
<td>[15, 52]</td>
</tr>
<tr>
<td>Geothermal: Average</td>
<td>3600</td>
<td>[15, 52]</td>
</tr>
<tr>
<td>Geothermal: High</td>
<td>4500</td>
<td>[15, 52]</td>
</tr>
</tbody>
</table>

### Table F.9: Consumptive water intensity of hydropower

<table>
<thead>
<tr>
<th>Hydropower</th>
<th>Consumptive Water Intensity (gal/MWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydropower</td>
<td>4500</td>
<td>[6, 15, 20, 30]</td>
</tr>
</tbody>
</table>